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Integrated Diesel System Achieving Ultra-Low Urban and Motorway NOx Emissions on the Road

Reduzierung von NOx-Emissionen im realen Stadt- und Autobahnfahrbetrieb mit optimiertem Dieselantrieb

Abstract

The paper discusses the technical approach to meet Euro 6d Real-Driving Emissions (RDE) requirements and beyond, with a particular focus on reducing diesel NOx emissions in urban and motorway driving situations. Novel technology aspects of the diesel powertrain are an RDE-optimized aftertreatment system layout to improve both low- and high-load deNOx performance and a 48V P0 hybrid system. An additional key element of the powertrain concept is the advanced model-based deNOx control strategy.

The first part of the paper provides a brief summary of Euro 6d and possible post-Euro 6 RDE requirements. Based on this, the technology strategy for the powertrain and aftertreatment architecture is derived. Challenges for the related control functions are discussed as well. The optimized exhaust aftertreatment layout combines Lean NOx Trap (LNT) and Selective Catalytic Reduction (SCR) technologies. For maximum low load deNOx performance, the close-coupled SCR, consisting of an additional slice upstream of an SCR coated on DPF (SDPF), is assisted by an LNT. High load conditions are covered by a dual SCR system with twin AdBlue® dosing. The P0 48V electric motor supports the NOx control in addition to ensuring good driving performance and fuel efficiency. A smart and advanced control strategy is implemented to ensure optimal interaction between all components.

The second part of the paper focusses on experimental data from PEMS measurements of a demonstrator car on public roads and on the chassis roller test bench. The RDE tests investigated cover a wide range of driving conditions. Special attention is paid to the robustness of the emission performance under urban and motorway driving conditions.

Finally, further possible technology and system evolutions are discussed.

Kurzfassung

Der vorliegende Beitrag stellt dar, wie Schadstoffemissionen im praktischen Fahrbetrieb (RDE) so reduziert werden können, dass sie sowohl aktuelle Euro 6d Abgasnormen als auch zukünftige Anforderungen einhalten. Besonderes Augenmerk wird hierbei auf die Reduzierung der Stickoxidemissionen (NOx Emissionen) im Stadt- und Autobahnverkehr gerichtet. Neuartige technische Aspekte sind hierbei: eine optimierte Anordnung des Katalysatorsystems zur Verbesserung der Tief- und Hochtemperatur-deNOx-Funktionalität in Verbindung mit einem elektrifizierten Antrieb auf Niederspannungsniveau (48V P0-Hybrid – Riemenstartergenerator (BSG)). Neben der Hardwareoptimierung besteht ein weiteres Schlüsselelement in einer leistungsfähigen, modellbasierten Regelungsfunktionalität.

Der erste Teil des Beitrags gibt einen Überblick über die aktuellen Anforderungen der Euro 6d Abgasnorm, sowie über die zukünftig erwarteten Anforderungen. Aus diesen Anforderungen werden die benötigten Hardwarebausteine, die Systemarchitektur und die Steuerungsfunktionen abgeleitet und diskutiert. Die Optimierung der Abgasnachbehandlung erfolgt über einen motornahen NO_x-Speicherkatalysator (LNT) in Kombination mit einem Hochleistungs-SCR-System auf. Die benötigte hohe NO_x-Umsatzrate bei Niedriglast wird durch eine Kombination aus LNT und motornahem Partikelfilter mit SCR-Beschichtung (SDPF), sowie einer vorgeschalteten SCR-Katalysatorscheibe realisiert. Den Hochlastbereich deckt ein Twin-SCR-System mit einer weiteren AdBlue-Dosiereinheit ab. Zusätzlich zum aktiven Abgasnachbehandlungssystem unterstützt der 48V Elektromotor des Hybridantriebs sowohl die Funktion der Katalysatorregelung als auch die erwünschte Fahrdynamik. Gleichzeitig wird die Effizienz des Antriebes und damit der Kraftstoffverbrauch verbessert. Die Koordination dieser komplexen Regelungsaufgabe übernimmt eine neuartige Funktion in der Motorsteuerung.

Im zweiten Teil des Beitrags werden Versuchsergebnisse des Demonstratorfahrzeugs mit dem oben beschriebenen weiterentwickelten Abgasnachbehandlungskonzept vorgestellt. Die Versuchsergebnisse beinhalten Messungen auf Abgasrollenprüfstand und PEMS Messungen auf öffentlichen Straßen. Die Messungen decken einen weiten Bereich von realen Fahrsituationen ab. Besonderes Augenmerk richtete sich hierbei auf eine hohe Robustheit der Schadstoffreduktion im Stadtfahrbetrieb.

Abschließend werden technische Weiterentwicklungsoptionen für mögliche zukünftige regularische Szenarien diskutiert.

Introduction

Current regulatory requirements

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 only.

The perceived gap between diesel vehicle emissions in laboratory tests compared to those in use has been addressed and modern diesel technology demonstrates low emissions on the road over a wide range of driving conditions [2]-[6]. More importantly, 555 RDE-compliant diesel cars are available on the EU market at the time of writing [7] (i.e. models type-approved to the Euro 6d-temp standard effective since September 2017), giving low on-road tailpipe emissions [8]. Figure 1 visualises the significant reduction in NOx 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 [9]-[10]. This improvement is observed for emissions over the entire test (total RDE) as well as over the urban part only (urban RDE).

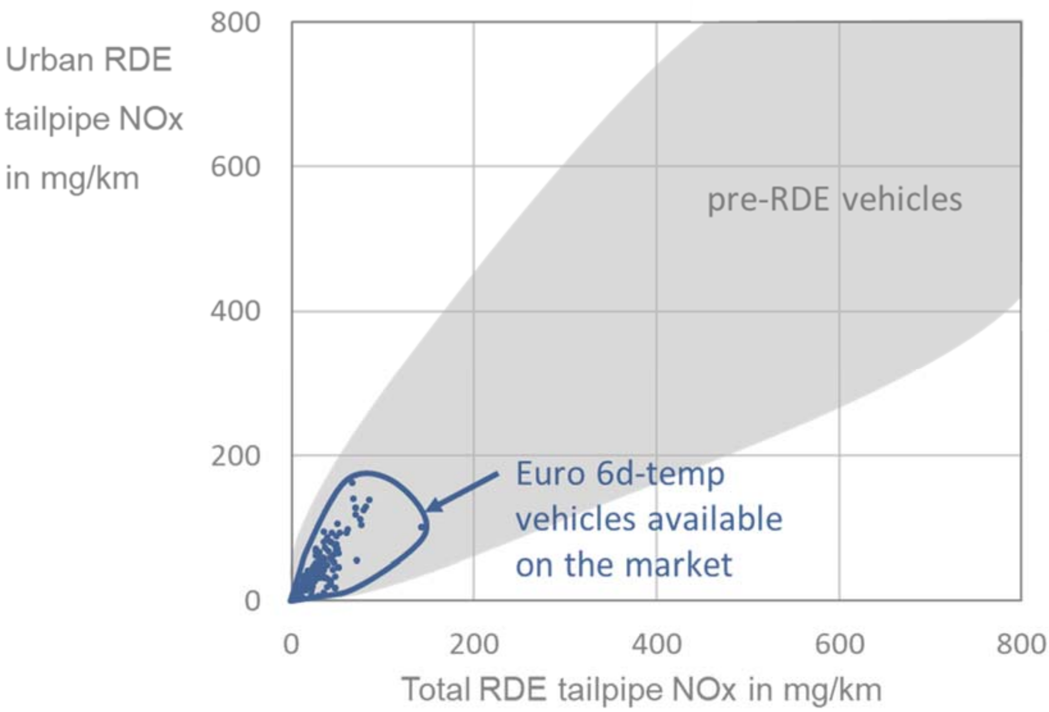


Figure 1: Reduction in real-world diesel NOx emissions brought by the introduction of RDE requirements

Each data point in Figure 1 represents a vehicle's NOx emission over an RDE-compliant route comprising urban, rural and motorway driving conditions. Figure 2 visualises how the NOx tailpipe emission level varies according to 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, 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). 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).

