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Diesel Passenger Car with Ultra-low NO_x Emissions in Real Driving Conditions

In future, a further reduction of the nitrogen oxide emissions for passenger cars with diesel engines is to be expected. As part of a joint project, IAV and the Association for Emissions Control by Catalyst (AECC) have investigated the extent to which emissions from diesel vehicles can be further reduced in real driving operation through mild hybridization and optimized exhaust aftertreatment.

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MOTIVATION

The European Union legislation on light-duty vehicle emissions has undergone major changes in the last years. The Worldwide harmonized Light-duty vehicles Test Procedure (WLTP) was developed and implemented to determine fuel consumption and CO_2 emissions that are more representative of normal vehicle use. In parallel, Real Driving Emissions (RDE) regulation has entered into force that regulates nitro-

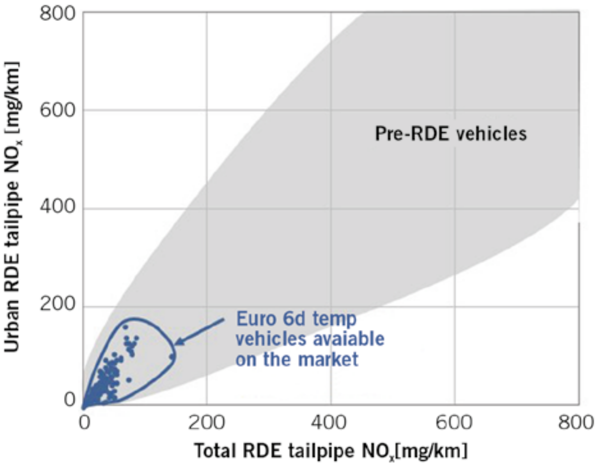

FIGURE 1 Reduction in real-world diesel NO$_x$ emissions brought by the introduction of RDE requirements (© AECC)

gen oxides (NO$_x$) and Particle Number (PN) emissions on the road. The gap between diesel vehicle emissions in laboratory tests compared to those in use has been addressed and modern diesel technology demonstrates low emissions while driving on the road [1, 2, 3]. **FIGURE 1** visualizes the significant reduction in NO$_x$ emissions from pre-RDE (grey area) to RDE-compliant (blue dots) diesel vehicles, by plotting Portable Emissions Measurement System (PEMS) data from the RDE tests conducted at type approval [4, 5].

Each data point in **FIGURE 1** represents a vehicle's NO$_x$ emission over an RDE-compliant route comprising of urban, rural and motorway driving conditions. **FIGURE 2** visualizes how the NO$_x$ tailpipe emission level varies according to average vehicle speed/loads. For pre-RDE vehicles type-approval was limited to the New European Driving Cycle (NEDC), a laboratory test characterized by a single average speed/load value, giving the NO$_x$ emission value in the middle of the graph in **FIGURE 2**. The robustness of tailpipe NO$_x$ emission control across this wider range of driving conditions encountered on public roads has been improved significantly over recent years through powertrains and emission control systems optimization to meet RDE requirements, **FIGURE 2** (blue arrows).

As part of their so-called post-Euro 6 study, the European Commission is now considering whether elements of the current regulatory framework should be further modified and extended. The range of driving conditions to be covered in the RDE test is one of the elements under consideration.

The objective of the work presented here is to further show low diesel NO$_x$ and particulate emissions capability across a wide range of operating conditions. To achieve the objective, a Diesel Particulate Filter (DPF) was implemented on a mild-hybrid diesel passenger car together with a combination of NO$_x$ emission control technologies. The functional control integration of all technologies in the software was key. More specifically, the aim was to address low average speeds in the city, **FIGURE 2** (left side), and high average speeds on the motorway, **FIGURE 2** (right side).

PROJECT SET-UP

The base vehicle for the demonstrator project is a C-segment car equipped with a Euro 6b diesel engine. The vehicle has a six-speed manual gearbox in combination with front wheel drive. Key features of the downsized, four-cylinder, two-valve diesel engine include a displacement of 1.5 l, 1600-bar common rail fuel injection system, single-stage turbocharger with Variable Turbine Geometry (VTG) with e-actuator and air/air intercooler. It also features a 48-V mild hybrid system in so-called P0 position. NO$_x$ engine-out emissions are controlled by a combination of uncooled high- and cooled low-pressure Exhaust Gas Recirculation (EGR) systems. The original exhaust aftertreatment system was removed and replaced by a Lean NO$_x$ Trap (LNT) + dual-Selective Catalytic Reduction (SCR) system, **FIGURE 3**.

