

SCR and SCRi® as After-treatment Systems for Low CO₂ and Low NO_x Vehicles

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ABSTRACT

On one hand, latest worldwide emissions legislation developments aim to reduce NO_x and Particulate Matter (PM) emissions of all diesel engines, while on the other hand lower fuel consumption diesel engines are still required for lower fleet average CO₂ emissions. As a consequence of the chosen CO₂ optimized combustion mode, the raw NO_x emission increases and as such Selective Catalytic Reduction (SCR) technology will be the future choice for high efficiency NO_x after-treatment. This paper deals with SCR technology and its derivative SCRi® technology, when diesel particle reduction is required, especially for Heavy Duty applications. Alongside the developed metal catalyst technologies, a complete SCR reducing agent dosing system is presented. Emission results gained with the SCR or SCRi® technologies on European commercial engines illustrate the potential of these technologies for conversion of NO_x and PM emissions. This enables drafting of a road map for future emission control solutions, considering the local situation in India, for upcoming legislations.

Keyword : SCRi®, DPF, PF, Hydrolysis Catalyst

INTRODUCTION

Since air pollution has been recognized as a threat to human health, the environment active politics worldwide were put in place in order to control it, and to gradually minimize it, by reducing the emissions of hydrocarbons, carbon monoxide, Nitrogen Oxides (NO_x) and Particulate Matter (PM) at their sources. This results in, for the areas of transport and mobile machinery, which account for a good share of the pollution sources, sets of regional emission legislation, which are periodically revised and continuously strengthened. Leader regions are the United States of America, Europe and Japan

with similar legislations. Meanwhile developing countries, like India and China, are following with some delay due to the local affordable engine technologies / fuel availability etc. It must be said that the most severe emission legislation can be fulfilled only, if new engine as well as new exhaust after-treatment technologies are put in the market, which is particularly true for diesel engines [1]. As emissions of stoichiometric gasoline engine are under control, thanks to the three way catalyst technology, efforts in the latest decade have been put on the lean diesel engine in order to reduce PM and NO_x emissions. The situation in Europe, for example, is as follows:

Diesel Passenger Cars

The enforcement of European legislation Stage EU 5 with 5mg/km PM and 180 mg/km NO_x has made mandatory the Diesel Particle Filter (DPF) technology, the NO_x emissions being controlled with an accurate engine management. The introduction of the following Stage EU 6, with a strong reduction of the NO_x emissions (80 mg/km) makes necessary introduction of NO_x after treatment systems. Two technologies will be used: the Lean NO_x Trap technology will be catering to light vehicles requiring a low NO_x reduction efficiency and the SCR technology, with the help of additional reducing agents (urea aqueous solution for example), will be used in the case of heavy duty commercial vehicles requiring a high NO_x reduction efficiency. With the enforcement of stage EU 6, NO_x emission in traffic areas will continue to drop further but it will be the start for the reduction of nitrogen dioxide (NO₂) which has stayed constant since the introduction of stage EU 3 [2,3] and the introduction of more efficient Diesel Oxidation Catalysts (DOC). In Addition to Stage EU 6, in order to fight against global warming, European manufacturers are committed to

reduce the average CO₂ emissions of their fleets to less than 130 g/km by 2012 and less than 95 g/km by 2020, under the threat of penalties. Consequently the efficient diesel engine, which already is a good contributor to low average CO₂ emissions, will be further improved by choosing this time a combustion mode that reduces CO₂ emissions instead of the NO_x emissions. This optimization will be carried out as far as the combustion noise, the OBD regulation with defined peak threshold and the today in-development high efficient SCR systems allow it.

On Road Heavy Duty

In this field low fuel consumption and low operating cost are two important requirements for the development of new engines. The current emission legislation is stage EU V is since 2008 the current one and Stage EU VI is under discussion. EU Stage V (0.03 g/kWh PM and 2.0g/kWh NO_x in ETC) is fulfilled without PM and NO_x after treatment equipments by a new engine generation resulting from the introduction of new combustion process, higher fuel injection pressure (>2000 bars), external cooled EGR, 2 stage turbo-charging, etc. MAN introduced such EU V EGR engine [4] because of the positive feed back of the customers who appreciated EURO IV EGR/PM-Cat technology of MAN's first solution with EGR for the control of NO_x combined with a partial Diesel Particle Filter (p-DPF) reducing continuously the particles [5] according to the Continuous Regenerative Trap (CRT) process with NO₂, where no maintenance of the exhaust gas after-treatment system was required. The EU V engine represents a big technology advancement, if comparison is made with the most common fuel consumption optimized EU V engines, combined with an SCR system and internal PM control. To fulfil EU VI (0.010g/kWh PM, 0.4 g/kWh NO_x and a particle number limit still under discussion) the effort for the exhaust gas after treatment system will depend on the engine technology and its positioning on its PM-NO_x trade off curve.

Non Road Mobile Machinery

Emission legislation in Europe for this category has been developed very recently, based on regulations in US, which are organized according to engine power classes. For engine power lower than 19 kW, there are no foreseen limits. For engine class 19kW – 37 kW, today legislation EU stage III A limit (7.5 g/kWh HC + NO_x, 0.6 g/kWh PM) is fulfilled without special PM and NO_x after-treatment systems and will not be replaced by a more severe legislation stage according to today situation. For other engine classes with power higher than 37 kW and below 560 kW the next legislation EU stage III B, that gradually is entering into force according to engine classes, focuses on drastic PM emissions reduction with a limit of 0.025 g/kWh, whereas EU Stage III A limits values were between 0.2 g/kWh and 0.4 g/kWh. EU Stage III B NO_x emissions limits are slightly reduced to a maximum 50% (case for class 130 kW - 560 kW) of EU Stage III A

limits. The next legislation EU Stage IV will apply to classes above 56 kW and under 560 kW and will focus on NO_x reduction with a new limit of 0.4 g/kWh. As for Off road Heavy Duty applications, the exhaust after treatment system definition for EU Stage III B and EU Stage IV will depend on engine technology state. Developed solutions for On road applications also will probably be transferred and adapted to Off road applications.

