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Exhaust Gas Aftertreatment Systems for Commercial Vehicles – Technologies and Strategies for the Future

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ABSTRACT

More stringent emission legislation, particularly with regard to particulate and nitrogen oxide (NOx) emissions, is currently being discussed in Europe. In view of American US2010 emission legislation there is a call for the introduction of stricter limits in Europe by 2012 (EU VI). The question concerning commercial vehicle manufacturers and automotive suppliers is what direction the development should take. The experience from EU IV and EU V applications clearly shows that the requirements of EU VI cannot be met solely by new engine developments that aim to reduce particulate and/or NOx emissions, but require a cost-effective overall solution that includes exhaust gas aftertreatment. The reduction of these emissions has to be seen in the light of the trade-off with CO_2 emissions, especially in commercial vehicle applications, since the resulting fuel consumption has a significant effect on operating costs. The possible scenarios for future emission concepts are discussed and illustrated by means of examples below.

Introduction

European directives on immission loads in cities are an effective tool for the implementation of further demands for environmental protection. Since cities and other local authorities have to demonstrate that they have done everything in their power to comply with these directives, current debate has widened to include the creation of environmental zones or the exclusion from the affected cities of cars falling into a certain emission category. The example of the clean air directive showed that it was possible to propose additional requirements and implement them with public backing in spite of existing emission limits, which in the case of cars applied until 2010. One of the consequences of this pressure was the early introduction of particulate filters in vehicles that already met current legislation through engine-based measures alone.

This also explains why the tightening of the NO2 directive due in 2010 had a direct effect on EU5 and EU6 limits for cars and is subsequently going to shape the future European EUVI limits for trucks.

The European Commission is expected to issue its first official proposals in autumn 2007. A variety of scenarios were put forward by legislators and car manufacturers prior to the publication of these proposals. The general tenor seems to be that the limits would approximate the American US2010 limits, at least in the long term. However, apart from emission limits the debate also focuses on the replacement of the current test cycles by a world harmonised test cycle (WHTC), which includes cold starts, and on the introduction of a new particulate number limit. Both measures have to be clearly defined and evaluated by comparing them to current test and measuring methods as they are going to have a great impact on future catalyst and filter technology.

Current emission limits regulate the emission levels of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxide (NOx) and particulate matter (PM). Increasingly serious discussions about climate change will be followed by demands for the lowest possible CO_2 emissions. Fuel consumption and hence CO_2 emissions have always been a priority in the commercial vehicle industry since both have a significant effect on the cost-effectiveness of vehicles.

In order to meet future emission limits – for instance, the American US2010 limits since European limits have not yet been agreed – an economically optimum overall solution that combines engine technology and exhaust gas aftertreatment will have to be developed.

One of the objectives of future engine developments has to be the reduction of emissions without raising fuel consumption. State-of-the-art engine components are the only solution and are likely to increase the costs of the overall system. A combination of engine-based measures and a suitable, low-pressure loss, lightweight exhaust gas aftertreatment system opens up opportunities for innovative, economically viable overall solutions that are likely to further reduce CO_2 emissions.

The development of engine raw emissions

As mentioned above, it is impossible to look at engine design, including related raw emissions, or the catalyst system in isolation when it comes to extremely stringent emission limits. Engine-based measures that reduce raw emissions lead to simpler, lighter and perhaps even more reliable exhaust gas aftertreatment systems. The modification of an inexpensive EU III engine with typical raw emissions to enable it to meet US2010 NO_x emission limits without exhaust gas recirculation would require a SCR system (Selective Catalytic Reduction system) with a minimum effectiveness above 93%. Since this value would have to be achieved not only when the system was new but over the entire service life of the vehicle, legal compliance would require enormous effort according to currently available data. In terms of long-term stability a modern SCR system can realistically achieve an efficiency of 75 to 85%. This seems to indicate that engine designs with state-of-the-art engine components to reduce raw emissions will become the worldwide standard, starting in Europe, the US and Japan.

In addition to the basic design of the combustion chamber and the combustion process, technical papers on engine developments mainly focus on the following measures to reduce raw emissions:

- High-pressure fuel injection with more than 2500 bar
- Two-stage turbocharging
- Controlled and cooled exhaust gas recirculation with recirculation rates over 30%

High, cooled EGR rates (Exhaust Gas Recirculation) especially lead to vehicle follow-up costs since the available cooling capacity is generally insufficient and therefore has to be increased. The requirements for the control quality of the recirculated exhaust gas also increase with regard to quantity and temperature. Any deterioration in cooling capacity primarily affects NO_x raw emissions. EGR catalysts protect against sooting and hence increase the durability of the coolers [1] and the control valves. The sum of these measures is a reduction of both critical NO_x emissions and particulate emissions [2,3].

The use of EGR beyond a certain limit is generally regarded as critical to fuel consumption. However, this is offset by an increase in turbocharging pressure [4] so that the first available engines are even more fuel-efficient than engines without EGR [5]. The extent to which these investments in engine technology are financially viable as part of an overall solution does not least depend on the required or feasible catalyst or filter system.

Figure 1 shows the NO_x/particulate trade-off curves of various engine designs with possible exhaust gas aftertreatments. The data was based on raw emissions from currently available or certified engines. EU V and US2007 limits were included to illustrate current requirements or requirements that apply until 2010 in the US and 2012 in Europe.

