

# Performance of a Urea SCR system combined with a PM and fuel optimized heavy-duty diesel engine able to achieve the Euro V emission limits.

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## ABSTRACT

In order to meet the Euro V heavy-duty diesel emission standard legislation limits, a diesel engine can be optimized by internal means to give low particulate emissions and lower fuel consumption. These modifications of the engine lead inevitably to higher NOx emissions due to the NOx/PM trade off. An efficient Urea SCR after-treatment system is then able to reduce the higher NOx emission to below the Euro V 2.0g/kWh legislation limit. This paper presents tests made on a PM optimized 12 liter heavy-duty diesel engine together with a urea SCR after-treatment system. The optimized engine had engine out particulate emissions of about 0.04 g/kWh and NOx emissions of 9 g/kWh for the ESC and 8,5 g/kWh for the ETC. The fuel consumption of the optimized engine was 194 g/kWh for the ESC and 198 g/kWh for the ETC as compared to state of the art Euro III engines of typically 210 g/kWh for the ESC, giving significant fuel savings of 7.5 %.

Combining the engine with a 20 liter 300-cpsi SCR catalyst, catalyst volume to cylinder ratio of 1.7, the particulate emissions dropped to 0.017 g/kWh for the ESC and 0.020 for the ETC. Particle size measurements also showed a decrease in the number of fine particles. With a urea injection corresponding to about 8-9% of the fuel flow the NOx emissions were reduced to 1.4 g/kWh for the ESC and 1.5g/kWh for the ETC with low ammonia slip. These reductions correspond to a NOx conversion of 84 % and 82% for the ESC and ETC respectively.

Thus the optimized engine combined with the urea SCR after-treatment system was compliant with the Euro V emission limits.

## INTRODUCTION

In order to comply with the Euro V regulations for heavy-duty diesel engines due in 2008, both the NOx and particulate emissions must be greatly reduced for today's state of the art diesel engines. The regulations of 2008, namely 2.0 g/kWh NOx and 0.02 g/kWh particulates for the ESC and 0.03 g/kWh for the ETC driving cycles, cannot be achieved solely by engine management or improved engines, rather some sort of aftertreatment must be used.

A preferred solution to comply with the Euro V emission limits is to optimize a diesel engine by internal means to give very low particulate emissions and considerably lower fuel consumption [1]. Due to the NOx/PM trade-off for diesel engines this will lead to higher NOx emissions, from Euro III levels of 5-6 g/kWh to 8-10 g/kWh, that have to be reduced with an efficient NOx aftertreatment system below the 2.0 g/kWh limit, preferably Urea-SCR. The Urea SCR systems have been shown to be both very efficient and durable in vehicle applications [2,3,4,5,6]. The higher NOx emission of the optimized engine therefore requires the Urea SCR system to have a high NOx conversion efficiency of about 80-85%.

The combination of the optimized engine and Urea SCR system eliminates the need for a particulate filter to comply with Euro V emissions leading to a lower pressure drop of the exhaust system and also less complexity of the total system.

Furthermore the significant fuel savings of the optimized engine compared to a standard Euro III engine could give a payback time for the optimized engine and the SCR system depending on the urea price and the application as to make the concept commercially interesting even prior to the legislation limits.

This concept could also be a serious candidate for the Euro IV legislation (NO<sub>x</sub> limit of 3.5 g/kWh and particulates the same as Euro V). The optimized engine and SCR concept has an even greater fuel saving compared to a concept of a standard Euro III engine with EGR and particulate filter. EGR increases the fuel consumption of the engine and the addition of the particulate trap increases the fuel consumption further by increasing the pressure drop giving the combination of the optimized engine and Urea SCR system an even greater fuel consumption advantage.

The purpose of this work was to demonstrate a PM and fuel optimized heavy-duty diesel engine and Urea SCR concept able to comply with the Euro V legislation emission limits. The total work consisted of 3 parts:

- SCR catalyst optimization and selection [7]
- Engine optimization
- Combination of the optimized engine with the chosen SCR system.

In previous work the catalyst selection to achieve a high NO<sub>x</sub> conversion above 80% with ammonia slip less than 10 ppm and development of a novel Urea SCR injection system were discussed [7]. This present paper deals with the optimization work on the engine, performance of the optimized engine, final selection of catalyst and the performance of the combination of the PM and fuel optimized engine with the efficient Urea-SCR system.

The optimization targets of the engine optimization were to achieve low soot emissions (i.e. carbon particulates less than 0.010/0.015 g/kWh in ESC/ETC test) by internal means while maintaining very low fuel consumption at engine-out NO<sub>x</sub> emissions of 8 to 10 g/kWh in the ESC test.

## EXPERIMENTAL

### ENGINE

The engine to be optimized was a direct injection 12 litre heavy-duty diesel engine with rated power of 300 kW. This engine was equipped with a modern injection system, 4 valves per cylinder with central injectors, turbo charged with intercooler and high cylinder pressure potential. The engine tested was in principle a standard Euro III engine, but already equipped with a new version of injection system.

### UREA SCR SYSTEM

The Urea-SCR system that was used is schematically shown in Figure 1. It is a sensor based, open loop system that uses real-time kinetic calculations for controlling the urea injection. Four sensors are used, a NO<sub>x</sub> sensor after the turbocharger, a mass airflow sensor in air intake of the engine and two temperature sensors, before and after the catalyst. An electronic

control unit (ECU) calculates the amount of urea to be injected based on the sensor readings and the actual injection is carried out by means of a digital-dosing pump. The system is described further in a previous paper [7]. The reducing agent used was a 32.5% urea-water with a density of 1.085 kg/litre.

