Ultra-low on-road NOx emissions of a 48V mild-hybrid diesel with LNT and dual-SCR

J. Demuynck[a], C. Favre[a] and D. Bosteels[a]
A. Kuhrt[b], J. Spitta[b] and F. Bunar[b]

a Association for Emissions Control by Catalyst
bd. Auguste Reyers 80, 1030 Brussels, Belgium

b IAV GmbH
Carnotstrasse 1, 10587 Berlin, Germany

Abstract: The gap between diesel vehicle emissions in laboratory tests compared to those in use has been addressed by the introduction of the Euro 6d RDE (Real Driving Emissions) regulatory requirements. Modern diesel technology now demonstrates low emissions on the road over a wide range of driving conditions. This paper further demonstrates that consistent low nitrogen oxide (NOx) emissions can be achieved over a wider range of driving conditions than the Euro 6d RDE requirements, with emission control technologies combined in an integrated approach.

A Lean NOx Trap (LNT) is combined with a dual Selective Catalytic Reduction (SCR) system. Low-load NOx control is achieved by the LNT in combination with a close-coupled SCR coated on the Diesel Particulate Filter (SDPF). High load conditions, on the other hand, are covered by the underfloor SCR system fed by a second AdBlue® injector. A P0 48V mild-hybrid system is also available on the car to support the NOx control and to ensure good driving performance and fuel efficiency. An advanced control strategy is implemented to ensure optimal interaction between all emission control functionalities. The system was implemented on a C-segment demonstrator vehicle.

A combination of tests on the road and in the lab were carried out to demonstrate low emissions over a wide range of driving conditions. Special attention was paid to the robustness of the emission performance under urban and motorway driving conditions. Results demonstrate that each aftertreatment component contributes to achieving consistently low NOx emissions under all driving conditions.

Key Words: NOx; on-road; diesel; LNT; dual-SCR; mild-hybrid

1 Introduction

European Union legislation on light-duty vehicle emissions has undergone major changes in the last years. The World-harmonized Light vehicle 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, a four-package Real-Driving Emissions (RDE) regulation [1] has entered into force that regulates nitrogen oxides (NOx) and Particle Number (PN) emissions from passenger cars and light-commercial vehicles while driving on the road. The manufacturer must now guarantee that the emissions of the vehicle will stay below a maximum declared value on any trip within the RDE boundary conditions for route characteristics, driving dynamics and ambient conditions. These requirements apply not only to the entire trip, consisting of urban, rural and motorway parts, but also to the urban part separately.
The gap between diesel vehicle emissions in laboratory tests compared to those in use has been addressed and modern diesel technology now demonstrates low emissions on the road over a wide range of driving conditions [2]-[6]. More importantly, more than 700 RDE-compliant diesel car models are available on the EU market [7] (i.e. models type-approved to the Euro 6d-temp standard effective since September 2017), giving low on-road tailpipe emissions [8]. By plotting Portable Emissions Measurement System (PEMS) data from the RDE tests conducted at type-approval [9]-[10], one can visualise on Figure 1 the significant reduction in NOx emissions from pre-RDE (grey area) to RDE-compliant (blue dots) diesel vehicles. This improvement is observed for emissions over the entire test (total RDE) as well as over the urban part only (urban RDE).

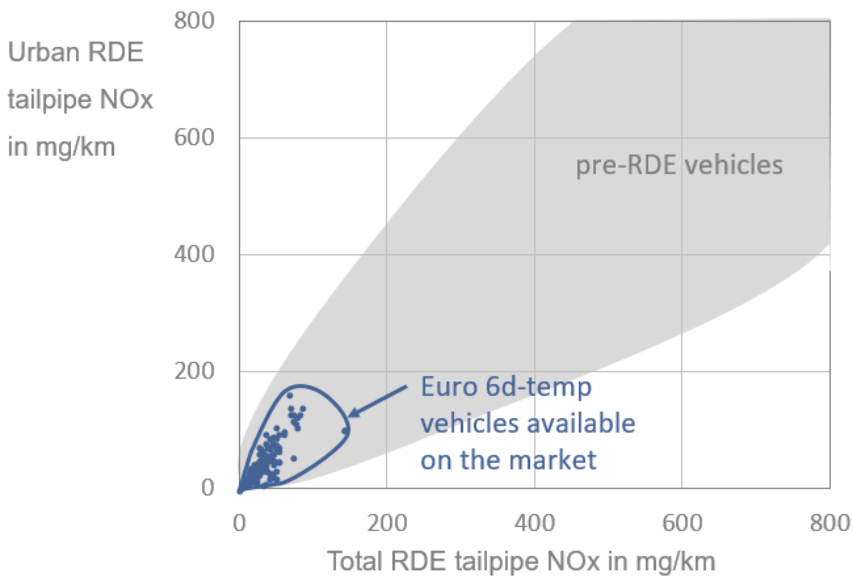

Figure 1: Reduction in real-world diesel NOx emissions brought by the introduction of RDE requirements

Each data point in Figure 1 represents a vehicle's NOx emission over an RDE-compliant route comprising of urban, rural and motorway driving conditions. Figure 2 then shows how the NOx tailpipe emission level varies depending on average vehicle speed/loads. For pre-RDE vehicles type-approval was limited to the NEDC, a laboratory test characterized by a single average speed/load value, giving the NOx emission value in the middle of the graph. Towards the left and right sides (i.e. lower and higher average speeds/loads), pre-RDE NOx emissions used to increase due to the impact of the broader test conditions encountered on public roads (e.g. driving route, road gradients, vehicle load, driving style and ambient conditions). However, the robustness of tailpipe NOx emission control across this wider range of driving conditions has been improved significantly over recent years through powertrains and emission control systems optimisation to meet RDE legislation requirements (blue arrows in Figure 2).