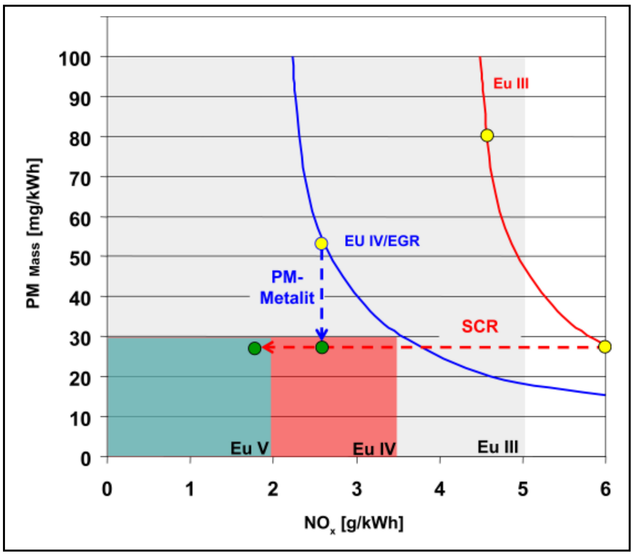


Figure 1: NOx/particulate trade-off of currently available engines and the catalyst/filter technologies required for EU V and US2007 limits

Depending on raw emissions or the design point, there are a number of possible scenarios that can achieve the required conversion rates with regard to the reduction of particulates and NO_x. For instance, a PM-optimised non-EGR engine is able to meet EU V limits with a SCR system (with a conversion rate of 60%). A NO_x-optimised EGR engine can be made to comply with EU V limits following the installation of a partial-flow deep-bed filter (PM-METALIT^{TM}) [6,7], while the same engine would require a wall-flow filter to meet US2007 limits.

The design of a scenario for the future must be based on an evaluation of ongoing engine developments and post-2012 limits. In the absence of defined European limits the emission targets were based on the American US2010 values.

Figure 2 shows the NO_x/particulate trade-off curves of various new engines, some of which are not yet in production, as a function of the applied technology [8,9].

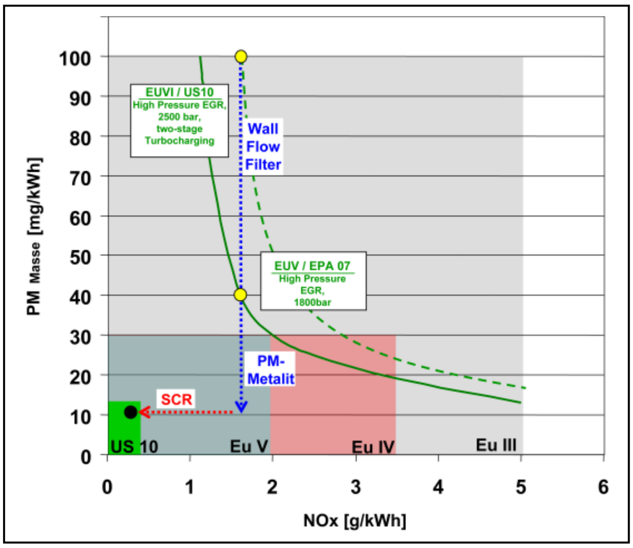


Figure 2: NO_x/particulate trade-off of various new engines and the catalyst/filter technologies required to meet US2010 limits

It is assumed that the aim of each engine design is to minimise fuel consumption by fully exploiting the highest possible NO_x reduction rates. In terms of long-term stability the maximum conversion rate of the SCR system considered in this paper was assumed to be 80%. This results in particulate reduction rates between 65 % and 86% depending on engine technology and related raw emissions.

3. Catalyst technology

3.1 Nitrogen oxide reduction

There are essentially two technologies available today to reduce nitrogen oxides. The first is the above-mentioned SCR technology, and the second is NO_x storage technology. Both methods have been developed to the production stage, however, series production experience is only available for commercial vehicles with SCR systems. In the second case fuel consumption rises because NO_x adsorbers regenerate at brief intervals during phases with a rich exhaust gas mixture and also have to be desulphated at regular intervals at a temperature around 650°C. The substrates also have to be relatively large so that the intervals between the rich regeneration phases do not become too short. The high precious metal content of these substrates means that the costs for typical commercial vehicle engine applications are relatively high. These two drawbacks are reasons against their future production. Therefore this paper deals exclusively with SCR technology.

The "Selective Catalytic Reduction" of nitrogen oxides under lean operating conditions, i.e. in the presence of excess oxygen, by means of ammonia (NH_3) has been used in the chemical industry or the aftertreatment of power station emissions for decades. In the automotive industry the SCR system was initially developed for and used in commercial vehicles. Apart from increasingly stricter emission limits the reasons also included a possible change in the ratio between NO_x and particulate emissions when adjusting the engine in favour of lower fuel consumption, i.e. towards higher NO_x emissions. The aim of the development at that time was to find an additional financial incentive to promote the sale of this type of engine. Since the engines themselves continued to undergo further development at the same time and similar advantages could be achieved almost solely on the basis of engine-based measures, the start of SCR series production was repeatedly delayed. The requirement to carry another operating material in the vehicle, in this case an urea-water solution (AdBlue) to generate ammonia onboard, added to the delays. The situation was made worse by the fact that the necessary logistics for the reduction agent had to be set up from scratch.

A typical SCR system consists of a reduction catalyst, urea injection and dosing components, pipes and a storage tank. Some systems also include an upstream oxidation catalyst, a hydrolysis catalyst and, if necessary, a downstream ammonia trap.

Most modern catalysts are extrudate catalysts or coated ceramic catalysts with vanadium pentoxide as the catalytically active component. Catalytic coatings on a zeolite basis are currently being developed because of the limited temperature stability of these catalysts and the fact that vanadium pentoxide has been classified as a health risk in some countries. The coating technology for the substrates corresponds to the well-known processes used in the production of three-way or oxidation catalysts. Increased temperature stability is especially important in SCR catalysts installed behind a particulate filter since relatively high temperatures are generated during filter regeneration. Zeolite catalysts are highly sensitive to the NO_2/NO ratio in the exhaust gas especially at low temperatures. Since zeolite SCR systems are most efficient at a ratio of 1-1 they must include an oxidation catalyst because the engine emits almost exclusively NO.