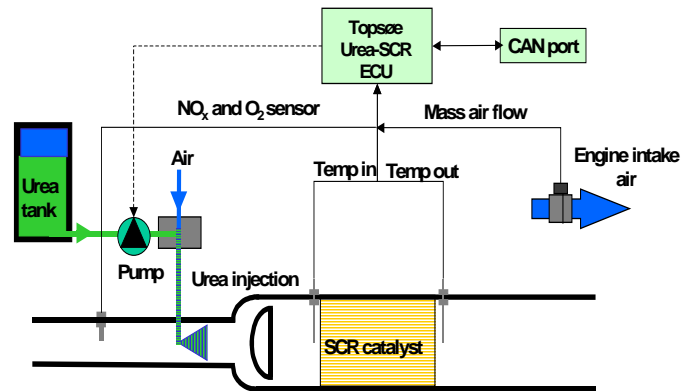


Figure 1. Urea SCR system

### CATALYSTS

During previous work, different catalysts and catalyst combinations were tested in order to find suitable catalyst combinations that had the required NO<sub>x</sub> reducing potential [7]. Since the optimized engine PM out emission was higher than the Euro IV and V levels, the catalyst or combination of catalysts should also be able to reduce at least 50% of the particulate matter. From these previous tests [7] the following catalyst setups were chosen for further testing, see also Figure 2 and Tables 1 and 2. All SCR catalysts were corrugated full catalysts with a diameter of 393 mm.

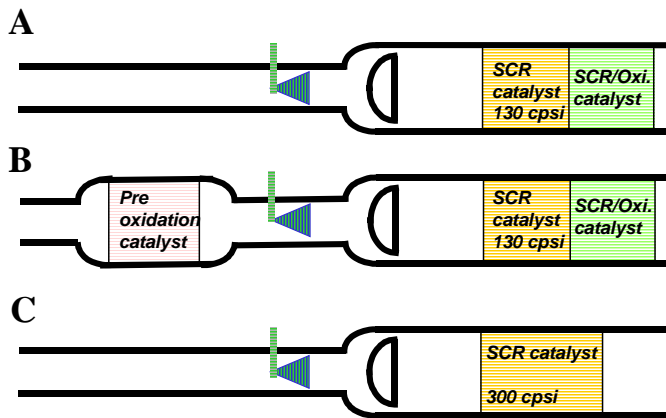
- A. A 15 litre 130 cpsi SCR catalyst (DNX15) combined with a 15 litre 130 cpsi SCR-Pd (DNX15-Pd) slip oxidation catalyst.
- B. Combination A with the addition of an 8 litre (CKM) pre oxidation catalyst
- C. In the previous work [7] it was also shown that the catalyst volume could be reduced by 1/3 by increasing the cell density from 130 to 300 cpsi. Therefore a newly developed 20 liter of 300 cpsi pure SCR catalyst (DNX20) that had the required NO<sub>x</sub> reduction potential was included in the test.

**Table 1.** Catalysts used

Catalyst name	Cell dens. (cpsi)	Volume (litre)	Active material
DNX15	130	15	V/TiO <sub>2</sub>
DNX15-Pd	130	15	V, Pd/TiO <sub>2</sub>
CKM	130	8	Pt/Al <sub>2</sub> O <sub>3</sub>
DNX20	300	20	V/TiO <sub>2</sub>

**Table 2.** Different catalytic setups used

Catalyst setup	Catalysts	Total Volume (l)
A	DNX15+DNX15-Pd	30
B	CKM+DNX15+DNX15-Pd	38
C	DNX20	20

**Figure 2.** Different catalytic setups

## TEST FACILITIES

All tests, with and without SCR were performed on the AVL transient test bed with CVS system. Non-regulated emissions such as NH<sub>3</sub> were measured with an FTIR. PM size distribution analyses were performed with a DDMPMS (Dual Differential Mobility Particle Spectrometer) supplied by AVL. The CVS system consisted of full flow dilution tunnel with critical flow venturi and exhaust gas emission equipment for standard gaseous components (NO<sub>x</sub>, CO, HC, CO<sub>2</sub>) and particulates.

In order to collect a particulate sample, the diluted exhaust gas (temperature 51.4 deg. C at the sample filter) was drawn through a pre-weighed Teflon coated glass fiber filter with a back-up filter of same

specifications (Pallflex TX40, 70 mm diameter). After sample collection, the filters were reweighed and the particulate mass recorded. For determining the contribution of soluble organic fraction the filters were extracted for 2 hours using dichloromethane in a Soxhlet apparatus. After drying and reweighing, the weight loss yields the amount of soluble fraction. The soluble organic fraction was further analyzed to yield the amount of fuel and lube oil contribution. In a 2nd extraction of the remaining compounds (carbon, sulfates, water...), the portion of sulfates plus water (molecular bound) was determined.

For the determination of particle size distribution in exhaust gas the DDMPMS was used. The simultaneous measurement of multiple areas of the particle size distribution enables a time resolution of approximately one minute per particle size distribution of 57 particle size classes in the diameter range of 2-600 nm. For each operating point and configuration 3 repeated measurements were made.

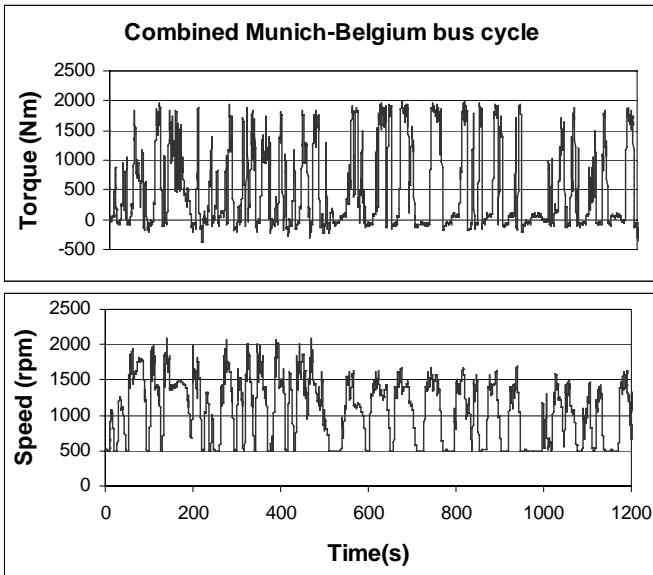
## FUEL SPECIFICATIONS

Two different fuels were used in the testing. The first was standard Austrian diesel fuel with a 230 ppm sulfur content. The second fuel was an ultra low sulfur diesel fuel with less than 10 ppm sulfur.

## TEST CYCLES

The test cycles used in the project were the standard European cycles used for emission certification of heavy-duty diesel engines, ETC and ESC. The ETC cycle is a 1800 s transient driving cycle that comprises of three 600 s parts. The parts correspond to urban driving, rural driving and highway driving conditions. The ESC is a 13-mode stationary test cycle. The test cycles were conducted according to regulations. In order to evaluate the optimized engines transient operation the European Load Response (ELR) cycle was also used.