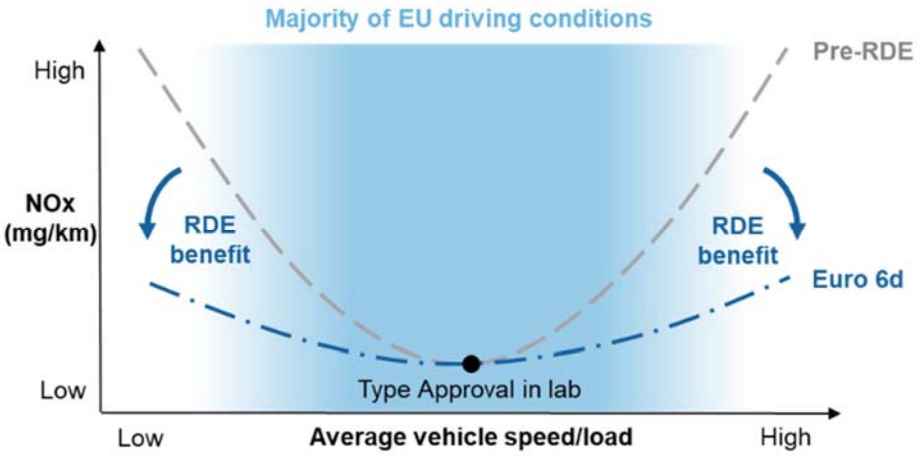

Figure 2: Schematic illustration of tailpipe NOx emissions vs. average vehicle speed/load

As part of the "post Euro 6" study, the European Commission is now considering whether elements of the regulatory framework should be further developed, modified and/or broadened [11]. The range of driving conditions to be covered in the RDE test is one of the 'post-Euro 6' elements under consideration.

The aim of the project reported here was to get consistent low NOx and particulate emissions across a wide range of operating conditions, while maintaining CO_2 emissions. To achieve the objective, a DPF (Diesel Particulate Filter) was implemented on a mild-hybrid diesel passenger car together with a combination of NOx emission control technologies. The functional control integration of all technologies in the software was key. More specifically, the aim was to address:

1. urban driving
2. motorway driving

2 Project set-up

2.1 Vehicle and powertrain characteristics

The base vehicle for the demonstrator project is a C-segment car equipped with a diesel engine, originally type-approved to Euro 6b. The vehicle has a 6-speed manual gearbox in combination with front wheel drive. The vehicle test weight is 1700 kg (including driver and PEMS).
Key features of the downsized, 4-cylinder, 2-valve diesel engine include a displacement of 1.5l, a compression ratio of 15.5:1, a nominal power output of 54 kW/l at 4000 rpm and a torque of 173 Nm/l at 1750 rpm. It is equipped with a 1600 bar common rail fuel injection system (solenoid injectors), one-stage variable geometry turbo charger with e-actuator and air/air intercooler. NOx engine-out emissions are lowered by a combination of uncooled high- and cooled low-pressure Exhaust Gas Recirculation (EGR) systems, supported by an exhaust gas pressure flap downstream of the LP-EGR system.

2.2 Exhaust aftertreatment system layout and controls

The original exhaust aftertreatment system was removed and replaced by an LNT + dual-SCR system, as shown in Figure 3.

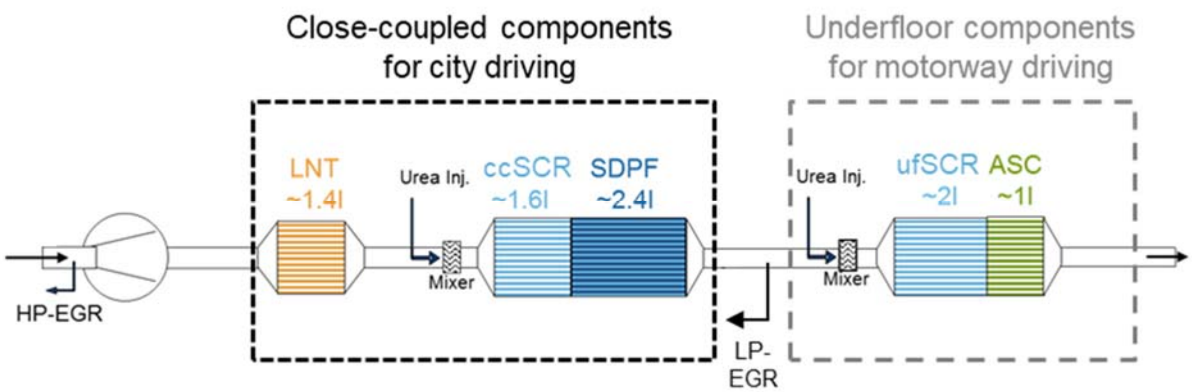

Figure 3: Exhaust aftertreatment system layout

The 1.4l LNT actively covers NOx emissions control mainly during low-speed, city driving conditions. A low thermal mass SCR is added in close-coupled position for an optimum SCR light-off performance after cold-start and to support the LNT. The close-coupled SCR consists of a 1.6l SCR slice upfront of a 2.4l SCR catalyst coated on a DPF (SDPF). This enables optimal synergy between LNT and SCR deNOx performance during city driving at low exhaust temperatures, as visualised on the left side of Figure 4.

