NOx-free Exhaust Gas – AdBlue Dosing is the Key

1. Abstract

Exhaust emissions from diesel engines in automotive applications have been dramatically reduced in the new millennium. The hydrocarbon, carbon monoxide and particle concentrations emitted by EURO 6/VI diesel engines are in some cases lower than those in the ambient air, which means that, in terms of these emissions, the engines do not pollute the environment. Unfortunately, the same cannot yet be said for nitrogen oxide (NOx) emissions. A comparison between the European air quality immission limit for NO2 (40µg/m³) and the Euro 6/VI limits for NOx would reveal that the exhaust gas of EURO VI/6 engines is allowed to contain approximately 3 orders of magnitude higher NOx concentrations. The US, specifically California, is taking one step further with another 90% reduction in NOx limits through the introduction of SULEV legislation and the current debate on limits for commercial vehicles in California from 2020.

As a result, the development of future emission control will shift its focus toward NOx reduction, which must go hand in hand with the requirement for further reductions in CO2 emissions, fuel consumption and system costs. As a key technology for NOx reduction, SCR will have to be integrated in future powertrains in such a way as to reduce NOx emissions by ≥98% in a wide engine map range without increasing fuel consumption. In addition to further improvements to SCR catalyst technology, this also requires the precise metering, evaporation and deposit-free decomposition of the reducing agent AdBlue to form the actual reductant ammonia in a system with minimum space requirement. To complicate matters further, the effectiveness of exhaust aftertreatment has to be checked in practically the entire engine map range in accordance with European legislation brought in with the introduction of Real Driving Emissions (RDE) for passenger cars and In Use Compliance requirements for commercial vehicles.

This paper describes how the above challenges can be met by systems based on counterflow reducing agent injection combined with pre-turbocharger designs and presents and discusses the results of comprehensive calculations and tests, including RDE, for concept development.

2. Introduction

While just about one in two people chooses a diesel when buying a new car, diesel engines dominate the commercial vehicle market. There is no alternative to their power density and torque characteristics combined with maximum fuel economy, and hence minimum CO2 emissions, in the commercial vehicle sector. Pure driving pleasure is a major reason behind the success of diesel engines on the passenger car market.

Recent studies have shown that diesel cars in Germany are well ahead of electric vehicles in terms of CO2 emissions caused by the generation of electricity with the current power station mix [1]. Even modern natural gas-powered vehicles cannot beat the CO2 levels of comparable diesel cars [2].

The way forward is to combine diesel engines and electric drives to recuperate braking energy and focus the engine map range on optimum fuel consumption. As a result, diesel
engines will remain an integral component of the powertrain, and their number will continue to grow worldwide until 2050 [3].

Besides excellent fuel consumption, diesel engines have also become an environmentally friendly power source since the cross-market introduction of diesel particulate filters. Exhaust aftertreatment can reduce the concentrations of carbon monoxide, hydrocarbons and ultrafine particles in modern Euro6/VI diesel engines to levels that in some cases are lower than those in the ambient air in European cities.

Unfortunately, the same does not apply to NOx levels, where concentrations are much higher in the exhaust gas than in the ambient air. Together with ozone and particulate matter, NO2, an irritant gas, is one of the three most hazardous substances in the air, which according to EU estimates is responsible for over 400,000 premature deaths in Europe alone. According to Brussels, some 90 per cent of all city dwellers in the EU are said to be exposed to exhaust gas concentrations the World Health Organisation considers to be dangerous [4]. A study by the German Federal Ministry for the Environment [5] expects that the measures that have already been taken will reduce NO2 immissions by a sufficient extent by 2030 so that there should be no need for a further significant reduction of the Euro 6/VI limits for NOx. However, in future greater emphasis will be placed on compliance with emission limits under real-life driving conditions. The challenges for current and future developments are Real Driving Emission (RDE) legislation for passenger cars and In Use Compliance (IUC) requirements for commercial vehicles.

In the US, the potential hazard of NOx is considered to be even more critical, which has led to SULEV 20 legislation for passenger cars and the current debate on a further optional reduction of NOx limits for commercial vehicles in California by up to 90% [6].

The challenge facing the automotive industry and engine manufacturers is to realise the lowest possible NOx emissions and minimum CO2 emissions at the same time.