Besides the ETC and ESC a bus cycle was used for further evaluation. This bus-cycle was an adaptation of the Munich and Belgium real world bus-cycles into a combined 1200 s cycle for this particular engine. The speed and torque of the adapted cycle are presented in Figure 3. The engine was preconditioned at 1400 rpm and 110 kW, a typical road-load point of this engine class before starting the bus cycle.



**Figure 3.** Speed and Torque for the combined Munich-Belgium Bus cycle

## RESULTS

### ENGINE OPTIMIZATION WORK

The combustion of this engine was to be optimized for low soot emissions (i.e. carbon particulates less than 0.010/0.015 g/kWh in ESC/ETC test) by internal means while maintaining very low fuel consumption at engine-out NOx emissions of 8 to 10 g/kWh in ESC test.

The original engine tested was in principle a standard Euro III engine, but already equipped with a new version of injection system. Also advanced timing was applied to the engine application ECU to see the effect on soot emission and fuel consumption. The ESC test results demonstrated with the original engine were 199 g/kWh BSFC at a NOx level of 6.5 g/kWh and 194 g/kWh BSFC at a NOx level of 8.7. But in both cases the soot emission was too high to be able to meet EU5 particulate targets without a filter. An interesting fact was, that no improvement in soot emissions could be observed with advanced timing.

After the baseline testing the engine was rebuilt to a first version for Euro V emission compliance by changing different engine components.

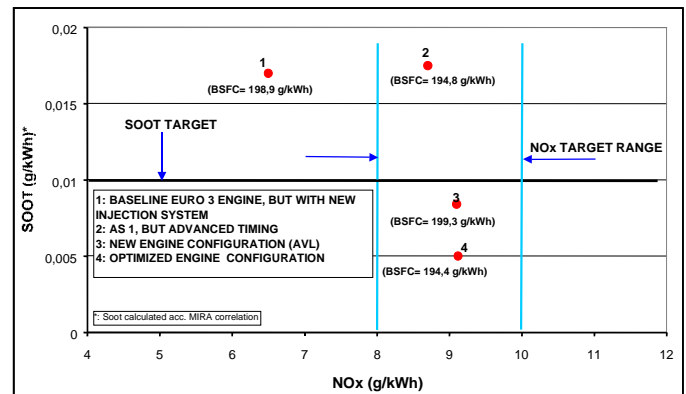
Modifications on the following parts were carried out:

- Injection system type
- Injection cam profile and position
- Injection nozzle
- Combustion bowl shape
- Compression ratio

- Intake swirl number
- Turbo charger match
- Adaptation of engine management control functions for injection timing, fuel and boost control during transients

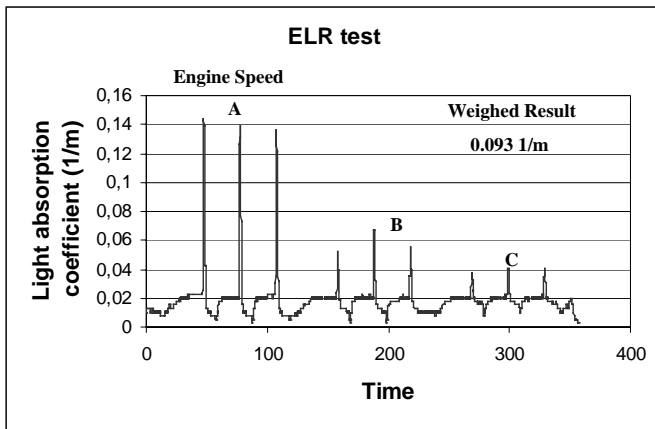
All engine components which were changed or adapted for the optimized combustion system were coming from serial parts, which makes this optimized engine appropriate for serial application.

The first test results showed significant improvement in soot emission at a NOx level of about 9 g/kWh, but still too high ESC fuel consumption of 199 g/kWh. Further optimization work such as turbocharger matching and applying a completely new injection timing map to the ECU made it possible to demonstrate the lowest soot emissions (0.0048 g/kWh) and cycle fuel consumption of 194 g/kWh in the ESC. The NOx and soot emissions of the engine for the different optimization steps are presented in Figure 4.



**Figure 4.** Summary of optimization work of the engine.

With the final engine hardware configuration the electronic engine management now had to be optimized for transient operation in ELR and ETC. In addition the usual demands for reasonable smoke limiter times had to be considered to get an excellent driveability of the engine in the vehicle. With the new smoke limiter interfere times programmed to the engine ECU and operating the engine in the ELR according to the EU4/5 legislation a light absorption coefficient of 0.093 1/m could be demonstrated (EU5 limit = 0.5 1/m). The light absorption recording from the ELR test is presented in Figure 5.



**Figure 5.** Light absorption coefficient for ELR test on the optimized engine.

The optimized engine was tested under the ESC and ETC cycles with both standard and ultra low sulfur fuel to get the baseline engine-out emissions of the engine. The results of the gaseous emissions and fuel consumption averaged from 3 cycles each are presented in Table 3. The particulate mass and the composition of the particulate mass are presented for the same cycles in Table 4.

**Table 3.** Baseline emissions and fuel consumption of the optimized engine with both fuels.

Baseline	NOx (g/kWh)	HC (g/kWh)	CO (g/kWh)	BSFC (g/kWh)
ESC 230 ppm	9,2	0,319	0,298	194,0
ESC <10 ppm	9,1	0,282	0,296	193,5
ETC 230 ppm	8,7	0,289	0,361	198,2
ETC <10 ppm	8,5	0,260	0,382	197,9

**Table 4.** Particulate mass emission and particulate mass composition for the optimized engine and both fuels.

Baseline PM	PM (g/kWh)	Insoluble (g/kWh)	Soluble (g/kWh)
ESC 230 ppm	0,038	0,0083	0,0300
ESC <10 ppm	0,037	0,0071	0,0304
ETC 230 ppm	0,040	0,0141	0,0259
ETC <10 ppm	0,039	0,0147	0,0243

The optimized engine exhibits excellent fuel consumption of 194 g/kWh for the ESC and 198 g/kWh for the ETC regardless of the fuel used. As is commonly known, the average of the fuel consumption of Euro III engines in the market place is about 210 g/kWh for the ESC. The optimized engine thus has a significant fuel saving of approximately 7.5 % compared to today's Euro III engines.

