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Development of an Integrated NO_x and PM Reduction Aftertreatment System: SCRiTM for Advanced Diesel Engines.

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ABSTRACT

Diesel engine emission regulations throughout the world have progressed over the last 20 years. In the U.S. the most stringent medium/heavy duty standard will be implemented for on highway vehicles starting in 2010. Although changes to engine design will improve engine out emissions, in order to meet both PM and NO_x regulations, combination systems including PM and NO_x aftertreatment, are planned to be utilized. In order to achieve the required regulations, a new substrate technology has been developed using advanced "turbulent" flow characteristics, and it has been combined with a novel approach to reduce system complexity: the "SCRiTM" or "SCR integrated" system. Such a system uses a continuously operating PM-Metalit with advanced "turbulent" SCR-catalysts in a unique configuration. The reduction of both PM and NO_x also has to be seen in context with its effect on CO₂ emissions. This paper will discuss the work carried out to understand and characterize the SCRiTM system performance and illustrate its advantage in complexity compared to other exhaust systems.

INTRODUCTION

The currently implemented emission limits for HD vehicles regulate the levels of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxide (NO_x), and particulate matter (PM). A number of competing technologies are being developed to achieve US 2010 regulations.

As result of a serious global discussion about climate change and the recent ruling of the U.S. Supreme Court, a review of future CO₂ emission limits and automotive fuel consumption has started. Fuel consumption has always been a priority in the commercial vehicles industry, as it has a significant effect on the operating costs of a vehicle fleet.

In order to meet the future CO₂ emission limits and reduce fuel consumption, an economically optimized solution that combines engine technology and exhaust gas aftertreatment will have to be developed.

At least two approaches exist from an engine technology perspective. The first would be to have an engine that is optimized for lower engine out NO_x emissions and higher PM emissions. Typically this would require high efficiency PM filtration as in a wall flow DPF, while NO_x control can be achieved with engine measures and a relatively low efficiency NO_x aftertreatment. However, it has been shown that such engines would have higher fuel consumption and therefore CO₂ emissions [10]. The other approach currently discussed would be to have an engine that is designed for optimized fuel economy, achieving lower operating costs, and low CO₂ emissions, which results generally in lower PM emissions but possibly slightly higher NO_x engine out emissions. The aftertreatment system for such an engine would require a high efficiency NO_x reduction technology, but could at the same time consist of a moderate efficiency PM filtration system, such as a partial filter [16,21].

There are essentially two highly effective technologies available today to reduce nitrogen oxides: Selective Catalytic Reduction (SCR), and NO_x storage (NO_x Adsorber, or Lean NO_x Trap LNT). Both technologies have been developed to the production stage; however, series production experience for heavy duty commercial vehicles is only available with SCR systems. Because of advantages in fuel consumption and system costs, it now seems that the heavy duty industry is moving forward with the SCR solution.

This paper discusses the status of a multi phase project, in which Emitec has developed an advanced compact NO_x and PM aftertreatment system to apply to CO₂ optimized heavy duty diesel engines. During the first phase, different components of a modular and compact SCR system were investigated and optimized. In the second phase, a PM-METALITTM partial filter was combined with an effective SCR technology into one integrated system [6]. In the third phase, the newly developed system was tested on a modified 2007 HD engine to study its potential for meeting the US 2010 emission legislation.

THE SCRi™ SYSTEM CONCEPT

The SCRi™ or “SCR integrated” exhaust system offers both PM and NO_x aftertreatment but in one compact exhaust module. The concept is best defined by the statement “Full Continuous Aftertreatment”. The SCRi™ system has a number of benefits:

1. The PM-METALIT™ is located in front of the SCR catalyst → allows NO₂ from an upstream DOC for continuous regeneration, i.e. no post injection, no additional fuel injector.
2. Initial configurations were optimized for NH₃ production using a parallel arrangement of a DOC and a hydrolysis catalyst. Advantages include a more complete formation of NH₃ through the use of special foil technologies and longer residence time of urea.
3. Further optimized integration integrates the hydrolysis function into the PM-METALIT™, taking a system that was already a class leader in size. In this design, the PM-METALIT™ has the function to generate NH₃ and at the same time trap and oxidize PM. Because of the internal shovel design, the PM-METALIT™ can also improve uniformity due to gas mixing. Pre-development of this concept confirmed that soot oxidation was not negatively influenced in the presence of NH₃ [10]. Reference **Figure 1** and **Figure 2** for example.

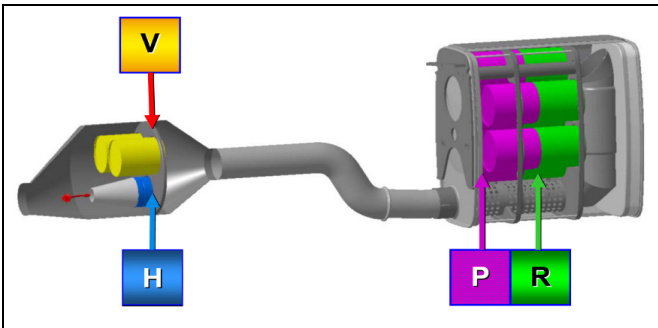


Figure 1: First generation SCRi™ system, V = Pre-DOC, H = Hydrolysis, P = PM Metalit, R = Reduction Catalyst.

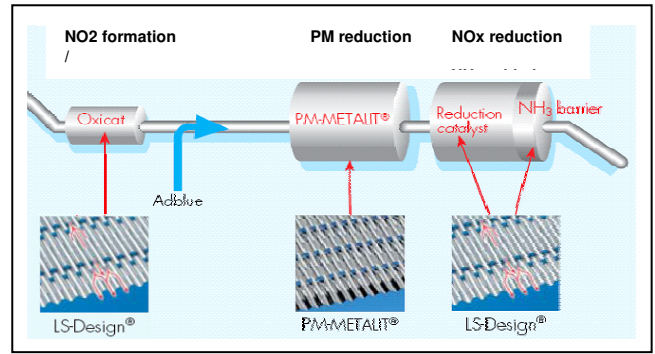


Figure 2: Second generation SCRi™ exhaust system showing PM-METALIT™ used as both Hydrolysis Catalyst and PM reduction.

OPTIMIZATION OF NOX AND PM AFTERTREATMENT SYSTEM COMPONENTS

i) Diesel Oxidation Catalysts (DOC)

Oxidation catalysts are used to reduce HC and CO emissions. In addition, NO is oxidised to form NO₂ at a temperature between 200 and 450°C. The NO₂ can be used to burn up particulates and 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 range.

