

Control of a Combined SCR on Filter and Under-Floor SCR System for Low Emission Passenger Cars

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ABSTRACT

Similar to single-brick SCR architectures, the multi-brick SCR systems described in this paper require urea injection control software that meets the NO_x conversion performance target while maintaining the tailpipe NH_3 slip below a given threshold, under all driving conditions.

The SCR architectures containing a close-coupled SCRoF and underfloor SCR are temperature-wise more favorable than the under-floor location and lead to significant improvement of the global NO_x conversion, compared to a single-brick system. But in order to maximize the benefit of close-coupling, the urea injection control must maximize the NH_3 stored in the SCRoF.

The under-floor SCR catalyst can be used as an NH_3 slip buffer, lowering the risk of NH_3 slip at the tailpipe with some benefit on the global NO_x conversion of the system. With this approach, the urea injection strategy has a limited control on the NH_3 coverage of the under-floor SCR catalyst.

To take more advantage of the under-floor SCR catalyst for improving the NO_x conversion, the NH_3 coverage of the under-floor SCR must be taken into account, and therefore a combined control of both catalysts is required. This paper presents a control strategy proposal for such multi-brick SCR systems: the NH_3 coverage of the SCRoF is optimized while taking into account the current states of front and rear SCR catalysts. The strategy focuses on achieving highest NO_x conversion efficiency while preventing excessive tailpipe NH_3 slip, even in the worst driving conditions, such as sudden full-load acceleration.

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INTRODUCTION

Diesel engine technology is steadily improving toward lower fuel consumption and lower raw emission of pollutants. The aftertreatment of hydrocarbons (HC), carbon monoxide (CO), and particulates matters (PM) is widely implemented and the underlying technologies are very mature: Diesel Oxidation Catalysts (DOC) and Catalyzed Diesel Particulate Filters (CDPF) are now standard on every passenger car meeting the latest emissions regulations in Europe and North America. The reduction of NO_x is more challenging in the lean combustion environment of diesel engines. Mainly, two de- NO_x technologies coexist: the Lean NO_x Trap (LNT), relying on extra fuel injection as a means to reduce NO_x ; and the Selective Catalytic Reduction catalyst (SCR), used in combination with the injection of reductant in the exhaust gas stream, such as direct ammonia injection (NH_3) or more commonly a liquid urea solution decomposing to NH_3 in the exhaust gas (typically Adblue).

The LNT can replace a DOC in current exhaust system architectures, which means low on-cost compared to a standard DOC-CDPF architecture. The drawback of the LNT is the fuel economy side (and CO_2 emissions), because of the extra fuel required to release and convert the NO_x stored on the LNT. NO_x aftertreatment by LNT is mostly targeted for light applications or less stringent emission legislations.

The SCR technology does not require extra fuel to reduce NO_x emissions, making it a better candidate regarding CO_2 emissions. The higher NO_x reduction potential of SCR system is suited for heavier applications and severe emission legislations. In addition to the significant on-cost of a complete SCR system, some technical issues may need to be solved to realize the full benefit of the SCR technology. The urea dosing, mixing and proper decomposition to NH_3 can be challenging, regarding spray preparation but also on the packaging side. While SCRs have successfully been introduced in the diesel passenger car market, they are used solely in additional

Under-Floor (U/F) converters because of the significant length required to achieve a good urea to NH_3 conversion and mixing. The main disadvantage of under-floor SCR architectures are the relatively low operating temperature of the under-floor SCR, leading to potential limitations in NO_x conversion performance.

The technology of liquid urea dosing systems constantly evolves toward finer spray and use of mixers, allowing shorter mixing length. In parallel, the catalyst industry is continuously improving SCR washcoats, which are increasingly more efficient, high-temperature resistant and which can be coated directly on particulate filter substrates [1] (SCRoF for SCR on Filter).

These latest developments have opened the door to close-coupled SCR architectures.

SCR Architectures and European Cycles

In Europe, historically the main market for diesel passenger cars, emission legislation is now focusing on NO_x reduction. The EURO 6 regulation in 2014 will introduce new limits for NO_x , and to a lesser extent for HC, which are part of a $\text{NO}_x + \text{HC}$ composite limit.