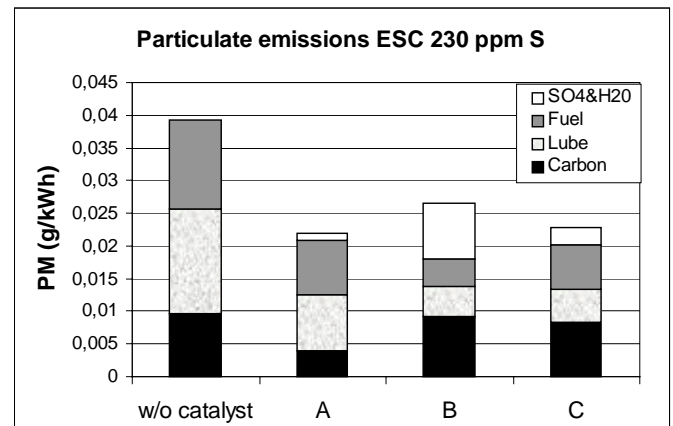
The NOx emissions are approximately 9 g/kWh for the ESC and 8.6 g/kWh for the ETC cycle and are practically the same for both fuels. The NOx emission of the engine is within the optimization target. The insoluble part of the particulates is below the 0.01 and 0.015 g/kWh optimization targets for the ESC and ETC respectively for both fuels. However the total particulate emission was

above the Euro V limits due to the relatively high contribution of the soluble content on the total particulates namely 80% for the ESC and 60% for the ETC.

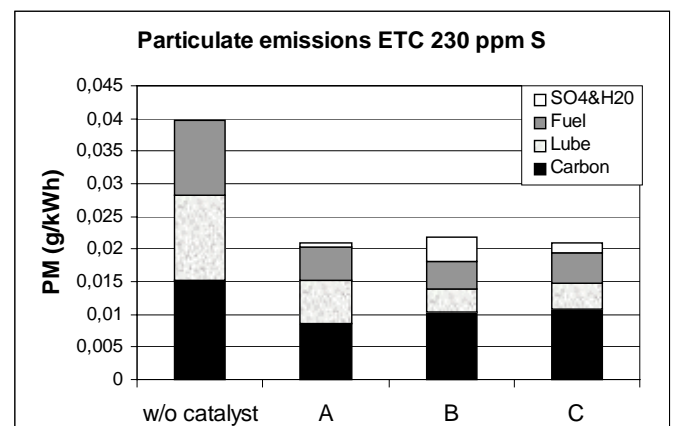
From the baseline emissions of the engine it was evident that the SCR system, apart from reducing the NOx content of the exhaust by at least 80%, also should be able to reduce the total particulate mass by about 50% in order for the whole concept to comply with the Euro V emission limits.

#### CATALYST SELECTION TO REDUCE PARTICULATES

In order to investigate the PM reduction potential of the different catalysts, tests were conducted with the three different catalyst combinations without urea injection for both ESC and ETC cycles and for both high and low sulfur fuels. The particle sample filters were subjected to standard chemical analysis as specified previously in order to determine the composition of the particulate mass. For the higher sulfur fuel the results are presented in Figure 6 and 7 for the ESC and ETC respectively.



**Figure 6.** Particulates for ESC with 230 ppm S fuel and the three different catalytic setups without urea injection

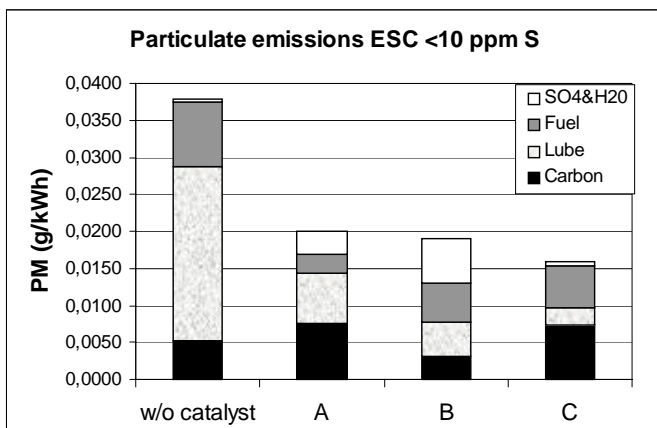


**Figure 7.** Particulates for ETC with 230 ppm S fuel and the three different catalytic setups without urea injection

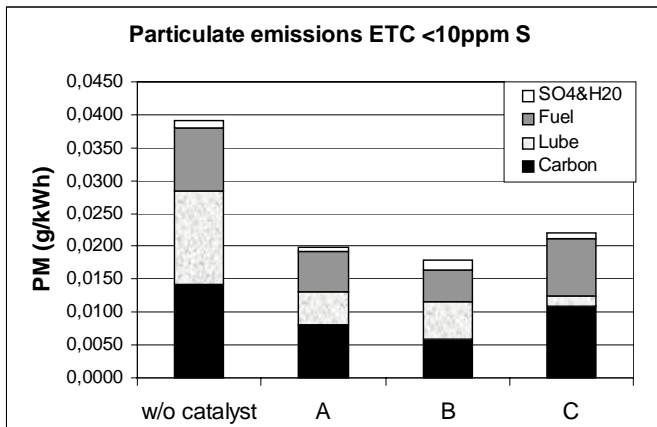
It can be seen that all three catalyst combinations reduce the total particulate mass. The largest reduction of the particulates comes from the reduction of the soluble fraction (characterized as lube and fuel). It can also be seen that setup C, the DNX20 pure SCR catalyst, is as good as the other two combinations in reducing the soluble fraction, even though it contains no precious metals.

In the ETC all three catalyst combinations reduce the particulates below the 0.03 g/kWh limit with a good margin. However, the ESC 0.02 g/kWh limit is not met with any combination. Catalyst combination B with both pre and slip oxidation catalyst and thus a lot of precious metal has large sulfate formation and thus high particulate mass. However the same effect but less pronounced can be seen with the pure SCR catalyst.

Since the future fuel sulfur specification in Europe is likely to be below 10 ppm sulfur it was decided to conduct tests with the ultra low sulfur fuel. The results of the ESC and ETC measurements of particulate mass for the different catalyst combinations with the ultra low sulfur fuel are presented in Figures 8 and 9 respectively.