The oxidation catalyst is also used to generate the necessary exotherm energy for the regeneration of the wall-flow filters. The fuel required for this is either supplied by engine post-injection or by a fuel injection nozzle in the exhaust stream behind the engine.

Oxidation catalysts with structured foil are particularly efficient at minimising HC slip since they are able to equalise any uneven fuel distribution and improve volume specific conversion. Previous studies have demonstrated the benefits in oxidation performance of such “turbulent” DOC’s in several examples [1, 2, 3].

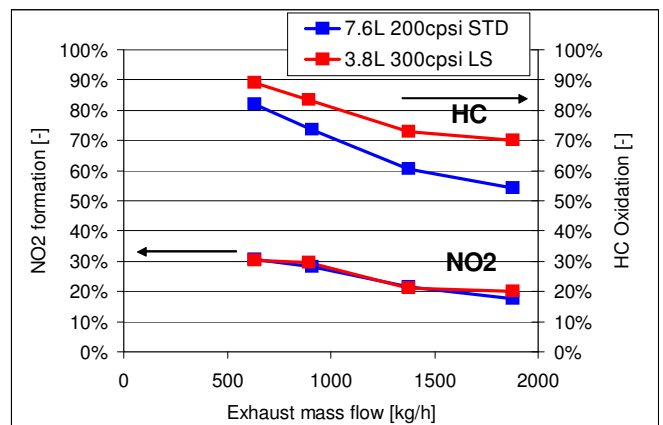


Figure 3: HC-Conversion of 200 cpsl standard structure compared to 300/600 LS with 50% volume [2].

Figure 3 illustrates the advantage that LS structured foil provides for both HC conversion (at test conditions 1000ppm HC and T=475C) and NO₂ production (at test conditions T=350 C).

Such a tremendous reduction in volume contributes to a more compact and highly cost effective exhaust system. The typical loading for DOCs in this study is in the range of 40 – 70 g/ft³, so the advantage of a reduction in volume by 50% represents a significant step in DOC technology.

ii) Hydrolysis Catalysts (H-Catalyst)

Previous studies have shown that advanced two stage hydrolysis catalysts using structured foils such as Mixing foil (MX) and LS/PE foil in combination with a hydrolysis washcoat can achieve a more complete conversion of Urea to NH₃ [6,7,8] as shown in **Figure 4** below.

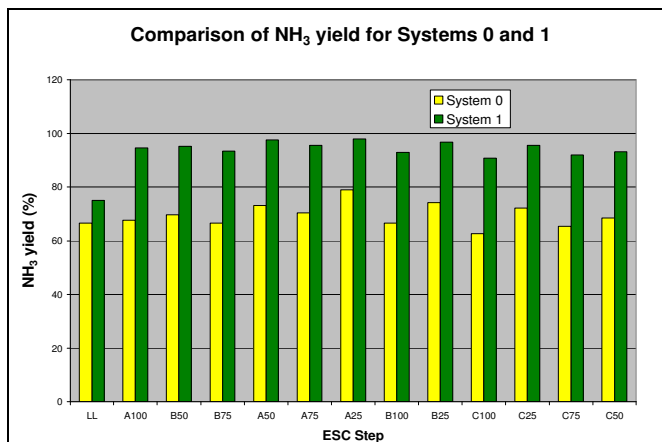


Figure 4: Comparison of NH₃ formation using MX + LS/PE Hydrolysis Catalyst (System 1).

According to this and other independent research studies, the installation of a hydrolysis catalyst in the partial flow path allows a significant reduction of SCR catalyst size. Urea hydrolysis catalysts are also used in the full exhaust stream. It was shown that hydrolysis in partial-flow is more effective, particularly in the absence of NO₂. Research carried out at the Paul Scherrer Institute (PSI) shows that the formation of NH₃ from H₂NCO is significantly reduced in the presence of NO₂ especially at temperatures between 150 and 225 °C [9], as shown in **Figure 5**.

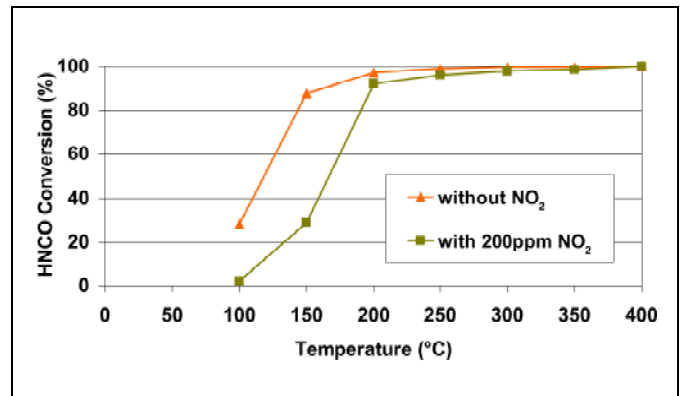


Figure 5: Effect of NO₂ on hydrolysis efficiency [9]

This fact could almost be neglected if exhaust gas temperatures are typically above 300 °C as in today's commercial vehicle engines and during hot emission tests.

However, the exhaust gas temperature of future engines and emissions tests such as the proposed WHTC is likely to be considerably lower. See **Figure 6**.

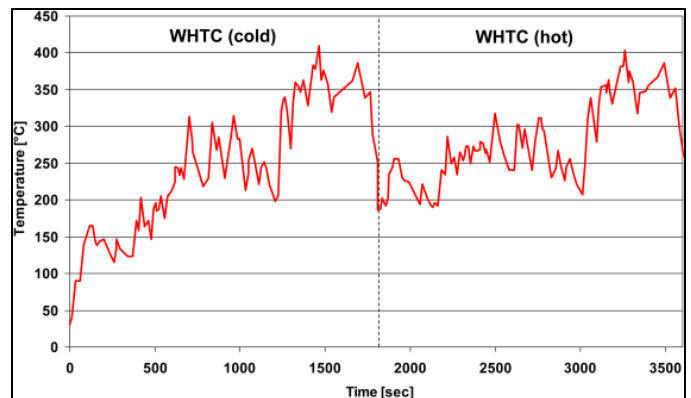


Figure 6: Exhaust gas temperatures during WHTC with a production HD engine.

This clearly shows that the effect of NO₂ has to be included in future exhaust system concepts.

Figure 7 shows one possible partial-flow hydrolysis system. The hydrolysis catalyst is placed inside a metal ring catalyst. 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 urea droplets without sustaining any damage.

