



Diesel Vehicle with Ultra-Low NOx Emissions on the Road

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Abstract

The gap between diesel vehicle emissions in laboratory tests compared to those in use has been addressed by the introduction of the Real Driving Emissions (RDE) 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 (NO_x) and particle number (PN) emissions can be achieved over a wide range of driving conditions beyond Euro 6d RDE requirements, with emission control technologies combined in an integrated approach.

An LNT (Lean NO_x Trap) is combined with a dual-dosing SCR (Selective Catalytic Reduction) system. Low-load NO_x 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 with a second AdBlue® injector. A P0 48V mild-hybrid system is also available to support the NO_x 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.

The paper discusses the emissions tests performed and the results achieved. A combination of tests on the road and in the lab were carried out to cover 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 NO_x emissions under all driving conditions. Particulate emissions are effectively controlled by the DPF.

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 CO₂ 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 (NO_x) 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 demonstrates low emissions on the road over a wide range of driving conditions [2]-[6]. More

importantly, more than 700 RDE-compliant diesel cars 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]. [Figure 1](#) visualises 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 [9]-[10]. This improvement is observed for emissions over the entire test (total RDE) as well as over the urban part only (urban RDE).

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](#) visualises how the NO_x 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 NO_x emission value in the middle of the graph. Towards the left and right sides, pre-RDE NO_x 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

FIGURE 1 Reduction in real-world diesel NO_x emissions brought by the introduction of RDE requirements

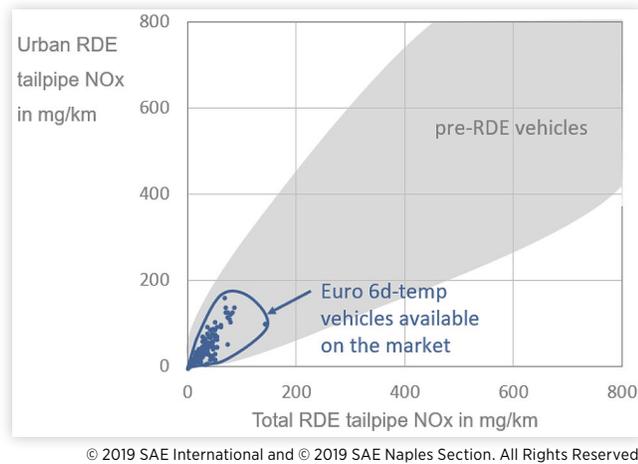
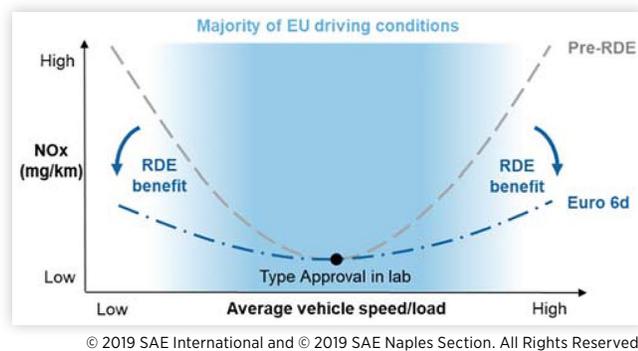


FIGURE 2 Schematic illustration of tailpipe NO_x emissions vs. average vehicle speed/load



ambient conditions). The robustness of tailpipe NO_x 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).

As part of their “post Euro 6” study, 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.

The objective of the project was to further show low NO_x and particulate emissions across a wide range of operating conditions, including the challenging conditions towards the edges of Figure 2, while maintaining CO₂. To achieve the objective, a DPF (Diesel Particulate Filter) 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:

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

Project Set-Up

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), 1-stage variable geometry turbo charger with e-actuator and air/air intercooler. NO_x 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.

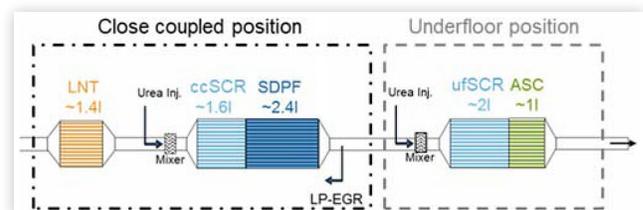
Exhaust Aftertreatment System Layout and Controls

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

The 1.4l LNT actively covers NO_x 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). This enables optimal synergy between LNT and SCR deNO_x performance during city driving at low exhaust temperatures, as visualised on the left side of Figure 4.