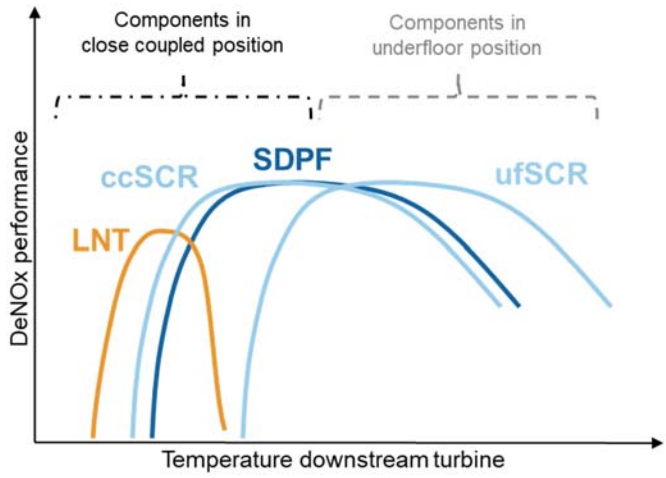

Figure 4: Schematic visualisation of how a combination of technologies is used to enlarge the overall system deNOx performance

To cover high-speed and high-load driving conditions, a second SCR catalyst and an Ammonia Slip Catalyst (ASC) are added in underfloor position. These downstream catalysts experience lower temperatures compared to the close-coupled SCR system, enabling them to be effective at higher vehicle speed/loads. Combined with a second AdBlue® dosing unit, they improve deNOx performance at motorway conditions (high speed, load, and post-turbine temperatures). This is visualised on the right side of Figure 4. In summary, the combination of different components positioned along the exhaust line increases the overall system deNOx performance across a wide variety of driving conditions.

Achieving high NOx 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 NOx level. For individual control of the different components in the dual-SCR system and coordination of the AdBlue® injectors, a model-based closed-loop dosing control software is introduced (Figure 5).

Considering system tolerances and drift of sensors and actuators, the low-dimensional SCR models are continuously checked against the information measured by the downstream NOx sensors in order to maintain high deNOx performance by means of an extended Kalman filter (EKF) for each component.

The benefit of adding a second urea dosing unit is to reduce NH_3 formation in the low-pressure EGR duct (the second dosing unit was located downstream of the exhaust gas extraction point) and to reduce NH_3 oxidation at high temperatures, which would occur if high Adblue® dosing upstream of the close-coupled SCR system was required from a single injector.

Prior to testing, all catalyst components used in this work were hydro-thermally aged via a rapid ageing procedure representative of the vehicle lifetime. In addition, around 15 000 km was accumulated during the project before the final emissions tests were conducted.

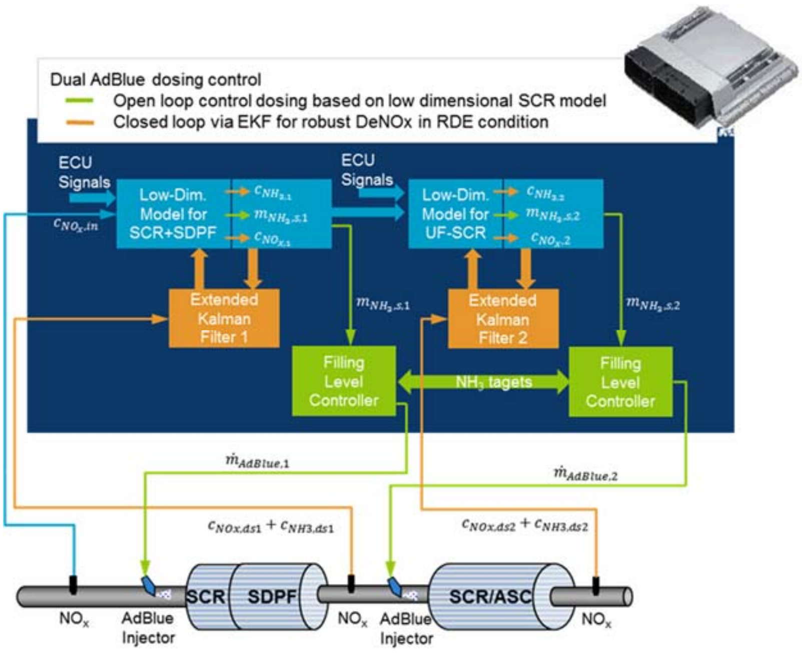

Figure 5: model-based SCR control

2.3 Hybrid system layout and controls

The belt-driven electric motor (EM) of the 48V mild-hybrid system is located close to the 4-cylinder diesel engine in a P0 configuration. The integrated EM can support the internal combustion engine (ICE) up to 10 kW electric power. During acceleration phases, hybrid-assist provides torque in order to support the diesel engine and reduce fuel consumption and CO_2 emissions. Additional CO_2 reduction is obtained by stop-start functionality when the car is stationary. During deceleration and braking phases, the electric generator recovers the kinetic energy in order to recharge the battery. During take-off or acceleration at low engine revolutions, hybrid-assist will also provide additional torque to improve reactivity and avoid gear downshifting.

The following additional emission control functionalities for the 48V mild-hybrid system are implemented in the project:

1. Active thermal management of the aftertreatment system in order to reach and maintain exhaust temperatures above the catalyst light-off temperature. In this case, the electric motor works as a generator and adds additional load to the combustion engine.
2. Support of LNT regeneration at low-load conditions. The electric motor stabilises the engine torque to absorb fluctuations in the driver-requested torque which could otherwise interrupt LNT regeneration phases.
3. Transient driving conditions with high torque gradients can lead to significant NOx emissions. The electric motor therefore supports the combustion engine during these transient phases to reduce NOx emission peaks.