One of the problems of current SCR systems is the injection and equal distribution of the urea-water solution that is introduced into the exhaust gas stream as a finely dispersed liquid. The larger the size of the droplets the longer it takes for them to evaporate in the exhaust gas. This factor plus radially uneven droplet concentrations in the gaseous phase can lead to concentration differences on the catalyst surface resulting in reduced conversion rates. The use of “turbulent” catalyst substrates with radial flow and concentration equalisation offers a significant improvement. Figure 3 shows turbulence-generating catalysts with a PE, LS/PE and MX design.

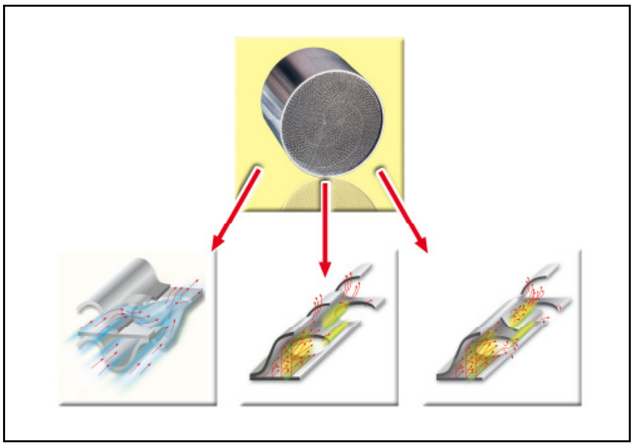


Figure 3: “Turbulent” catalyst substrates with a PE, LS/PE and MX design [10, 11]

3.2 Particulate reduction

There are currently two major filter systems in production that can be used to reduce particulate matter. The first is the classic wall-flow filter [12, 13] and the second is Emitec’s PM-METALIT^{TM} partial-flow deep-bed filter, which passively regenerates on a continuous basis.

Wall-flow filters have a filter efficiency of over 98% after building up a filter cake. The filter has to be actively thermally regenerated at regular intervals at temperatures above 550 - 600°C. Since the temperature in the exhaust gas of commercial vehicles does not rise to these levels under normal conditions, fuel is added in front of the oxidation catalyst either by post-injection in the combustion chamber or via a separate fuel injector in the exhaust gas system. This fuel heats the exhaust gas through an exothermic reaction in the catalyst. Pressure loss changes between an actively regenerated and hence unloaded state and a loaded state at regular intervals.

Thermal regeneration increases the temperature load of both the oxidation catalyst and the downstream SCR catalyst behind the particulate filter from typically 550°C (without active regeneration) to 750°C in active systems.

In this method, fuel consumption is raised by the necessary regeneration on the one hand and the regular increase in pressure loss on the other [14]. Depending on its design and size, the filter should be able to operate reliably for more than 500,000 km as largely harmless ash is filtered from the oil or fuel and blocks the filter [15]. As a result, operators may be faced with additional costs and possibly even vehicle downtimes.

Emitec’s PM-METALIT^{TM} partial-flow deep-bed filter (figure 4) has been used in commercial vehicles and cars over the past two years. The MAN EU IV, fitted with a PM-METALIT^{TM}, has worked reliably in over 60,000 vehicles. The filter has operated over 800,000 kilometres without malfunction or having to be cleaned. The PM-METALIT^{TM} is the only mass-produced OEM filter system on the market worldwide that is designed for the entire service life of the engine without needing further maintenance.

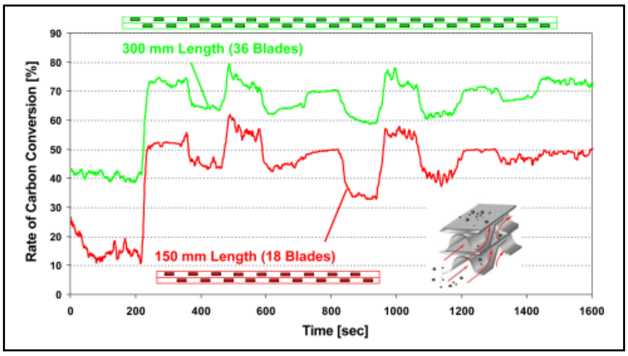


Figure 4: PM-METALIT^{TM} partial-flow deep-bed filter and soot conversion rate of a 300 mm long filter in the ESC cycle

The filtered soot is burnt on a continuous basis using the NO_2 contained in the exhaust gas or generated in the oxidation catalyst.

The efficiency of the filter in relation to the soot mass is between 50% and 80% depending on filter length [16]. The reduction of the particle number in the 10 – 300 nm range is between 80 and 95%.

3.3 The oxidation catalyst

Oxidation catalysts are used to reduce HC and CO emissions. In addition, NO is oxidised to form NO_2 at a temperature between 200 and 450°C. The NO_2 can be used to burn up particulates or to improve the low-temperature efficiency (180 – 350°C) of zeolite SCR catalysts. Oxidation catalysts have either a Pt or a Pt/Pd coating depending on the temperature load.

In a highly efficient SCR system there is a risk of ammonia slip behind the SCR catalyst. This can be prevented by fitting an oxidation catalyst behind the SCR catalyst or by applying an oxidation coating to the rear part of the SCR catalyst in order to oxidise the NH_3. A sensor catalyst represents a good solution. This design involves a NH_3 sensor integrated in the metal catalyst substrate resulting in more catalyst volume behind the sensor to prevent NH_3 slip.

Depending on the choice of filter system the oxidation catalyst is also used to generate the necessary exothermic energy for the regeneration of the wall-flow filters. The fuel required for this is either supplied by fuel post-injection via injection nozzles or by a fuel injection nozzle in the exhaust stream behind the engine. Oxidation catalysts with internal flow equalisation (figure 3) are particularly efficient at minimising HC slip since they are able to equalise any uneven fuel distribution.