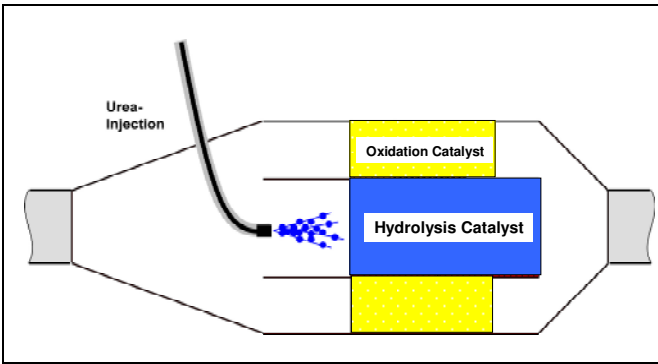


Figure 7: Concentric partial flow Hydrolysis System [10]

Another potential system design for hydrolysis includes a parallel arrangement, as shown in **Figure 8**.

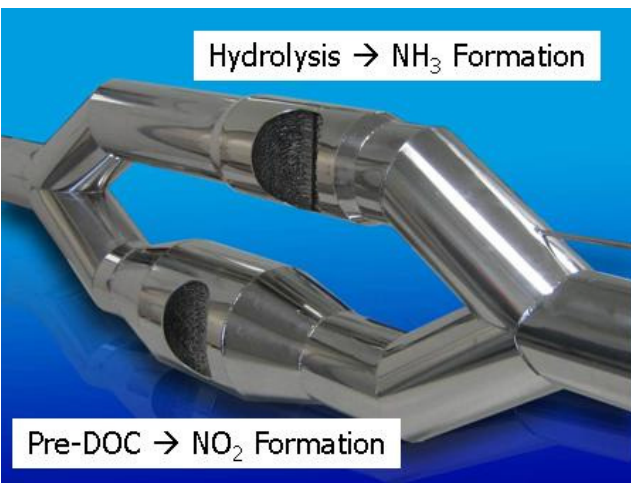


Figure 8: Example parallel flow hydrolysis catalyst system.

iii) NO_x Reduction Catalyst

The “Selective Catalytic Reduction” of nitrogen oxides under lean operating conditions, i.e. in the presence of excess oxygen, by means of ammonia (NH₃) has been used in the chemical industry or power stations for decades. In the automotive industry the SCR system was first developed for commercial vehicles.

A typical SCR system consists of a reduction catalyst, urea injection and dosing components, pipes and a storage tank. Many systems also include a downstream ammonia slip catalyst. Most modern catalysts are extruded substrates or coated substrates with vanadium pentoxide as the catalytically active component. Catalytic coatings of zeolite bases SCR are currently being developed because of the limited temperature stability of the vanadium 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 SCR catalysts are highly sensitive to the NO₂/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 (as opposed to NO₂).

Previous studies [6] have shown that the use of turbulent catalyst substrates for SCR can improve the volume specific NO_x reduction efficiency and achieve lower NH₃ slip. See **Figure 9** and **Figure 10** below.

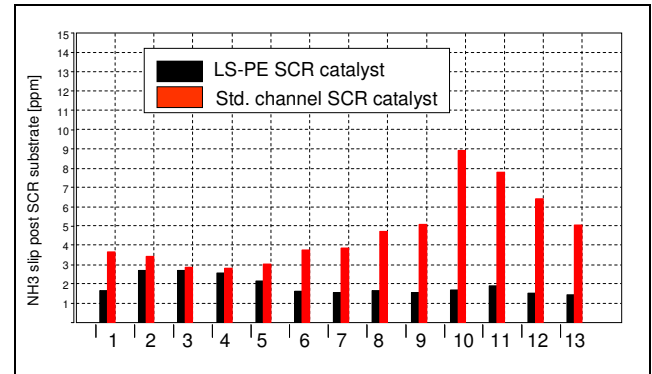


Figure 9: System 2 with turbulent reduction catalyst shows lower NH₃ slip compared to traditional substrates

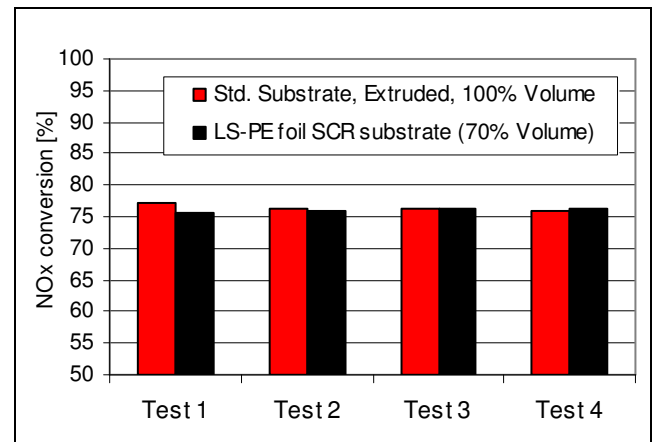


Figure 10: NO_x reduction with standard channel substrate and 30% smaller turbulent substrate.

iv) Particulate Matter Reduction

There are currently two major filter systems in production that can be used to reduce particulate matters. One design is the classic wall-flow filter [11,12] and another design is Emitec's PM-METALIT™ 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 soot cake. The filter has to be actively regenerated at regular intervals at temperatures above

550 - 600°C. To achieve this temperature, fuel is added in front of an oxidation catalyst either by post-injection in the combustion chamber or through a separate fuel injector in the exhaust gas system. This fuel heats the exhaust gas through an exothermic reaction in the DOC. Pressure loss changes between an actively regenerated and therefore “soot free” state and a soot loaded state at regular intervals.

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

Another drawback of an active system is that fuel consumption is raised due to frequent regenerations and the increase in pressure loss [5].

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 exhaust gas and blocks the filter [4].

As a result, operators may be faced with additional costs and vehicle downtimes.

Emitec’s PM-METALIT™ partial-flow filter (Figure 11) has been used in commercial vehicles and cars over the past four years.

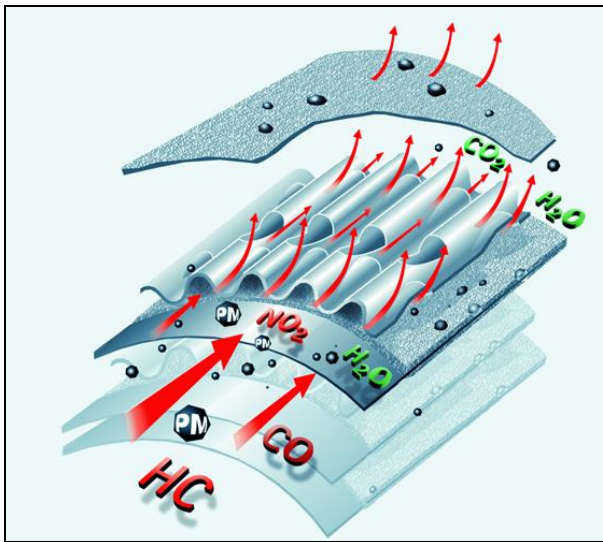


Figure 11: Operation example, Emitec PM METALIT™.