Functions 1 and 2 ensure early deNOx operation after a cold-start in urban driving conditions. Figure 6 illustrates these in more detail. The vehicle speed and combustion mode (NRM=normal; NPU=NOx Purge/LNT regeneration) are plotted at the top, the different torque levels within the powertrain system are plotted underneath. At the bottom, the temperature or lambda trace are plotted.
For the first function (thermal management), the electric motor charges the 48V battery and therefore increases the combustion engine load compared to what the driver is requesting. As a consequence, the exhaust temperatures are higher compared to the base case where there would be no support by the 48V mild-hybrid. The bottom figure shows that, as a consequence, during a nearly constant driving condition at low load, two temperature peaks are created.
For the second function (LNT regeneration support), the electric motor performs either a constant torque offset under low-load driving (middle figure) or a variable torque contribution to stabilise fluctuations in the driver-requested torque (right side figure). Due to the support of the 48V mild-hybrid system, the engine torque is thus kept in the area where a stable LNT regeneration is possible. This creates extra opportunities to conduct LNT regenerations and therefore improves NOx emission control, especially in urban driving conditions.

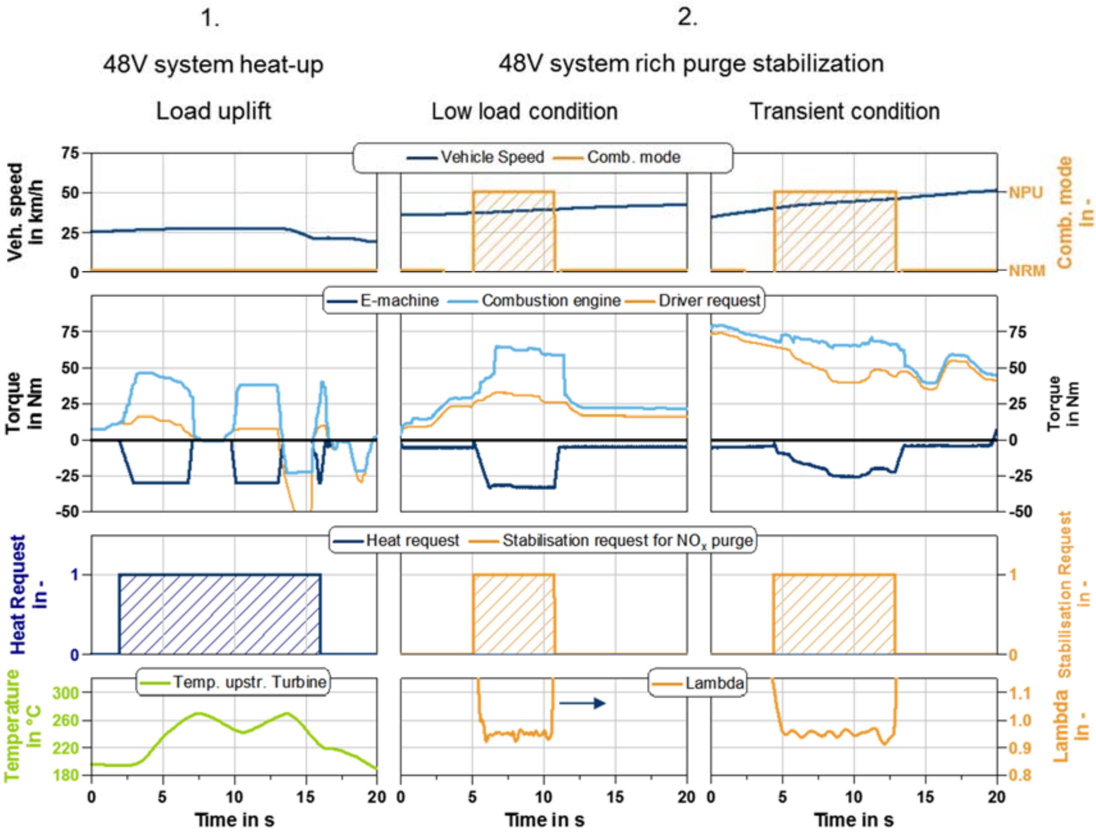

Figure 6: Illustration of emissions control support by the 48V mild-hybrid system

2.4 Emissions tests

The objective of the programme was to demonstrate low emissions over a wide range of driving conditions. In addition to regulatory emissions tests (WLTC and RDE), different tests were conducted on the road and in the lab to cover urban (Berlin and Transport for London “Interpeak” cycle), 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 Transport for London (TfL) test is included as a challenging cold-start test due to its combination of short distance (9 km) and low average vehicle speed (13.9 km/h including idle). The exhaust temperature histogram of this test, in Figure 7, shows that most of the time, the exhaust conditions are below the typical SCR light-off temperature (indicated with the red line).

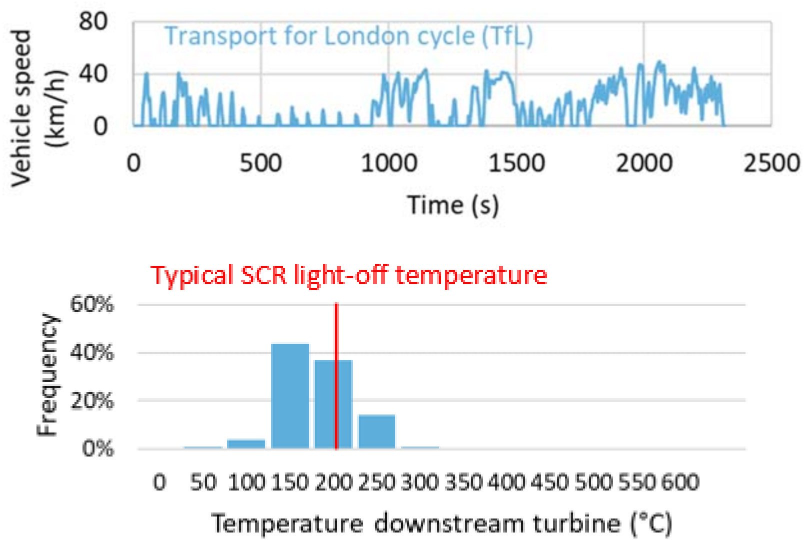

Figure 7: Illustration of the driving speed trace and exhaust temperature histogram for the Transport for London test

Figure 8 shows the range of ambient conditions that were covered for the different emissions tests. Two different levels of ambient altitude are covered. RDE route 1 and tests in the lab are at altitude levels below 100 m, RDE route 2 is at around 700 m. This test also includes more dynamic driving up to the RDE boundary condition of 1200m/100 km.