**Figure 8.** Particulates for ESC with <10 ppm S fuel and the three different catalytic setups without urea injection



**Figure 9.** Particulates for ETC with <10 ppm S fuel and the three different catalytic setups without urea injection

As with the high sulfur fuel the general trend is the same with a reduction in particulate mass for all catalyst combinations. The ETC PM limit of 0.03 g/kWh is easily met. Furthermore it can be seen that setup C, the DNX20 pure SCR catalyst, is below the limit of 0.02 g/kWh on the ESC. The particulate mass was consistently below the 0.02 g/kWh limit for all tests conducted with the DNX20 on the ESC with the ultra low sulfur fuel. The other two combinations were also very close to the emission limits on the ESC, but it was decided to continue the tests with the 20 litre DNX20 catalyst together with the ultra low sulfur fuel.

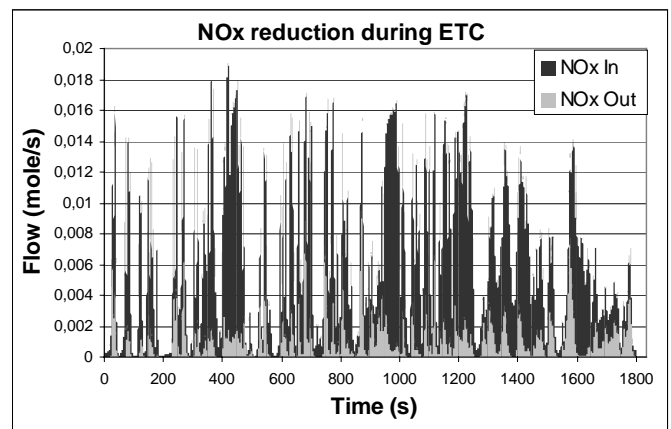
The choice of setup C, the 20 liter DNX20 catalyst, was an obvious one to continue the test work with since it had the best particulate reduction, and also had the least volume of all catalyst combinations.

### NOX REDUCTION PERFORMANCE

With the selection of the 20 litre DNX20 catalyst and the ultra low sulfur fuel, tests were conducted with the ETC and ESC in order to optimize the real time urea injection algorithms. The aim was to achieve NOx emissions below the 2.0 g/kWh legislation limits of Euro V while maintaining the NH<sub>3</sub> slip below 10 ppm on average.

#### ETC test cycle

The NOx reduction over the DNX20 catalyst for an ETC cycle is presented in Figure 10 while the NH<sub>3</sub> slip from the same test is presented in Figure 11. The NOx conversion is high for all parts of the ETC while the NH<sub>3</sub> slip peaks do not exceed 10ppm. For this ETC cycle the NOx emission was reduced to 1.55g/kWh with an ammonia slip of 6ppm on average.



**Figure 10.** NOx flow with and without DNX20 catalyst for ETC

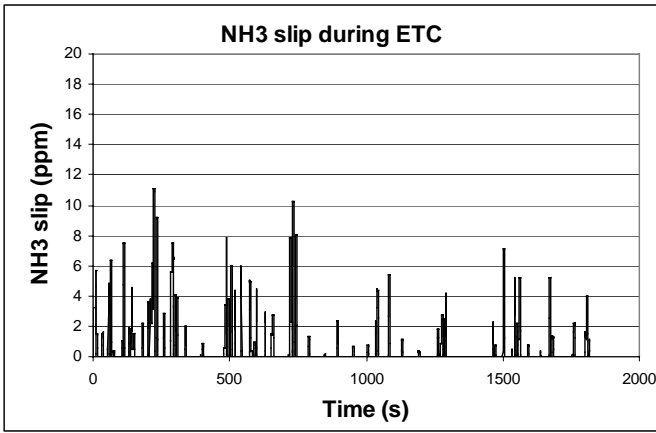


Figure 11. Ammonia slip for ETC

ESC test cycle

The stationary ESC tests were carried out using the same injection strategy as for the transient tests. The NO<sub>x</sub> reduction over the DNX20 catalyst for the ESC cycle is presented in Figure 12 while the NH<sub>3</sub> slip from the same test is presented in Figure 13.

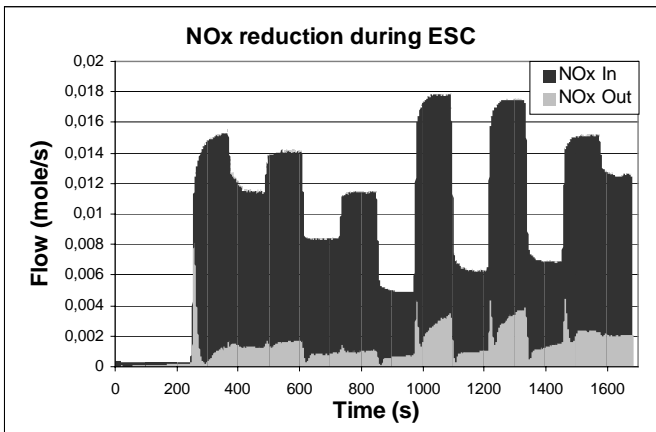


Figure 12. NO<sub>x</sub> flow with and without DNX20 catalyst for ESC

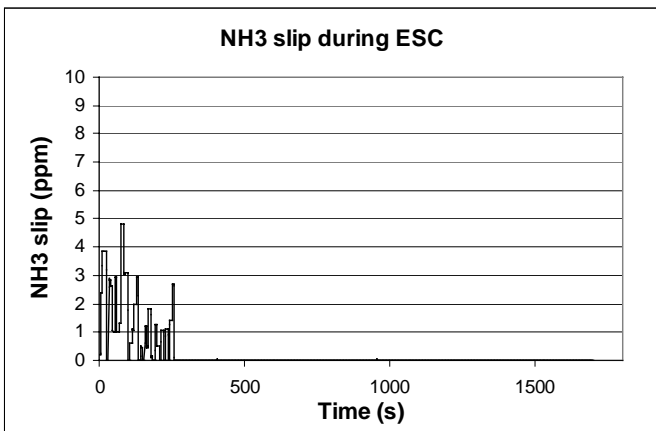


Figure 13. Ammonia slip during ESC

The NO<sub>x</sub> emission for this ESC cycle was 1,40 g/kWh and the ammonia slip was considerably lower than for the ETC cycle with peaks of up to 4-5 ppm only on the first portion of the ESC. This injection strategy was therefore adequate to meet the NO<sub>x</sub> reduction required to comply with the Euro V NO<sub>x</sub> limits for both cycles, while having a slip below 10 ppm on average.