The thermal capacity of the oxidation catalyst should also be as low as possible since it acts as an inert mass and delays the heating of the particulate filter, thus extending regeneration times.

HC efficiency is shown in figure 5a while the HC slip of a standard oxidation catalyst compared to a catalyst with an LS/PE structure is shown in figure 5b.

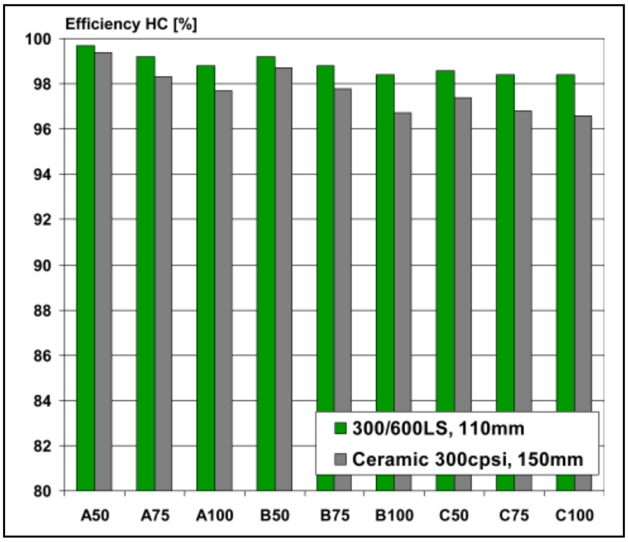


Figure 5a: HC efficiency in front of the particulate filter of a standard 300-cpsi catalyst compared to a 300/600-cpsi LSPE catalyst

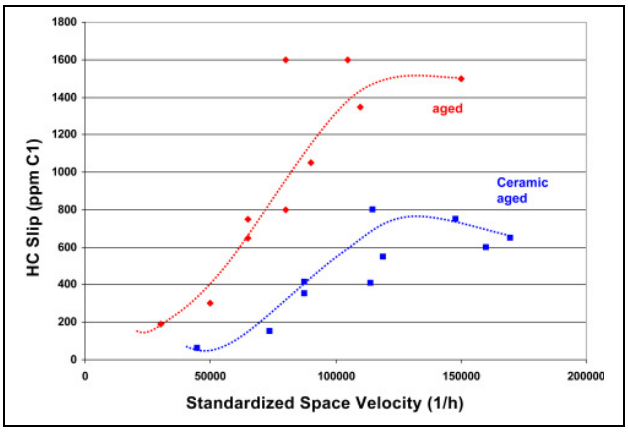


Figure 5b: HC slip of a standard 300-cpsi catalyst compared to a 300/600-cpsi LSPE catalyst

3.4 The hydrolysis catalyst

According to research the installation of a hydrolysis catalyst in the partial flow allows to reduce significantaly the size of the SCR catalyst, which is normally used for hydrolysis in the full stream, especially at low temperatures. The reasons for this are the longer contact time in the partial-flow hydrolysis catalyst and the obstruction of the hydrolysis caused by the presence of NO_2 generated in the upstream oxicat (figure 6).

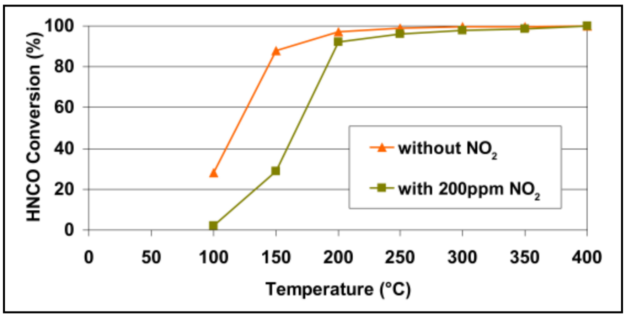


Figure 6: Effect of NO_2 on the efficiency of the hydrolysis [17]

Research carried out at the Paul Scherrer Institute (PSI) shows that efficiency is significantly reduced in the presence of NO_2 especially at temperatures between 150 and 225°C. The effect should be almost negligible because exhaust gas temperatures generally rise above 300°C in modern commercial vehicle engines and during hot tests. The exhaust gas temperature of future engines is going to be considerably lower (figure 7a). If one additionally takes the WHTC, which is to be introduced in Europe at least, into consideration, temperature levels will be even lower due to engine loads. A cold test also has to be carried out. Figure 7b shows the temperature curve of an engine without catalyst heating in the WHTC.

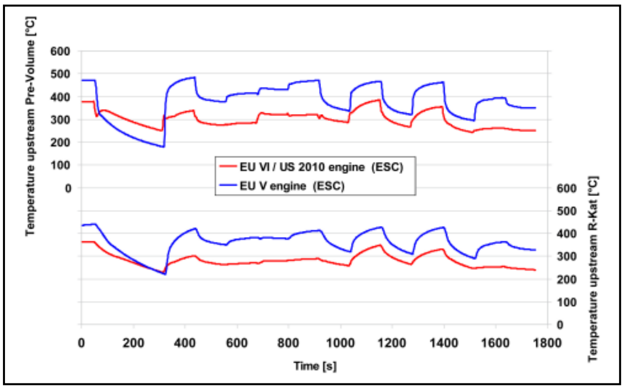


Figure 7a: Comparison between the exhaust gas temperatures in front of the catalyst of a production engine and an US2007 engine in an ESC test.