SCR technology has established itself as a highly efficient means of reducing NOx through exhaust aftertreatment. Large-scale production began in 2005 when EU IV legislation for commercial vehicles was adopted in Europe. This was soon followed by the first non-road applications for Tier 3 or Stage III A guidelines in 2008, EU Stage III B in Europe from 2010 and TIER4i in the US from 2012 [7]. SCR technology in combination with diesel particulate filters was introduced for passenger cars in the US in 2008 to meet TIER II BIN 5 limits and in Europe in 2010 to comply with EURO 6 legislation. Today, SCR technology is the dominant form of aftertreatment for NOx reduction. It relies on highly active catalysts, precise metering of the reducing agent, subsequent decomposition of the aqueous urea solution and uniform distribution of ammonia, as the actual reducing agent, in front of the SCR catalyst to achieve the necessary high NOx reduction rates. These are challenges that require highly sophisticated technical solutions to address the lower exhaust gas temperatures of more efficient combustion and produce increasingly compact exhaust aftertreatment systems to fit into the limited available space.

There are various potential measures that can be used individually or in combination to achieve the high level of NOx reduction required.

- Integration of a component in the exhaust system that is able to store NOx at low temperatures and desorb it again in the SCR operating range (a combination of NOx storage catalyst and SCR).
- Raising the exhaust gas temperature to ensure efficient SCR operation through engine-based measures (temperature management) – although this is associated with higher CO2 levels – or through the use of an electrically heated catalytic converter.
Positioning the oxidation catalyst, the injection of the reducing agent and the SCR catalyst close to the combustion, if possible in front of the turbocharger, which is a major temperature sink at least at low load.

In view of the fact that the temperature required for the evaporation and decomposition of the reducing agent is higher than that required for the activation of the SCR catalyst, the optimum position for the reducing agent injection and the diesel oxidation catalyst (DOC), in terms of exhaust aftertreatment, would be in the direction of flow in front of the turbine despite the obvious thermodynamic disadvantages for the turbocharger and, particularly, for transient engine operations.

Turbocharging technology currently in development, such as electrically assisted turbochargers or electric compressors, and the electric motor in hybrid drives have the potential to compensate for the thermodynamic disadvantages affecting engine dynamics. The following sections examine the options for incorporating catalytic converters and dosing systems in the exhaust line and set out the first basic principles for this approach with the aid of test and simulation results.

3. State-of-the-art technology

The following subsections describe finished designs and those still at the planning stage, specifically the universal decomposition pipe (UDP) for commercial vehicle engines and the CompactCat® with counterflow injection for passenger cars.

3.1. Universal decomposition pipe (UDP)

While close-coupled catalytic converters have become part of the standard configuration in the passenger car industry, frame-mounted, downstream silencer systems with integrated exhaust aftertreatment components represent the state of the art in the commercial vehicle sector. Modular close-coupled catalytic converter technology was successfully brought in for agricultural machinery with the introduction of Tier 4i and EU Stage IIIB legislation to address the lack of installation space [8]. Irrespective of its configuration, the exhaust aftertreatment system must reduce NOx levels by substantially more than 90%. New technologies, such as SCR-coated diesel particulate filters, and the call for further reductions in system costs and weight require catalytic converters with greater volumetric efficiency, which can be achieved in part by optimising the preparation of the injected reducing agent. Accordingly, the quality of reducing agent injection is an essential factor for highly efficient SCR technology.

The process of adding reducing agent can be divided into the following steps:

- Injection of the aqueous urea solution (AUS)
- Evaporation of water
- Thermal decomposition of the urea to form isocyanic acid and ammonia
- Formation of ammonia and carbon dioxide from isocyanic acid and water (hydrolysis)
The evaporation process is particularly important because as long as liquid components can condense on cold surfaces in the exhaust system there is an increased risk of manifold wall film formation and, ultimately, deposit formation. This limits the maximum dosing quantities for the aqueous urea solution when operating at low temperatures. At best, the deposits consist of solid urea, which can evaporate again at higher temperatures, however, often they are made up of more complex compounds such as biuret, ammeline, ammelide and cyanuric acid, which can no longer be decomposed under normal driving conditions. Therefore, the temperature-dependent conditions to initiate dosing represent a compromise between NOx reduction at low exhaust gas temperatures and the prevention of manifold wall fuel condensation and deposit formation in the exhaust system.

In order to make the process of adding reducing agent as efficient as possible, Continental-Emitec developed a design for a universal decomposition pipe (UDP) with the following aims:

- All of the above-mentioned functions of reducing agent dosing and initial mixing of reducing agent and exhaust gas to be combined in a single module
- Compact construction and flexible integration in a wide variety of applications
- Operation irrespective of the system configuration above the UDP or the incoming flow
- Reliable droplet evaporation on a hot surface
- Maximisation of the evaporation surface through the use of a metal substrate
- Improvement of evaporation and decomposition through the application of a hydrolysis coating
- Maximum backpressure increase of 25 mbar

Figure 1 shows the basic configuration of the UDP. The injector for the aqueous urea solution is positioned in a wedge-shaped widening of the casing (cockpit) perpendicular to
the gas inlet side of the MX metal substrate with a hydrolysis coating. The channels in the MX metal substrate are partially closed by guide blades so that the injected droplets reach a hot surface. The flat layer has been perforated to allow the gas to flow from one channel to the next, which helps mix the reducing agent with the exhaust gas. The partially closed channels also keep the rise in backpressure at a low level. The confusor is an additional component that aligns the flow toward the MX metal substrate at the gas inlet side and also generates backflow in the cockpit, which removes the droplets from the tip of the injector to prevent the formation of deposits at the back of the cockpit.