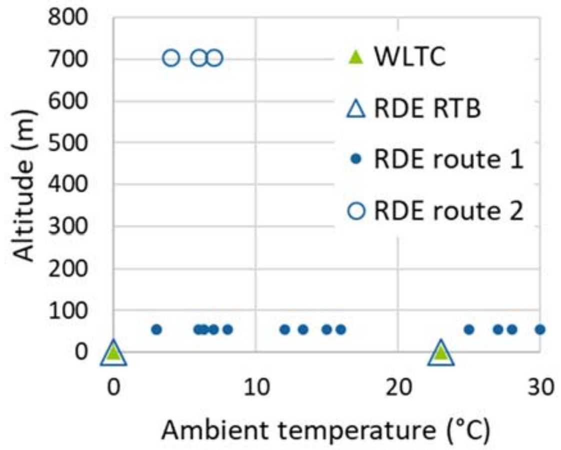

Figure 8:Range of ambient conditions covered for the different emissions tests.

3 Results and Discussion

The NOx emissions measured over the wide range of driving conditions will be introduced step-by-step. First, the results over average driving conditions will be discussed. Then, a more detailed analysis will be presented of emissions under urban and motorway driving conditions respectively.

3.1 Average NOx emissions

The NOx emissions measured on RDE and WLTC are shown in Figure 9. Results are plotted against increasing average ambient temperature. Both on-road and in-lab RDE results are included. NOx emissions range from 8 to 40 mg/km. No impact of the ambient temperature can be observed over the different tests. Figure 9 also include early tests in the project, conducted at a time when the system calibration was still being updated. The tests carried out at the end, with the refined calibration, are marked with a blue asterisk. These NOx emissions are all below 20 mg/km.

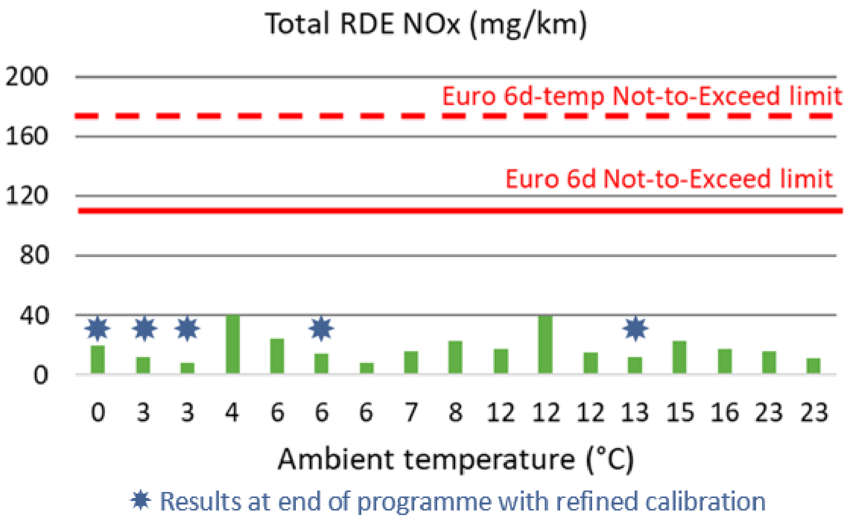

Figure 9: NOx emissions of entire test vs. ambient temperature

3.2 Urban emissions

NOx emissions measured during urban driving are plotted in Figure 10. Data is shown for the urban part of the RDE test (both on the road and in the lab) and the two dedicated urban emissions tests (Berlin driving on the road and the Transport for London cycle in the lab). Results are again plotted against ambient temperature. Consistent low NOx emissions are measured under these conditions as well, ranging from 24 to 47 mg/km. Again, no impact of the ambient temperature is observed.

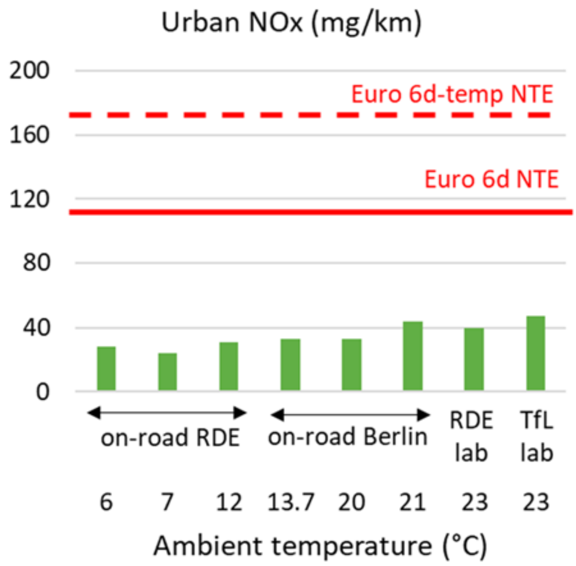

Figure 10: NOx emissions during urban driving conditions vs. ambient temperature

The contribution of the different exhaust aftertreatment components to the NOx reduction is shown in Figure 11 for the urban part of an RDE test. Engine-out NOx emissions are at 373 mg/km in this test. With 156 mg/km and 187 mg/km of NOx reduced respectively, the LNT and close-coupled SCR+SDPF contribute almost equally. A deNOx efficiency of 92% is achieved in this test, achieving 31 mg/km NOx at the tailpipe.