The LNT and close-coupled SCR mainly reduce the NO$_x$ emissions during city driving at low exhaust temperatures, as visualized in **FIGURE 3** (top left). A low thermal mass SCR is added in addition to an SCR catalyst-coated DPF (SDPF) for an optimum SCR light-off performance after cold-start. For NO$_x$ control under motorway driving conditions, a second SCR catalyst and an Ammonia Slip Catalyst (ASC) are added in an underfloor position with a second urea dosing unit. These downstream catalysts experience lower temperatures compared to the close-coupled system enabling them to be effective at higher vehicle speed/loads, **FIGURE 3** (top right). In summary, the combination of different components positioned along the exhaust line broadens system deNO$_x$ performance across a wide variety

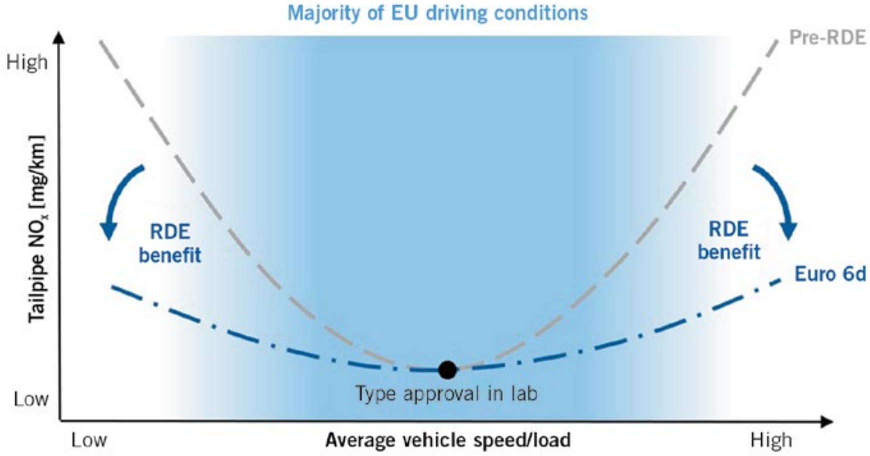

FIGURE 2 Schematic illustration of tailpipe NO$_x$ emissions versus average vehicle speed/load (© AECC)

of driving conditions. Achieving high NO_x conversion rates, while preventing ammonia (NH_3) slip, requires exact and active adjustment of the NH_3 filling levels inside each SCR component in response to the exhaust temperature and transient engine-out NO_x level. This is taken care of by using a model-based closed-loop dosing control software. All catalyst components used in this work were tested following a hydrothermal oven aging procedure representative of the vehicle lifetime. In addition, around 15,000 km were accumulated during the project before the final emissions tests were conducted.

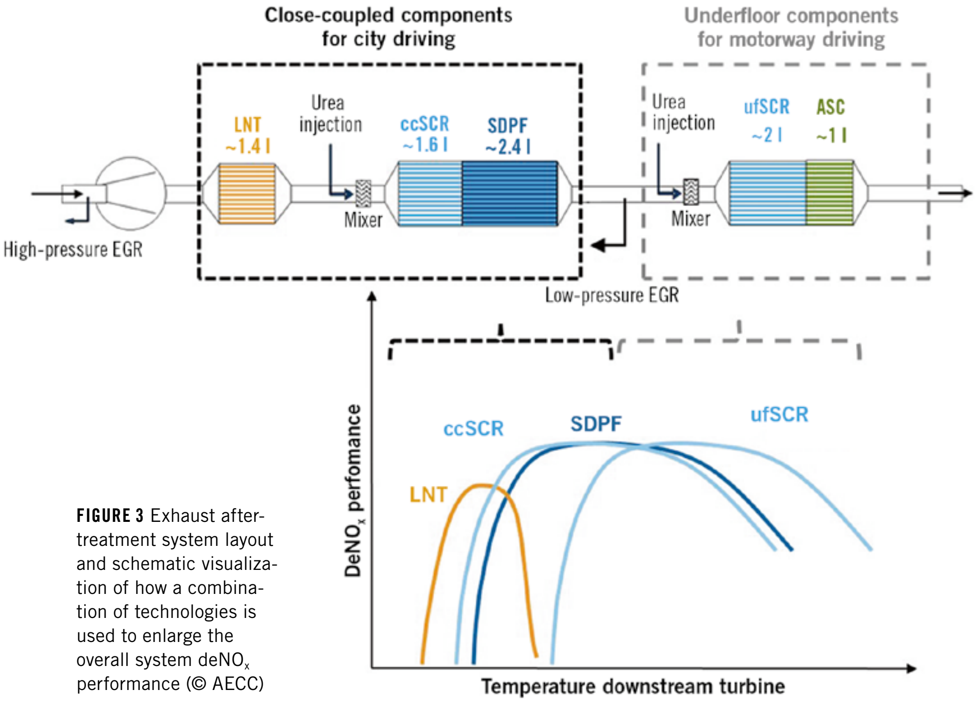

FIGURE 3 Exhaust aftertreatment system layout and schematic visualization of how a combination of technologies is used to enlarge the overall system deNO$_x$ performance (© AECC)

The 48-V mild-hybrid was used to support the emissions control as well. It supported LNT regeneration at low-load conditions, by stabilizing the engine torque to absorb fluctuations in the driver-requested torque which could otherwise interrupt LNT regeneration phases. Additionally, it supported the combustion engine during accelerations to reduce engine-out emissions peaks. The electric motor was also used within the active thermal management strategy of the aftertreatment system (load point shifting).