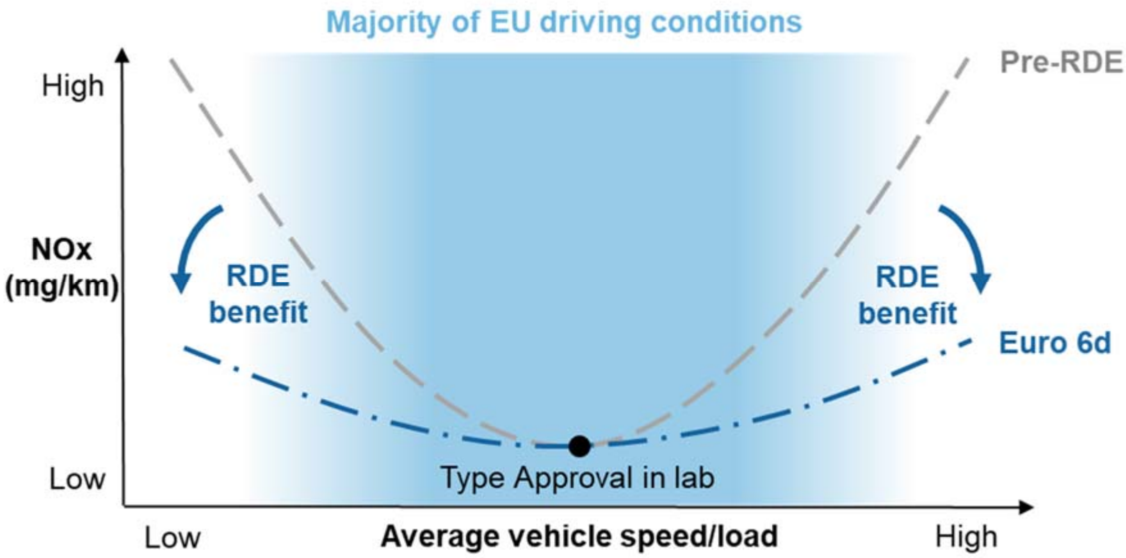


Figure 2: Schematic illustration of tailpipe NOx emissions vs. average vehicle speed/load

Future regulatory requirements

With these major changes in legislation being finalized and published, the European Commission is now considering whether elements of the regulatory framework should be further modified and broadened [11]. The range of driving conditions to be covered in the RDE test is one of the 'post-Euro 6' elements under consideration.

Project objectives

The aim of the project reported in this paper was to enhance the overall robustness of the NOx emission control, while maintaining CO_2, across a wider range of operating conditions. To achieve the objective, a combination of NOx emission control technologies was implemented in an integrated approach on a mild-hybrid diesel passenger car. More specifically, the aim was to address:

1. low average speed representative of urban driving
2. high average speed representative of motorway driving

The paper will not focus on the real-world PN emissions, which are already controlled effectively under all driving conditions by the Diesel Particulate Filter (DPF).

Technology strategy

Exhaust aftertreatment system layout

Similarly to other publications [12]-[13], a state-of-the-art Lean NOx Trap (LNT) in close-coupled position is combined with a dual Selective Catalytic Reduction (SCR) system (see Figure 3) to optimise the NOx reduction (deNOx) performance of the exhaust aftertreatment (EAT) system over all operating conditions.

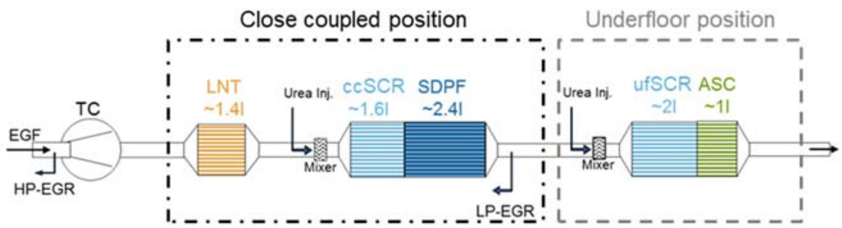


Figure 3: Exhaust aftertreatment system layout

The 1.4l LNT actively covers NOx emissions 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) [14]. This enables optimal synergy between LNT and SCR deNOx performance during city driving at low exhaust temperatures, as visualised at the left side of Figure 4.

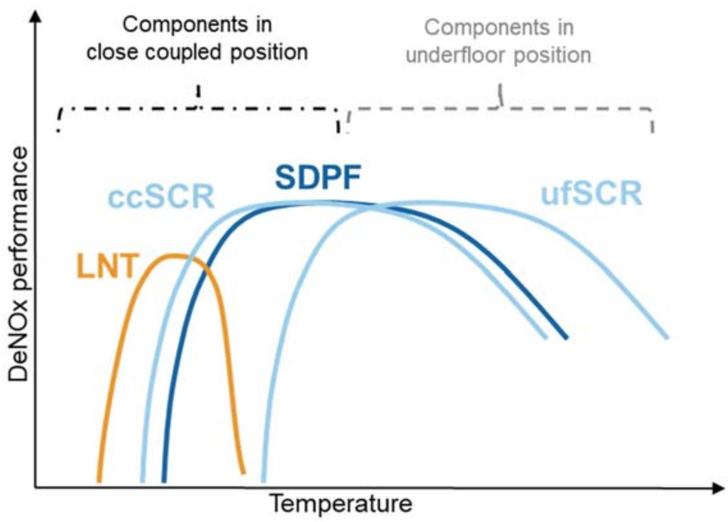


Figure 4: Schematic visualisation of how a combination of technologies is used to enlarge the overall system deNOx performance

To cover high speed and high load driving conditions another SCR catalyst followed by an Ammonia Slip Catalyst (ASC) are added in an underfloor position [12] and [15]. 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 2nd AdBlue® dosing unit, they improve deNOx performance at motorway conditions (high speed and load). This is visualised at the right side of Figure 4. In summary, the combination of different components positioned along the exhaust line provides increased system deNOx performance across a wide variety of driving conditions.

All catalyst components used in this work were tested following a hydro-thermal 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.

Exhaust aftertreatment system controls

Achieving high NOx conversion rates, while preventing 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 [16].
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 as shown in Figure 5.