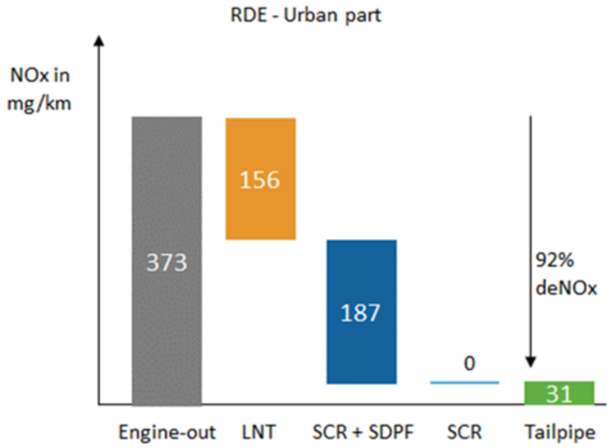

Figure 11:Breakdown of NOx reduction during urban driving conditions

As described above, system control measures were implemented to allow early NOx conversion in urban conditions following a cold start. Contributions mainly come from the LNT regeneration stabilisation by the 48-V mild- hybrid system and the active thermal management. This is visualised for the TfL cycle in Figure 12, by comparing the initial (measures not yet implemented, in blue) and refined calibration (measures implemented, in green).

The occurrence of LNT regeneration is indicated in the top chart. No blue spike can be seen during the TfL test as there was no opportunity for an LNT regeneration. With the support of the 48V mild-hybrid system though, opportunities to regenerate the LNT arise under very low load and speed conditions. With the refined calibration, an LNT regeneration therefore occurs in the middle of the test.

The thermal management implemented uses different functions to increase the exhaust temperature: either the throttle valve, a late post-injection (ICE) or the support by the 48V mild-hybrid system as explained earlier. Figure 12 illustrates that these measures remain active throughout the entire TfL test and that the typical light-off temperature of the LNT (the one which enables LNT regeneration; NOx adsorption already occurs at lower temperatures) and SCR catalyst are reached within 200 s, which is 800 s earlier compared to the situation without active thermal management.

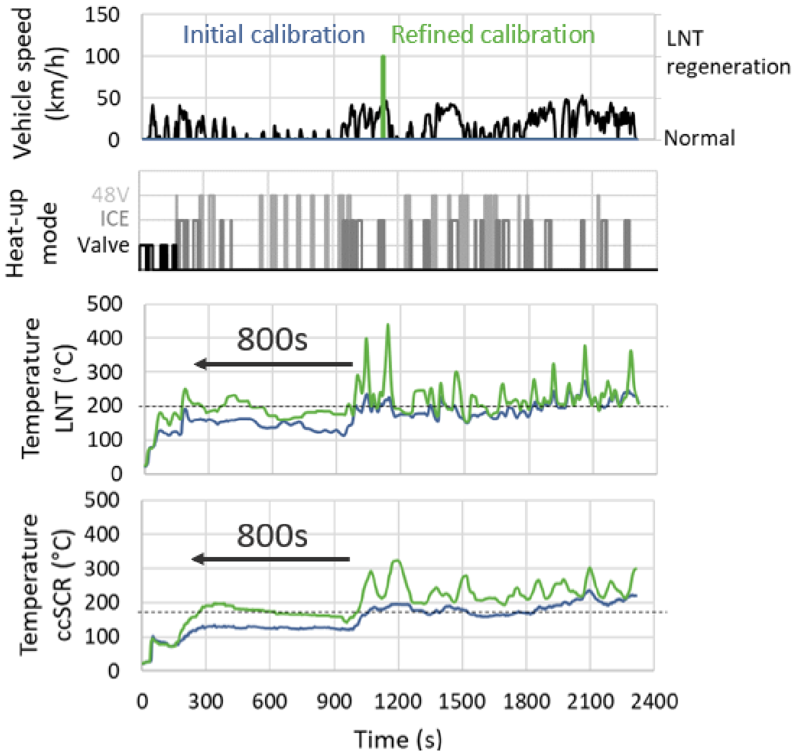

Figure 12: Illustration of the impact of control measures implemented to allow early NOx conversion in urban conditions following a cold-start (Transport for London cycle)

The improvement brought by these measures is visualised in Figure 13, where cumulative NOx emissions are plotted for the Transport for London cycle. Without the additional system control functionalities, tailpipe NOx emissions of 216 mg/km are measured. With the LNT regeneration stabilisation and active thermal management, an 80% improvement of the NOx emissions is observed, reaching 47 mg/km of NOx.

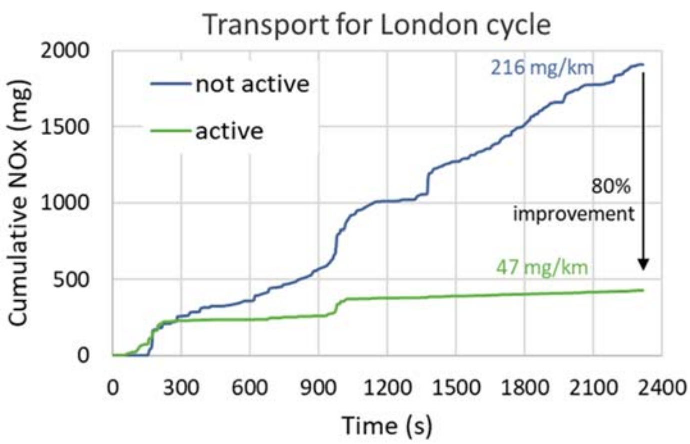

Figure 13: Cumulative NOx emissions on the Transport for London cycle for a test at the beginning of the project (additional system control measures not active - blue) and at the end (active – green)

3.3 Motorway emissions

Motorway emissions are investigated on the road during a dedicated motorway test, including driving up to 160 km/h on the German autobahn. Different sections of this test are investigated separately to evaluate the relationship between the average vehicle speed and NOx emissions. Depending on the section selected, an average speed ranging from 75 to 140 km/h can be obtained.