To cover high speed and high load driving conditions a second SCR catalyst and an Ammonia Slip Catalyst (ASC) are added in an 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 2nd AdBlue[®] dosing unit, they improve deNO_x 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 provides increased system deNO_x performance across a wide

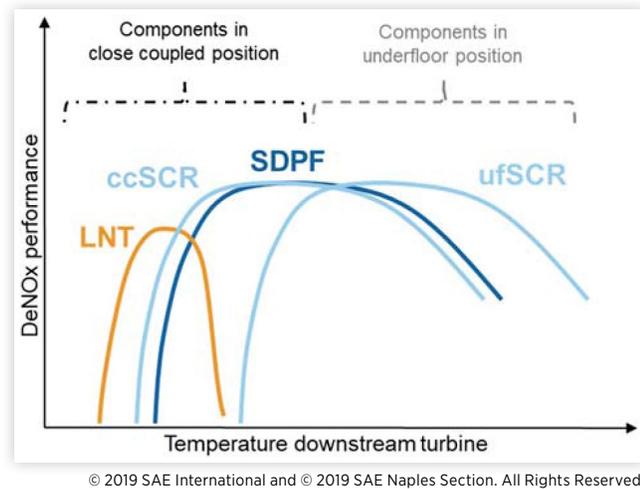
FIGURE 3 Exhaust aftertreatment system layout



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



variety of driving conditions. The intention of the work was not to evaluate all possible alternative systems, other approaches are also available to achieve low emissions [5, 12]-[14].

Achieving high NOx conversion rates, while preventing ammonia (NH₃) slip, requires exact and active adjustment of the NH₃ 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. Real-time capable, low-dimensional models of the SCR components are implemented. Based on information at the inlet of each component, they calculate so-called relevant states, e.g. NH₃ filling states, separate NOx and NH₃ 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 NH₃ 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 NH₃ filling level in both SCR systems provides a high degree of robustness to any inaccuracies developing in the dosing system hardware. Closed-loop operation is expected to become a new standard feature to better deal with sensor/actuator tolerances [15]-[17]. This robust control combined with durable hardware components contributes significantly to stable deNOx performance over lifetime.

The benefit of adding a second dosing unit is to reduce NH₃ formation in the low-pressure EGR duct (the second dosing unit was located downstream of the exhaust gas extraction point) and to reduce NH₃ oxidation at high temperatures, which would occur if high Adblue® dosing upstream of the close-coupled SCR system was required from a single injector.

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

Hybrid System Layout and Controls

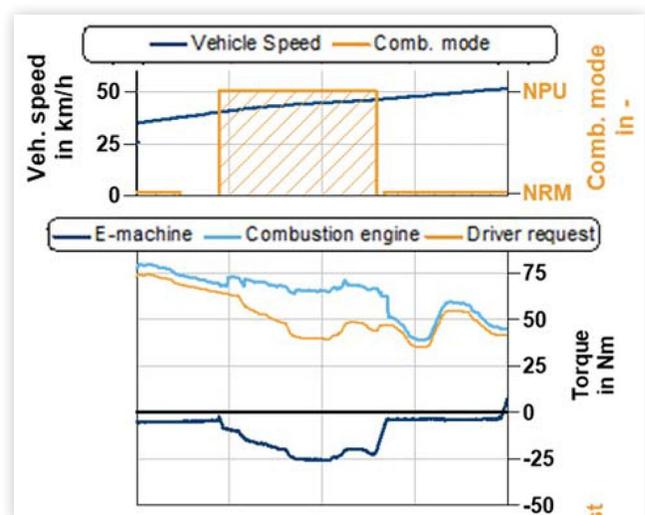
A belt-driven electric motor (EM) of the 48V mild-hybrid system is located close to the 4-cylinder diesel engine in a P0 position. The integrated EM can support the internal combustion engine (ICE) up to 10 kW electric power. During acceleration phases, hybrid-assist provides torque in order to support the diesel engine and reduce fuel consumption and CO₂ emissions. Additional CO₂ 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 are implemented in the project for the 48V mild-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.