The results from this short emission legislation survey are that:

- High effective SCR systems for the reduction of NO_x for On - and Off – road Heavy Duty, as well as for passenger cars, must be developed for the next legislation stages. Higher NO_x engine out could be tolerated, there by resulting in lower fuel consumption, lower CO₂ emissions
- In case of On - and Off - road Heavy Duty, required technology for particle reduction is not fixed yet. The choice between the two available technologies DPF and p-DPF will depend on the amount of required PM conversion efficiency

The paper deals with the SCR technology and its derivative SCRi[®] technology, when diesel PM reduction is required, focusing on Heavy Duty applications. The SCRi[®] technology is briefly compared to the SCRT technology. Alongside the developed metal catalyst technologies supporting the SCR and SCRi[®] systems, a complete SCR reducing agent dosing system is presented. Emission results from different European application examples of commercial vehicles illustrate their capabilities for the after treatment of diesel engines. Finally considering the local situation in India, a road map for emission control solutions is proposed.

METAL TURBULENT STRUCTURED CATALYSTS

It is a well known fact that catalyst effectiveness in warmed-up condition is influenced by substrate properties, i.e. by increasing the specific surface (the Geometric Surface Area: GSA) and improving contact between gas and wall, regardless of the type of catalytic reaction which takes place. This is characterized by the mass transfer coefficient β that describes the transport by diffusion of the pollutants from the core flow where their concentration is high to the catalytically active wall where their concentration is low. Flow conditions in Standard catalysts (Std) with straight and smooth channels are laminar after a first and short inlet section of the catalytic channel where the flow is not fully developed. Under laminar flow conditions the catalytic process is determined by a low mass transfer coefficient β , whose value could be five times lower than in the channel inlet section [6]. Beside the improvement of the mass transfer by mean of channel or cell size reduction, i.e. increasing the cell density for a given catalyst section, an innovative solution has been the

development of “turbulent” metal substrates, whose foil structures introduced channel flow perturbations and therefore enhanced the mass transfer [6]. Of particular interest for the paper subject are the metal substrates with Longitudinal foil Structures (LS), Perforated foil Structures (PE) and with combination of both structures (LS/PE).

Longitudinal Foil Structure (LS) Substrates

The substrate with longitudinal foil structure, applied in mass production [7], is characterized by LS-Counter corrugations shown in Fig. 1, built in the corrugated foil during the manufacturing process. The LS-Counter corrugations is formed by pushing a fraction of the corrugated foil into the centre of the channel, resulting in a local subdivision of the channel into two parts, aiming to recreate the “inlet length like” turbulent flow conditions, but also to bring the catalytically active wall to the centre of the flow where pollutant concentrations are higher. Therefore, and especially at low exhaust pollutant concentrations, the diffusion process is no longer limiting the mass transfer, which improves the total catalytic efficiency.

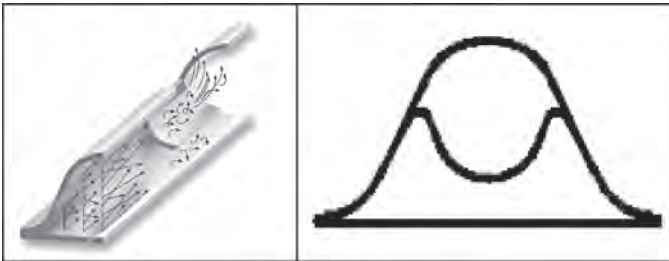


Figure 1. LS Substrate Structure

Perforated Foil Structure (Pe) Substrates

Perforated foil (PE) technology has already been successfully applied in the mass production of components for a variety of applications and has been discussed in detail in previous papers [8-10]. PE technology uses perforated flat and corrugated foils to generate radial flow between adjacent channels. The PE structure design with flow details is shown in Fig. 2. The juxtaposition of the perforations from adjacent foils builds caverns within the catalyst, which act as mixing chambers and offers the possibility to recreate, here too, the “inlet length like” turbulent flow conditions when gas leaves the cavities and enters into the following channels.

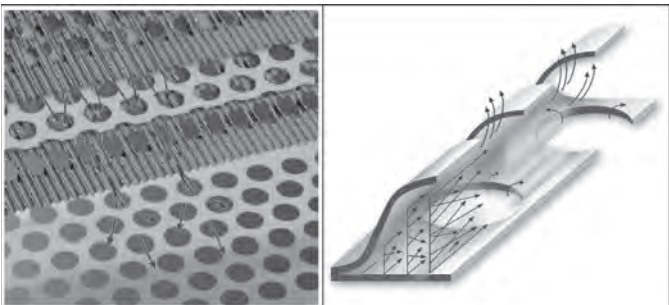


Figure 2. PE Structure Design with Flow Details

The development of perforated metal foils offers a number of advantages:

- Reduced heat capacity
- Homogeneous distribution of exhaust gas flow and pollutant concentrations
- Reduced backpressure

Effectiveness Improvement with “Turbulent” Metal Substrates

Catalyst effectiveness is characterized by the emission-relevant product $\beta \times \text{GSA}$. β Values for LS and PE substrates recently have been calculated [11], based on experimental data gained with different substrates with characteristics are given in Table 1 with same dimensions $\text{Ø } 40 \times 50.8\text{mm}$ and same amount of coating (140 g/l), that have been compared under the variation of exhaust mass flow at a constant temperature of 450°C in the propene oxidation reaction because mass transfer controlled regime begins here at fairly low temperatures ($>350^\circ\text{C}$).

Table 1. Substrate Data Used to Calculate $\beta \times \text{GSA}$ Values

Cell density [cpsi]	Wall thickness [μm / mil]	Structure
400	50	Standard
200 / 400	50	LS
300 / 600	50	LS
400	50	PE

Fig. 3 shows the calculated $\beta \times \text{GSA}$ values for metal substrates with three basic cell densities of 200, 300 and 400 cpsi as a function of channel velocity at 450°C .

The following conclusions can be derived from the data:

- Both LS structures are substantially more affected by channel velocity than any other type
- This means that there is a typical channel velocity for each type above which it can be replaced by an LS structure with lower basic cell density (for example: LS 200/400 replaces 400 STD at a velocity above approx. 10 m/s)
- This means that in given conditions it is possible to replace a standard catalyst system by a more compact system with LS structure for a given effectiveness.