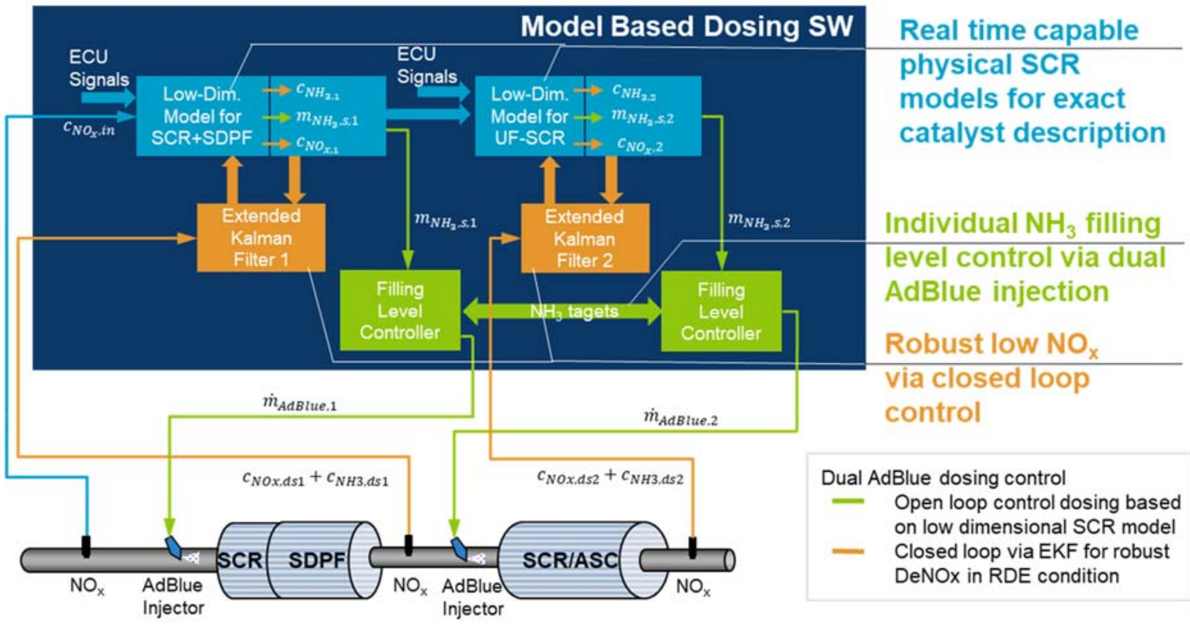


Figure 5: Schematic diagram of dual injector AdBlue® dosing software with physical SCR model, extended Kalman filter and filling-level controller

Real-time capable, low-dimensional models of the SCR components are implemented [17]. Based on information at the inlet of each component, they calculate so-called relevant states, e.g. NH_3 filling states, separate NOx and NH_3 concentrations in each catalyst or any other parameter that cannot be measured on the vehicle. To operate each SCR component at its optimum performance, estimated individual NH_3 filling levels are controlled via an interactive filling level controller.
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. This closed-loop control of the NH_3 filling level in both SCR systems provides a high degree of robustness to any inaccuracies developing in the dosing system hardware [18].
Closed-loop operation is expected to become a new standard feature to better deal with sensor/actuator tolerances. This robust control combined with durable hardware components contributes significantly to stable deNOx performance over lifetime.

The control strategy is implemented based on the NOx sensor and dual dosing unit layout shown in Figure 5. The benefit of adding a 2nd dosing unit is to reduce NH_3 formation in the low-pressure EGR duct (the 2nd 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. The modular software could also be used with closed-loop advantages even in single dosing unit configurations. Advanced algorithms (e.g. machine-learned regression models to estimate engine-out NOx emissions), alternative sensor options (e.g. direct measurement of NH_3 filling level in SCR or measurement of NH_3 concentrations) or alternative sensor layout variants might bring additional positive impacts to the system stability.

Hybrid system layout and controls

Figure 6 shows the architecture of the diesel hybrid system of the vehicle used. The belt-driven electric machine (EM) of the low-voltage (48V) mild-hybrid system is located close to the 4-cylinder diesel engine in a P0 position. 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 does not move. 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.

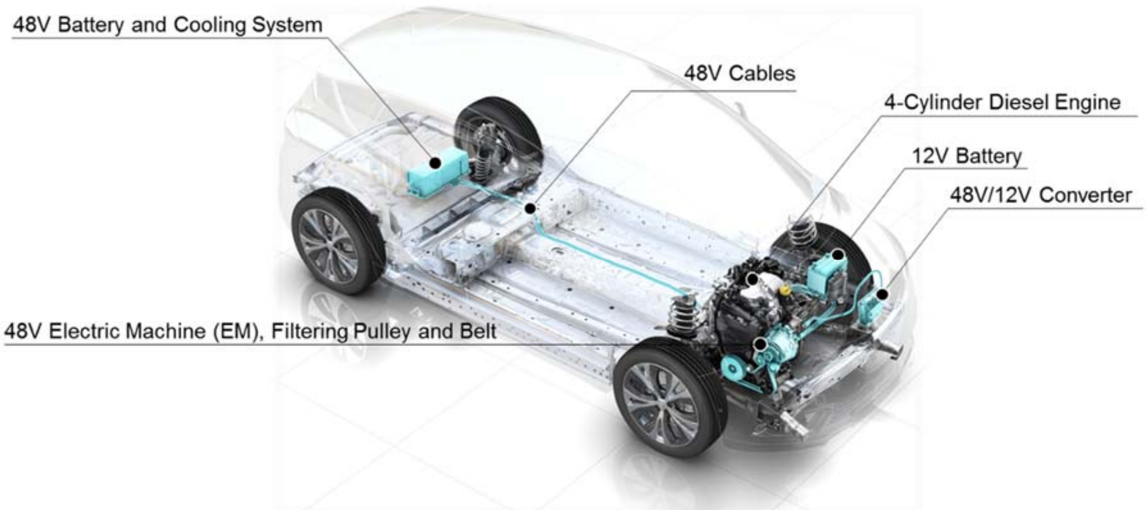


Figure 6: Schematic vehicle layout of the 48V P0 diesel hybrid system

48V cables connect the EM with the 48V battery system mounted between the rear wheels. Key specifications of the 48V battery are an energy content of 150 Wh using Lithium-Ion technology. This allows a time-limited electrical-assist of the ICE. The vehicle weight increases by around 50 kg. The following emission control functionalities are implemented in the project for the 48V hybrid system:

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 emission peaks.

Figure 7 illustrates the first two functions. The vehicle speed and combustion mode (NRM=normal; NPU=NOx Purge) are plotted at the top, the different torque levels within the powertrain system are plotted underneath. Then the status bit for the 48V support is shown. At the bottom, the exhaust temperature is plotted for the first case, the lambda for the second case.
The first function is visualised at the left, i.e. the hybrid system is used to increase the engine torque (light blue) by up to 30 Nm when the exhaust temperature is not yet in the optimal window. During this phase, the electric machine (dark blue) is acting as a generator and charges the battery (negative torque). Exhaust temperatures will increase compared to the situation where the engine would only deliver the driver-requested torque (orange).
The second function of the hybrid system is to support the LNT rich purges. This is performed either with a constant torque offset under low-load driving (in the middle) or with a variable torque contribution to stabilise fluctuations in the driver-requested torque (at the right). The engine torque is brought (or kept) into the area where a stable rich purge is possible thanks to the support of the 48V hybrid system. Rich purges would not be possible under these conditions without the support of the 48V hybrid system. This creates extra opportunities to conduct rich purges and therefore improves NOx emission control, especially in urban driving conditions.