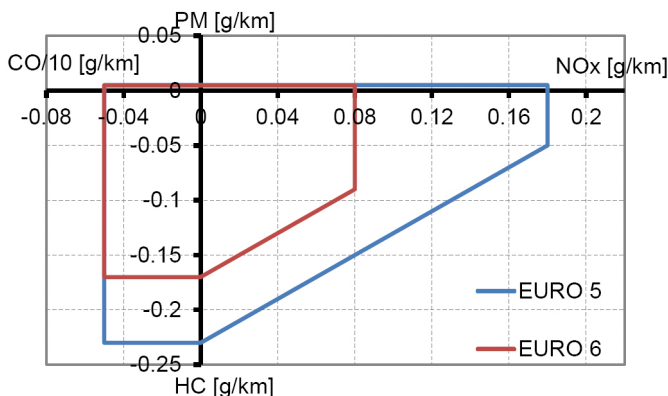


Figure 1. EURO 5 and EURO 6 emission limits

A consequence of these lower limits is the requirement for heavier vehicles/smaller displacement engines applications to treat the engine-out NO_x emissions with either SCR or LNT when the raw emissions exceed 0.08 g/km NO_x .

Emission Cycles

In terms of certification, the emission cycle currently in use in Europe is the New European Driving Cycle (NEDC), which consists of mild and constant vehicle accelerations and of constant speed plateaus.

EURO 6 regulation comprises a second step for 2017. This EURO 6c step, still under discussion, will introduce two new tests in the certification process [2]:

- a Worldwide harmonized Light duty vehicle Test Procedure (WLTP, and its emission cycle WLTC) - a Real Driving Emissions (RDE) test.

The purpose of WLTP is to measure CO_2 on a cycle representative of real driving profiles. This cycle could then be used at a later stage to also measure pollutants emissions and replace the NEDC.

The intent of the RDE procedure is to better account for the impact of real-life driving conditions on emissions, especially on NO_x . For this purpose, the certification process will include an on-board emission measurement test on open roads, with Portable Emission Measurement System. The driving profile will be composed of representative random conditions. During emission calibration development, the RDE conditions can be evaluated by using a random cycle generator that is based on a database of representative short trips. As in real life, a combination of these short trips can randomly lead to a large variety of severities, going from low to high engine-out NO_x and from cold to warm operation for the aftertreatment system.

At the time this paper was written, the emission limits for RDE were not yet defined. The most probable scenario is a compliance factor to be applied to the NEDC emission.

Figure 2 shows a comparison of the three types of test that will be used for EURO 6c: NEDC, WLTC and a high load RDE.

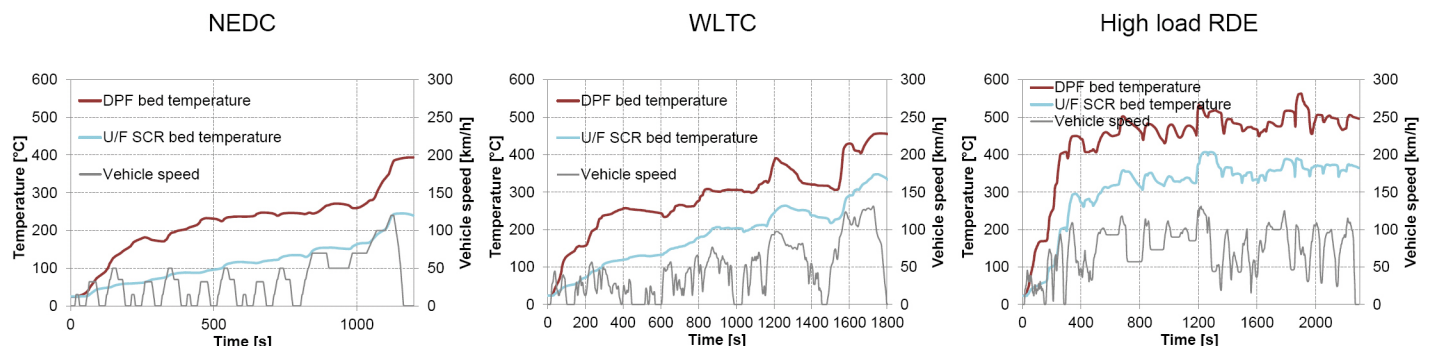


Figure 2. NEDC, WLTC and high load RDE cycles

The temperature traces on these cycles show that WLTC and a high-loaded RDE are more favorable to the aftertreatment system than NEDC, where temperature can be critically low, especially at the under-floor location.

The results presented in this paper, like the temperatures shown in Figure 2, were measured on a 1700 kg passenger car, fitted with a 2.2 L engine.

The new EURO 6c cycles may be more favorable to the aftertreatment on a thermal standpoint, but the engine operating conditions, as shown on Figure 3, are more severe: For a given engine speed, WLTC and a high loaded RDE show higher Indicated Mean Effective Pressure (IMEP) than NEDC. The RDE comes close to the full load operation of the engine. This leads to a significant increase in raw NO_x emissions and becomes more challenging for the aftertreatment system.