The PM-METALIT™ is used i.e. to meet EU IV regulations and has worked reliably on over 100,000 vehicles from various manufacturers. The filter has operated over 800,000 kilometres without malfunction or having to be ash cleaned. The PM-METALIT™ is the only mass-produced OEM filter system on the market worldwide that is designed for the entire life of the engine without maintenance.

Because it is maintenance free, the PM- METALIT™ is also certified and used in various retrofit applications in the U.S. and worldwide [13].

In a previous study the PM- METALIT™ was fitted into a first experimental version of a compact SCR system. This integrated NO_x/PM aftertreatment system was introduced as “SCRi™”, [6].

Initial results have shown that a PM reduction in the range of 50% was possible by outfitting a serial production EU IV heavy duty engine without any further engine modifications. See Figure 12 below.

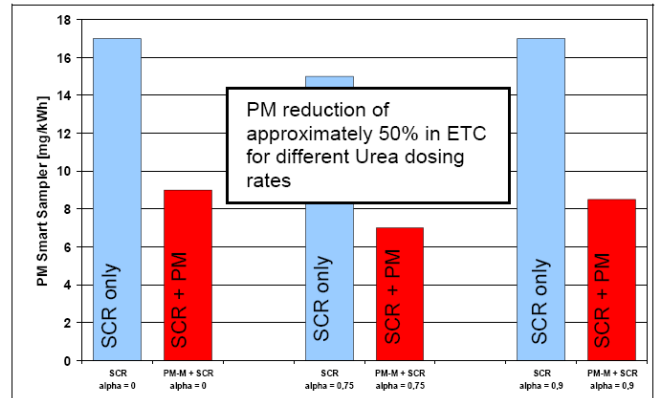


Figure 12: PM reduction with an experimental SCRi™ system on a EU4 engine [6].

The initial results achieved with the SCRi™ system were encouraging and have lead to further development and testing on a modified engine for U.S. 2010 demonstration.

EXHAUST BACKPRESSURE, EFFECT ON FUEL ECONOMY

A number of sources [15, 22, 23] have discussed the effect of backpressure on fuel consumption. As mentioned earlier, CO₂, and hence fuel consumption, is under intense scrutiny due to its effects on climate change. Although a range of values are discussed, a 2% increase in fuel consumption is typical based on an additional 100 mbar exhaust backpressure [22, 23].

The flow restriction of a traditional substrate at uniform flow conditions is the sum of 1) pressure drop at the inlet due to contraction of the exhaust gas and 2) the flow restriction inside the substrate due to friction between the gas and the substrate wall and 3) the pressure drop at the exit due to expansion of the gas.

METALIT™ substrates for DOCs and SCR applications are typically manufactured with either 40 or 50 micrometer foil (2mil or less). Typical ceramic substrates are made with wall thicknesses in the range of 115 – 230 micrometer (4.5 – 8 mil) and as a result have a lower open frontal area (OFA) and higher backpressure, reference Figure 13.

Additional flexibility in substrate shape gives even more freedom to increase cross section and reduce backpressure, reference Figure 14.

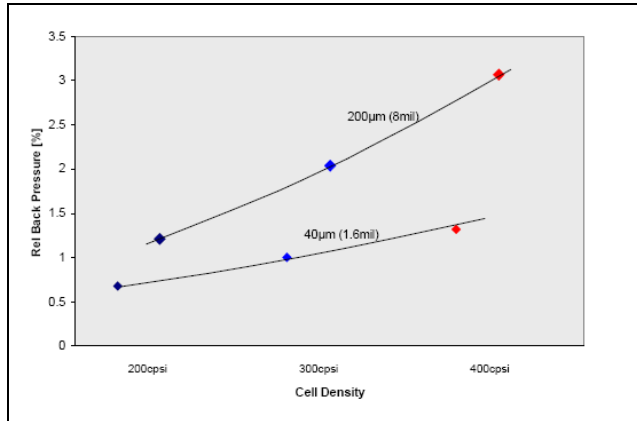


Figure 13: Backpressure depending on cell density and wall thickness [15]

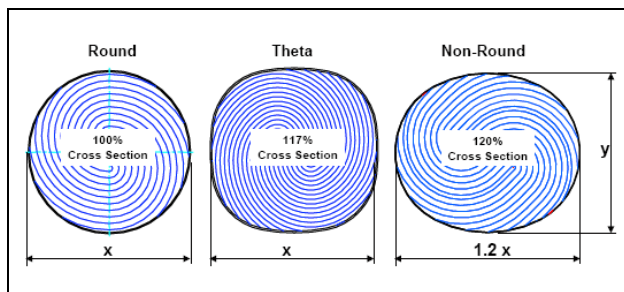


Figure 14: Non round shapes offer packaging and backpressure advantages [15]

For heavy duty exhaust systems, assuming a total SCR catalyst volume of approximately 25 liters, backpressure can be optimized via thin metal foils and cross sections as shown in **Figure 15**.

Substrate Attribute	System 1	System 2	System 3
Description	Round, Thick Wall	Round, Thin Wall	Elliptical, Thin Wall
Diameter (mm)	264	264	317 x 264
Length (mm)	450	450	375
Volume (ltr)	24.6	24.6	24.6
Wall Thickness (µm)	168 (6.5 mil)	40 (1.6)	40 (1.6)
OFA (%)	62	77	77
Cross Sectional (mm ²)	54739	54739	65686
Backpressure (mbar)	92	64	45

Figure 15: Technologies to reduce backpressure.

Using the estimation cited in [22, 23], a backpressure reduction of 50 mbar yields about 1% in annual fuel costs saving. Assuming a heavy duty truck with a fuel economy of 6 mpg and 150,000 miles/year, this can result in savings of more than \$750 per year.

DEVELOPMENT OF ENGINE OUT EMISSIONS VS AFTERTREATMENT DESIGNS

In order to understand what the most appropriate exhaust aftertreatment system will be, it is first needed to understand the trend in engine-out emissions. Engine-based measures that reduce raw emissions lead to simpler, lighter and more reliable exhaust gas aftertreatment systems.