The breakdown of NOx reduction measured at 100 and 140 km/h are plotted in Figure 14. The challenging driving conditions increase engine load and speed, resulting in an increase in engine-out emissions, up to 594 and 1465 mg/km for the respective cases. At higher speeds, the close-coupled SCR+SDPF still contributes the most part of the NOx conversion, but the underfloor SCR is needed to secure the consistent low NOx emissions under all motorway conditions. The presence of the underfloor SCR catalyst also allows to operate the close-coupled SCR+SDPF at higher NH_3 dosing levels without risking NH_3 slip at the tailpipe, supporting the high NOx reductions over the close-coupled SCR+SDPF. The overall NOx conversion efficiency is 97% and tailpipe NOx emissions are 20 mg/km at 100 km/h and 49 mg/km at 140 km/h.

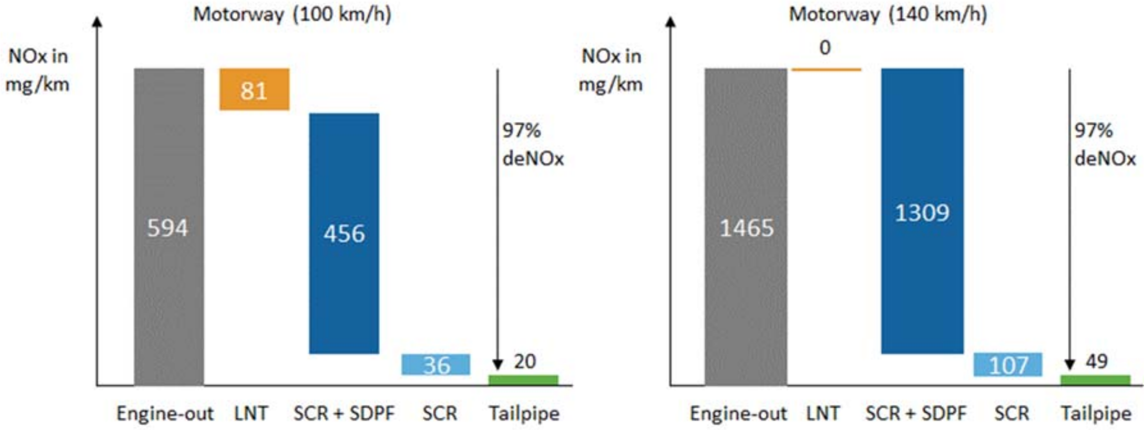

Figure 14: Breakdown of NOx emissions during motorway driving conditions

3.4 Summary of emissions

All tailpipe NOx emissions measured during the programme are plotted against average vehicle speed in Figure 15. Consistent low NOx emissions are measured over the range of driving conditions covered. The results on the left (i.e. low load/speed) not only reflect the impact of the vehicle speed, but also the contribution of the cold start at the beginning of the test. The variation in the total system deNOx efficiency is shown in Figure 16.

The increase in CO_2 emissions caused by the implementation of active thermal management remained below approximately 3% on the WLTC and RDE tests. On these WLTC and RDE tests, the urea consumption stayed below 1.5 l/1000 km while the NH_3 slip remained at concentrations below 10 ppm (peak) or 1 mg/km (total test result).

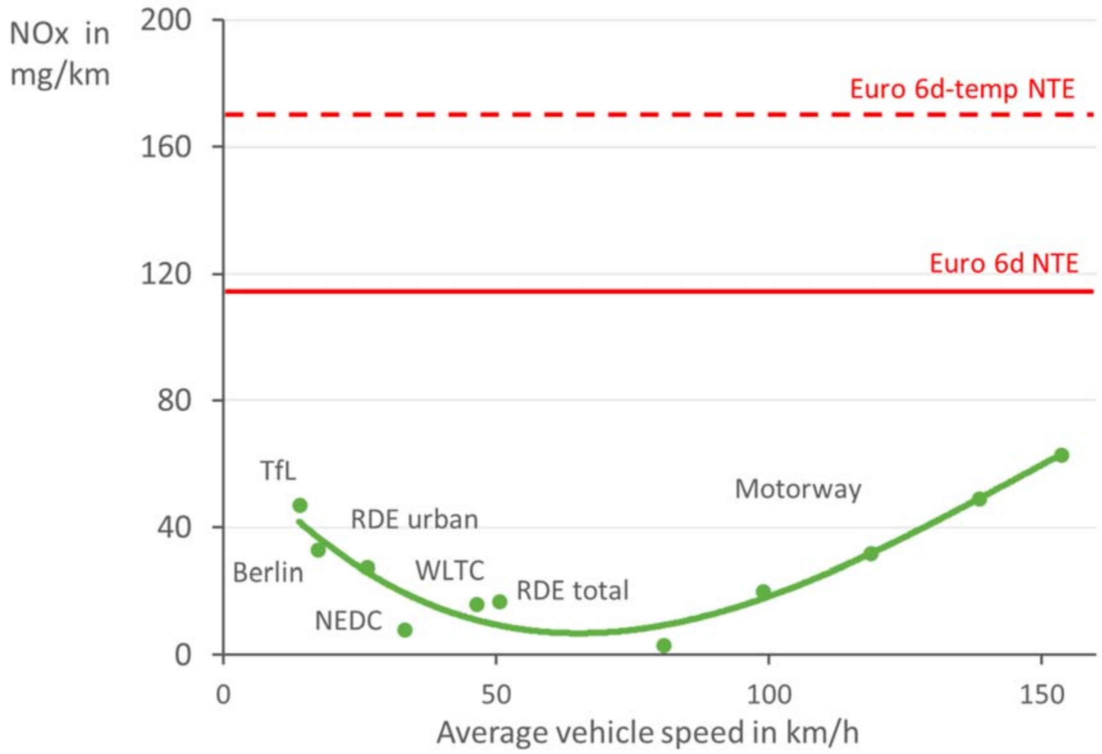

Figure 15: Summary of tailpipe NOx emissions achieved over the range of driving conditions covered in the programme