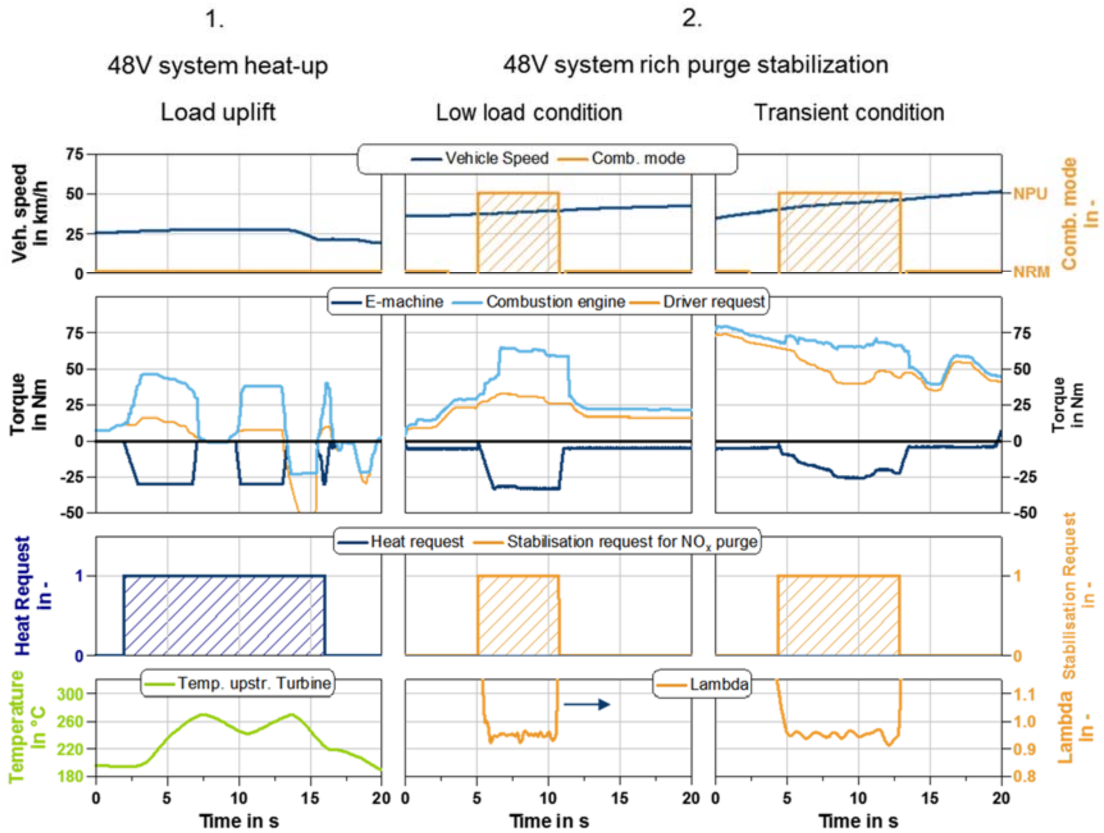


Figure 7: Illustration of how the 48V hybrid system supports the deNOx function

Experimental setup

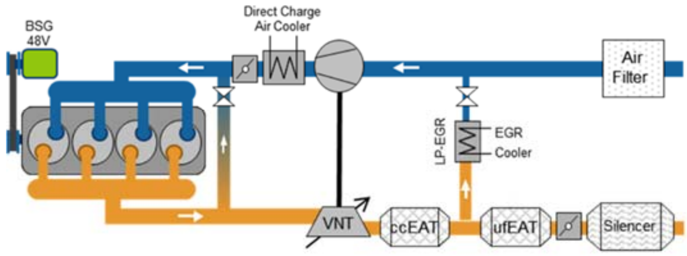
Vehicle and powertrain characteristics

The demonstrator vehicle is a C-segment car equipped with a pre-RDE diesel engine (Euro 6b). Its characteristics are summarised in Figure 8.

Type	Value
Vehicle class	C-Segment
Vehicle test weight	1700 kg
Drivetrain	Front Wheel Drive
Transmission	6-Speed Manual Gearbox
Tires	195/55 R20
c_w x A	0.29 x 2.59m²

Figure 8: Vehicle and drivetrain characteristics

The vehicle test weight is approximately 1700 kg (including driver and PEMS). The front wheel drive powertrain is equipped with a 6-speed manual transmission. Characteristics of the diesel engine are summarised in Figure 9.



Type	Value
Layout	Line 4 Cylinder 2V
Displacement	1.461 cm³
Bore / Stroke	76 / 80.5
Compression Ratio	15.5 : 1
Turbo Charger System	1x Variable Nozzle Turbine + elect.-Actuator Air/Air-Intercooler
Exhaust Gas Reciculation System	High Pressure- & cooled Low Pressure-EGR
Fuel Injection System	Common Rail 1600 bar
Nominal Power ICE	81 kW @ 4000 rpm
Nominal Torque ICE	260 Nm @ 1750 rpm
Nominal Power EM	10 kW
Nominal Torque EM	40 Nm
Capacity 48V Battery	0.15 kWh

Figure 9: Diesel engine layout and characteristics

Key features of the downsized, 2-valve, 4-cylinder 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), 1-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 EGR systems, supported by an exhaust gas pressure flap downstream of the LP-EGR system.

Instrumentation plan

The demonstration project paid special attention to the detailed investigations of NOx reduction in the different components of the exhaust aftertreatment system. Figure 10 describes the instrumentation plan of the demo car that was needed for the investigations.

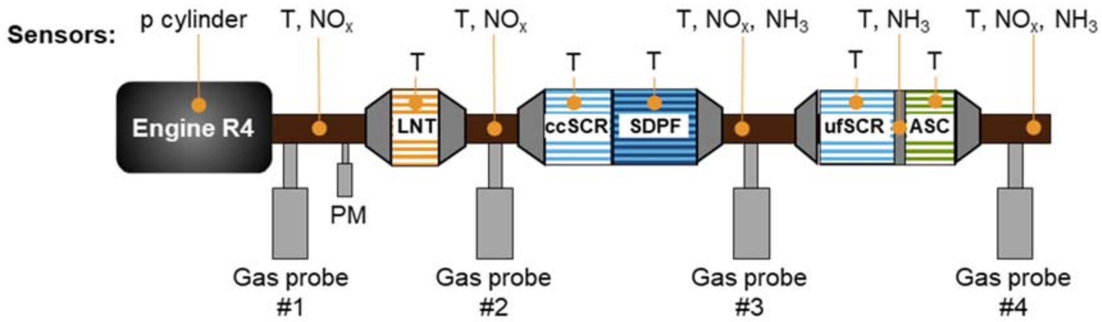


Figure 10: Instrumentation plan of the engine and exhaust aftertreatment system

In addition to the available Engine Control Unit (ECU) sensors of the diesel engine, the combustion process was analysed by a typical cylinder pressure sensor.
From engine-out to tailpipe, the stepwise reduction of NOx emissions was monitored by individual sensors upstream and downstream of each catalyst component (LNT, ccSCR/SDPF, ufSCR/ASC). This enables the analysis of the contribution of individual catalysts to the overall system NOx reduction. NOx and NH_3 storage capacity as well as the deNOx performance strongly depend on individual catalyst temperatures. Each catalyst bed and gas temperature were therefore monitored upstream and downstream. Ammonia transfer between the SCR catalysts and towards tailpipe were measured by NH_3 sensors. The actual control of the SCR catalysts however only relied on the sensors mentioned earlier in Figure 5.