- On the other hand, PE structures behave similarly to standard channels, although compared to the STD substrates the $\beta \times GSA$ value for PE is not reduced to the extent expected due to the GSA loss (30%). This results from a gain in β of PE relative to the standard structure.

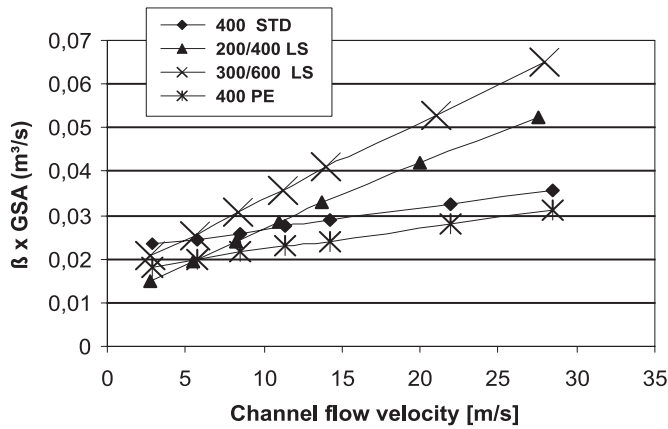


Figure 3. Calculated Values of $\beta \times GSA$ at 450°C for Different Substrate Structures as a Function of Channel Velocity (140 g/l washcoat)

SCR TECHNOLOGY

The SCR 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 after-treatment of power station emissions for decades. In the automotive industry the SCR system was initially developed and used in, commercial vehicles in order to reduce fuel consumption. Since the engines themselves continued to undergo further development at the same time 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 an additional reduction material in the vehicle, in this case a urea-water solution (AdBlue) to generate ammonia onboard, added to the delays. The situation became worse by the fact that the necessary logistics for the supply of 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 clean-up (oxidation) catalyst could also be integrated at the outlet end of the SCR catalyst as an oxidation zone coating. This section will focus mainly on the reduction catalyst, other components will be discussed in the following sections.

In Europe catalyst technologies currently used are extruded catalysts or coated substrates with vanadium pentoxide as the catalytically active component.

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. For these applications coatings based on zeolite technology were developed. 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 NO_2/NO ratio of 1/1, an oxidation catalyst should be included in the system to generate required NO_2 because the engine emits almost exclusively NO.

The LS and LS/PE structures have proven very effective at increasing the specific efficiency of the SCR catalyst or alternatively reducing installation size and hence cost. Fig. 4 and 5 show results of previous studies [12] that a 30% volume reduction could be gained with the use of the structured 300/600 cpsi LS/PE NO_x reduction catalyst in comparison with the standard extruded 300 cpsi SCR catalyst. Furthermore, a lower NH_3 slip has been achieved. This could be explained by a better NH_3 usage, thanks to the catalyst internal distribution capability.

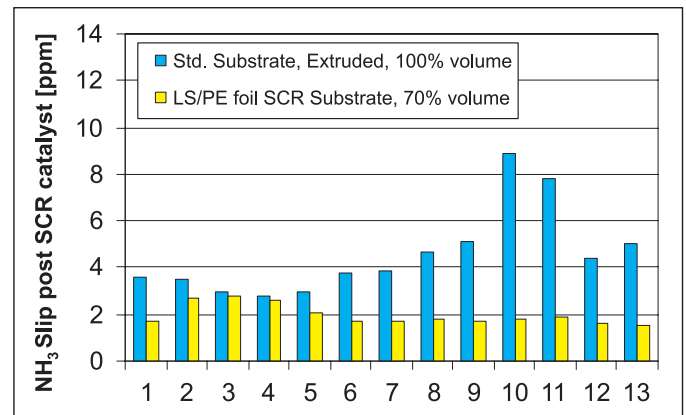


Figure 4. System with Turbulent Reduction Catalyst Shows Lower NH_3 Slip Compared to Traditional Substrates in ESC Test Cycle [12].

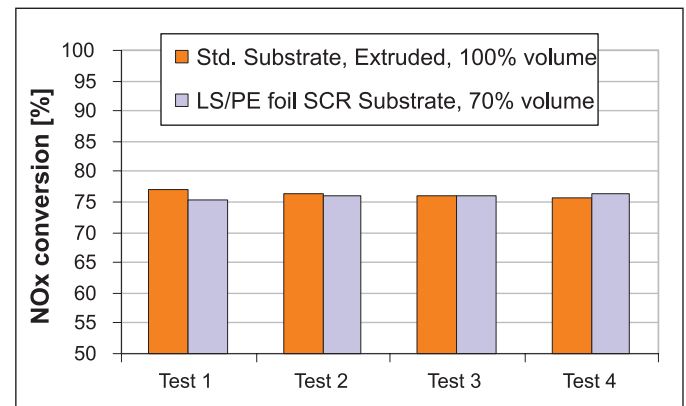


Figure 5. NO_x Reduction with Standard Channel Substrate and 30% Smaller Turbulent Substrate in ESC Test Cycle [12]

SCRi® TECHNOLOGY

SCRi® technology was developed to reduce soot particle emissions in the exhaust gas with the integration of a partial-flow deep-bed filter PM METALIT® in front of the reduction catalyst. The basic principle of SCRi® system is described in the earlier literature [12, 13]. Fig. 6 shows the SCRi® catalyst system.

The functions/construction of the individual components, with the exception of the SCR catalyst already discussed before, are briefly described below.