The modification of a US 1998 engine with typical engine-out emissions to enable it to meet US2010 NO_x emission limits would require a SCR system (Selective Catalytic Reduction system) with a minimum effectiveness above 95%. With the application of EGR, a US2002 engine would require a NO_x efficiency of approximately 90%, and looking at a US2007 engine a NO_x reduction of about 83% will be needed.

Since this value would have to be achieved not only when the system was new but over the entire service life of the vehicle, emission compliance would require enormous effort according to currently available data. At the end of required emission life time, a modern SCR system can realistically achieve an efficiency of 75 to 85%. This suggests state of the art engine designs with low engine out emissions will be required to meet the stringent emission standards, starting in Europe, the US and Japan.

i) Review of current engine technology

Figure 16 shows an example of a “PM optimized” non-EGR EU III engine which would be able to meet EUV limits and come close to US 2007 with a moderate efficiency SCR system in the 60 – 70% range.

The other engine in this example is optimized for lower NO_x engine out emissions and could comply with EUV by installing only a partial flow PM-METALIT™.

To achieve US 2007 however, both engines in this example would most likely require a wall flow DPF.

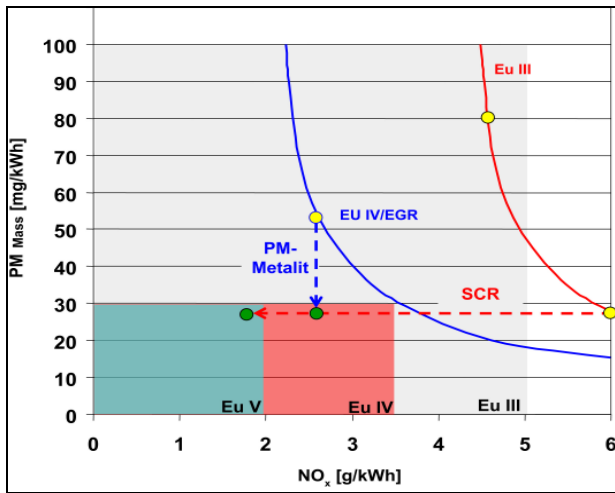


Figure 16: NO_x/PM tradeoff of currently available engines.

ii) Future engine technology scenario

A review of various new engine trends indicates that the NO_x/PM curve is moving to the left. 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 costs since the cooling capacity has to be increased. The requirements for accurate control of quantity and temperature of the recirculated exhaust gas will also increase. Any deterioration in cooling efficiency would affect NO_x raw emissions. EGR catalysts protect against soot fouling and therefore increase the durability of the EGR coolers [20] and the control valves. The combined effect of all of these engine measures is a reduction of both NO_x and particulate emissions. **Figure 17** shows an interpretation of future engine development.

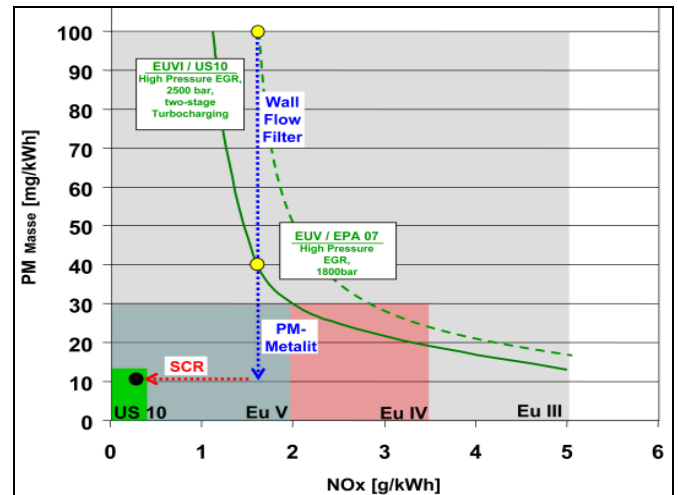


Figure 17: Effect of future engine technology on the NO_x/PM tradeoff curve.

If one assumes a maximum NO_x reduction of approximately 80% with long-term stability, then the following two scenarios for potential US2010 or EU VI systems based on the engine technology can be developed:

- a) 2007 type engines with controlled cooled EGR, single-stage turbocharging and an injection pressure of 1800 bar would generate NO_x emissions of 1.6 g/kWh and PM emissions of 0.10 g/kWh
- b) Modified engines with controlled cooled high EGR, two-stage turbocharging, and injection pressure of 2500 bar would generate NO_x emissions of 1.6 g/kWh but significantly lower PM emissions of 0.04 g/kWh

In design a) the engine is moved along the characteristic curve at the expense of particulate and CO₂ emissions in order to achieve NO_x raw emissions of 1.6 g/kWh. This engine technology would require a wall flow DPF.

The improved engine out 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), the higher injection pressure provides extremely low engine smoke and enables the use of higher EGR rates to manage NO_x. This allows for advanced injection timing and reduced fuel consumption and CO₂ emissions. [21, 24].

Comparing these two potential scenarios, it will become possible to meet the PM limits of 0.0135 g/kWh by using a PM-METALIT in a compact SCRTM system on an advanced US2010/EUVI engine.

TEST RESULTS WITH SCRi™ SYSTEM ON A MODIFIED HD ENGINE

TEST ENGINE

To investigate the potential of the SCRi™ system for US2010, a modified heavy duty engine was used. This engine was equipped with a high-pressure common rail fuel injection system (2500 bar), high pressure EGR, and two stage intercooled turbo-charging air system. The engine calibration was modified along the NO_x/PM tradeoff curve to achieve engine out emissions as close as possible to the target point of 1.6 g/kWh NO_x and 0.04 g/kWh PM.

The modifications resulted in a significantly lower exhaust temperature compared to the US2007/EUV calibration, as shown in **Figure 18** below. Lower exhaust temperatures such as in this test engine make it even more important to optimize the hydrolysis catalyst upstream of the SCR catalyst.

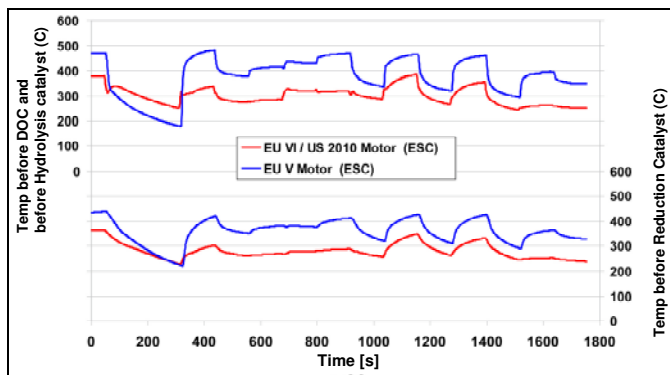


Figure 18: exhaust temperatures of the modified test engine

SCRi™ TEST SYSTEM

An experimental first generation SCRi™ system was evaluated with the concept engine in a test program. In contrast to traditional systems, where the hydrolysis function is part of the reduction catalyst, this SCRi™ system included an upstream hydrolysis catalyst and a DOC in a partial flow arrangement. The PM-METALIT™ modules used in this experiment were un-coated and installed upstream of the SCR catalysts. This combination of partial-flow PM-METALIT™ and reduction catalyst was installed in a rectangular muffler box housing. The optimized SCR substrates use turbulent LS-PE foil technology.