Figure 2: The effect of different UDP configurations on the maximum deposit-free AUS dosing quantity and the NOx reduction potential

The important design parameters include the distance between the injector tip and the gas inlet surface of the MX-Metalit®, the injector spray angle and the mass distribution of the aqueous urea solution on the impact surface of the MX-Metalit®. These parameters determine the local heat transfer and hence the evaporation and, ultimately, the susceptibility for deposit formation. Figure 2 shows the effect of the UDP configuration on the maximum deposit-free AUS dosing quantity. Starting with an empty tube for different UDP designs, the AUS dosing quantity was increased on the engine test bench at a low load operating point (see table in figure 3) until deposits were detected. The test involved a UDP with a 90 mm long MX-Metalit® and a UDP with a 74.5 mm long MX-Metalit® and an additional upstream electrically heated catalytic converter (EHC). The EHC was set to operate without heating and with an electrical output of 1.7 kW.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1/min 1200</td>
</tr>
<tr>
<td>Md</td>
<td>Nm 300</td>
</tr>
<tr>
<td>SCR catalyst temp.</td>
<td>°C ~205</td>
</tr>
<tr>
<td>SV (SCR catalyst)</td>
<td>1/h ~23000</td>
</tr>
<tr>
<td>DEF @ alpha = 1</td>
<td>g/h 880</td>
</tr>
</tbody>
</table>

Figure 2: The effect of different UDP configurations on the maximum deposit-free AUS dosing quantity and the NOx reduction potential
The additional installation of an MX-Metalit® was found to increase the NOx reduction potential by several factors. The addition of heating enabled deposit-free NOx reduction of over 15 g of NOx/kWh for the tested load point.

3.2. CompactCat® with counterflow injection

RDE legislation for passenger cars imposes a requirement for maximum emission reduction, especially the reduction of NOx, in the entire engine map. Without compact and modular powertrain design it would be impossible to produce today’s wide range of models demanded by customers. Highly compact solutions were developed by Volkswagen for their modular transverse matrix [9] and by Volvo Car for their four-cylinder petrol and diesel engines [10].

One of the requirements for the integration of SCR technology in such compact, close-coupled exhaust systems was the introduction of SCR-coated diesel particulate filters. However, space constraints inherent in the design place very high demands on the injection of the reducing agent to prepare the reducing agent as described above. The CompactCat® with counterflow injection described here is a possible solution.

![Configuration of a CompactCat® system with counterflow injection](image)

**Figure 3:** Configuration of a CompactCat® system with counterflow injection

As shown in figure 3, the first catalytic converter, either an oxidation catalyst or an NOx storage catalyst, is positioned directly behind the turbine. The direct inflow produces excellent uniform flow distribution in front of the catalyst inlet surface. The surrounding jacket ensures that the gas also flows around the catalyst and so provides high thermal insulation. Minimum radial heat losses combined with excellent inflow increase effectiveness and reduce heat loss during deceleration. The coneless interface with the SCR-coated particulate filter serves as a mixing chamber and leads to only a minor increase in exhaust backpressure despite the large flow cross-sections and the deflection of the flow by 180°.

The reducing agent is fed through an injector positioned in the direction of flow behind the first catalytic converter. The spray is directed against the flow and onto the hot gas outlet side of the catalyst where the reducing agent evaporates. Approximately 20 mm of the rear
end of the catalyst has a hydrolysis coating to ensure effective evaporation and decomposition. This dosing method requires specific spray and injector characteristics.

- **Droplet distribution:**
  All droplets must reach the catalyst outlet area. Due to the angle between the injector axis and the catalyst outlet the droplets have to travel different distances to the gas outlet surface. The momentum of each droplet has to be large enough for the majority of the injected reducing agent to reach the catalyst outlet area at all load points and so ensure complete evaporation/conversion on the hydrolysis coating.

- **Homogeneous distribution of the injected reducing agent quantity on the catalyst outlet area:**
  The evaporation enthalpy of the droplets leads to a local drop in temperature on the catalyst surface. The energy provided by the exhaust gas must be able to compensate for this drop in temperature to prevent potential deposit formation. This can be achieved by maximising the wetted surface area and by ensuring that the mass distribution on the wetted surface is as homogeneous as possible.