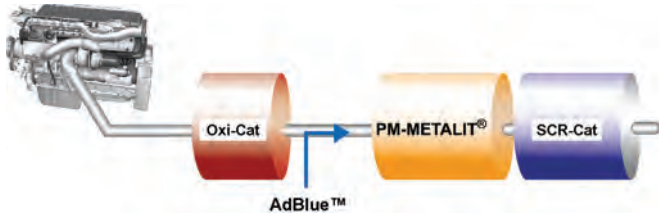


Figure 6. SCRi® Catalyst System

Oxidation Catalyst

Oxidation catalysts are used to reduce HC and CO and simultaneously oxidize NO to NO₂ at a temperature range of 200 to 450°C. The generated NO₂ is used for continuous particulate reduction in the PM METALIT® or to improve the low-temperature efficiency of zeolite based SCR catalysts [14]. Oxidation catalysts are coated with Pt or Pt/Pd depending on the temperature range. When the DOC is also used to generate the necessary exothermal energy for the regeneration of a wall flow filters (DPF), in case of the so-called SCRT process, the required fuel for this is either supplied by engine post injection or by a fuel injection nozzle in the exhaust stream behind the engine. LS/PE based catalysts proved to be very efficient at minimizing HC slip since they are not only able to equalize any uneven fuel distribution and improve volume specific conversion, but also very effective for NO₂ formation. This is illustrated in Fig. 7 [12, 15].

Oxidation catalysts or an oxidation coating can be used as an ammonia trap in the rear section of an SCR catalyst to prevent ammonia slip.

PM Reduction

There are two approaches to particulate matter reduction:

Wall Flow Filter DPF (used in SCRT)

The filter efficiency of DPFs is over 98% after the formation of a filter cake. Regeneration can be carried out according to the CRT effect or occurs at temperatures above 550°C to 600°C. Then, in the second case, standard engines require the addition of extra fuel to reach these temperatures. This process involves either post-injection into the combustion

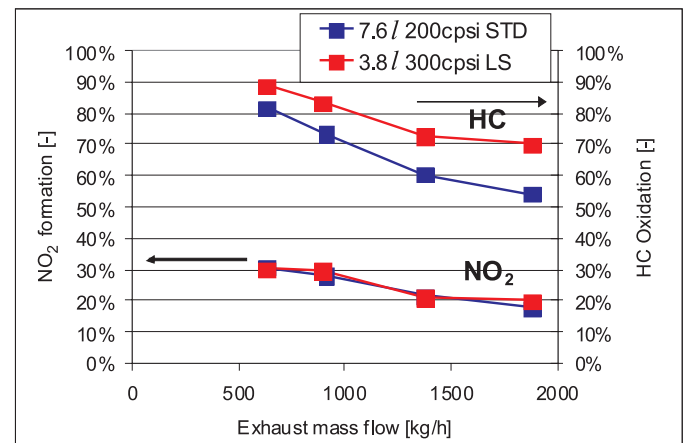


Figure 7. HC-Conversion (at test Conditions 1000 ppm HC and T=325 °C) and NO₂ Production (at Test Conditions T=325 °C) of 200 cpsi Standard Structure Compared to 300/600 LS/PE with 50% Volume Reduction [12]. Test Engine is a 15 Liters Diesel Engine with 455kW @ 1800 rpm

chamber or separate injection into the exhaust system. However, this creates the following problems:

- The oxidation catalyst and particulate filter are subject to high thermal loads during regeneration (coating)
- Higher temperatures lead to an increase in pressure loss (change in density)
- Fuel consumption increases as a result of post-injection
- The catalyst volume has to be increased to allow for the storage of ash deposits, otherwise regular maintenance intervals have to be scheduled
- Higher operating costs

PM METALIT® (used in SCRi®)

This partial-flow deep-bed filter is designed to last for the lifetime of the vehicle and operates continuously without additional fuel or maintenance. Soot particles are reduced by the NO₂ present in the exhaust gas or generated in the oxidation catalyst [16]. The systems can reach efficiency levels of between 50 and 80% with respect to soot mass. The reduction rates for particulate numbers in the 30 to 300nm range are between 80 and 95% [17]. It uses a corrugated layer of foil to divert the exhaust gas from each channel into the flat layer, constructed of stainless steel “fleece” material used to trap particulate matter [5,18] as shown in Fig. 8.

The PM-Metalit® (PM-M) has been introduced in series in two vehicle categories: passenger cars and Heavy Duty vehicles. It has been used to meet HD EU IV regulations and has worked reliably on more than 100,000 vehicles from various manufacturers. The filter has operated over 800,000 kilometres without malfunction or having to be ash cleaned.

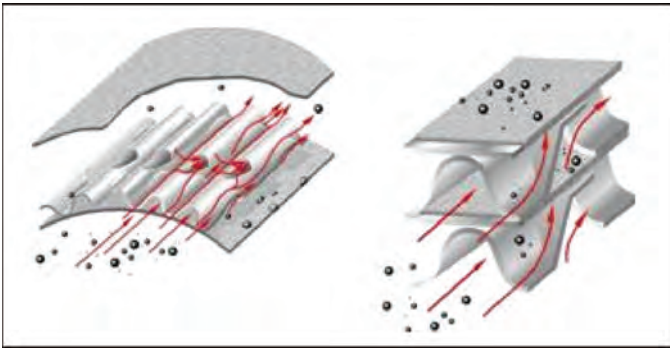


Figure 8. PM Metalit® Deflects Particulate Matter into Flat Fleece Layer for Reduction of Particles

Hydrolysis Catalyst

Hydrolysis catalysts are a more effective means of converting the injected aqueous urea solution to NH_3 so that the volume of the SCR catalyst can be reduced. As the injection, equal distribution and quick evaporation of the aqueous urea solution in the exhaust gas is another important aspect of the system's efficiency, the urea solution could be injected, in the SCRi® technology, in front of the PM Metalit® coated with hydrolysis coating, which permits radial flow equalization and consequently is also able to equalize the concentration. Previous studies [19, 20] have demonstrated all the benefits to use the PM Metalit® as a substrate for a hydrolysis catalyst, without losing its characteristics for particle matter reduction. Furthermore the urea solution injection could be performed behind the outlet face of the DOC in order to improve the urea solution droplet fragmentation and evaporation [21]. In this case the substrate of the DOC also receives a hydrolysis coating over a small length at the outlet face.

SCRi® Potential

The potential of the SCRi® system for legislation stage EU VI for Heavy Duty Diesel is under investigation. First emission results [11] with a non optimized system were gained on an engine test bench with an EU V series 400kW, 13 litres engine from a commercial vehicle, normally equipped with a series 34.8 l, 400 cpsi, ceramic, vanadium based SCR catalyst which includes a zone coating for NH_3 oxidation. Based on the engine out emissions Euro VI limits would be achieved when NOx and PM mass reduction efficiencies of the SCRi® system are higher than or equal to 95% and 66% respectively, in ETC.