Driving conditions

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), uphill (driving in the Harz area of Germany, up to 700 m) and motorway driving around Berlin (vehicle speeds up to 160 km/h).

The engine load points, vehicle speed traces and exhaust temperature histograms of some of these tests are shown in Figure 11. The coverage of the engine map increases from the Transport for London interpeak cycle (TfL) over WLTC to RDE and Motorway. Full load driving is included in WLTC, RDE and Motorway due to specific characteristics of the downsized 1.5l diesel engine in the C-segment vehicle. The engine load conditions needed to achieve at least 200°C downstream (ds.) of the turbine is also indicated on the engine map. The histograms of the exhaust temperatures are plotted at the right. The TfL test consists mainly of low-load driving, often below the 200°C line. 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. The exhaust temperature histogram shifts to higher temperatures when going to the WLTC, RDE and Motorway test.

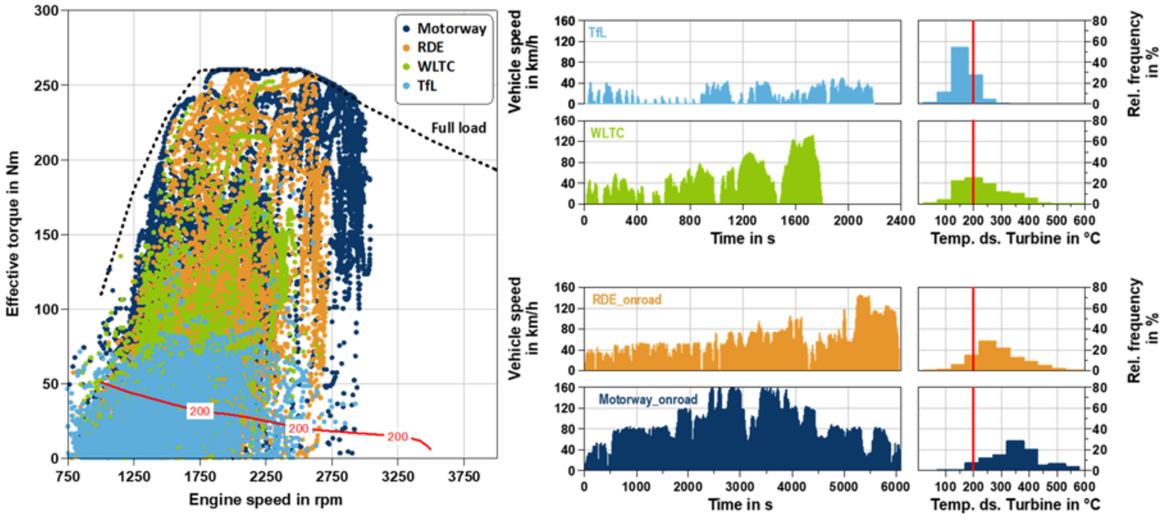


Figure 11: Driving conditions covered (engine load, vehicle speed and exhaust temperature)

Results and discussion

Results are presented for two stages within the project:

1. The initial calibration of the LNT + dual-SCR aftertreatment system.
2. The refined calibration where the integration of all the components in the control strategy has been optimised.

Active thermal management

Figure 12 illustrates the impact of the active thermal management on the LNT and ccSCR temperatures for the initial (blue) and refined (green) calibrations. Thermal management comes as a combination of the 48V system support, as explained above, and the release of a late post-injection in the combustion engine. The latter results in an exothermic reaction in the LNT when hydrocarbons are oxidized. The strategy is first to increase the LNT temperature with the 48V system heat-up. Once the LNT is hot enough to convert hydrocarbon emissions, the post-injection is started until the ccSCR reaches the optimum temperature window. To control tailpipe hydrocarbon emissions, the fuel injection quantity is ramped-up depending on the LNT temperature level. As a result, the typical light-off temperature of the deNOx system is reached much earlier in the cycle: benefit of 150-300s on WLTC and 700-800s on TfL. This significantly improves the cold-start deNOx control.
At the top of Figure 12, also the extra rich purge opportunities (NPU=NOx Purge) due to the 48V support can be seen during the WLTC and TfL tests. With the 48V support, a rich purge can be completed during a TfL test, which was not the case with the initial calibration.

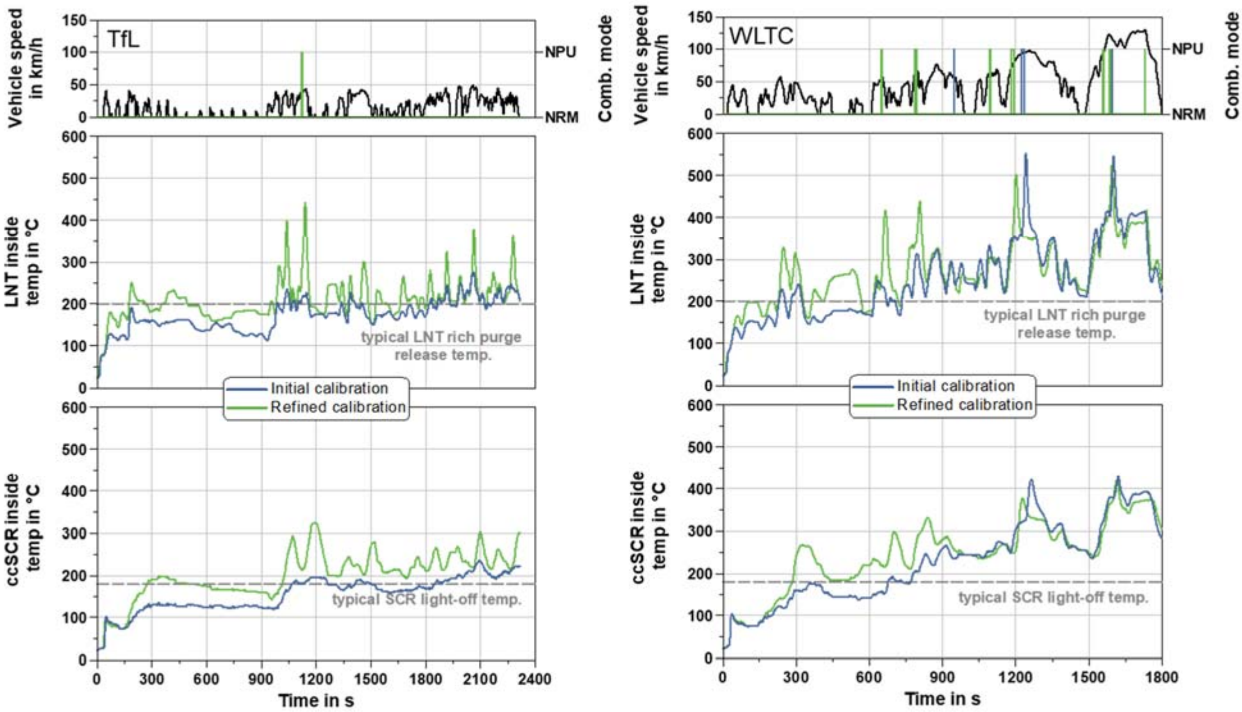


Figure 12: Visualisation of rich purges and exhaust temperatures during the TfL (left) and WLTC (right) tests for the initial (blue) and refined (green) calibrations

NOx reduction breakdown

Figure 13 shows the deNOx breakdown for the urban and motorway parts of an RDE test with the refined calibration. Tailpipe NOx emissions are 31 and 20 mg/km respectively, including cold-start. This result was achieved by contributions from all aftertreatment components. The LNT and close-coupled SCR both contribute during the urban part achieving 92% NOx conversion. The underfloor SCR is required during motorway driving where it converts an additional 45 mg/km of NOx. The underfloor SCR also allows higher NH_3 filling levels in the close-coupled SCR components by removing any transient excess ammonia and allowing full use of the close-coupled component deNOx capability.