Functions 1 and 2 ensure early deNOx operation after a cold-start in urban driving conditions. Figure 5 illustrates the

FIGURE 5 Illustration of LNT rich purge stabilization by the 48V mild-hybrid system



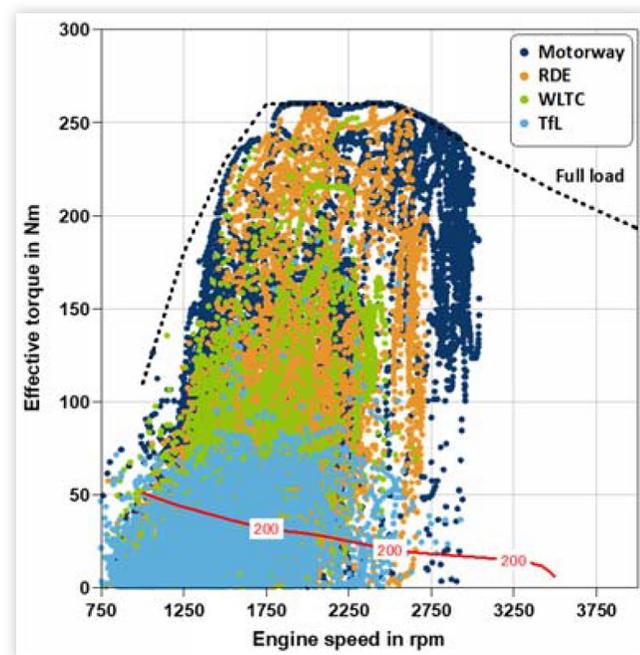
second function. The vehicle speed and combustion mode (NRM=normal; NPU=NOx Purge) are plotted at the top, the different torque levels within the powertrain system are plotted underneath. The function either performs a constant torque offset under low-load driving (not visualised) or a variable torque contribution to stabilise fluctuations in the driver-requested torque (visualised here). The engine torque is kept into the area where a stable LNT regeneration is possible due to the support of the 48V mild-hybrid system. LNT regeneration would not be possible under these conditions without the support of the 48V mild-hybrid system. This creates extra opportunities to conduct LNT regeneration and therefore improves NOx emission control, especially in urban driving conditions.

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

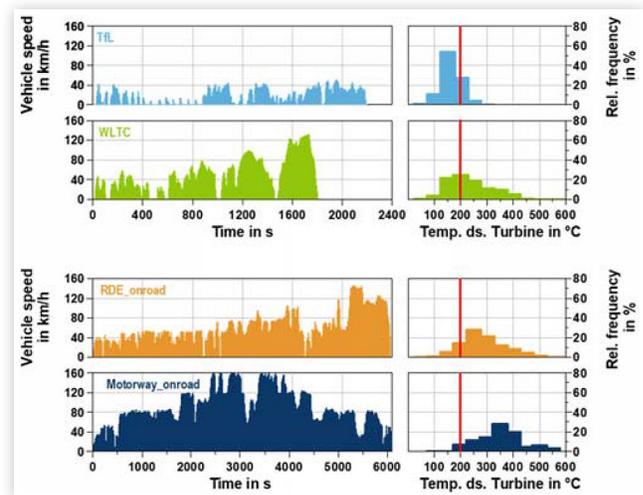
The engine load points, vehicle speed traces and exhaust temperature histograms of some of these tests are shown in Figure 6 and Figure 7. The coverage of the engine map increases from the Transport for London interpeak cycle (TfL) over WLTC to RDE and Motorway. Full load driving is included in WLTC, 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

FIGURE 6 Illustration of engine map coverage for the different emission tests



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FIGURE 7 Illustration of the driving speed traces and exhaust temperature histograms for the different emissions tests