The tested SCRi® system, described in Fig. 9 and Table 2, has been designed as following: The volume of the reduction catalyst with LS structure has been fixed to circa 75% of the EU V series SCR catalyst, which would allow, according to the previous paragraph on SRC catalyst with structured foils, at least the same performances, when the reduction catalyst would be tested alone. The reduction catalyst has received here a zeolite based SCR coating. In the SCRi® system ammonia is prepared and mixed with the exhaust gas

over a PM-M that has received a urea hydrolysis coating, without compromising its particle reduction function. As a consequence of the combination of the hydrolysis catalyst with the reduction catalyst it was expected to reach higher NOx reduction rates than with the series SCR catalyst. PM mass reduction performance of the SCRi® system is a function of the PM-M length [17]. It has been decided, based on internal experience, to install two PM-M bricks of 174 mm length, the first brick being coated with a Hydrolysis coating. The DOC volume varies from 0.5 > 1 times the engine displacement and is assumed to produce enough NO_2 for PM-M regeneration combined with fast SCR reaction at low temperatures over a zeolite based SCR coating. In this experiment the DOC volume was fixed in the upper range nearer to equivalence with engine displacement.

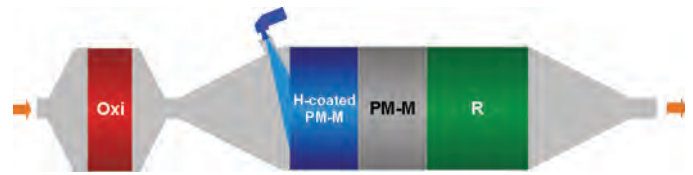


Figure 9. Simplified Description of Tested SCRi® System

Table 2. Description of Substrate Technologies and Coatings of the SCRi® Elements

Elements	Metal substrates	Coating
Oxidation catalyst	Ø 342 x 120 mm / 200/400 LS , 11.0 l	DOC 40 g/ft ³ Pt
H-coated PM-M	2 x [Ø 251,4 x 174 mm / 200 cpsi PM-M], 8.65 l	Hydrolysis 25g/l
PM-M	2 x [Ø 251,4 x 174 mm / 200 cpsi PM-M], 8.65 l	None
Reduction catalyst	2 x [251,4 x (174 + 90) mm / 300/600 LS], 26.2 l	SCR 220g/l

For emission measurement, the oxidation catalyst has been located after the turbocharger and the bloc hydrolysis catalyst – the PM-M -reduction catalyst took the place of the series SCR catalyst in the muffler, while the series urea solution injection installation and urea solution dosing strategy (presumed α (ratio NH_3 / NOx) = 0.8) implemented for ETC have been retained for the first measurements and increased to approximately 1 for a second measurement. SCRi® system efficiencies over ETC are resumed in Table 3.

The designed SCRi® system with dosing strategy at $\lambda = 0.8$, in degreened conditions, achieved with the series urea dosing strategy reduction efficiencies of 88% for NOx and 76% for PM mass, was not enough to fulfil the NOx objective, even though an improvement of 9% was obtained in comparison to the series SCR catalyst. After a change of the dosing

Table 3. Efficiencies of Degreened SCRi® System and Series Catalyst as a Function of the Urea Dosing Strategy

	NOx Efficiency (%)	PM-Mass efficiency (%)
Efficiency objectives for EU VI	95	66
EU V Series SCR Catalyst and Dosage strategy $\alpha = 0.8$	79	24
SCRi® system and Dosage strategy $\alpha = 0.8$	88	76
SCRi® system and Dosage strategy $\alpha = 1$	98	81
SCRi® system without uncoated PM-M elements and Dosage strategy $\alpha = 0.8$	81	60

strategy to an approximated $\lambda = 1$, reduction efficiencies of 98% for NOx and 81% for PM have been achieved, which fulfilled the objectives. These results confirmed the high specific efficiencies offered by LS SCR catalysts and the big role of the 2 PM-M bricks in the preparation and distribution of NH₃ throughout the catalyst section. To underline this, it can refer to the results obtained with the system without the uncoated PM-M elements and $\lambda = 0.8$ in order to judge the PM efficiency of the first hydrolysis coated PM-M brick. It appears that the coated PM-M accounted for 60% of PM mass reduction and allowed the system to reach 81% NOx reduction. Therefore the second uncoated PM-M brick allowed with the additional NH₃ mixing and distribution the extra 7% NOx efficiency of the complete SCRi® system.

Furthermore, PM number emissions with the SCRi® system have been checked. A PM number reduction of 82% has been observed, which is not enough to reach the limit value in discussion. Therefore further investigations on PM number are ongoing.

SCR REDUCING AGENT DOSING SYSTEM

In order to completely manage the development of SCR or SCRi® systems, a complementary reducing agent dosing system has been developed and consists of the following main components:

- Tank / Uptake pipe
- Dosing unit
- Injection nozzle
- Sensors and control unit

The layout and control of the system allow it to be installed as a stand-alone version (with its own sensors) or as original equipment (integrated in the vehicle's electronic system) as shown in Fig. 10. The individual components can be used in passenger cars (12-volt system) and commercial vehicles (24-volt system) and are easily adaptable (e.g. a vehicle-specific tank).