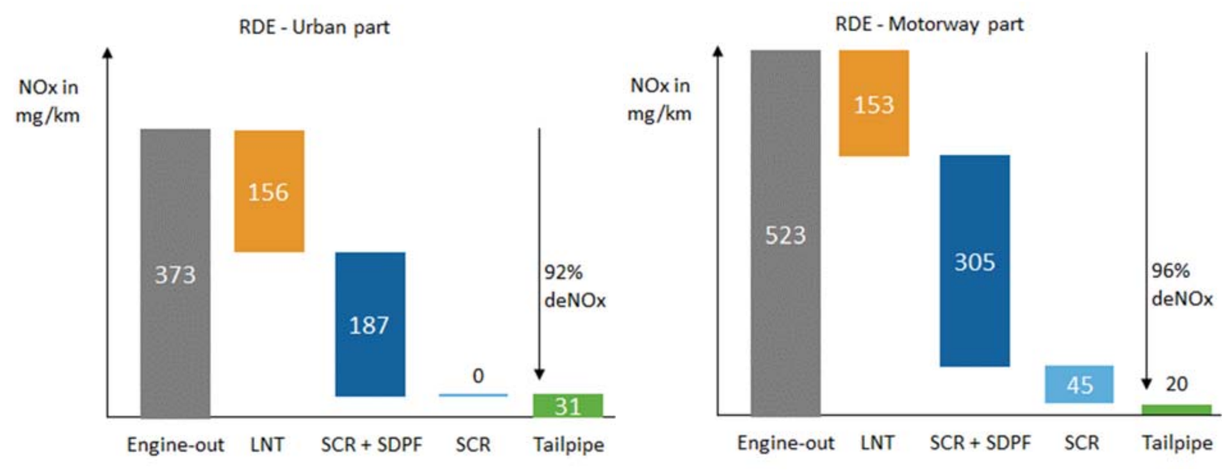


Figure 13: DeNOx breakdown for urban (left) and motorway (right) RDE tests

The calibration of the close-coupled components was refined for the low-speed urban conditions. The initial calibration resulted in 96 mg/km NOx (not shown here) at the tailpipe reducing to 31 mg/km with the refined calibration (Figure 13). The NOx reduction over the LNT improved from 66 to 156 mg/km due to the active thermal management and stabilisation of rich purges. The stabilisation of the rich purges created more opportunities to successfully complete a rich purge during city driving, so the LNT regeneration could occur at a sufficient frequency. The NOx reduction over the close-coupled SCR components improved from 121 to 187 mg/km due to active thermal management.

Figure 14 then shows the contribution of the LNT and close-coupled SCR/SDPF over the demanding low-speed start/stop TfL cycle with the refined calibration. The LNT has the highest deNOx contribution on this TfL test.

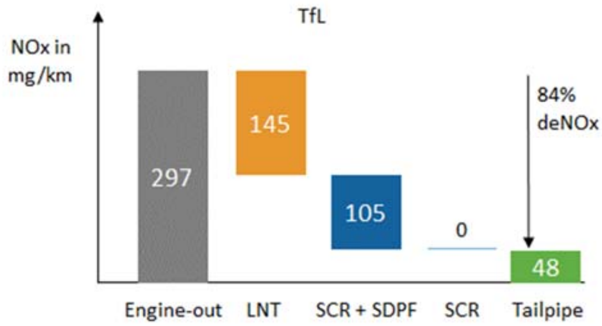


Figure 14: DeNOx breakdown for TfL

Under constant motorway driving, the challenge is to deal with increased engine-out emissions and elevated exhaust gas temperatures compared to an average RDE test (Figure 15). Tailpipe results varied between 20 and 49 mg/km with average speeds of 100 and 140 km/h respectively. The close-coupled SCR converts most of the NOx emission, but the underfloor SCR system also contributes significantly at higher vehicle speeds, converting 36 mg/km at 100 km/h and 107 mg/km at 140 km/h.

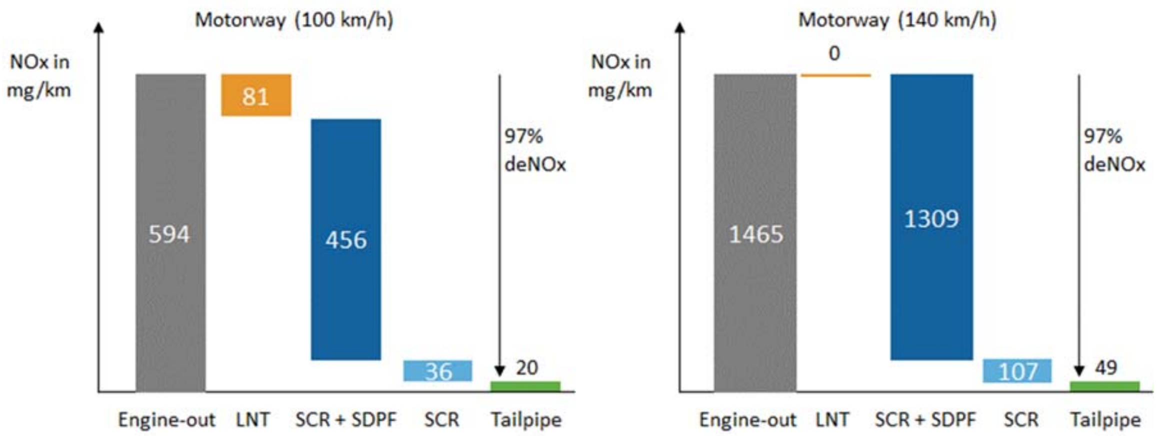


Figure 15: DeNOx breakdown for motorway driving at 100 km/h (left) and 140 km/h (right)

Overall system performance

Figure 16 and Figure 17 provide an overview of all NOx emission results obtained in the project. Both the tailpipe NOx emission and deNOx efficiencies of each test are plotted versus the average vehicle speed.