![Figure 4: Illustration of flow lines for a fixed point in time (exhaust mass flow 272 kg/h, exhaust gas temperature 397 °C)](image)

The tests described below used a developmental 8-hole injector with a spray cone angle of 28° x 36°, which produced an average (SMD) droplet diameter of 130 µm at the selected operating point. This is how the limiting conditions for the required injection quantity described above were realised. As shown in a CFD analysis (figure 4), the evaporated reducing agent and the exhaust gas are conducted around the oxidation catalyst. This increases the useful flow length for the reducing agent to decompose and mix with the exhaust gas. The convergence of the partial flows in front of the SDPF generates toroidal flow that provides for ideal mixing behaviour.
The CFD analysis was validated by tests on the engine test bench. A CompactCat® system with counterflow injection was integrated in the exhaust system of a 1.5-litre production diesel engine. The system included an oxidation catalyst with a hydrolysis coating (Ø114 x 140 mm, 300/600 LS with 50 µm foil thickness) and a downstream SCR catalyst.

NH₃ distribution was measured with FTIR measuring equipment, which was connected to a twin-axis positioning system to measure the concentration distribution behind the SCR. The NH₃ distribution in front of the SCR catalyst was determined by mass balance calculations.

The results for three load points are shown in figure 5. Uniformity indices between 0.943 and 0.967 confirm that the flow generated in the CompactCat® produces highly uniform NH₃ distribution, which eliminates the need for an NH₃ mixer.

4. Design for an oxidation catalyst and reducing agent injection in front of the turbine

4.1. Current state of knowledge

The logical next step to meet the challenge of low exhaust gas temperatures in the exhaust system is to position the catalytic converters in front of the turbine. Tests have shown that this type of integration is possible with careful design and construction. One such example is the positioning of a conical oxidation catalyst with a volume of one litre in front of the turbine of a 2-litre Euro 5 common rail diesel engine as an alternative to a standard catalytic converter positioned behind the turbocharger [11] [12].
A pre-turbocharger position resulted in a crucial temperature advantage in the NEDC. In this position, the temperature difference in front of the catalytic converter was up to 100 K in the first 800 s during acceleration and up to as much as 125 K afterwards.

This positive effect overcompensated for the 25 to 30 K lower temperatures during deceleration that were due to faster cooling. Figure 7 shows the positive impact of these measures on emissions [11][12].
The integration of a catalyst volume of between 0.5 l and 1 l in front of the turbocharger inevitably changes pressure ratios in front of the turbine and also introduces additional thermal capacity and affects the dynamic behaviour of the turbine. This raises the question as to whether and to what extent this negative effect can be neutralised.

A number of solutions were trialled during the course of the tests described above. When load was ramped up (from a BMEP of 2 bar to full load), the VTG control was adjusted (limiting the maximum adjusting range of the VTG or restricting the reduction of the turbine opening cross-section when load was ramped up) and the exhaust system in front of the turbocharger was heated. The combination of these measures, tested on a 0.5-litre conical catalytic converter, was able to partially compensate for the negative effect on turbocharger dynamics (see figure 8) [12].

Figure 8: Top: Load ramp-up with adjusted turbocharger control and varied heating (from 2 bar BMEP to full load at n = 2000 min⁻¹)
Bottom: Acceleration from 70 to 120 km/h in fifth gear with adjusted turbocharger control

The adjustment of the VTG control was repeated during acceleration from 70 km/h to 120 km/h with similar results.

In future, the above-mentioned dynamic disadvantages could conceivably be compensated for by an electrically assisted turbocharger or an electric compressor. Positioning the exhaust aftertreatment in front of the turbocharger is an attractive approach, especially for hybrid vehicles. The combustion engine could operate in an essentially stationary mode over great distances while the electric motor provides the driving dynamics. In this scenario, the driver would not be able to detect any dynamic disadvantage.
4.2. SCR limiting conditions and operating parameters

Knowledge of influencing factors and limiting conditions that affect SCR efficiency is essential when it comes to optimising SCR function. The temperature range for SCR catalyst activation, which is determined by the available surface area and the SCR coating, plays a crucial role. Cu-zeolite coatings are particularly effective in the low temperature range and ensure fast light-off. As shown in figure 9, modern coatings achieve NO\textsubscript{x} conversion rates of approximately 65% at as little as 140 °C and of almost 90% at 165 °C when the NO\textsubscript{2}/NO\textsubscript{x} ratio is 50% [13].

![Figure 9: NO\textsubscript{x} conversion after ageing (64 h at 750 °C) with a modern Cu-zeolite coating and an NO\textsubscript{2}/NO\textsubscript{x} ratio of 50% [13]](image)

The dosing strategy must take account of these limitations because to be effective dosing should start only when the temperature in front of the Cu-zeolite catalyst has risen above approximately 140 °C to 160 °C. In addition, the NO\textsubscript{2}/NO\textsubscript{x} ratio in front of the SCR catalyst should be sufficiently high.