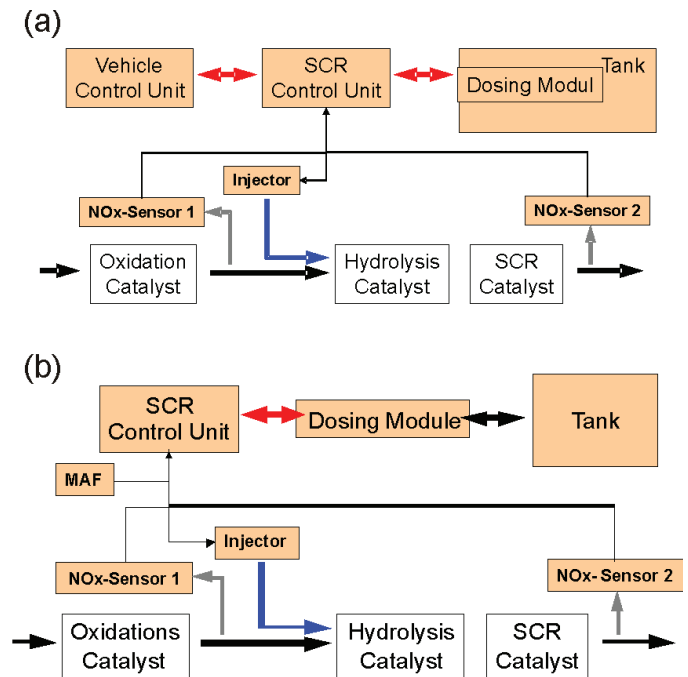


Figure 10. Examples of System Layout (A) Passenger Car, Integrated / (B) Heavy Goods Vehicle, Stand-Alone

The individual components of the SCR dosing system and their functions are described below.

Tank / Uptake pipe

A modular system was developed because the tank geometry and size (volume) depend on the type of vehicle and the available installation space. The aqueous urea solution is extracted from the tank via the uptake pipe. Its length can be adapted to take account of the tank geometry. The heating system and a level/quality sensor are integrated in the uptake pipe. Since the power requirement of the heating system depends on the length of the uptake pipe and cannot always be covered by the control unit, the power electronics have been integrated in the uptake pipe (Fig. 11). The heating system consists of PTC elements (positive temperature coefficient elements – conductive materials that conduct electricity better at lower than at higher temperatures), eliminating the need for additional temperature control.

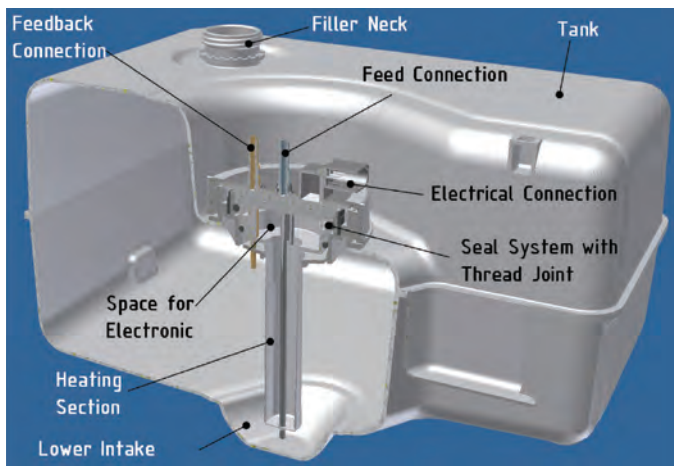


Figure 11. Sectional View of Tank with Uptake Pipe

Dosing Unit

The compact dosing unit is mounted to a base plate and can be fitted to the tank or installed elsewhere in the vehicle as a stand-alone version. This flexible design means that the units can be included in a wide range of different vehicles as original equipment or retrofitted and adapted to the available space.

The aqueous urea solution is filtered in the unit and compressed by a diaphragm pump to the pressure required for atomizing in the injection nozzle. This process is monitored by an integrated temperature/pressure sensor (Fig. 12).

The dosing module is connected to the tank via flexible hose lines and allows the aqueous urea solution to be drawn out of or, if necessary, pumped back into the tank. The hose lines, including connectors, are heated; the heating and defrosting strategy is controlled by the control unit and the sensors. A hose line of identical construction runs from the dosing module to the injection nozzle. The length of the hose lines can be adapted to the model and size of the vehicle.

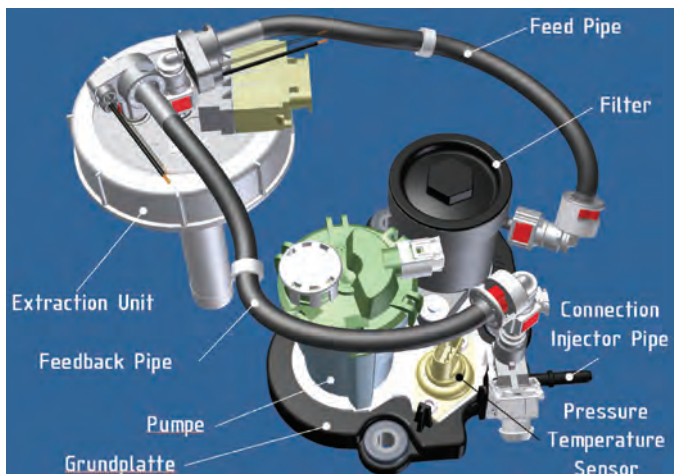


Figure 12. Assembly of Dosing Unit

Injection Nozzle

The injection nozzle feeds a defined amount of aqueous urea solution into the exhaust gas mass flow. The efficiency of the system is determined not just by the amount of urea solution but also by the droplet size distribution, the spray cone, the temperature of the exhaust gas and the geometry of the exhaust system. The injection nozzle (Fig. 13) used in this system has been designed and constructed with a constant opening time and a variable closing time. The duration of the opening time and the system pressure allow a defined amount of reducing agent to be injected into the exhaust gas.

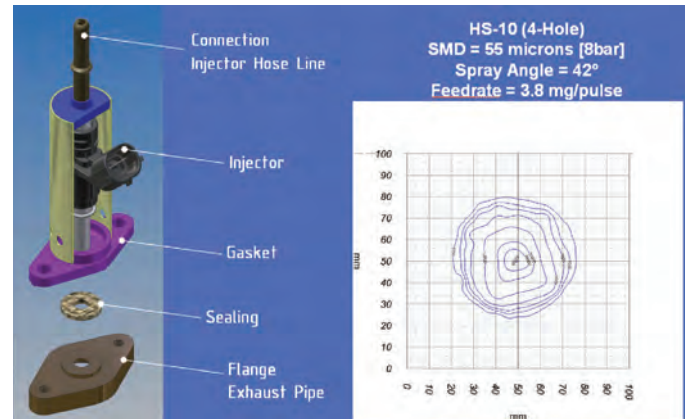


Figure 13. Injection Nozzles and Technical Data

Sensor and Control Unit

The dosing system requires sensors and a control unit (Fig. 14) to operate effectively.