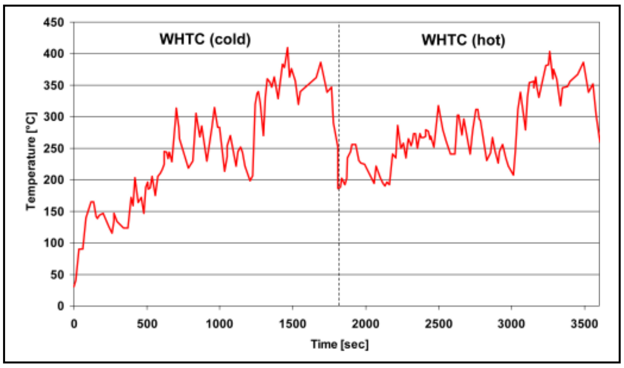


Figure 7b: Exhaust gas temperatures in the WHTC test with a production engine without catalyst heating (cold and hot test)

This clearly shows that the effect of NO_2 has to be included in future concepts if the aim is to produce a very compact, cost-effective catalyst system.

One option is for hydrolysis to take place in the partial flow of the main exhaust gas stream. Figure 8 shows a possible partial-flow hydrolysis system. The hydrolysis catalyst is placed inside a metal ring catalyst. Urea is centrally injected. The size of the partial flow is determined by the area ratio of the central hydrolysis catalyst compared to the circular oxidation catalyst and by the structure of the respective substrates. The hydrolysis coating can consist of a thin titanium dioxide layer, which is able to evaporate any remaining AdBlue droplets without sustaining any damage.

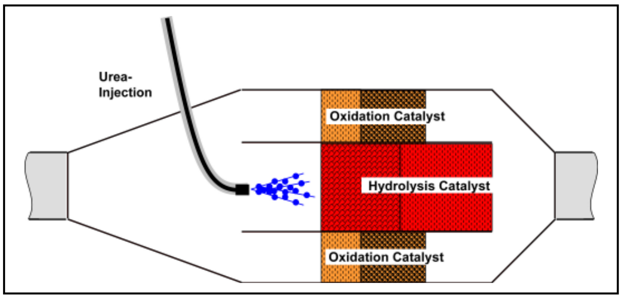


Figure 8: Partial-flow hydrolysis system with a concentric ring catalyst and urea injection in the centre.

In very cold applications an electrically heated catalyst may be fitted upstream from the hydrolysis catalyst in order to raise the exhaust gas temperature during critical operating conditions.

4. Design of US2010, EU VI exhaust gas system

The following two scenarios for potential US2010 or EU VI systems are based on the engine technology or raw emission levels shown in figure 2 and a notional maximum NO_x reduction of 80% with long-term stability:

a) Engines with NO_x emissions of 1.6 g/kWh and PM emissions of 0.10 g/kWh (cooled, controlled EGR, single-stage turbocharging, injection pressure 1800 bar)

b) Engines with NO_x emissions of 1.6 g/kWh and PM emissions of 0.04 g/kWh (cooled, controlled high EGR, two-stage turbocharging, injection pressure 2500 bar)

In design a) the engine is moved along the characteristic curve at the expense of particulate and CO_2 emissions in order to achieve NO_x raw emissions of 1.6 g/kWh.

The improved raw emission levels of a high-EGR engine with two-stage turbocharging and an injection pressure of 2500 bar (design b)) are initially accompanied by higher engine costs. However, in contrast to design a) this design allows fuel consumption and hence CO_2 emissions to be reduced because of higher charging pressures and a correspondingly improved lambda.

The aim of the assessment that follows below is to illustrate and evaluate the effect of engine design on the costs of exhaust gas aftertreatment systems and fuel consumption affected by the exhaust gas aftertreatment.

The evaluation takes account of current ESC and FTP tests and also the WHTC with cold start, which is currently being discussed.

Apart from emissions, the primary development objective is a reduction in fuel consumption and hence CO_2 emissions. This means, for instance, that the particulate filter dealt with below is installed in front of the NO_x catalyst in order to exploit the CRT effect, which reduces the filtered soot quantities and so also the number of active regeneration phases with fuel injection.

A corresponding exhaust gas system would consist of an oxidation catalyst, a hydrolysis catalyst – in a bypass if necessary – (see figure 8), a particulate filter and a downstream SCR catalyst with an integrated NH_3 trap, if necessary.

In a catalytically coated particulate filter urea injection and hydrolysis must take place behind the filter since the generated ammonia would otherwise react with the platinum and therefore no longer be available for the SCR reaction.

The design of the SCR catalyst, or the type of coating, depends on whether an actively regenerating particulate filter or a continuously regenerating filter system is to be used. Since temperatures can peak above 750 – 800℃ during active regeneration (s.a.) a temperature-resistant zeolite coating should be used in this case. Since the efficiency of current zeolite coatings is highly dependent on the NO_2 content in the exhaust gas at temperatures below 350℃ [17] the NO_2 concentration must be included in the overall SCR metering control. This factor must be critically examined especially with regard to the planned WHTC with cold test and new engines with significantly reduced temperature levels (figure 7b).

The maximum exhaust gas temperature of a continuously regenerating filter system is approx. 550℃ permitting the use of a vanadium pentoxide coating as an alternative active component. The efficiency of this type of coating is less dependent on the NO_2 content especially at lower temperatures and the coating is also much less expensive.

A test carried out at the University of Kaiserslautern showed that the vanadium pentoxide coating applied to a standard 300-cpsi metal substrate was as efficient in relation to temperature as a 300-cpsi full extrudate [18]. On the basis of these results a 300-cpsi full extrudate was compared to a "turbulent" metal catalyst with a 300/600 LSPE structure. The volume of the metal catalyst was reduced by 39 % to 13.2 litres to take account of the improved mass transfer of the "turbulent" structure and the internal concentration equalisation. The hydrolysis took place in an upstream hydrolysis catalyst in the partial flow. In addition, an oxidation catalyst had been installed in the main flow.

Figure 9 shows the emission results in relation to the injected urea quantity. The two catalysts produced similar results. The "turbulent" SCR metal catalyst achieved conversion rates over 90% despite its considerably smaller volume.