The tests were conducted at the AVL laboratory in Graz, Austria. Measurements were taken on a 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. Samples were taken before and after the catalysts. AdBlue® was injected with a Bosch Denoxtronic 1, see **Figure 19** below. Due to time

constraints the dosing algorithm developed for EU V applications could not be optimised for the low NO_x-SCR conditions during this research program, only the amount of AdBlue was adjusted to match a lower NO_x quantity.

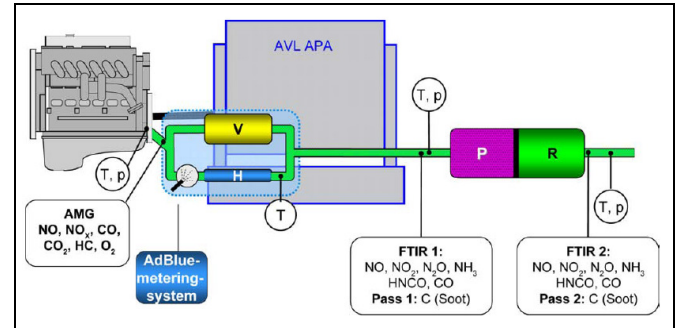


Figure 19: Test setup and instrumentation of the SCRi system, V = Pre-DOC, H = Hydrolysis, P = PM Metalit, R = Reduction Catalyst.

The engine was tested in transient and steady state operations. The SCRi™ system performed well, NO_x conversion with production urea dosing strategy was above 80%. **Figure 20** shows the results for NO_x reduction during ESC and ETC tests.

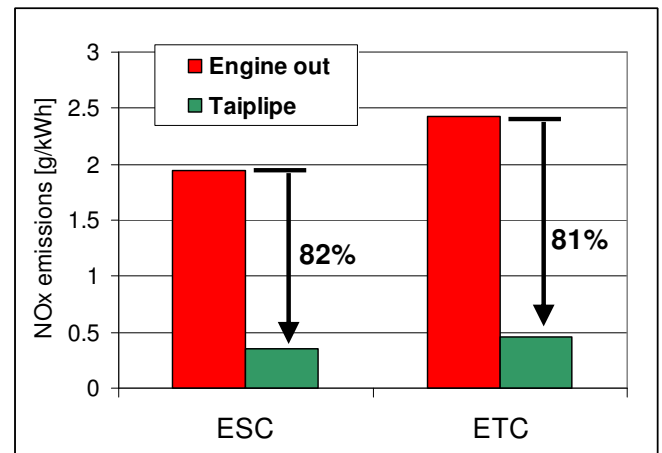


Figure 20: NO_x performance of tested SCRi™ system in ESC and ETC test

The PM reduction performance was evaluated in form of soot conversion, measured with a Micro Soot Sensor (MSS). The de-greened SCRi™ system with its short 145mm modules achieved a soot conversion of 44% in ESC and 38% in the ETC, as shown in **Figure 21**.

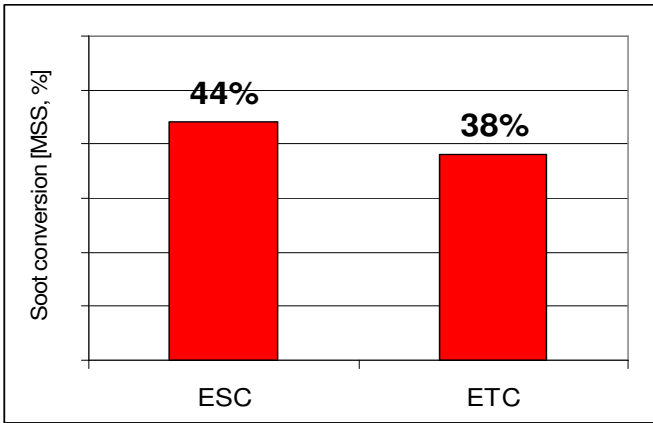


Figure 21: Soot conversion performance of tested SCRi™ system in ESC and ETC test

This result is lower than what was found in previous research [6] with engines that emitted higher NO_x concentrations.

Considering the very low NO_x emissions of the tested modified engine, a highly active pre-oxidation catalyst is important to provide a sufficient amount of NO₂ for the passive regeneration of the PM-METALIT™. With the small DOC as tested in the first generation SCRi™ system, an NO₂ content of 25 – 45% was achieved during the ESC. To optimize the system further for engines with low NO_x emission engines, the partial flow ratio between the DOC and the hydrolysis catalyst would have to be optimized. A larger portion of the exhaust gas could be directed through the DOC to increase NO₂ production and at the same time reduce HC concentration and SOF in the exhaust gas.

Although the US 2010 limit for PM and NO_x was not yet met in this particular test, it was shown that it is possible to achieve tailpipe emissions that are very close to US 2010 with this first experimental SCRi™ system on a modified US 2007 engine.

SYSTEM DESIGN IMPROVEMENTS

The results with the SCRi™ system as tested were encouraging. It is expected that US 2010 levels could be possible by optimizing the partial flow ratio between DOC and hydrolysis catalyst, further improving the design of the PM METALIT™, and by utilizing a more optimized urea dosing strategy. First measures have been started to modify the experimental SCRi™ system for future test programs:

IMPROVEMENTS IN PM TRAPPING EFFICIENCY

The design of the PM-METALIT™ was described in numerous previous publications [17,18,19]. It uses a number of small shovels inside the corrugated layer to

direct a part of the channel gas flow into fleece layers above and below each channel.

The PM trapping efficiency of the PM METALIT™ can be described generically as a function of temperature, NO₂ availability and exhaust gas flow characteristics. While temperature and NO₂ availability are mainly defined by engines and the upstream exhaust system, the flow characteristics inside the PM- METALIT™ is influenced primarily by its internal design:

i) PM- METALIT™ substrate length

Increasing the length of the PM- METALIT™ substrate leads to a larger number of shovels and increases the probability of particles being redirected into the fleece layer. A longer substrate also provides more fleece area to deposit particles, and this results in a higher PM trapping efficiency, as shown in **Figure 22**.