NO\textsubscript{x} conversion rates are also influenced by the ammonia storage capacity of the SCR catalyst. This can support NO\textsubscript{x} conversion in temperature ranges in which the injected dosing quantities are limited and has to be considered in the dosing strategy. Maximum conversion relies on uniform distribution of ammonia in the exhaust gas in front of the catalyst. Static mixers that homogenise the ammonia concentration are a standard solution, however, they cause an additional increase in pressure. This raises the question as to whether a skilfully designed exhaust system could make such components dispensable.

To sum up, it can be said that the SCR catalyst is able to achieve significant NO\textsubscript{x} reduction rates from approximately 150 °C if the NO\textsubscript{2}/NO\textsubscript{x} ratio is sufficiently high and there is still an adequate amount of ammonia (including stored quantities) homogeneously distributed in the exhaust gas.
4.3. System description for the evaluation of pre-turbocharger DOC/AUS systems

The tests described below were carried out on the engine test bench using a pre-series 2-litre Euro 5 diesel engine with a performance of 110 kW.

A total of 3 exhaust aftertreatment systems (shown in figure 10) were tested:

- **STANDARD**: This configuration corresponds to a typical Euro 6 application except for the reducing agent injection. The DOC is positioned close to the engine directly behind the turbine. The reducing agent is injected against the flow onto the gas outlet side, which has a hydrolysis coating. This is followed by a mixer structure and the SDPF.

- **PRE TURBO**: DOC and reducing agent injection are positioned in front of the turbine. In addition, an MX-Metalit® has been installed directly in front of the turbine inlet to protect the turbine against droplet impact. The MX-Metalit® also has a hydrolysis coating (figure 11). The mixer structure behind the turbine was dispensed with. The position of the SDPF is identical to the Standard configuration.

- **PRE TURBO PLUS**: An SCR catalyst volume was installed directly behind the turbine as an addition to the Pre Turbo configuration. The aim is to demonstrate the advantage of connecting an SCR catalyst volume directly to the turbine. An LS/PE structure was chosen to ensure fast light-off. Although this structure has a smaller available surface, it also has a very low specific thermal capacity and helps heat downstream components.

*Figure 10: The different exhaust system configurations used in the tests*
The table below contains information about the components used.

<table>
<thead>
<tr>
<th>Component</th>
<th>Diameter x length [mm]</th>
<th>Cell structure</th>
<th>Wall thickness [µm]</th>
<th>Volume n [l]</th>
<th>Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOC</td>
<td>114.4 x 95</td>
<td>300/600 LS</td>
<td>40</td>
<td>0.98</td>
<td>Series</td>
</tr>
<tr>
<td>Hydrolysis disc</td>
<td>118 x 10</td>
<td>300/600 LS</td>
<td>40</td>
<td>0.10</td>
<td>TiO₂</td>
</tr>
<tr>
<td>MX-Metalit®</td>
<td>60 x 50.8</td>
<td>40 cpsi MX</td>
<td>65</td>
<td>0.14</td>
<td>TiO₂</td>
</tr>
<tr>
<td>SCR catalyst</td>
<td>114 x 74.5</td>
<td>300/600 LS</td>
<td>40</td>
<td>0.76</td>
<td>Cu-zeolite</td>
</tr>
<tr>
<td>SDPF</td>
<td>159 x 140</td>
<td></td>
<td></td>
<td>2.78</td>
<td>Cu-zeolite, series</td>
</tr>
</tbody>
</table>

**Figure 11:** Configuration of the exhaust aftertreatment component in front of the turbine

CFD calculations were used to define the position of the injector for counterflow dosing and to develop the initial design of the dosing strategy. The effect of crank angle-related variations in backpressure and mass flow on the quality of the dosing was estimated. A number of different spray characteristics and injection times were examined for their suitability for pre-turbocharger dosing.

In this simulation, the catalytic converters and the turbocharger geometry were replaced by a porous medium with a porosity of 95%. This medium generated a temporal average for the backpressure in front of the turbine for a constant load point. A constant load point
\( N = 2050 \text{ min}^{-1}, 1.8 \text{ bar BMEP} \) was selected and the resulting mass flow at the DOC outlet is shown as a function of the crank angle at the top of figure 12.