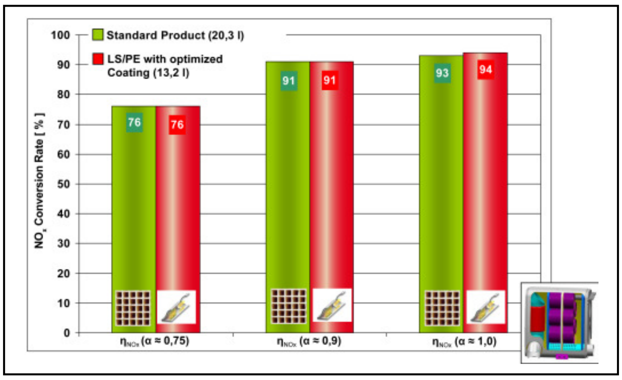


Figure 9: *NO_x conversion rate in relation to the urea quantity of a full extrudate and a "turbulent" metal catalyst.*

4.1 Exhaust gas system for engines with NOx emissions of 1.6 g/kWh and PM emissions of 0.10 g/kWh

These engines have to achieve NO_x conversion rates of 80% and a particulate reduction of 86% in order to meet US2010 limits. According to figure 9 the SCR volume required for "turbulent" metal catalyst substrates corresponds to the engine's cubic capacity.

According to currently available data a particulate reduction of 86% can only be achieved by a wall-flow filter that has been adapted to commercial vehicle applications. Figure 10 shows the layout of the exhaust gas system.

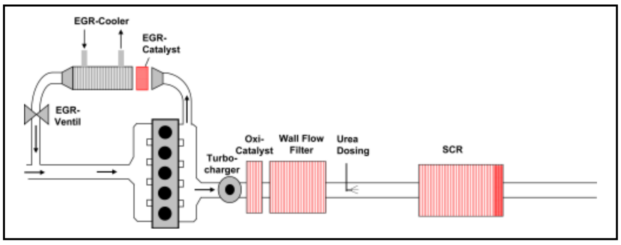


Figure 10: *Layout of the exhaust gas system for a low-NO_x, high-PM engine*

Wall-flow filters regenerate at regular intervals at temperatures above 600℃ (s.a.). The regeneration intervals depend on raw emissions and filter volume. A commercial vehicle for long-distance transport emits approx. 16.7 g of soot per 100 km at an average performance of 100 kW/h and an average speed of 60 km/h. At a maximum filter load of 8 g/l and a notional passive CRT efficiency of 60% the following regeneration intervals apply depending on filter volume:

Filter volume	10 l	20 l
Regeneration interval	1200 km	2400km

At present there is practically no data on fuel consumption raised by regeneration in commercial vehicles. Therefore a comparison was made on the basis of car data at this point. The fuel consumption of a car with a regeneration interval of approx. 1000 km rises by approx. 2 – 3% [19]. As a result, the fuel consumption of a commercial vehicle is likely to increase by 1.5% based on the regeneration interval of a 20-litre particulate filter. This assumption is based on the fact that compared to a car the relative additional consumption of a commercial vehicle would be partially offset by a correspondingly larger filter volume that has to be heated. The effect of the pressure loss, which is increased by the filter load, was not considered. However, it can be assumed that a 100-mbar increase in backpressure would raise fuel consumption by approx. 1% leading to an expected overall increase in fuel consumption of approx. 2.5%. Regeneration also requires a fuel injection nozzle in the exhaust gas system and the installation of pressure sensors that measure load conditions.

Over the next few months precise data on fuel consumption will become available from US2007 applications.

Vehicles will still have to be taken to the workshop at regular intervals so that the deposited ash can be removed from the wall-flow filters otherwise regeneration intervals would be drastically reduced and the pressure loss would continue to increase. The cleaning intervals are directly determined by oil consumption and the ash content of the oil. The oil consumption of a modern commercial vehicle engine with a fuel lubricated injection pump is approx. 0.2 litres per 1000 km (0.175 kg per 1000 km)

The amount of ash produced by low-ash oil with an ash content of 1% is 1.75 g per 1000 km or 0.88 ml per 1000 km. Classic 200-cpsi particulate filters with a wall thickness of 12 mil (0.3 mm) and a symmetrical cell size, as those currently used in commercial vehicles, have a free gas inlet channel volume of 0.34 litres per litre of filter.

This means that 1 litre of particulate filter is filled with ash after the vehicle has travelled a distance of approx. 385,000 km.

4.2 Exhaust gas system for engines with NOx emissions of 1.6 g/kWh and PM emissions of 0.04 g/kWh

These engines must achieve NO_x conversion rates of 80% and a particulate reduction of 65% in order to meet US2010 limits.

In contrast to 4.1, at a particulate reduction of 65% a maintenance-free partial-flow filter offers the best solution in view of the above raw emission levels. Figure 11 shows the layout of the exhaust gas system.

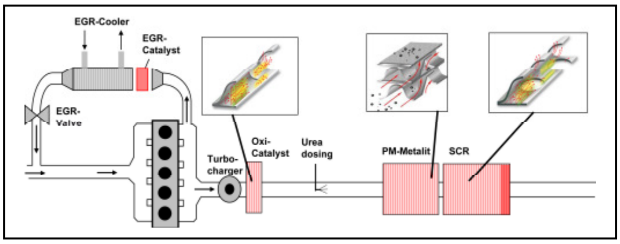


Figure 11: *Layout of the exhaust gas system for the low-NO_x, low-PM engine*

In contrast to the exhaust gas system of low-NO_x / high-PM engines, the urea injection unit is positioned in front of the partial-flow filter. The partial-flow filter can optionally be coated with titanium dioxide and function as a hydrolysis catalyst. Since the hydrolysis would otherwise have to take place in the front part of the SCR catalyst it is possible to reduce the SCR catalyst volume without any detrimental effect on the conversion rate.