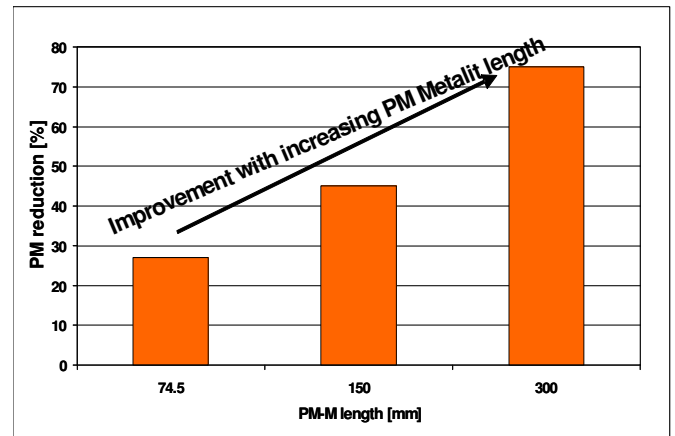


Figure 22: PM efficiency as function of PM-METALIT™ substrate length, based on HD truck ESC test results.

While extending the length of the substrate would be feasible, the focus of this project was to develop a compact exhaust aftertreatment system.

ii) Shovel density

A preferred way to increase the probability of redirecting as much exhaust flow as possible into the fleece is to increase the number of shovels of a given substrate length, the shovel density. Previous research work [16] had confirmed, that an increased shovel density can provide more area for PM trapping and reduce the “unused” fleece gaps between each row of shovels - see **Figure 23**.

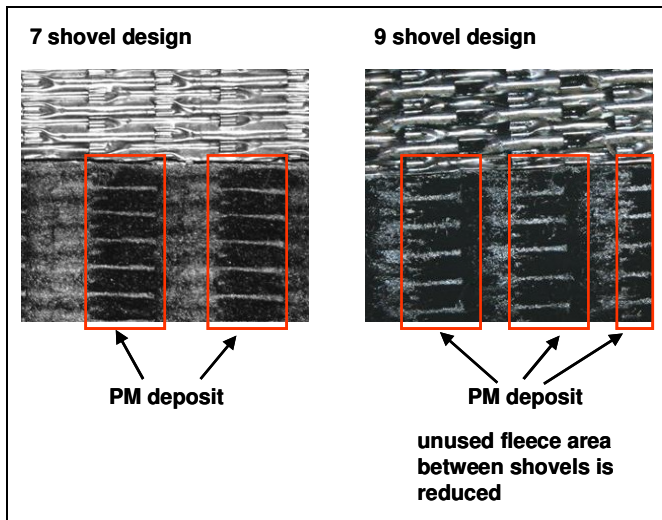


Figure 23: Fleece material used for PM deposit in PM-METALIT™ with 7 and 9 shovels

Based on this work, the number of shovels of the initial PM-METALIT™ design was increased from 7 to 9 per 150mm length. Reference **Figure 24**.

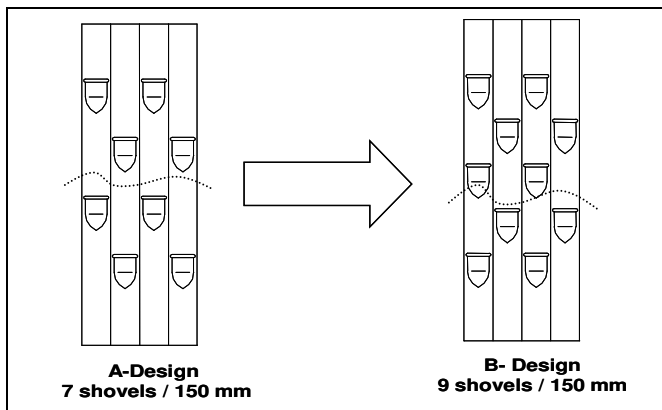


Figure 24: Shovel density of PM-METALIT™, of design A and B [16]

This approach was now taken even further. A prototype with increased shovel density has been developed, which also included an optimized shovel design. Initial studies have shown that this new design provides a significantly improved volumetric PM filtration efficiency. It was possible to increase the PM efficiency of a 150mm long PM-METALIT™ by 25-30% relative to a baseline production design (shown in **Figure 25**), an achievement that was possible in the past only by increasing the substrate length.

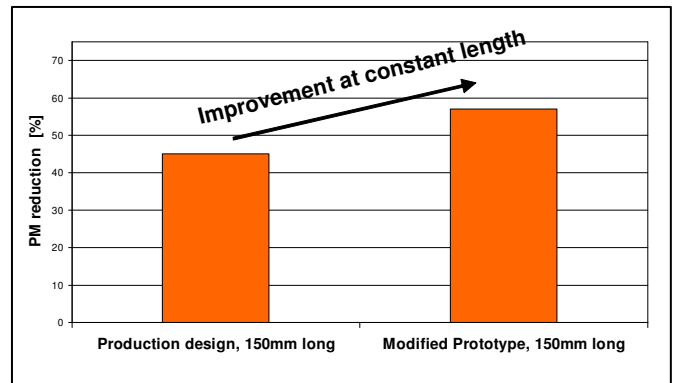


Figure 25: Improved volumetric PM efficiency with DOC and modified PM-METALIT™, HD truck ESC test results

With this improvement of volumetric efficiency it is expected that a SCRi™ system with the modified PM-METALIT™ would be capable to achieve the required PM reduction target (i.e. up to 70%) in a very compact arrangement similar to the one tested.

IMPROVEMENTS OF NOX REDUCTION EFFICIENCY

During the first phase of this development project [6] it was found that SCR reduction catalysts with turbulent foil geometry such as the LS or LS-PE foil can provide a lower NH₃ slip, as shown in **Figure 9**. It is believed that internal flow mixing as it is present in LS-PE substrates helps reducing non uniformity of NH₃ distribution inside the SCR substrate, while the better mass transfer of the LS-PE foil enhances the efficiency of NH₃ and NO_x reactions.

These design features offer the opportunity of a higher urea dosing rate, and thus higher NO_x conversions, while maintaining low NH₃ slip levels.

To investigate this potential, two modular SCR systems from the initial project phase were retested on a production EU IV HD engine. The existing urea dosing system was modified to allow an adjustment of the production dosing calibration. The SCR systems were then tested with the production dosing calibration and with dosing rates that were increased by factors of 1.2 (x baseline) and 1.45 (x baseline).

The experiment confirmed that it is possible to improve NO_x conversion at higher urea dosing rates with both types of tested SCR substrates, see Figure 26.