SUMMARY OF REGULATED EMISSIONS

The regulated emissions for the chosen injection strategy are presented in Tables 5 and 6 for the ESC and ETC cycles respectively and summarized in Figure 14. The results are averaged from 2 repeated measurements that had very consistent emission levels.

ESC test cycle

For the ESC the NO<sub>x</sub> emission with the SCR catalyst is 1.38 g/kWh, well below the 2,0 g/kWh EuroV limit. This corresponds to a NO<sub>x</sub> conversion of nearly 85% with a urea solution consumption of 9% (gravimetric) compared to the fuel flow.

The hydrocarbons of the exhaust are reduced with 82 % over the SCR catalyst whereas the CO is increased with about 60%. This is the standard behavior of pure SCR catalyst, which is also a good partial oxidation catalyst. The hydrocarbons are readily oxidized but some form CO instead of CO<sub>2</sub>. The increase in CO is however not crucial for the Euro V CO emission limit on the ESC that is 1.5 g/kWh.

The 54% reduction of PM over the catalyst is, as discussed earlier mainly due to the removal of the soluble fraction bringing down the PM below the 0.02 g/kWh limit to 0.017 g/kWh. The injection of urea does not affect the particulate mass which is indicated by the fact that the PM levels do not increase as compared with the tests conducted without urea injection.

The fuel consumption remains practically constant with the addition of the DNX20 catalyst as can be seen in Figure 14, implying that there is no significant fuel penalty by adding the SCR system to the engine.

**Table 5:** Regulated emissions with DNX20 catalyst and ultra low sulfur fuel for the ESC

ESC	NO <sub>x</sub> (g/kWh)	HC (g/kWh)	CO (g/kWh)	PM (g/kWh)
Without SCR	9,1	0,282	0,296	0,037
With SCR	1,38	0,051	0,480	0,017
Conversion	84,8	81,9	-62,2	54,1

ETC test cycle

For the ETC the NO<sub>x</sub> emission of the engine is reduced by 82% to 1.54 g/kWh with a urea solution consumption of 8% of the fuel flow, comfortably below the Euro V 2,0 g/kWh limit. The reduction of NO<sub>x</sub> is comparable for both test cycles and shows that one setting of the urea

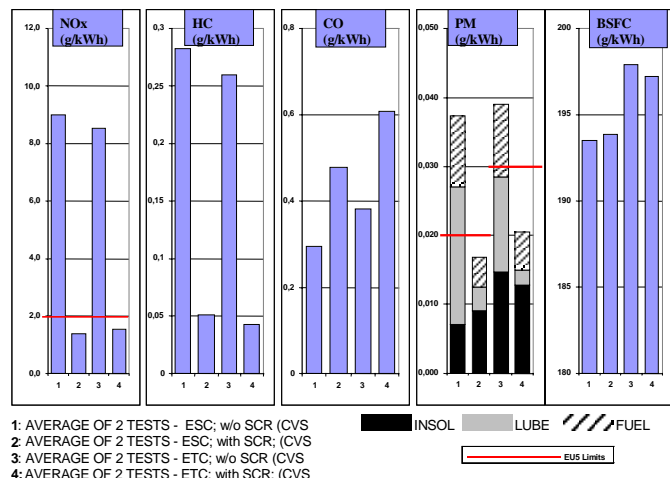
injection system is sufficient for both stationary and transient operation.

Like for the ESC the hydrocarbons are greatly reduced, by 83%, while there is an increase in CO of 60%. Again both HC and CO emissions are well below the Euro V limits.

The decrease in PM in the ETC is approximately 45% to a level of 0.02 g/kWh compared to the legislative limit of 0.03 g/kWh. The fuel consumption is the same after adding the SCR system, as for the ESC.

**Table 6** : Regulated emissions with DNX20 catalyst and ultra low sulfur fuel for the ETC

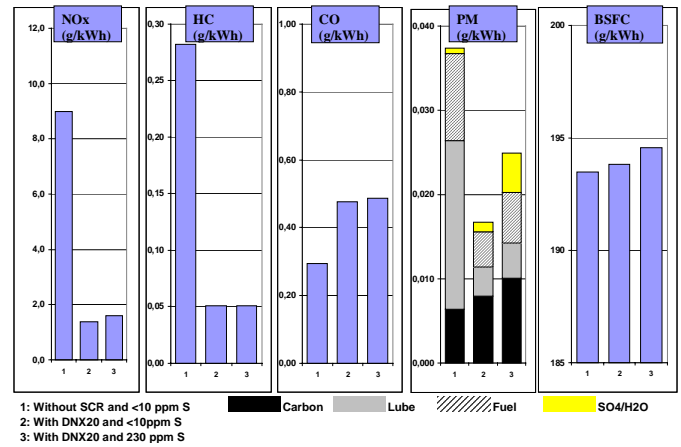
ETC	NOx (g/kWh)	HC (g/kWh)	CO (g/kWh)	PM (g/kWh)
Without SCR	8,5	0,260	0,382	0,039
With SCR	1,54	0,044	0,610	0,020
Conversion	81,9	83,1	-59,7	48,7



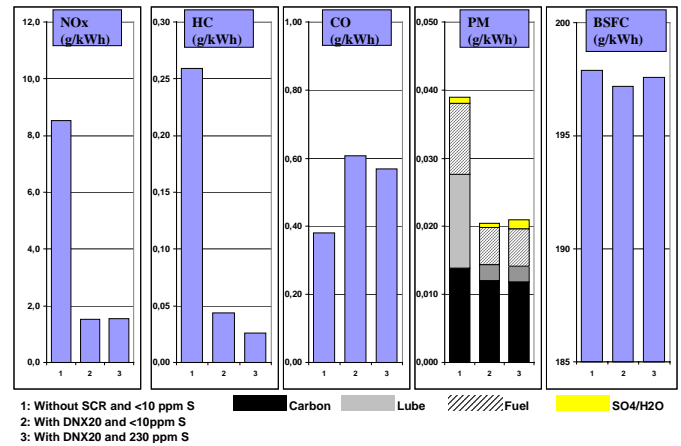
**Figure 14**: Summary of regulated emissions with DNX20 catalyst and ultra low sulfur fuel for ESC and ETC.