The intermittently overlapping exhaust emissions of two cylinder outlets cause excessive mass flow, increased by a factor of two, at the catalyst outlet in a number of crank angle phases. An analysis of the velocity distributions at the DOC outlet reveals a corresponding dependence on the crank angle. It is clear that a particular crank angle phase (in this case 750 °CA – 840 °CA) is associated with good local velocity ratios (low mass flow, good distribution) and hence favourable limiting conditions for droplet injection. A different crank angle phase (1210 °CA – 1300 °CA) produced the opposite result (bottom of figure 12). A larger surface generates velocities \( z \)-component of over 10 m/s so that a higher effect on the trajectory of the injected droplets can be expected.

![Figure 12](image-url)

**Figure 12:** Top: Exhaust gas mass flows in the hydrolysis catalyst as a function of the crank angle
Bottom: 3D flow lines and distribution of the vertical velocity on the outlet surface of the hydrolysis catalyst in a favourable (left) and an unfavourable (right) crank angle phase

However, a direct comparison between the two extremes shows that the dosing of the reducing agent is not very susceptible to variable flow velocities. Figure 13 shows the proportion of liquid droplet mass (in relation to the total injected quantity) arriving at the back of the DOC for both crank angle phases, minus the already evaporated droplet mass.
The maximum droplet mass in the favourable injection phase was found to be 93.88% for the selected injector spray and therefore only slightly higher than that in the unfavourable injection phase (93.46%). This means that at the load point shown here, injection does not have to be determined by prevailing velocity ratios. In both cases, the majority of droplets reach the hydrolysis-coated back of the DOC substrate. At this operating point, a second MX hydrolysis substrate would appear to be superfluous. A test to determine whether this statement applies to the entire engine map has yet to be developed.

![Graph comparing droplet masses](image)

**Figure 13:** Comparison of the droplet masses (in relation to the total injected quantity) arriving at the back of the DOC after injection (\(t_{\text{on}} = 3\) ms) in the favourable (>750 °CA) and the unfavourable (>1210 °CA) phase

The tests subsequently carried out on the engine test bench took account of stationary engine operating points and dynamic testing in the New European Driving Cycle (NEDC). The simulation was based on a vehicle with an unladen weight of 1345 kg. The NEDC was run with both a cold engine and a warmed-up engine.

5. Results

A series of stationary tests with varied AUS dosing were carried out. The selected load points were to cover low temperature and high temperature ranges and different engine load ranges. For LP1 the temperature behind the turbine was set to 180 °C (\(n = 1170\) rpm, 2.14 bar BMEP), for LP2 it was set to 392 °C (\(n = 1750\) rpm, 6.93 bar BMEP).

At 180 °C behind the turbine, the temperature in front of the SDPF stayed below 160 °C. \(\text{NO}_x\) conversion for alpha 1 and 1.2 is given as an example here (see figure 14). The results show that it is impossible to convert \(\text{NO}_x\) with the Standard configuration while the effectiveness of the Pre Turbo design is approximately 10%. Although the temperatures in front of the SDPF were identical in each case, the Pre Turbo design with dosing in front of the turbocharger achieves better ammonia preparation and uniform ammonia distribution.
**Figure 14:** \( \text{NO}_x \) effectiveness for LP1 \((T_{\text{behind\,turbine}} = 180 \, ^\circ\text{C}, \, n = 1170 \, \text{rpm}, \, 2.14 \, \text{bar BMEP}) \) with alpha = 1 and 1.2

The Pre Turbo Plus system makes even better use of the temperature advantage: the option of installing an additional SCR catalyst directly behind the turbocharger (where temperatures are approximately 20 K – 30 K higher than in front of the SDPF) leads to early light-off. The conversion rates of this design are approximately 20% for alpha = 1.

**Figure 15:**

- **Left:** \( \text{NO}_x \) emissions for LP2 \((T_{\text{behind\,turbine}} = 392 \, ^\circ\text{C}, \, n = 1750 \, \text{rpm}, \, 6.93 \, \text{bar BMEP}) \) depending on alpha measured with a CLD. Right: ammonia breakthrough measured with an \( \text{NO}_x \) sensor

These results highlight the potential of the pre-turbocharger design. The following improvements could conceivably achieve higher conversion rates in this low temperature
range: optimum configuration of the SCR catalyst directly behind the turbocharger, application of a suitable Cu-zeolite coating as described in section 4.2 and a supply of sufficient NO$_2$ in front of the SCR catalyst. Figure 15 compares the conversion behaviour of the Standard design with that of the Pre Turbo design for LP2 by showing the relevant NO$_x$ concentrations in front of the oxidation catalyst and behind the SDPF.

The left of figure 15 contains the results of the chemiluminescence detector (CLD) measurement. This measurement is unlikely to be affected by ammonia slip whereas the results of the ammonia cross-sensitive NO$_x$ sensor measurement, shown on the right, reveal increasing ammonia slip. Ammonia breakthrough occurs from alpha = 1.4 in the Pre Turbo Plus design. The Standard system is expected to be subject to ammonia breakthrough from as little as 0.8 because there is a noticeable difference between NO$_x$ sensor and CLD measurements despite a decreasing NO$_x$ concentration behind the SDPF. This points to less uniform ammonia distribution.