Depending on the degree of integration in the vehicle's electronics, the system relies on information from the vehicle's management system or from additional sensors. The control unit has a modular program structure to calculate the requirement and supply of reducing agent (Fig. 15).



Figure 14. View of the SCR Control Unit- Courtesy from Continental

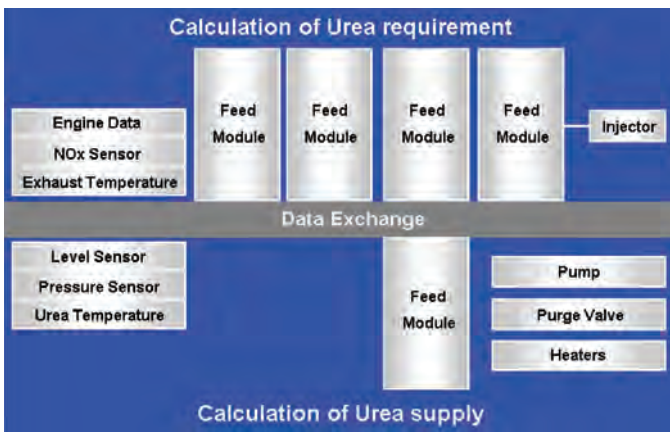


Figure 15. Control Unit – Assembly Model

Due to the wide range of different applications the control units of individual modules were programmed with corresponding models/characteristics allowing the application to be specifically parameterised. In addition to the self-check of the control unit and the sensors when the system is activated, further logical functions (actions and reactions between sensors and control unit under operating conditions) have also been integrated. The basic version of the control unit (independent control) requires the following sensors/information:

External information

- Air and exhaust gas mass flow
- NOx levels before SCR
- NOx levels after SCR
- Temperature of oxidation catalyst
- Temperature of SCR catalyst

Internal information

- Tank level
- Quality of reducing agent
- System pressure
- System temperature

Application Example

Capabilities of the dosing system have been demonstrated, combined with a SCRi[®] catalyst system on a multi-purpose vehicle (Multicar) [21].

This combination produced a retrofit system that upgraded the original EU IV vehicle with a DPF into an EU V EEV vehicle as shown in Fig. 16 and 17 with a NOx conversion rate above 80% and a PM reduction rate of about 75% in ETC.



Figure 16. The Multicar Test Vehicle Including the Installation of the SCRi[®] Catalyst System and the SCR Dosing System Under the Loading Area for Retrofit [21]

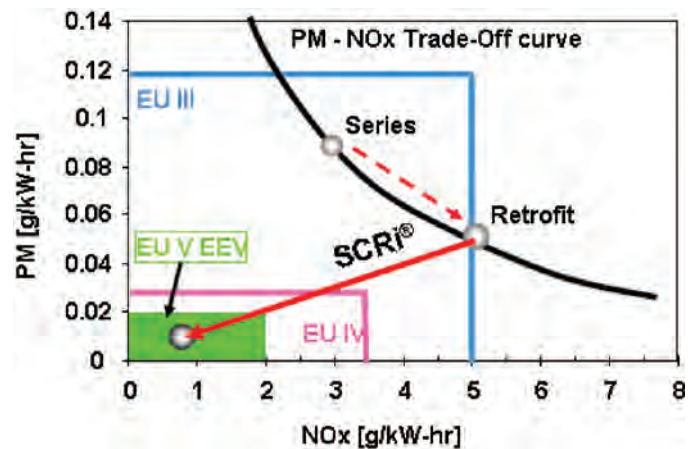


Figure 17. Retrofit Strategy and Achievement with SCRi[®] Catalyst System and Reducing Agent Dosing System: The Engine Calibration has been Changed to Lower PM Engine Out Emissions and Higher NOx Engine Out Emissions (i.e. Lower Fuel Consumption)

PROPOSED ROAD MAP FOR EMISSION CONTROL SOLUTIONS FOR INDIAN HEAVY DUTY DIESEL APPLICATIONS

Indian emission legislation for On road - and Non road - Diesel Heavy Duty is derived from the European emission legislation.

On Road applications

Indian legislation (Fig. 18) is regionally applied: Bharat Stage III (BS III) for the entire nation and the more severe Bharat Stage IV (BS IV) for the major Indian cities, by 2010.

Diesel engines for BS III regulation are essentially engines integrating electronic fuel injection system such as the Bosch

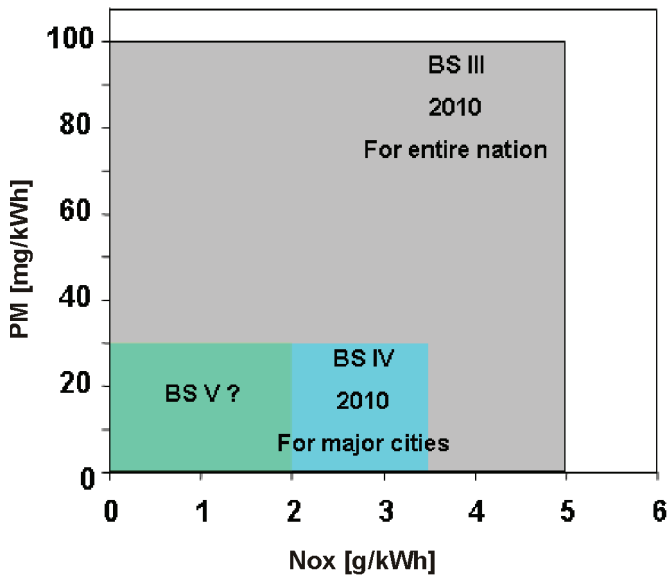


Figure 18. India- On Road Diesel Heavy Duty Emission Legislations (in ETC). Proposed Bharat Stage V is here an Assumption, Assuming Indian Legislation would follow European Legislation Progress

