Experiment of selective catalytic reduction retrofit for euro 6 NO\textsubscript{x} emission level compliance for euro 5 light duty vehicle

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Abstract. An independently developed retrofit selective catalytic reduction (SCR) system was implemented onto a Euro 5 light duty vehicle, in order to comply with the Euro 6 nitrogen oxides (NOx) limit over the legislative laboratory cycle. The SCR catalytic converter was fitted to the existing exhaust line, downstream of the diesel oxidation catalyst and the particle filter. The urea dosing system, including NOx sensors, was set up onboard the vehicle in order to catalytically treat the exhaust gas and effectively reduce NOx. The urea injection strategy was managed by an external dosing control unit, while the engine calibration was not modified and remained at the Euro 5 level. The legislative tests were performed in an emission laboratory on the chassis dynamometer installed in a climatic chamber. The reference emission level of the unmodified vehicle and aftertreatment layout was established. Following SCR retrofitting process, the emission cycles were repeated, and the results obtained were compared. The SCR system effectiveness was found to be in a close correlation with exhaust gas temperature. The presented test results gave an insight into the possibility of significant NOx reduction in modern light duty vehicles by means of usage of an add-on type of NOx catalytic reduction system, without modifications to the engine control unit.

Keywords: selective catalytic reduction, urea, retrofit, nitrogen oxides, reduction

1. Introduction
While the Euro 5 and lower emission limits for passenger cars were current in Europe, the main and most commonly applied technology for NOx emission control of diesel vehicles was Exhaust Gas Recirculation (EGR). This solution, termed an in-cylinder method, allowed legislative requirements to be fulfilled, but nevertheless it wasn’t sufficiently efficient. High EGR rates increase engine-out soot emissions, contaminating the engine air inlet ducts and lowering combustion efficiency, leading to a fuel penalty. Thus, the EGR operating window was restricted only to the zone of the engine map that covered the legislative test cycle (the NEDC). Consequently, off-cycle NOx emissions are disproportionately high and this does not ensure low emissions under real driving conditions [1].

The stringent Euro 6 emission limit and introduction of the real driving emission (RDE) test procedure forced implementation of NOx treatment converters to the exhaust line of a vehicle [2, 3]. There are two main technologies to reduce the NOx in the exhaust. The first one is the so-called Lean NO\textsubscript{x} Trap (LNT) which adsorbs and stores NOx during lean operation of a diesel engine. However an LNT’s storage capacity is limited and the accumulated NOx has to be reduced in oxygen-free exhaust gas. This requires engine operation at enriched mixture and temperature conditions for a certain time, causing a fuel penalty and making engine management complex.
This study on SCR retrofit of a Euro 5 light duty vehicle was carried out in order to verify NO\textsubscript{x} emission compliance with Euro 6 legislation limits. The project assumption was to develop a stand-alone SCR system and install it downstream of the existing exhaust aftertreatment, while not modifying the engine calibration. The work aims also to present and discuss the effort and difficulties of SCR system integration on a standard production Euro 5 vehicle.

2. SCR system functionality
The SCR system utilizes water urea solution (UWS) as a reducing agent, which is injected directly into the exhaust upstream of the SCR catalyst. An SCR system working at rated operating conditions allows the NO\textsubscript{x} emission to be decreased by more than 98%. The excellent NO\textsubscript{x} removal efficiency of SCR systems allows preparation of engine calibration strategies for more efficient fuel combustion, thus increasing the fuel economy and reducing the CO\textsubscript{2} emissions [4]. Depending on the vehicle type and the application, the amount of UWS consumption typically varies between 3-5% of the real fuel consumption. To achieve high NO\textsubscript{x} reduction efficiency of an SCR system, the urea dosed needs to be evenly mixed with the exhaust gas stream and evaporated, yielding the processes of thermolysis and hydrolysis to finally decompose to ammonia, which is the target reducing agent. The lowest gas temperature threshold at the SCR inlet for UWS dosing release is typically set to 170°C -180°C, and there is extensive research work on SCR system activation below those temperatures [5]. The UWS dosing at lower gas temperature results in low NO\textsubscript{x} conversion efficiency and may lead to solid urea deposit formation inside the SCR system. Zeolite-based SCR catalysts are commonly used for automotive applications. The zeolite can be modified with copper (Cu) or Iron (Fe), by means of which its catalytic properties are determined.

Cu-zeolite SCR catalysts exhibit higher NO\textsubscript{x} conversion efficiency at low temperatures. In addition, Cu-zeolite SCR catalysts are tolerant to high temperature excursions. For automotive applications, this is a critical requirement for the SCR component when it is combined with a Diesel Particulate Filter (DPF) in the emission control system. In order to effectively regenerate the DPF, the entire system is periodically exposed to temperatures above 630°C.