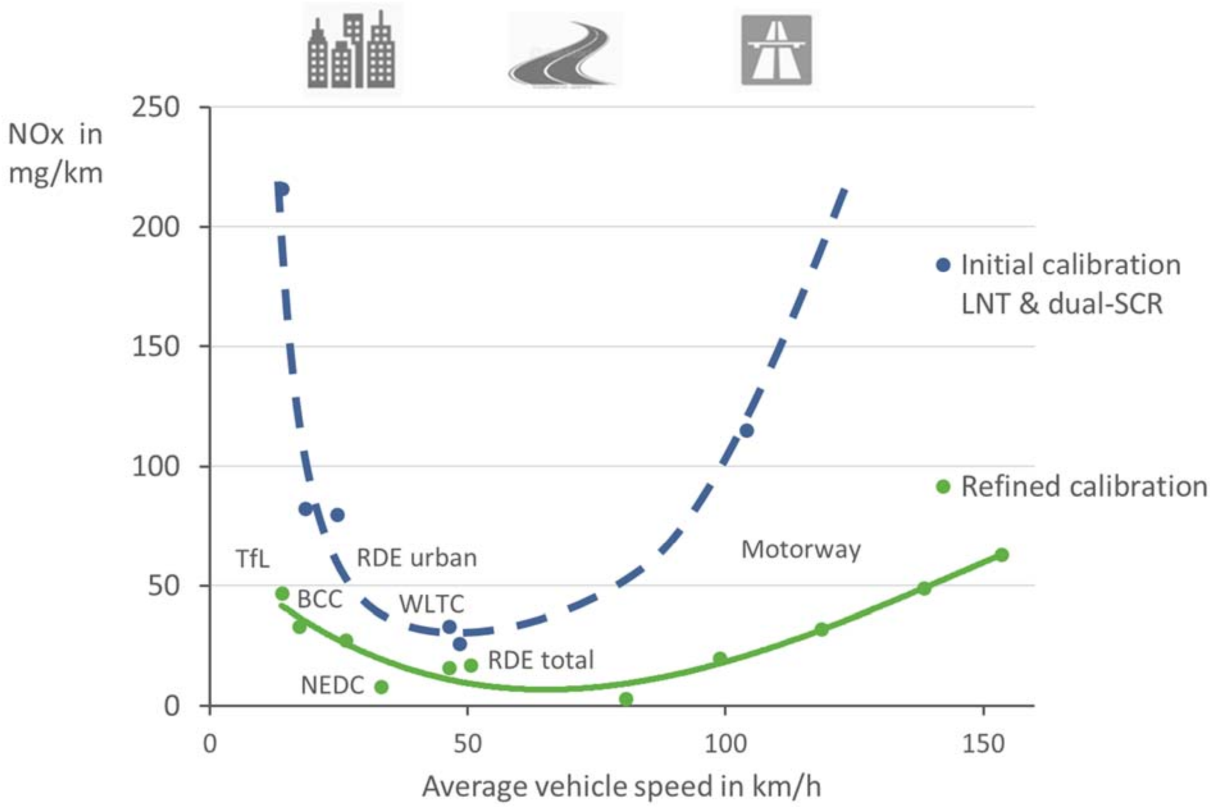


Figure 16: Tailpipe NOx emission vs. average vehicle speed with initial and refined calibrations

The initial calibration gave low emissions on WLTC and RDE, including a mix of urban, rural and motorway driving with average vehicle speeds from 30 to 80 km/h. But emissions increase during both urban (average speeds below 30 km/h) and constant motorway driving (average speeds above 100 km/h). The increase in the urban emissions towards the left of the chart are not only due to lower average vehicles speeds, but also because of a higher impact of the cold-start emissions at the start of the test.
The refined calibration results in consistently low tailpipe NOx emissions and high deNOx efficiencies throughout all tests.

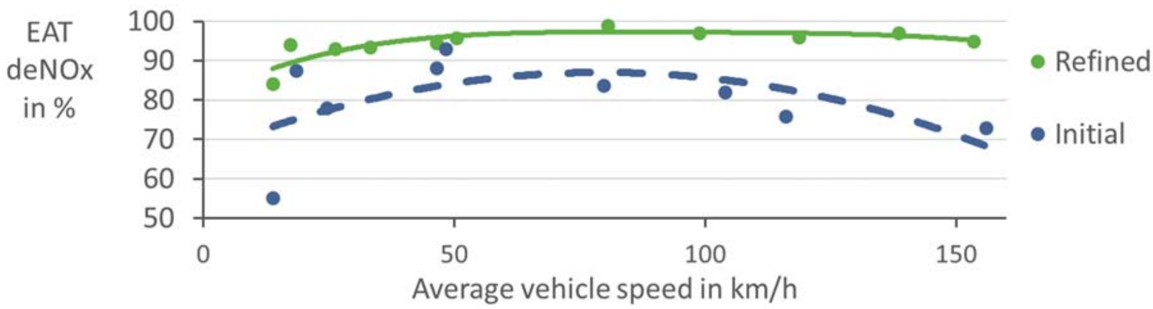


Figure 17: Total system deNOx efficiency vs. average vehicle speed

For the urban driving conditions at the left of the graph, the low NOx emission mainly results from the LNT rich purge stabilisation by the 48V hybrid system and the implementation of the active thermal management (engine load increase by the 48V system and post-injection). During the very challenging Transport for London low-load test, 84% deNOx efficiency is achieved after cold-start. On the other hand, the reduction in NOx emissions during motorway driving is achieved by improving the accuracy of the SCR models in the control logic. WLTC and RDE NOx results in the middle part of the graph are also further reduced as a result of the refined integration of all components in the NOx emission control. The increase in CO_2 emissions from the initial to the refined calibration caused by the implementation of active thermal management remained below approximately 3% on the WLTC and RDE tests measured. On these WLTC and RDE tests, the urea consumption stayed below 1.5 l/1000 km; the NH_3 slip remained below 10 ppm (peak) and 1 mg/km (total test result).

Investigating system robustness

Beside driving and ambient conditions, the robustness of the deNOx performance can also be affected by the initial powertrain system status during a cold-start, such as the NOx load on the LNT, the NH_3 filling level in the SCR or the state of charge of the battery.

Figure 18 shows the impact of the initial NOx load in the LNT for WLTC and RDE tests. No preconditioning was done in between different RDE tests, so the variation in the initial LNT NOx load is obtained by repeating tests over several days.
The blue area visualises the entire range of NOx load conditions observed within all the on-road tests, including the variation during the test itself. There were enough LNT rich purge opportunities to prevent the NOx load reaching saturation throughout all driving conditions, including within the urban part.
Overall, the range of LNT load conditions observed during on-road testing did not strongly impact the tailpipe NOx emissions. The case of starting with a saturated LNT was tested on the WLTC. Higher NOx emissions are then measured compared to the test where WLTC pre-conditioning regulatory procedures are followed (initial LNT status is empty), because the saturated LNT cannot contribute to the deNOx at the start of the test. As soon as the ccSCR reaches its light-off temperature it delivers complete deNOx control. The LNT contributes again to deNOx control after the first rich purge, which still happens within the first phase of the WLTC. The resulting tailpipe NOx is 39 mg/km.