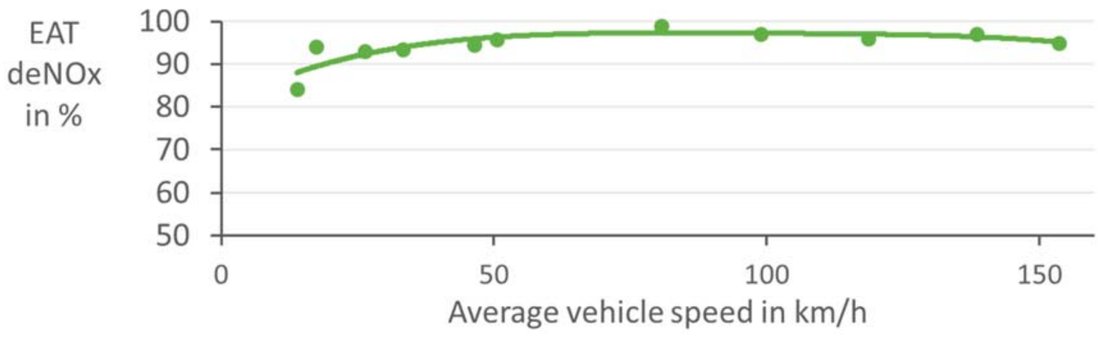

Figure 16: Summary of total system deNOx efficiency achieved over the range of driving conditions covered in the programme

4 Summary and Outlook

This demonstrator vehicle shows that diesel NOx emissions can be consistently kept at a very low levels over a wide range of driving conditions by combining available catalyst technologies with improved engine and aftertreatment control functions.

An optimised integration of an LNT + dual-SCR aftertreatment system together with a 48V mild-hybrid system and LP+HP EGR diesel engine was done on a C-segment demonstrator vehicle. In addition to the torque assistance and brake-energy recuperation, various hybrid support functionalities were implemented for the NOx control (stabilisation of LNT regeneration, contribution to active thermal management and support of engine-out NOx control). Model-based control of the SCR components was used to achieve high deNOx efficiencies without NH_3 slip.

A multitude of emission tests were conducted to check the robustness of the NOx control over a wide range of driving conditions, focussing in particular on urban and motorway driving. Ultra-low NOx levels of 8-40 mg/km were achieved on the WLTC and RDE tests. The integrated approach to optimise the contribution of each emission control component allowed the system to maintain a high deNOx conversion efficiency, above 84% during the dedicated urban (24-47 mg/km) and motorway (3-63 mg/km) driving conditions. Each aftertreatment component (LNT, close-coupled SCR/SDPF and underfloor SCR) contributed to achieving the consistently low NOx emissions.

Further technologies to fulfil possible post-Euro 6 requirements include advanced thermal management (e.g. variable valve train), further engine-out emission reduction directly after a cold-start and further catalyst development.

Acknowledgements

The authors would kindly like to thank members of AECC and IPA (International Platinum Group Metals Association) 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 a vehicle and engine hardware.

References

1. Commission Regulation (EU) 2017/1151 of 1 June 2017, amended by Regulation (EU) 2017/1154 and Regulation (EU) 2018/1832, https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1545234494664&uri=CELEX:32017R1151
2. B. Holderbaum, M. Kind, C. Menne, T. Wittka, G. Vagnoni, D. Bosteels, C. Favre and J. May, “Potential for Euro 6 Passenger Cars with SCR to meet RDE Requirements”, in Vienna Motorensymposium, 2015.
3. D. Bosteels, J. Demuynck and C. Favre, “Diesel engines on the pathway to low impact on local air quality”, in 4th International Conference Diesel Powertrains 3.0, Coventry, July 2018.
4. A. Kufferath, M. Krüger, D. Naber, E. Mailänder, and R. Maier, “The Path to a Negligible NO_2 Immission Contribution from the Diesel Powertrain,” in Vienna Motorensymposium, 2018.

5. G. Avolio, R. Brück, J. Grimm, O. Maiwald, G. Rösel, H. Zhang, “Super Clean Electrified Diesel: Towards Real NOx Emissions below 35 mg/km.” 27th Aachen Colloquium Automobile and Engine Technology 2018.

6. Concawe-Ricardo report “Expectations for Actual Euro 6 Vehicle Emissions”, www.concawe.eu/wp-content/uploads/2018/04/RD18-000697-2-CONCAWE_Expectations_for_Actual_Euro_6_Vehicle_Emissions.pdf

7. „PKW-Modelle mit der Abgasnorm Euro 6d-TEMP / Euro 6d“, ADAC website consulted 8 February 2019, www.adac.de/infotestrat/umwelt-und-innovation/abgas/modelle_mit_euro_6d_temp/default.aspx.

8. „Moderne Diesel sind sehr sauber“, ADAC Ecotest report 18 September 2019, www.adac.de/rund-ums-fahrzeug/abgas-diesel-fahrverbote/dieselkauf-abgasnorm/euro-6d-temp/

9. ACEA RDE monitoring database, www.acea.be/publications/article/access-to-euro-6-rde-monitoring-data

10. JAMA RDE monitoring database, www.jama-english.jp/europe/publications/rde.html

11. “Preparing automotive emission standards for the future”, European Commission stakeholder event, 24 October 2018, Brussels, https://ec.europa.eu/growth/content/stakeholder-event-preparing-future-european-emission-standards-light-and-heavy-duty-vehicles_en.