Fe-zeolite SCR are another group catalysts that are resistant to exposure to high temperatures and exhibit good SCR activity. Fe-zeolite catalysts show higher NO\textsubscript{x} reduction efficiency at temperatures above 350°C compared to their Cu-zeolite counterpart [4]. However, at temperatures between 200 and 300°C, which are common for normal diesel engine operating conditions, Cu-zeolite catalysts are significantly more active than Fe-zeolite catalysts. Furthermore, their low temperature activity is less sensitive to the NO\textsubscript{2}/NO\textsubscript{x} ratio in the feed gas. Although Cu-zeolite catalysts are less selective than Fe-zeolite ones in utilizing NH\textsubscript{3} for NO\textsubscript{x} reduction at high temperatures, this lower selectivity can be compensated by a slight NH\textsubscript{3} over-injection. All these features make Cu-zeolite SCR catalysts the preferred technology for light-duty automotive diesel NO\textsubscript{x} emission control.

![Figure 1](image)

**Figure 1.** NO\textsubscript{x} conversion comparison for Cu- and Fe-zeolite SCR catalysts; 500 ppm NO, 500 ppm NH\textsubscript{3}, 10% O\textsubscript{2}, 5% H\textsubscript{2}O, 5% CO\textsubscript{2} [4]
Figure 1 shows the stoichiometric (NH$_3$/NO$_x$=1) reactivity of both Fe- and Cu-zeolites when operated under standard SCR conditions. Significantly improved low-temperature reactivity of Cu is evident below 350°C and the high temperature benefits of Fe-zeolite are apparent [4]. Furthermore, a consistent trend reported in the SCR literature has been that Fe-zeolites have less NH$_3$ storage than Cu-zeolites.

3. Materials and methods

The application of the SCR method required build-up of the entire SCR system infrastructure [6]. For the purpose of the project, an independent stand-alone SCR system was developed. The system incorporated both hardware and software. A schematic overview of the component layout and functionality is presented on figure 2.

![Figure 2. Schematic overview of the stand-alone SCR system](image)

The central hardware component was an SCR reactor of Cu-zeolite type. An UWS injector was installed upstream of the SCR reactor and the UWS was fed to the injector from the pump equipped tank. In order to improve the uniformity level of the introduced UWS, a mixer was placed downstream of the UWS injector. A NO$_x$ sensor and temperature sensor were fitted at the system inlet. The setup was controlled by an external notebook computer with dedicated software. The input parameters derived from sensors were the NOx concentration and the exhaust temperature. The exhaust mass flow was read from the engine control unit via On-Board Diagnostic (OBD) interface. Moreover, the alpha factor ($\alpha$) set point was manually defined. The applied software included exhaust gas temperature as a threshold parameter to start UWS injection during the engine warm-up phase. The computation result was an UWS mass flow rate calculated according to formula 1.

$$\text{UWS}_{\text{rat}} \left[ \frac{\text{mg}}{\text{s}} \right] = \text{NO}_x [\text{ppm}] \cdot \text{Exh}_{\text{flow}} \left[ \frac{\text{kg}}{\text{h}} \right] \cdot \frac{46}{29} \cdot 5.425 \cdot 0.37 \cdot \frac{1}{3600} \cdot \alpha$$

where:
- NO$_x$ – nitrogen oxides concentration measured upstream of SCR reactor
- Exh$_{\text{flow}}$ – exhaust mass flow read from engine control unit
- $\alpha$ – equivalence ratio factor

The quantity of UWS dosed was expressed by the stoichiometric ratio $\alpha$, which was defined as the quotient of the amount of ammonia molecules from the urea NH$_3$$_{\text{in}}$ and the amount of nitrogen oxides molecules NO$_x$$_{\text{in}}$ in the elementary exhaust gas mass flow:

$$\alpha = \frac{\text{NH}_3_{\text{in}}}{\text{NO}_x_{\text{in}}}$$
Consequently, $\alpha = 1$ is defined as the theoretical flow of UWS required for conversion of 100% of the incoming NO$_x$ flow while not causing the presence of any ammonia downstream SCR of the (ammonia slip).

The developed SCR system was retrofitted on a Euro 5 light-duty commercial vehicle of category N1. The factory-fitted exhaust aftertreatment system consisted of close-coupled DOC catalyst with DPF filter and those components were left unchanged. The engine calibration was not modified and it remained at the Euro 5 level. The SCR system was installed downstream of the existing aftertreatment system (figure 3) and the UWS tank with associated electronic infrastructure was located in the cargo compartment of the vehicle. The vehicle was prepared as a fully functional test object for laboratory emission verification.

The emission testing was performed on chassis dynamometer inside a climatic chamber with temperature and humidity control systems (figure 4). Integrated in the laboratory, the Horiba VETS management system permitted the execution of NEDC driving cycles. Laboratory emissions analysis consisted of a constant volume sampling - critical flow Venturi (CVS-CFV) sampling system together with a dilution tunnel, a gravimetric particulate sampling system, and particle number counting system. The emission bench consisted of Horiba exhaust gas analysers for simultaneous measurement of carbon monoxide, carbon dioxide, total hydrocarbons, non-methane hydrocarbons, methane and oxides of nitrogen. Emission testing was carried out with the aid of CVS bags and modal analysis; in the case of the former for batch analysis of each phase of the cycle, and modal analysis of tailpipe gas at 10 Hz. Overall, the emission bench’s accuracy can be considered to be ±1%. All emissions test were conducted from a cold start with the engine coolant at ambient temperature (24±1°C) with a fully charged battery.