The PM-METALIT^{TM} partial-flow deep-bed filter reduces particulate mass by 50% to 80% depending on the length of the filter. Figure 12 shows the functional principle of the deep-bed filter and the filtration mechanism of the nanoparticles.

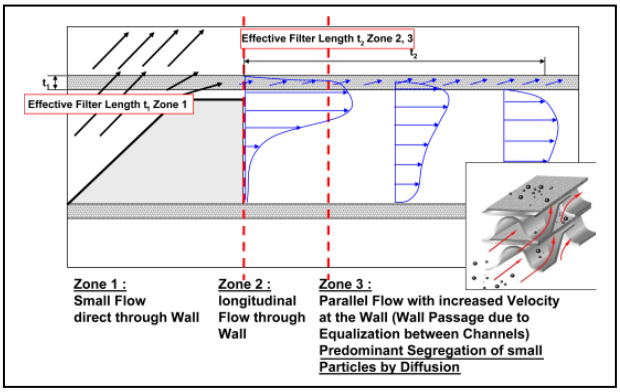


Figure 12: *Functional principle of the PM-METALIT^{TM} deep-bed filter and the filtration mechanism of the nanoparticles*

Due to the functional principle the particle number – and in this case especially nanoparticles in the 10 – 300 nm range – is reduced by up to 90%. Figure 13 shows a comparison between gravimetric particulate mass reduction and number reduction in a particle size range of 10 – 300 nm of various car and commercial vehicle applications.

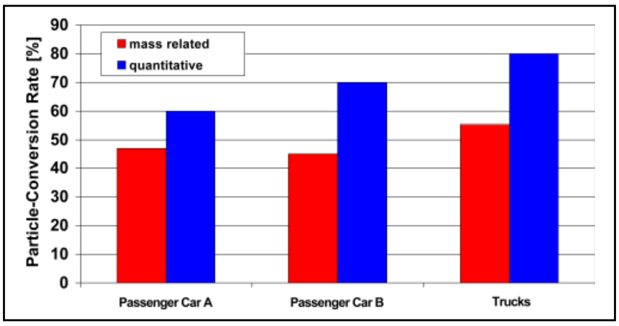


Figure 13: *Comparison between gravimetric particulate mass reduction and particle number reduction of various car and commercial vehicle applications*

Model gas tests were carried out to ensure that the reaction between soot and NO_2 is not inhibited by the presence of ammonia. For the purpose of the test soot was collected behind the oxidation catalyst on the engine test bench and made to react with a NO_2 concentration of 200 ppm with and without NH_3 at temperatures between 200 and 300℃ (figure 14). The slightly raised oxidation rate at 200℃ is attributed to the intermediate generation of ammonium nitrate. Ammonium nitrate partially dissociates into ammonia and nitric acid at temperatures as low as 200℃. Compared to NO_2 nitric acid oxidises soot at a higher rate.

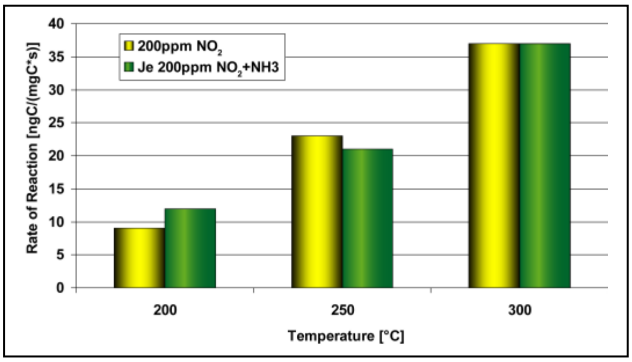


Figure 14: Soot oxidation rates of NO_2 with and without NH_3

Due to the passive regeneration of the particles filtered in the PM-METALIT™ no further regeneration measures are required.

The PM-METALIT™ is a maintenance-free, reliable filter component that meets particulate reduction requirements at low backpressure.

A SCR system with partial-flow deep-bed filter was tested in a test programme. In contrast to the layout shown in figure 10, this system includes an upstream hydrolysis catalyst in the partial flow. The PM-METALIT™ used in the test was not coated (figure 15).

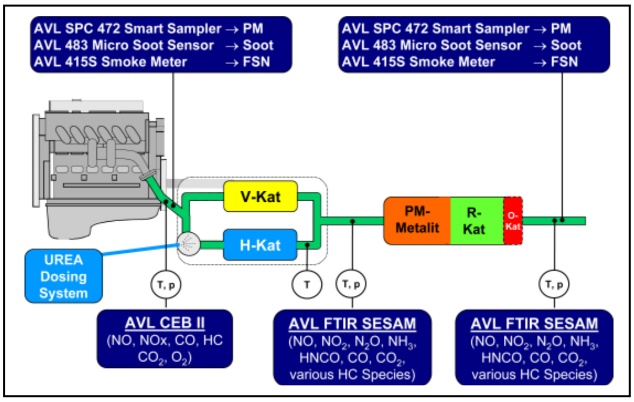


Figure 15: Structure of the SCR system with continuous particle reduction and measuring technology and figure of the rear silencer with integrated SCR and particulate filter system

A high-EGR test engine was modified with two-stage turbocharging and intercooling and used as a test substrate. Sulphur-free fuel (8 ppm S) and engine oil according to MAN's in-house standard M 3277 with a sulphate ash content of 1.9% were used in the test. The structure of the catalyst system is shown in figure 15. The PM-METALIT™ is 145 millimetres long; the volume of the reduction catalyst is 13.2 litres. This combination of partial-flow deep-bed filter and reduction catalyst is installed in the MAN-TGA silencer housing, which has been in general use since the introduction of EU III. Measurements are taken on a highly dynamic engine test bench using an FTIR spectrometer to record the gaseous components and a photo-acoustic soot sensor (MSS or PASS) to measure soot particle concentrations on a continuous basis. PM mass is gravimetrically determined. Samples are taken from in front of and behind the catalysts. AdBlue® is injected with a Bosch Denoxtronic 1. Due to time constraints the dosing algorithm developed for EU V applications could not be adapted to and optimised for the low NO_x-SCR conditions during this research programme, only the amount of AdBlue was adjusted to match a lower NO_x volume. Figure 16 shows the reduction in NO_x and particulate mass.