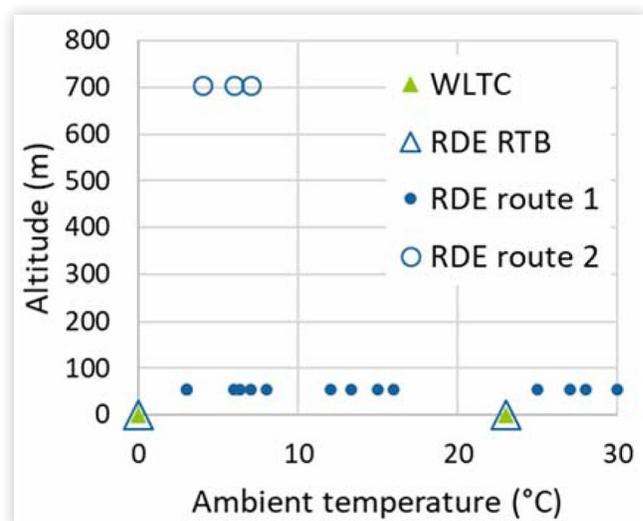


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achieve at least 200°C downstream (ds.) of the turbine is also indicated on the engine map. The histograms of the exhaust temperatures are plotted on the right. The TfL test consists mainly of low-load driving, often below the 200°C line. The combination 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 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 100m, RDE route 2 is towards 700m. This test also includes more dynamic driving up to the RDE boundary condition of 1200m/100km.

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



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Results and Discussion

NOx Emissions

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.

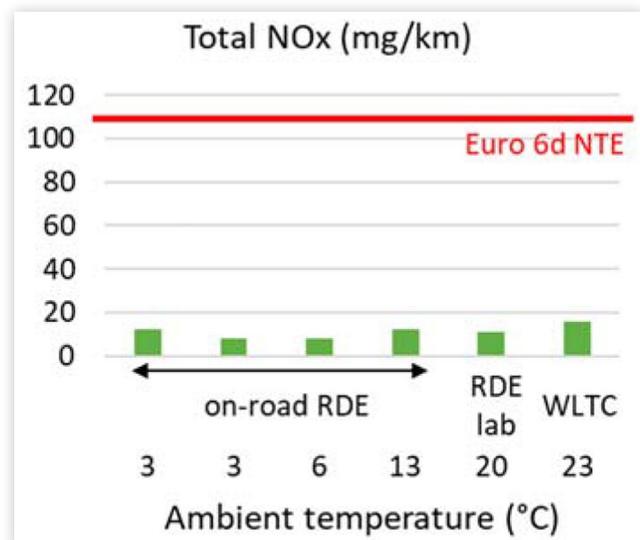
The NOx emissions measured on RDE and WLTC are shown in Figure 9. Results are sorted according to the average ambient temperature from left to right. Both on-road and in-lab RDE results are included. The NOx emissions range from 8 to 16 mg/km. There is no impact of the ambient temperature over the range covered during the tests.

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 sorted according to the ambient temperature. Consistent low NOx emissions are measured under these conditions as well, ranging from 24 to 47 mg/km. No impact of the ambient temperature is observed.

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

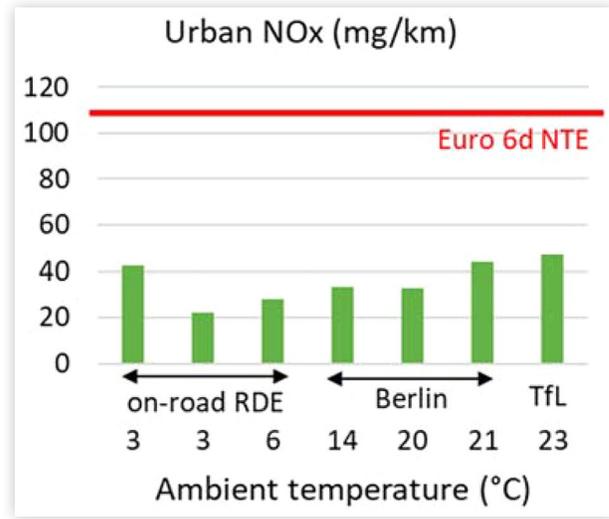
As described above, system control measures were implemented to allow early NOx conversion in urban conditions following a cold-start. Contributions mainly come from the LNT regeneration stabilisation and the active thermal management. The improvement of these measures is visualised in Figure 12, plotting cumulative NOx emissions on the