#### EFFECT OF SULFUR CONTENT ON REGULATED EMISSIONS

To evaluate the effect of fuel sulfur content on the emissions, ETC and ESC were also run with the standard 230 ppm sulfur fuel and the 20 litre SCR catalyst. The comparisons of the results for the different fuels are presented in Figures 15 and 16 for the ESC and ETC respectively.



**Figure 15** Comparison of ESC emissions with DNX20 catalyst and both high and low sulfur fuel.



**Figure 16** Comparison of ETC emissions with DNX20 catalyst and both high and low sulfur fuel.

It can be seen that the NOx, hydrocarbon and CO emissions are practically unaffected by the sulfur content of the fuel for both test cycles. The gaseous emissions are comfortably below the Euro V limits also with the higher sulfur fuel. However, with the higher sulfur fuel, as investigated previously, the particulate mass emission is higher than the limit for the ESC cycle mainly due to the sulfate formation over the catalyst. For the ETC cycle the particulate mass is practically the same for both fuels and below the legislation limit. Here the sulfate formation is not as pronounced as for the ESC cycle. This could be explained by the higher exhaust temperature levels of the ESC cycle as compared to the ETC cycle. Higher temperature favors the formation of sulfate over the catalyst.

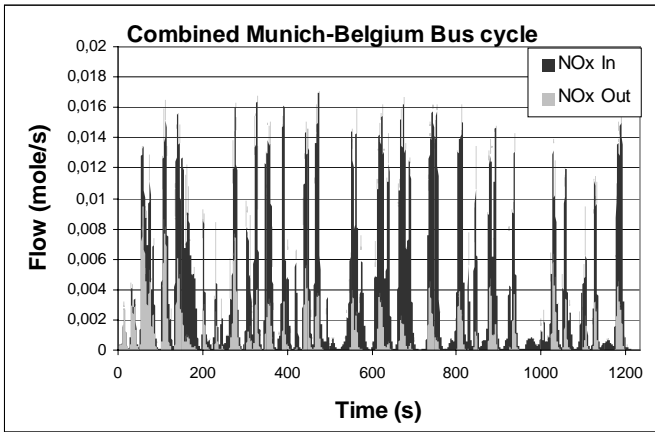
#### MUNICH-BELGIUM BUS CYCLE

With the final settings of urea injection and the 20 l SCR catalyst and the ultra low sulfur fuel, the combined Munich-Belgium real world buscycle was also run. The NOx conversion and ammonia slip for the buscycle are presented in Figures 17 and 18 respectively. The NOx

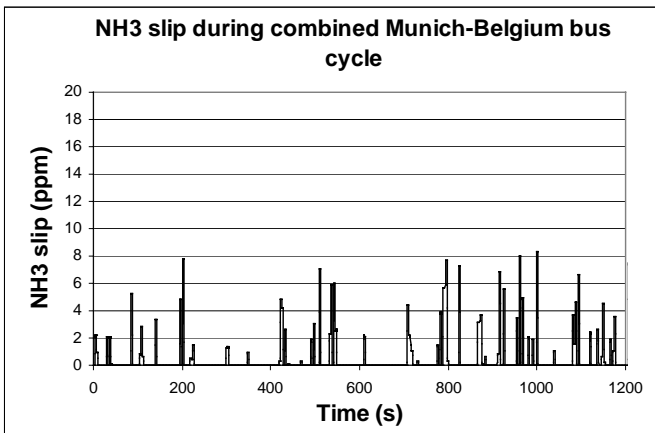
conversion is not as high at the first part of the cycle due to starting the cycle at colder conditions as compared to the ETC. After the first 200 seconds the NO<sub>x</sub> conversion is high and stays at a high level for the duration of the 1200 s cycle. The ammonia slip is comparable to that of the ETC. The results for gaseous emissions and PM are summarized in Table 7.

**Table 7:** Emissions with DNX20 catalyst and ultra low sulfur fuel for the combined Munich-Belgium bus cycle.

BUSCYCLE	NO <sub>x</sub> (g/kWh)	HC (g/kWh)	CO (g/kWh)	PM (g/kWh)
Without SCR	8,27	0,289	0,613	0,049
With SCR	1,78	0,067	0,978	0,039
Conversion	78,5	76,8	-59,5	20,4



**Figure 17.** NO<sub>x</sub> flow with and without DNX20 catalyst for combined Munich-Belgium bus-cycle



**Figure 18.** Ammonia slip during combined Munich-Belgium bus-cycle

The results for the bus-cycle are similar to those for the ETC and ESC. A high NO<sub>x</sub> conversion is achieved throughout the cycle of approximately 79%. The hydrocarbon oxidation is high over the SCR catalyst with a total of 77 % reduction. The same levels of CO increase are observed as with the ETC and ESC. The particulate mass is reduced by 20%.

#### PARTICLE SIZE DISTRIBUTION W/WO SCR SYSTEM

Particulate size distribution measurements were performed for all the ESC operating points (except for idle) with 3 different configurations i.e. without SCR, with SCR but without urea injection and with SCR with urea injection. Three repeated tests were performed for each operating point and configuration and the averages are presented in Figures 19,20 and 21.

It can be seen for all operating points that there is a vast reduction, in some areas by two orders of magnitude, in the number of particles by adding the DNX20 SCR catalyst in the exhaust. The most significant reduction in particle number occurs in the size range of approximately 2-30 nm. The decrease in particle number is less profound for the size range from 30-100 nm but is still evident. Above 100 nm the particle numbers are virtually unaffected by the SCR system.

Hence even if the SCR catalyst does not decrease the larger solid particles that contribute the most to the insoluble particulate mass, it has a large effect on the nanoparticles that are attributed with the adverse health effects of diesel exhaust PM.

Additionally it can be seen that the numbers of particles are practically the same for the SCR catalyst with and without urea injection implying that there are no urea droplets or urea bi-products that pass through the catalyst.