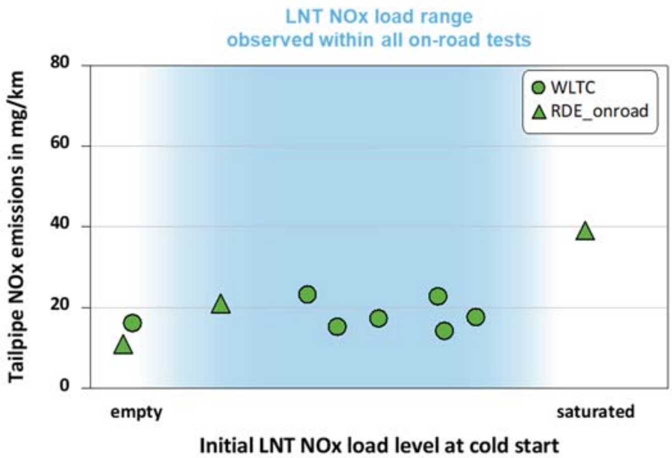


Figure 18: Variation in tailpipe NOx emissions for different initial LNT NOx loads

Summary and conclusions

This vehicle demonstrates that diesel NOx emissions can be consistently kept at a very low level over a wide range of driving conditions by combining existing catalyst technologies with improved engine and aftertreatment control functions. The paper also illustrates the improved NOx emissions observed with cars on the market today due to the introduction of RDE requirements (Figure 19).

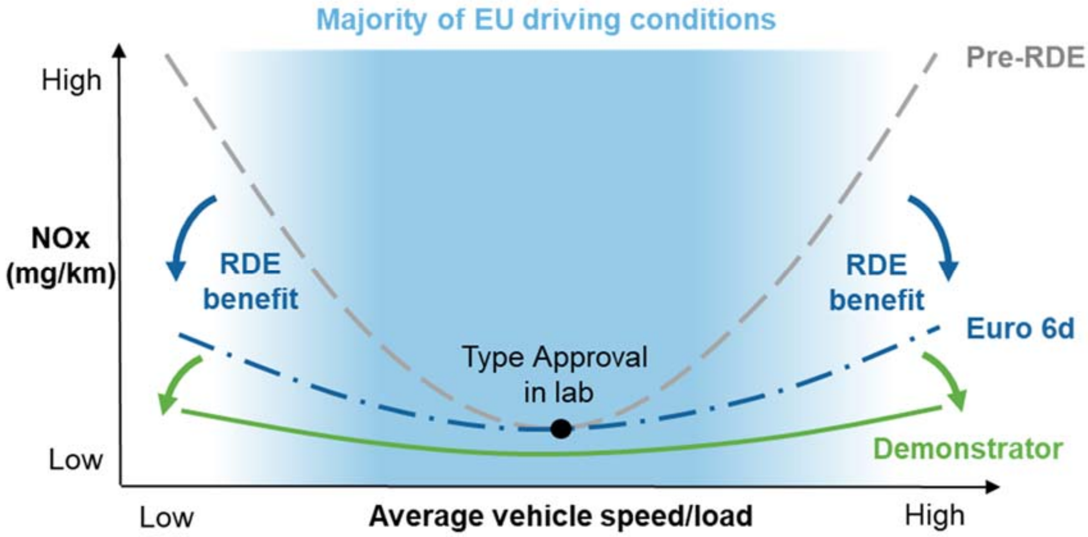


Figure 19: Schematic illustration of NOx emission improvement vs. average vehicle speed/load

The project focused on an optimised integration of an LNT + dual-SCR aftertreatment system together with a 48V mild-hybrid and LP+HP EGR diesel engine. In addition to the torque assistance and brake energy recuperation, various functionalities were implemented for the hybrid system. For example, the hybrid system contributed to the active thermal management of the aftertreatment system. It was also used to stabilise the engine torque under low load conditions and enable rich purges for the LNT regeneration. Furthermore, the hybrid system was used to minimise transient NOx peaks during accelerations. Model-based control of the SCR components was used to achieve high deNOx efficiencies without NH_3 slip.

Different emission tests were conducted within the project to check the robustness of the NOx control over a wide range of driving conditions, focussing on urban and motorway driving. The initial calibration for the LNT and dual-SCR aftertreatment system allowed to achieve ultra-low NOx levels of 25-33 mg/km on the WLTC and RDE tests. The system calibration refinement aimed at integrating the contribution from different components and allowed to maintain a high deNOx conversion efficiency above 84% during the dedicated urban (28-47 mg/km) and motorway (3-63 mg/km) tests. Each aftertreatment component (LNT, close-coupled SCR/SDPF and underfloor SCR) contributed to achieve the consistently low NOx emissions. The CO_2 emissions increased from the initial to the refined calibration due to the active thermal management but stayed below approximately 3% on the WLTC and RDE tests.

Outlook

The transport sector has made significant improvements to reduce harmful emissions from conventional vehicles, including diesels. For instance, the Diesel Particulate Filter (DPF) was introduced to prevent the emission of exhaust soot particles. In addition, NOx emissions are now effectively controlled through the introduction of RDE requirements. As a result, modern diesel vehicles have a limited impact on air quality, including in the city. The growing market penetration of modern diesel vehicles will contribute to improving urban air quality.

Key technologies to fulfil possible post-Euro 6 requirements include advanced thermal management, further engine-out emission reduction directly after a cold-start and further catalyst development. A non-exhaustive list of technologies under assessment is:

- Variable Valve Train (VVT) technology is under development to keep the EAT system in its optimum temperature window of operation during a long urban driving phase with minimal impact on fuel consumption [19].
- An electrically-heated catalyst can help to quickly ramp-up EAT system temperatures [12], [15] but it requires a powerful electrical system (48V) and it comes with a potential increase in engine-out emissions due to the increase of engine load for the electric power supply.
- Improved in-cylinder thermal management by injection rateshaping [20] and variable valve train can help to improve EGR tolerance of the cold combustion system and can thus decrease engine-out NOx directly after engine start.
- Dedicated low temperature NOx storage technologies can help to cover the time span until the downstream SDPF has reached its operating temperature and which can then provide high deNOx efficiency by converting the NOx released by the upstream NOx storage device.
- Advanced sensor and control technologies will further contribute to operate the powertrain in a robust manner [17], [18]. Dew point free Lambda and NOx sensors would be helpful for early active closed-loop control of the exhaust aftertreatment system immediately after cold start. In addition to state-of-the-art NOx and NH_3 sensors, an active online NH_3 filling level sensor of SCR catalysts may further improve the robustness of the SCR system control.

In parallel to pollutant emissions control, the Paris Agreement and the EU's 2030 Climate & Energy Framework will require steep cuts in CO_2 emissions from transport. Currently, 25% of all EU greenhouse gas emissions come from transport, and 40% of this comes from passenger vehicles. As a result, the vehicle mix of the future will be more diverse than it is today and be made up of hybrid and plug-in hybrid petrol and diesel vehicles [21], [22] as well as fully electric vehicles. The transition towards low- and zero-emission mobility will be gradually. The fleet CO_2 emission requirements will imply improvements in engine weight, friction reductions and electrification.

Cost-optimised low voltage hybrid technology has a potential for further improvement of the overall fuel efficiency of the vehicles. P2-, P3- or P4-layouts are beneficial from functional point of view. Overall system costs need to be balanced against functional performance, [21], [23]. In the mid-term, the fastest CO_2 emission reduction could be achieved by introducing higher blending rates of non-fossil fuels (e.g. Hydrotreated Vegetable Oil (HVO) for diesel and ethanol for gasoline engines). With this, CO_2 emissions from the existing car fleet could be reduced significantly while using the existing fuel infrastructure. However, current CO_2 regulations for vehicles only look at tank-to-wheel emissions; a harmonized Life Cycle Assessment methodology of greenhouse gas emissions is yet to be developed for a fair comparison of the overall impact of different powertrains on the environment [24].

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