The advantages of the Pre Turbo Plus exhaust system are clearly evident. The NO$_x$ levels behind the SDPF measured by the CLD are already almost 0 ppm at alpha ~ 1.1. This is an indication of excellent uniform ammonia distribution by the turbine. The Standard system displays a reduction in NO$_x$ emissions behind the SDPF up to alpha = 2 but without coming anywhere near the level of the Pre Turbo Plus system. By comparison, the NO$_x$ conversion rate of the Pre Turbo Plus design was approximately 93% at alpha = 1 while it was approximately 63% with the Standard exhaust system.

The curve of the NO$_x$ engine-out emissions, that is, in front of the oxidation catalyst, is shown in figure 16. The curves are almost identical irrespective of the measuring method and the system configuration, which is an indication of the good reproducibility of the
measurements. However, NO\textsubscript{x} concentrations decrease as alpha increases. The decrease of the NO\textsubscript{x} concentration in the recirculated exhaust gas caused by the low pressure EGR system reduces engine-out emissions with increasing conversion rates. Figure 16 compares the results with and without low pressure EGR. The engine is also fitted with high pressure EGR, which, however, is not active at this operating point. While NO\textsubscript{x} engine-out emissions without EGR are much higher but unaffected by alpha, NO\textsubscript{x} emissions with EGR display the previously observed behaviour. Besides, even without EGR, NO\textsubscript{x} conversion rates in the Pre Turbo Plus system are extremely high with a substantially greater dosing quantity.

![Figure 16: Light-off behaviour as a function of DOC position in the engine sweep test (n = 1500 rpm; BMEP from 0 to 6 bar)](image)

For light-off characterisation, the systems were heated on the engine test bench by increasing the engine load at a constant 1400 rpm. During the test, the exhaust gas mass flow increased steadily from 55 kg/h to 80 kg/h and the exhaust gas temperature rose from 120 °C to over 300 °C at 2.5 K/min. As a result of increasing exhaust gas mass, the DOC space velocities rose from 44k 1/h to 80k 1/h and the space velocity in the SDPF from 15k 1/h to 33k 1/h. Figure 17 shows the measured HC and CO conversion rates as a factor of the exhaust gas temperature behind the turbine. If the oxidation catalyst is positioned behind the turbine, CO light-off starts at 120 °C and achieves almost 100% conversion at 180 °C. At the same time, hydrocarbons are adsorbed at low catalyst temperatures during the initial stage; and the HC conversion rate first drops and then rises steadily to almost 100% from 170 °C. This temperature drop across the turbine explains the light-off advantage of a pre-turbocharger/DOC configuration. HC and CO conversion rates exceed 85% even at very low loads due to the 35 K higher temperature level. The different systems were also tested in the NEDC. Prior to the tests, the exhaust systems were preconditioned to be ammonia-free at higher loads. Figure 18 shows the
exhaust gas temperatures in front of the oxidation catalyst for the different designs in the NEDC.

![Graph showing exhaust gas temperatures and start of dosing for different designs in NEDC.](image)

**Figure 18:** Comparison of exhaust gas temperatures at the inlet of the oxidation catalyst for the different designs in the NEDC

The gas temperatures of the Pre Turbo designs were identical and over 120 K higher than those of the Standard system. The gas reaches temperatures well above 150 °C in front of the turbine at a very early stage. In the Standard system, temperatures briefly exceed 150 °C for the first time after 800 s and only rise to 200 °C after 1050 s.

![Graph showing exhaust gas temperatures and start of dosing for different designs in NEDC.](image)

**Figure 19:** Exhaust gas temperatures and start of dosing for the different designs in the NEDC
To assess the maximum possible NO\textsubscript{x} conversion rate of the systems, the temperature at which dosing starts was set at 130 °C. In the Pre Turbo systems, the reducing agent could be added 65 s after engine start whereas in the Standard system this could not be done until 685 s later. Figure 19 shows the temperature curve at the injector position with start of dosing and the dosing quantities in the NEDC. At the start of dosing the system was overdosed with alpha = 2.0 for 300 s, after which the dosing quantity was reduced to alpha = 1.3. After completing the “cold” NEDC a second test was started with pre-controlled dosing at alpha = 1.3. Finally, a third NEDC with deactivated dosing was started. Through this test sequence, the SCR catalyst was enriched and conditioned with ammonia in the first two NEDC tests. Despite stoichiometric overdosing, no ammonia slip was detected in the Pre Turbo systems until 850 seconds into the second test. By contrast, there was no measurable ammonia slip in the Standard system even after the completion of the second NEDC test, which can possibly be explained by the low temperature level in the SCR catalyst and its correspondingly higher ammonia storage capacity.