## CONCLUSION

The 12 litre heavy-duty diesel engine was optimized by internal means to achieve low soot emissions and low fuel consumption while keeping the NO<sub>x</sub> emissions below 10 g/kWh. For the ESC and a NO<sub>x</sub> emission of 9.1 g/kWh, low insoluble content of below 0.01 g/kWh was achieved. For the ETC the engine out NO<sub>x</sub> emission was 8.6 g/kWh while the insoluble content of the particulates was below 0.015 g/kWh. Total particulate mass was however 0.038 g/kWh for the ESC and 0.039 g/kWh for the ETC, higher than the Euro V legislation limits. The SCR system thus had to be able to reduce a large part of the PM, around 50%, for the ESC.

Excellent fuel consumption could be achieved with the optimized engine of 194 g/kWh and 198 g/kWh for the ESC and ETC respectively. Compared to standard Euro III engines that have an average fuel consumption of about 210 g/kWh for the ESC, the optimized engine exhibits considerable fuel savings of about 7.5 %.

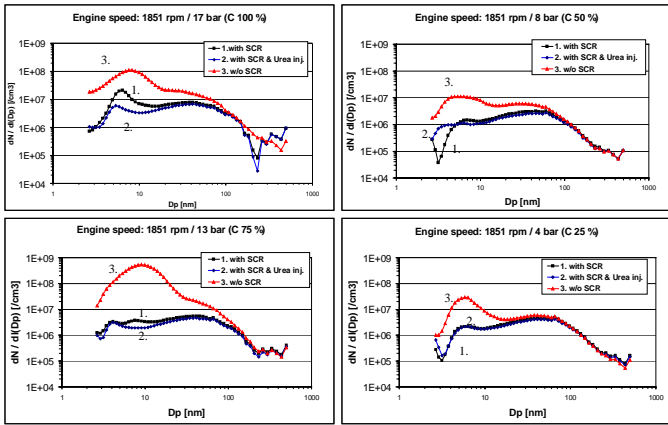
20 litres of newly developed 300-cpsi SCR catalyst were sufficient to reduce the NO<sub>x</sub> levels of the 12 litre PM and fuel optimized engine below the EuroV 2.0 g/kWh for both ESC and ETC. With a catalyst to cylinder ratio of only 1.7 the NO<sub>x</sub> reduction was 84 % and 82% for the ESC and ETC respectively with ammonia slip below 10 ppm on average and the same urea injection algorithms. This NO<sub>x</sub> reduction was achieved by having a urea solution injection of 9% and 8% of the fuel flow for the ESC and ETC respectively.

Furthermore the 20 litre 300-cpsi SCR catalyst is capable of reducing approximately 80% of the hydrocarbons while having an increase in CO due to partial oxidation of hydrocarbons over the catalyst. This CO increase is not critical since the CO emissions are well below the Euro V limits.

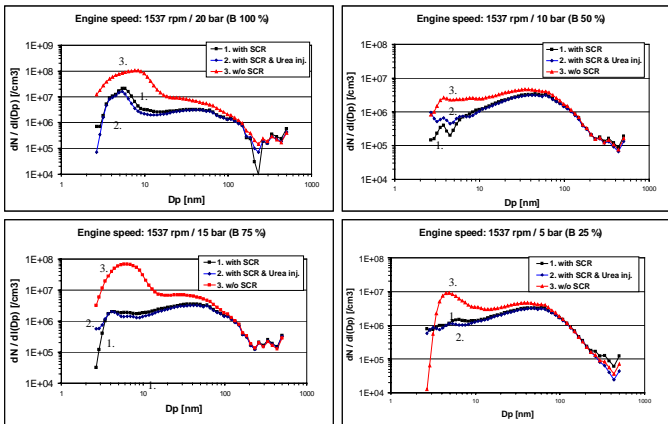
The 20 litre SCR catalyst is also able to reduce the particulate mass by 54% on the ESC and 45% on the ETC to 0.017 g/kWh and 0.02 g/kWh respectively with the ultra low (<10 ppm) sulfur fuel. For both cycles the emissions of PM are well below the Euro V legislation limits. The large reduction in particulate mass is attributed mainly to the oxidation of the soluble fraction.

The combination of the 12 litre PM and fuel optimized engine with the 20 litre 300 cpsi SCR catalyst is compliant with the EuroV emission limits using ultra low (<10ppm) sulfur fuel.

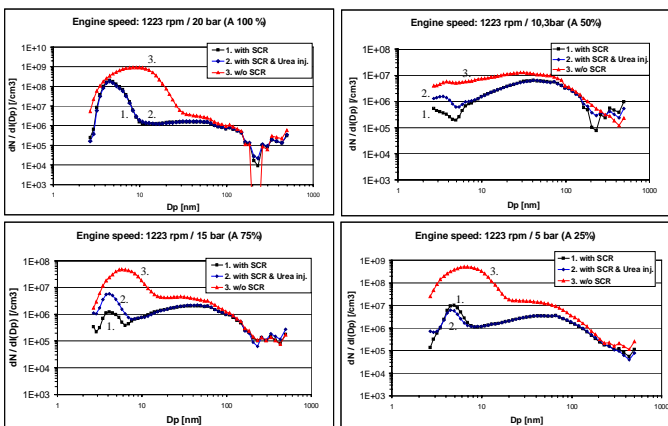
With the standard Euro III (230 ppm) sulfur fuel the PM emissions are slightly above the 0.02 g/kWh limit for the ESC namely 0.022-0.025 g/kWh. Concerning the ETC the PM emission limit is easily met also with the standard sulfur fuel. The sulfur content of the fuel is shown not to influence the performance of the SCR catalyst concerning NO<sub>x</sub> and hydrocarbon reduction.



**Figure 19.** Particle size distribution for 1850 rpm with and without catalyst DNX20



**Figure 20.** Particle size distribution for 1537 rpm with and without catalyst DNX20



**Figure 21.** Particle size distribution for 1223 rpm with and without catalyst DNX20

Particle size distribution measurements show that there is a considerable decrease of particles in the size range of 2-30 nm over the SCR catalyst, with and without urea injection. There is also a decrease in the size range of 30-100 nm. No significant difference is found when comparing particle numbers after the SCR system with and without urea injection.

Further improvements of the whole concept are to optimize the engine further in order to lower the baseline NOx emission while keeping the particulates and fuel consumption at the same low levels. With lower NOx baseline emissions the urea consumption required to reach the legislation limits would be lower making the whole concept more economical in operation.

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