4. Test results and discussion
A comparison data of modal analysis is presented in figure 5 and the bag analysis emission results are shown in figure 6 and figure 7.

The initial part of activities was to run a series of emission tests on the unmodified Euro 5 vehicle with standard production configuration and thereby to establish the reference emission level for further comparison. The second step consisted of retrofitting the vehicle with the SCR system and repeating the tests. The test procedure was the legislative New European Driving Cycle (NEDC), based on which the emission data were compared [7].

The vehicle and exhaust system was preconditioned before performing the first emission cycle of each vehicle configuration. The procedure used was to run one complete NEDC cycle followed by 3 repetition of extra urban (EUDC) parts. The preconditioning phase was especially important before the...
emission check after SCR retrofit with, as the SCR catalyst needs to properly saturated and stabilized at given test conditions for optimal NO\textsubscript{x} conversion efficiency and high repeatability of test results. The vehicle’s battery was charged between the end of the preconditioning and the start of the following emissions test. The UWS injection quantity was set to be stoichiometric, with α factor equal 1.0. Figure 5 compare modal analysis data from first emission cycles for standard and retrofit configuration.

In case of standard vehicle configuration (without SCR), the NO\textsubscript{x} result of 265 [mg/km] was achieved proving vehicle’s compliance with Euro 5 NO\textsubscript{x} limit. Three NEDC cycles were performed, with NO\textsubscript{x} results within 4% of each other. Nevertheless, the obtained NO\textsubscript{x} result was taken as a reference value for further analysis.

For the SCR retrofit configuration tests, the UWS dosing threshold was set to the exhaust temperature of 160°C measured at the SCR inlet. During the NEDC, the UWS injection commenced after 350 seconds of the test, which corresponded to a nearly half of the urban driving phase (UDC). The relatively long SCR system activation time derived from the extended distance between the SCR catalyst and the engine, resulting in a sluggish SCR system warm up rate.

Over the extra-urban (EUDC) phase of the cycle, exhaust gas temperature further rises from 180°C to 320°C and this leads to an rapid increase of NO\textsubscript{x} conversion rate in the SCR. The tailpipe NO\textsubscript{x} concentration was significantly decreased with respect to the standard production configuration during this phase.

![Figure 5. NEDC cycle profile with modal data analysis](image)

Figure 6 presents NO\textsubscript{x} and HC results from the first NEDC test for the standard and SCR retrofit configurations of the vehicle. Application of the SCR method resulted in a decrease of NO\textsubscript{x} emission by 58% over the entire test cycle. The NO\textsubscript{x} emission was reduced to 110 [mg/km], allowing fulfilment of the Euro 6 requirements, even including the deterioration factor for NO\textsubscript{x} (equal to 1.1).
Test results for other compounds required by emissions legislation for the first NEDC are presented in figure 7. They comply with Euro 5 and 6 limits, both for the standard and SCR retrofit configurations. The NEDC cycle with SCR system was run twice and none of the regulation emissions (any compound, other than NOx) has exceed 80% of the Euro 6 legislative limits.

Table 1. EU emission standards for light-duty vehicles category N1 with diesel engines

| Stage | CO [mg/km] | HC+NOx [mg/km] | NOx [mg/km] | PM [#/km] | PN [#/km] |
|-------|------------|----------------|-------------|-----------|-----------|
| Euro 5b | 740        | 350            | 280         | 4.5       | 6.0*10^{11} |
| Euro 6 | 740        | 215            | 125         | 4.5       | 6.0*10^{11} |

5. Summary
The exhaust after-treatment with selective catalytic reduction system is a complex but very effective means of NOx removal from exhaust gas. The research work conducted has shown that by SCR retrofitting, a significant NOx reduction is feasible at warm engine operating conditions, even without engine calibration modifications. For reliable operation of a retrofit SCR system, further detailed analysis needs to be performed, including evaluation of ammonia slip or urea deposit formation. Nevertheless, the SCR is an inevitable method for NOx compliance with legislation during the RDE test.

There is an ongoing effort and continuous development process of SCR optimization for light-duty applications. Research focuses on enhancing the urea evaporation process, shortening the activation time and on elaborating alternative methods of volatile ammonia introduction upstream of the SCR catalyst [8]. For passenger cars and light-duty vehicles powered with diesel engines, the main constraints for SCR systems are the warm up phase, enlarged external dimensions and the high cost of the entire system. The SCR method allows elimination of the divergence in NOx emission values between laboratory certification driving cycles and the RDE test, legally enforced in 2017 for passenger vehicles.

Application of an efficient SCR system permits also to shift in the NOx/PM trade-off towards high engine-out NOx emission [9]. That leads to improved engine efficiency, and thus fuel economy and decreases the soot emissions. The last factor mentioned lowers the diesel particulate filter soot loading, diminishing (or even eliminating) the need for active filter regeneration events. This kind of strategy is referred as ‘SCR-only’ and it aims for the principle of a continuously regenerating trap (CRT).

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