![Figure 20: HC, CO and NO\textsubscript{x} conversion rates in the NEDC](image)

The higher temperatures reached with pre-turbocharger injection encourages fast droplet evaporation and thermal decomposition as already described for the stationary tests. The high degree of turbulence in the turbine’s gas flow also improves the uniform distribution of NH\textsubscript{3}. Figure 20 shows a comparison of emission reduction rates during the “cold” NEDC test. In the Pre Turbo configuration, the DOC position is able to achieve HC conversion rates of over 90% at a very early stage in the test cycle. In the Standard system, the temperature plateaus between ~875 and 975 seconds, which leads to a reduction in HC conversion, and full conversion rates are achieved only by the end of the test. Because of the low SCR catalyst temperature, NO\textsubscript{x} reduction falls well short of expectations in the pre-turbocharger systems despite the early addition of dosing agent. The measured conversion rates for the NEDC test series are summarised in figure 21. An additional SCR catalyst directly behind the turbine (Pre Turbo Plus design) clearly highlights the potential for an increase in conversion rates.
Figure 21: NO\textsubscript{x} conversion rates in the NEDC for different starting conditions

The pre-turbocharger systems achieved 20% and 25% NO\textsubscript{x} conversion in the “cold” NEDC. However, virtually no NO\textsubscript{x} was reduced in the Standard system because of the low temperature level, and even in the warm NEDC test NO\textsubscript{x} conversion rates were around a maximum of 27%.

Figure 22: Accumulated NO\textsubscript{x} emissions in the NEDC over the SCR catalyst temperature for Standard and Pre Turbo Plus systems and NO\textsubscript{x} light-off curves to assess the potential
Figure 22 shows the accumulated NO\textsubscript{x} engine-out emissions in the NEDC test for the Standard and the Pre Turbo Plus systems and the SCR light-off curves.

The mean exhaust gas temperature at the SCR catalyst was 112 °C for the Standard design and 145 °C for the Pre Turbo design. The hatched area marks the actual proportion of NO\textsubscript{x} emissions in the light-off range of the SCR catalyst and explains how the NO\textsubscript{x} reduction is limited by the exhaust gas temperature. The diagram also includes the light-off curve from figure 9. This would increase the conversion range in the Pre Turbo Plus system, particularly because of the higher temperature level. A refined SCR coating, such as the one shown in figure 9, would make it possible to achieve higher NO\textsubscript{x} conversion rates, especially between 150 °C and 190 °C.

6. Summary and conclusion

The summary of the results in figure 23 shows that the pre-turbocharger designs are able to stay well below the EU 6c limits for HC and CO. The early injection of reducing agent, fast thermal decomposition and highly effective mixing by the turbine provide the basic conditions for efficient NO\textsubscript{x} conversion. However, the exhaust gas temperatures in the NEDC are too low, that is, the low temperature activity of the tested SCR catalysts is not sufficient to meet Euro 6 limits as a minimum.

![NEDC (cold) and warm conversion](image)

**Figure 23:** Summary of NEDC results and the potential for Pre Turbo systems

Nonetheless, the potential of optimum positioning of the DOC and reducing agent injection is clearly evident also in terms of complying with RDE limits. It is certainly worth further investigation, especially since the increase in fuel consumption is only 1.5 to 2% with respect to the rise in CO\textsubscript{2} emissions measured in the NEDC (see figure 24).
Figure 24: Comparison of fuel consumption and CO₂ emissions of the Pre Turbo Plus exhaust system with those of the Standard system in the NEDC

There are a number of technical options to continue the tests described here. Combination with suitable temperature management would certainly be expedient. A DOC in pre-turbocharger position would also be advantageous in this setup as the exothermic conversion of unburned fuel could at least partially compensate for the delayed response of the turbine. This would require a turbine design with a corresponding control algorithm that is optimised with respect to thermal mass and flow resistance. The addition of electrically driven turbocharger assistance is also believed to have great potential.

Furthermore, the injection of the reducing agent should also be examined with respect to injection time, injection interval and injection pressure and a corresponding dosing strategy should be developed.

Finally, the exhaust aftertreatment system behind the turbine could be arranged according to the CompactCat® design to achieve lower heat loss and lower pressure rise. This design would allow for the integration of an electrically heated catalytic converter to prevent the catalytic converters from cooling at low load or during deceleration. The quantification of the effect of all these measures and the subsequent definition of a feasible overall system will be the subject of further studies, which we will report on in future.

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8. References

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