Active thermal management is key to heat up the emissions control components as quickly as possible and to maintain the heat throughout the rest of the trip. A step-wise strategy was implemented, monitoring the temperatures of the first two components in the system. A throttle is used to reduce the exhaust mass flow as a first step after cold-start. As soon as the LNT reaches 170 °C, a late post-injection is activated. The post-injection is switched off when there is an opportunity to support the thermal management with the 48-V mild-hybrid. Thermal management remains active until the first SCR reaches 220 °C.

Several tests were performed to characterize the emissions performance of the vehicle. In addition to regulatory emissions tests (WLTP and RDE), measurements were conducted on the road and in the lab to cover urban (Berlin and the so-called Interpeak cycle from the organization Transport for London (TfL)), hilly (driving in the mountainous Harz area of Germany, up to 700 m) and motorway driving around Berlin (vehicle speeds up to 160 km/h). The TfL test consists mainly of low-load driving, often below the catalyst light-off temperatures. The combination of short distance (9 km) and low average vehicle speed (13.9 km/h including idle) make it a very challenging cold-start test.

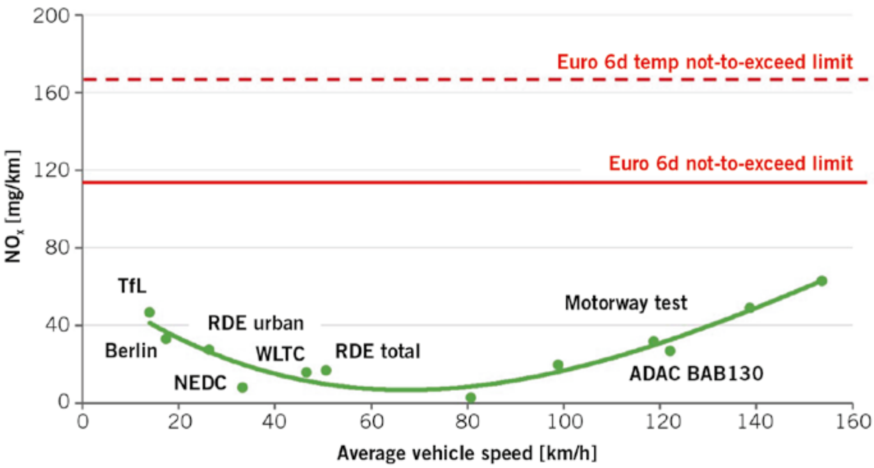

FIGURE 4 Summary of tailpipe NO_x emissions achieved over the range of driving conditions covered in the program (© AECC)

NO_x EMISSIONS

FIGURE 4 shows a summary of all tailpipe NO_x emissions versus average vehicle speed. Consistent low NO_x emissions are measured over the driving conditions covered. The NO_x emissions measured on RDE and WLTP in the middle of the curve remain below 20 mg/km. There is no impact of the ambient temperature over the range covered during the tests (0 to 30 °C). These results are achieved due to the integrated system approach. The contribution of the different exhaust aftertreatment components to the NO_x reduction is visualized in **FIGURE 5** for the urban and motorway part of an RDE test, where a deNO$_x$ efficiency of 92 % is achieved. The LNT and close-coupled SCR+SDPF contribute almost equally in the urban part. The underfloor SCR is required to secure the low emissions on the motorway.