THE NEXT GENERATION SCRi™ SYSTEM

While the first generation SCRi™ system came close to achieving the targeted US 2010 emission levels, it can be expected that with improvements in PM trapping efficiency of the modified PM-METALIT™ and better NH₃ slip control of turbulent SCR substrates this target can be met in the future.

Prototypes of second generation SCRi™ systems are currently being developed. Modifications also include combining the hydrolysis function and PM trapping in one substrate, taking the approach of a compact system to a new level. As this paper was written, initial results on a LD engine were available that yielded a significantly improved PM trapping efficiency of more than 85% (gravimetric), reference **Figure 28** below.

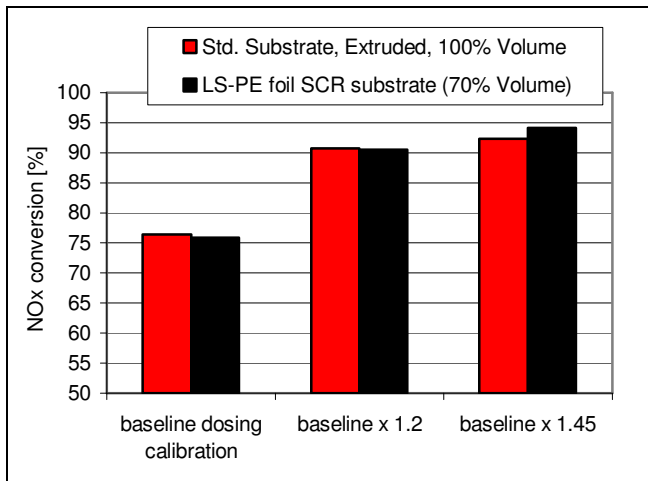


Figure 26: NO_x conversion of SCR system with standard substrates (fully extruded, V₂O₅) and 30% smaller turbulent substrates at different urea dosing rates

With an increased urea dosing rate of 1.2x baseline, both systems achieved a higher NO_x conversion at slightly increased NH₃ slip. A further increase of the urea dosing rate to 1.45 x baseline did not result in a significant improvement of NO_x conversion, however, Figure 26 shows that the turbulent system with LS-PE foil has a slightly higher performance. This additional reserve is interpreted as a result of its better mass transfer and better internal mixing.

At the same time it was found that for higher dosing rates (1.2 x baseline and 1.45 x baseline) the standard SCR substrates allowed significantly higher NH₃ slip compared to the turbulent SCR substrates. This indicates that the System with standard substrates is already at its limits for NO_x and NH₃ conversion, possibly supported by non-uniform distribution of Urea and NO_x inside the substrate. It is possible that local overdosing in some channels of the standard substrate can cause this NH₃ breakthrough. A turbulent substrate such as the LS-PE allows mixing, and thus reduces local overdosing in SCR catalysis. Reference **Figure 27**.

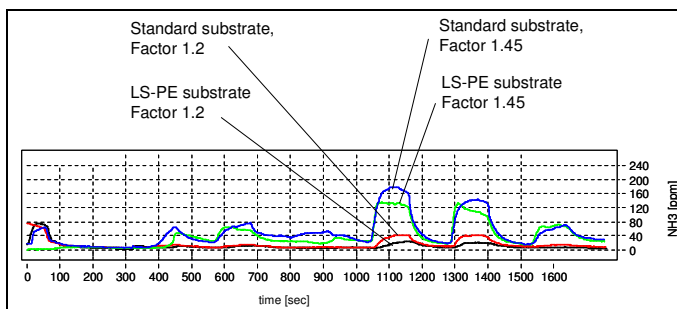


Figure 27: NH₃ slip behind SCR system with standard substrates and 30% smaller turbulent substrates at increased urea dosing rates.

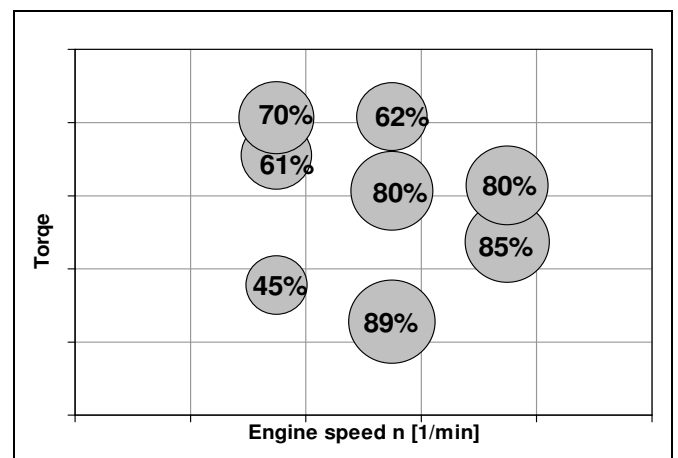


Figure 28: PM trapping efficiency of a second generation SCRi™ system with combined hydrolysis catalyst and PM-METALIT™.

Further tests with an updated SCRi™ system on new engines with similar raw emissions are also being carried out to study the emission performance, the effects on operating costs, and the benefit in fuel consumption and CO₂ emission.

CONCLUSION

A new combined NO_x and PM aftertreatment system -the SCRi™ concept - has been developed. Each component of the system was first optimized in a multi-phase development. The system was tested on a modified 2007 engine, and achieved emissions results close to US 2010 limits, demonstrating the capability of the technology.

Initial results of further optimized systems yielded significant performance improvements.

A combination of modern, advanced HD diesel engines and the SCRi™ concept has a high potential to meet the US 2010 limits at lowest operating costs and CO₂ emissions.

Table 1 summarizes the design parameters of the two engine-aftertreatment scenarios:

Attribut	Engine Concept/ High PM/Low NOx	Engine Concept/ Low PM/Low NOx
DOC	yes	yes
PM Filter	Wall Flow	Partial Flow
Filter Coating	Yes, Pt (platinum)	No, optional with hydrolysis coating
Filter Volume	2 x ESV	1 - 1.5 ESV
Active Regeneration	Yes	N
Fuel Injection Nozzle	Yes	N
Pressure Sensors	Yes	Optional
SCR Catalyst	Yes	Yes
Volume of SCR Catalysts	1.5 x ESV	1.5 x ESV
SCR Coating	Zeolite	Zeolite or Vanadium
Maintenance Interval	Max 500,000 km (ash storage)	Maintenance Free
CO ₂ emissions	Higher	Lower
Fuel Costs	Higher	Lower

Table 1: Comparison of two engine/aftertreatment scenarios for US 2010/EU VI.

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