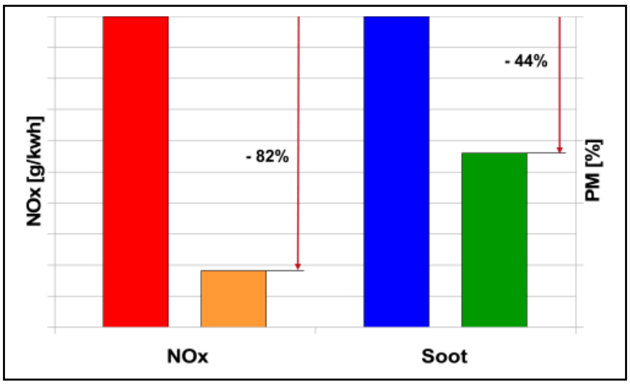
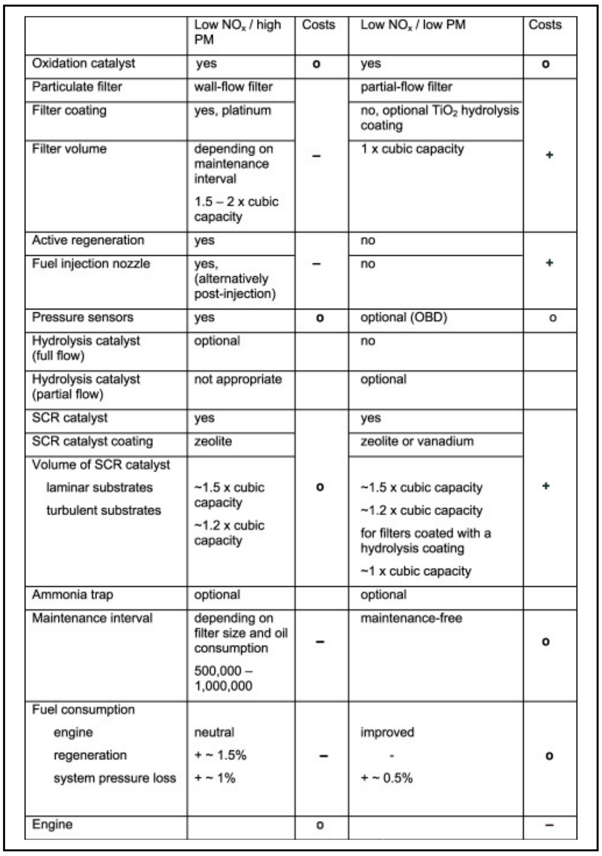


Figure 16: Reduction in NO_x and particulate mass in the SCR system with continuous particle filtration

The test result shows that a compact catalyst system in a series silencer volume was able to achieve NO_x conversion rates of 82 % and soot mass conversion rates of 44 %. As mentioned above, the PM efficiency can be adapted to different requirements by extending the PM-METALIT™.

4.3 Comparison of the two exhaust gas systems

Before the designs can be evaluated the costs for the different engine designs, the costs for the exhaust gas systems described in 4.1 and 4.2 and the operating costs (fuel consumption, CO_2 emissions) have to be compared.



	Low NO_x / high PM	Costs	Low NO_x / low PM	Costs
Oxidation catalyst	yes	o	yes	o
Particulate filter	wall-flow filter	–	partial-flow filter	+
Filter coating	yes, platinum		no, optional TiO_2 hydrolysis coating	
Filter volume	depending on maintenance interval 1.5 – 2 x cubic capacity		1 x cubic capacity	
Active regeneration	yes	–	no	+
Fuel injection nozzle	yes, (alternatively post-injection)		no	
Pressure sensors	yes	o	optional (OBD)	o
Hydrolysis catalyst (full flow)	optional		no	
Hydrolysis catalyst (partial flow)	not appropriate		optional	
SCR catalyst	yes	o	yes	+
SCR catalyst coating	zeolite		zeolite or vanadium	
Volume of SCR catalyst				
laminar substrates	~1.5 x cubic capacity		~1.5 x cubic capacity	
turbulent substrates	~1.2 x cubic capacity		~1.2 x cubic capacity for filters coated with a hydrolysis coating ~1 x cubic capacity	
Ammonia trap	optional		optional	
Maintenance interval	depending on filter size and oil consumption 500,000 – 1,000,000	–	maintenance-free	o
Fuel consumption		–		o
engine	neutral		improved	
regeneration	+ ~ 1.5%		-	
system pressure loss	+ ~ 1%		+ ~ 0.5%	
Engine		o		–

Tabelle 1: Comparison between a low-NOx / high-PM system and a low-NOx / low-PM system

5. Summary

The overall design of future exhaust gas aftertreatment systems will be determined by production costs, cost-effectiveness relating to CO_2 emissions as well as reliability and customer satisfaction. This paper described a new, very compact catalyst system for modern engines with cooled, controlled high EGR, two-stage turbocharging and an injection pressure of 2500 bar. The system offers a combined reduction of nitrogen oxides and particulates. The functional capability of an SCR system with continuous particulate emission was demonstrated by model gas tests and on the engine test bench.

The fact that particulate matter could be reduced on a continuous basis even in the presence of ammonia confirmed that it is possible to install the urea injection unit in front of the PM-METALIT^{TM}.

The advantages of the new system were highlighted by a comparison with a “normal” system currently under development.

Further tests on new engines with similar raw emissions have to be carried out in order to be able to calculate the effects on operating costs and fuel consumption more accurately.

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