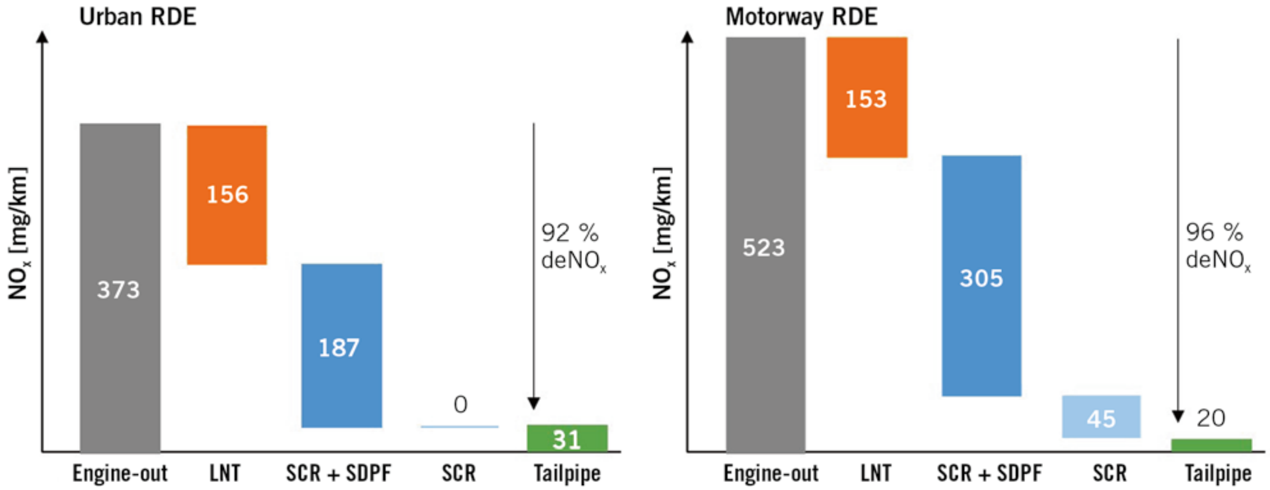

FIGURE 5 Breakdown of NO$_x$ reduction during urban (left) and motorway (right) part of an RDE test (© AECC)

The emissions in the city tests, **FIGURE 4** (left), not only reflect the impact of the low vehicle speed, but also the contribution of the cold-start at the beginning of the test. The highest NO$_x$ emissions measured occur during the TfL test. **FIGURE 6** shows how the calibration measures (LNT regeneration stabilization and active thermal management) improve the NO$_x$ emissions by 80 % (from 216 to 47 mg/km) on the TfL test.

Motorway emissions are investigated on the road, including driving up to 160 km/h. Different sections of this test are investigated separately to check the impact of the average vehicle speed on NO$_x$ emissions. Depending on the test section selected, an average speed between 75 and 140 km/h is obtained. The challenging driving conditions increase engine load and speed, resulting in an increase in engine-out emissions up to 1.5 g/km. The dual-SCR enables to maintain the tailpipe NO$_x$ emissions below 63 mg/km at the highest vehicle speed. DeNO$_x$ efficiencies are between 95 and 99 %.

The increase in CO$_2$ emissions caused by the calibration measures remained below approximately 3 % on the WLTP and RDE. On these WLTP and RDE tests, the urea consumption stayed below 1.5 l/1000 km; the NH$_3$ slip remained below 10 ppm (peak value) and 1 mg/km (total test result).

CONCLUSIONS AND OUTLOOK

At a time when the future of diesel vehicles is being discussed, these results clearly show that it is possible to continue to reduce their emissions and achieving similar levels as passenger cars with gasoline engine. Consequently, diesel powered vehicles can carry on evolving for many years to come while maintaining their inherent CO$_2$ advantage. Tailpipe CO$_2$ emissions do not cover the entire greenhouse gas footprint of a vehicle. Renewable fuels will be key to further reduce greenhouse gas emissions on a well-to-wheel or life cycle analysis basis. Tests with Hydrotreated Vegetable Oil (HVO) are being conducted with the demonstrator car as an example. Initial results indicate there is no impact on the achieved NO$_x$ emissions.

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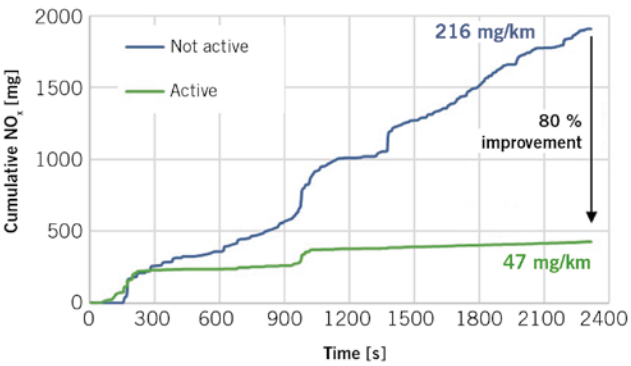

FIGURE 6 Cumulative NO$_x$ emissions on the TfL cycle for a test at the beginning of the project (additional system control measures not active: blue) and at the end (measures active: green) (© AECC)

THANKS

The contribution of Cécile Favre, Andreas Kuhrt and Olaf Friedrichs is highly appreciated. The authors would also kindly like to thank the members of Association for Emissions Control by Catalyst (AECC) and the International Platinum Group Metals Association (IPA) for the financial support, the supply of catalyst parts and for their highly valuable contributions to this study. In addition, the authors would like to thank Renault for providing vehicle and engine hardware.