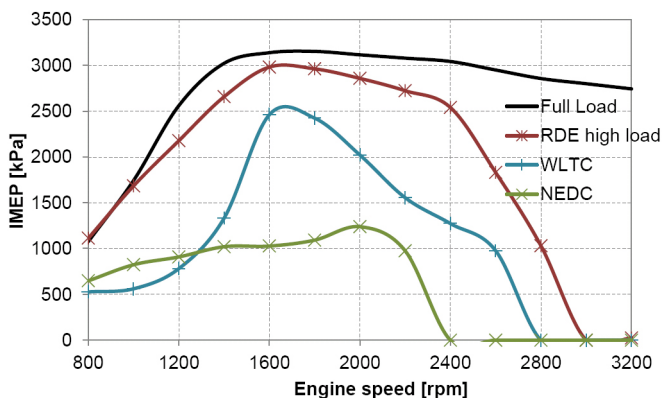


Figure 3. Speed/Load chart of EURO 6c cycles

SCR Architectures

Figure 4 describes three typical SCR architectures applicable to passenger car applications.

The first layout, with a single, large under-floor SCR catalyst, is in production on several U.S. and EU applications [3]. This architecture is advantageous for the urea mixing and decomposition to NH_3 , but suffers from a delayed light-off due to the presence of high thermal inertia components located upstream of the SCR (DOC and DPF). In moderate / low load operation, the thermal losses generated by the intermediate pipe also affect negatively the performance of the SCR.

The second layout, with a single close-coupled SCR, coated on the particulate filter (SCRoF), benefits from a fast light-off and higher temperatures, but its volume is limited by packaging reasons. The limited length available for urea mixing and decomposition to NH_3 also requires an optimized dosing system [4] and an exhaust mixing device.

The third layout including a close-coupled SCRoF is advantageous for NO_x performance, especially due to faster light-off and higher temperature of the close-coupled SCRoF combined with an extra volume in the under-floor location. The

lower temperature of the U/F SCR is also beneficial for managing higher NH_3 coverage in the SCRoF and NH_3 slipping out of the SCRoF during thermal transients.

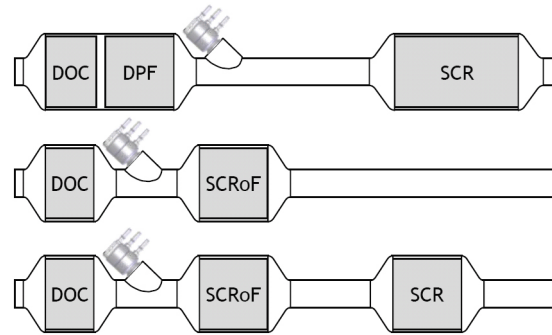


Figure 4. Potential SCR architectures

Figure 5 shows how the various architectures perform on the three European cycles described earlier. All the catalysts used in this study were aged to an equivalent of 160000 km. For comparison purposes, no heat-up strategy was applied, which is coherent with increasing priority on fuel economy. Again for comparison purposes, the total volume of the SCRoF + U/F SCR does not exceed the volume of the single (large) U/F. The urea demand control and calibration were adapted such that NH_3 emissions at the tailpipe were kept at a low level.

The engine load increase between NEDC, WLTC and RDE has a direct impact on engine-out NO_x .

The large under-floor SCR is hardly able to meet the EURO 6 limit, even though engine-out NO_x are relatively low. This is due to the unfavorable location of the U/F SCR regarding gas temperature.

On NEDC, the close-coupled SCRoF performs better than the large U/F SCR, due to the higher gas temperature at this location. But the large U/F becomes more favorable for coping with the high space velocity and high NO_x on WLTC and RDE. This is due to increased temperatures of the large U/F SCR on WLTC and RDE (see Figure 2 for temperature traces). The third layout, combining SCRoF and U/F SCR is able to perform optimally on each cycle.

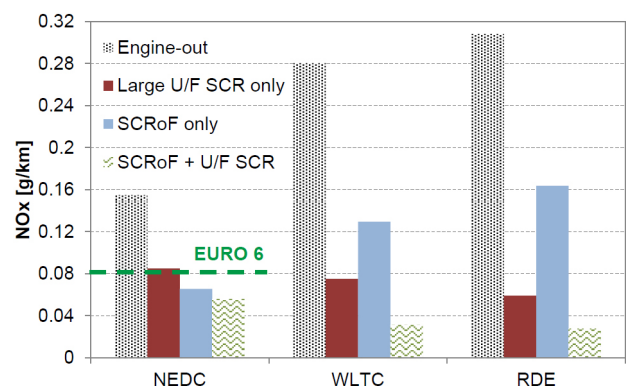


Figure 5. Performance of several architectures on NEDC, WLTC and high load RDE