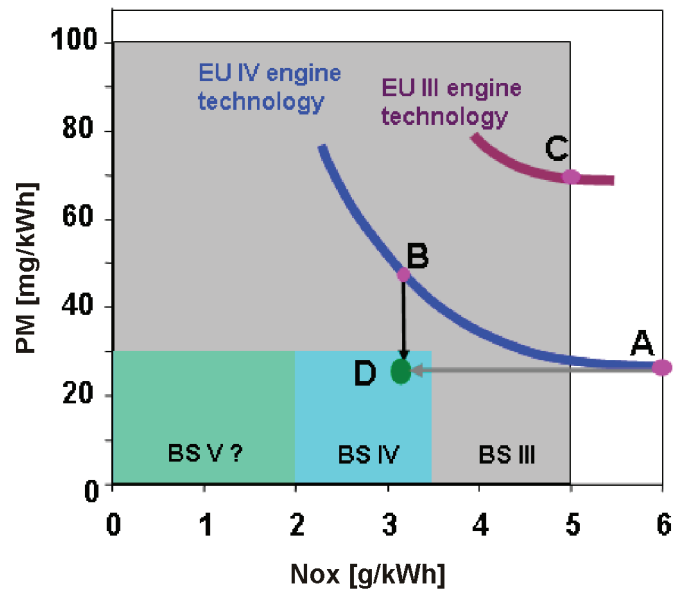


Figure 19. Examples of PM- NOx Trade off Curves for EU III and EU IV Engines

VP37 electronic pump or the common rail technology [22], but without exhaust gas after treatment components. However, the few BS III engines, resulting from upgrade of a BS II engine with its robust and cost effective mechanical low pressure fuel pump, which can prevent any break down due to the admission of different fuel quality found in remote area of developing countries, are equipped with an oxidation catalyst to control the Carbon Monoxide, Hydrocarbons and PM by oxidation of the soluble organic compounds [23]. For BS IV engines with SCR/EGR are developed. These engines are requires two types of exhaust gas after treatment systems depending on the starting point on the engine PM -NOx trade off curve. Fig. 19 shows an example of PM-NOx trade off curve for such engines on ETC. Starting from point A, an SCR system with almost 50% efficiency would be required. From point B an oxidation catalyst and the PM Metalit[®] as p-DPF with a particle reduction efficiency of 50% would fulfil the requirements. The choice between both solutions will be motivated by low fuel consumption in case of SCR solution or by a passive after treatment system without maintenance for the second solution.

It may be desired to equip a BS III engine with the most appropriate exhaust gas after treatment in order to fulfil BS IV. In that case, starting from point C in Fig. 19, a PM and NOx reduction efficiencies of 64% and minimal 30%, respectively, are required. Therefore an SCRi[®] system could fulfil the requirements. It must be said here, that point C

is not fuel consumption optimized and a starting point at higher NOx emission level, corresponding to lower fuel consumption, could be selected by implementing a SCRi[®] with a higher NOx reduction efficiency.

As shown in Fig. 18 and 19 PM and NOx emission limits for Bharat stage V are assumed to be following European legislation Stage V. These limits could be fulfilled by increasing the NOx reduction efficiency up to 75% and 68% for the SCR system in case of engine starting point A or engine starting point C, respectively. Engine starting point B will be ignored for BS V because the addition of SCR in the exhaust line will require optimization of the fuel consumption followed by a move to the engine starting point towards A. Alternatively if we assume that BS V would be similar to EU V EEV (20 mg/kWh PM, 2.0 g/kWh NOx) which could represent a more balanced legislation stage with a further reduction of PM as well as NOx, then an SCRi[®] system, according to previous results, would allow the BS IV engine to fulfil the emission requirements.

Non Road Application

As shown in Figure 20 the emission legislation stage BS III is enforced in 2010 and 2011. Emission limits are equivalent to those of EU III. For such applications exhaust gas after-treatment systems are not required. For the next legislation stage, which is still to be defined, solutions for On Road applications might be adapted.

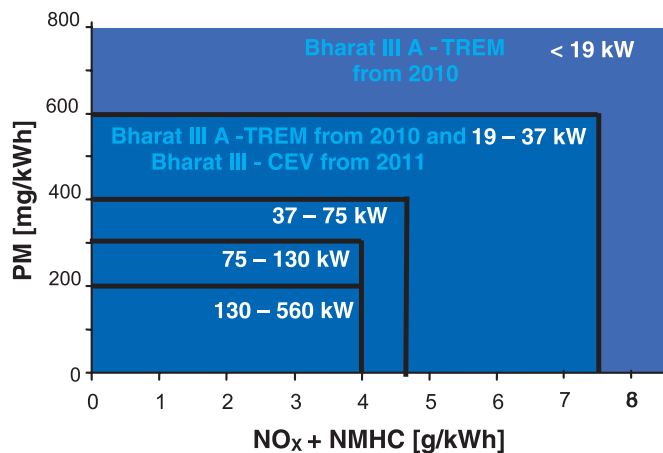


Figure 20. India- Non Road Mobile Machinery Emission Legislations (Agricultural Tractor Emission: Trem, Construction machinery Emission: CEV)

CONCLUSIONS

Highly efficient SCR systems will help today automotive development engineers to manage two tasks:

- allow the development of low CO₂ emitting diesel engine, by choosing combustion mode that optimizes fuel consumption instead of NO_x emission reduction
- reduce tail pipe NO_x emissions to the level required by tightest emission legislations

Metal structured “turbulent” substrates, particularly the substrate with the longitudinal structure LS, have demonstrated good performances that outperforms standard substrates with smooth channels, which allows the design of more compact efficient SCR catalysts for On-road and Off-road applications.

The SCRi® technology, which integrates a partial flow deep bed filter PM-Metalit® into SCR systems, can treat in parallel up to 80% of the particles. Furthermore the PM-Metalit®, by receiving a hydrolysis coating, plays an important role in the preparation and distribution of NH₃.

An SCR reducing agent management system, consisting in a tank / uptake pipe, a dosing unit, an injection nozzle, sensors and a control unit, has been presented. Together with relevant catalyst technologies, this would allow engineering complete SCR or SCRi® applications for original equipment (as integrated in the vehicle’s electronic system) or for retrofit systems (as stand alone).

Based on application developments in Europe, a road map for emission control solutions for the specific situation of India has been recommended using SCR and SCRi® systems, depending on the base engine technology level.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ETC: European Transient Cycle
EEV: Enhanced Environmentally Friendly Vehicle

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