FIGURE 9 NOx emissions of entire test vs. ambient temperature



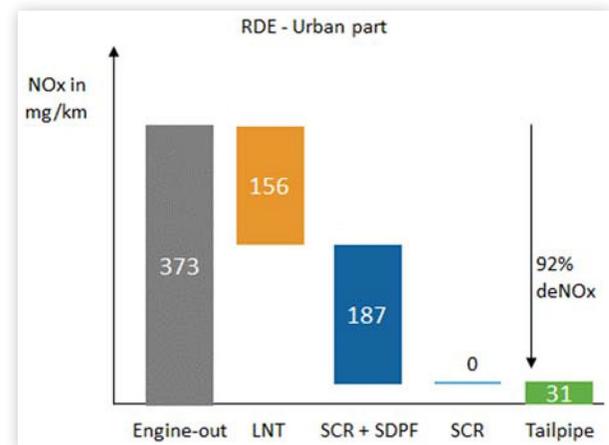
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FIGURE 10 NOx emissions during urban driving conditions vs. ambient temperature



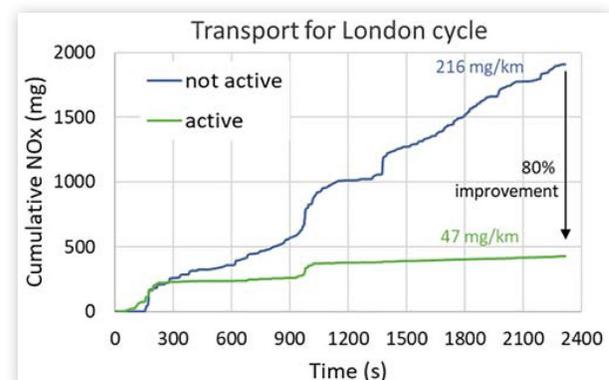
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FIGURE 11 Breakdown of NOx reduction during urban driving conditions



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FIGURE 12 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)



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Transport for London cycle. Without the additional system control functionalities, a tailpipe NO_x of 216 mg/km is measured. Activating the LNT regeneration stabilisation and active thermal management results in an 80% improvement of the NO_x emissions, reaching 47 mg/km.

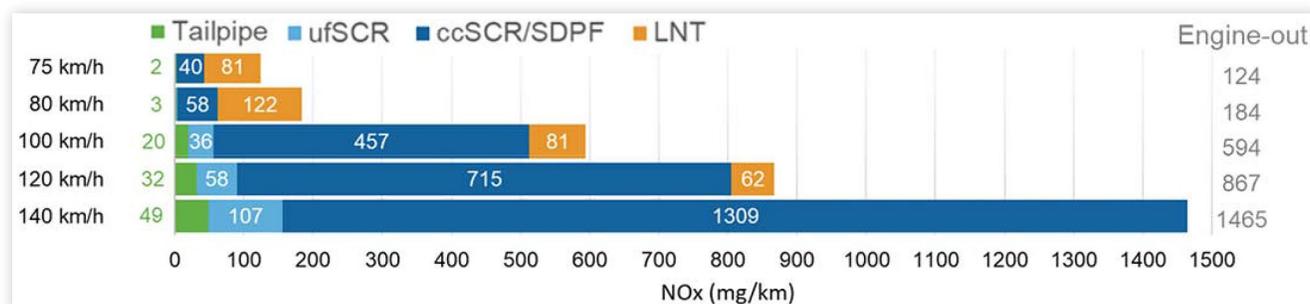
Motorway emissions are investigated on the road during a dedicated motorway test, including driving up to 160 km/h. Different sections of this test are investigated separately to check the impact of the average vehicle speed on NO_x emissions. Depending on the section selected, an average speed between 75 and 140 km/h is obtained. The breakdown of NO_x reduction during the different sections is plotted in Figure 13. The challenging driving conditions increase engine load and speed, resulting in an increase in engine-out emissions from 124 to 1465 mg/km. The LNT is covering the largest part of the NO_x control up to 80 km/h. For higher speeds, the close-coupled SCR+SDPF covers the largest part. The underfloor

SCR is required to secure the consistent low NO_x emissions under all motorway conditions. The presence of the underfloor SCR also allows to operate the close-coupled SCR+SDPF at higher NH₃ dosing levels without risking NH₃ slip at the tailpipe, supporting the high NO_x reductions over the close-coupled SCR+SDPF. Tailpipe NO_x emissions vary between 2 and 49 km/h. deNO_x efficiency is varying between 96 and 99%.

In summary, all tailpipe NO_x emissions are plotted vs. average vehicle speed in Figure 14. Consistent low NO_x emissions are measured over the driving conditions covered. The results on the left 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 deNO_x efficiency is shown in Figure 15.

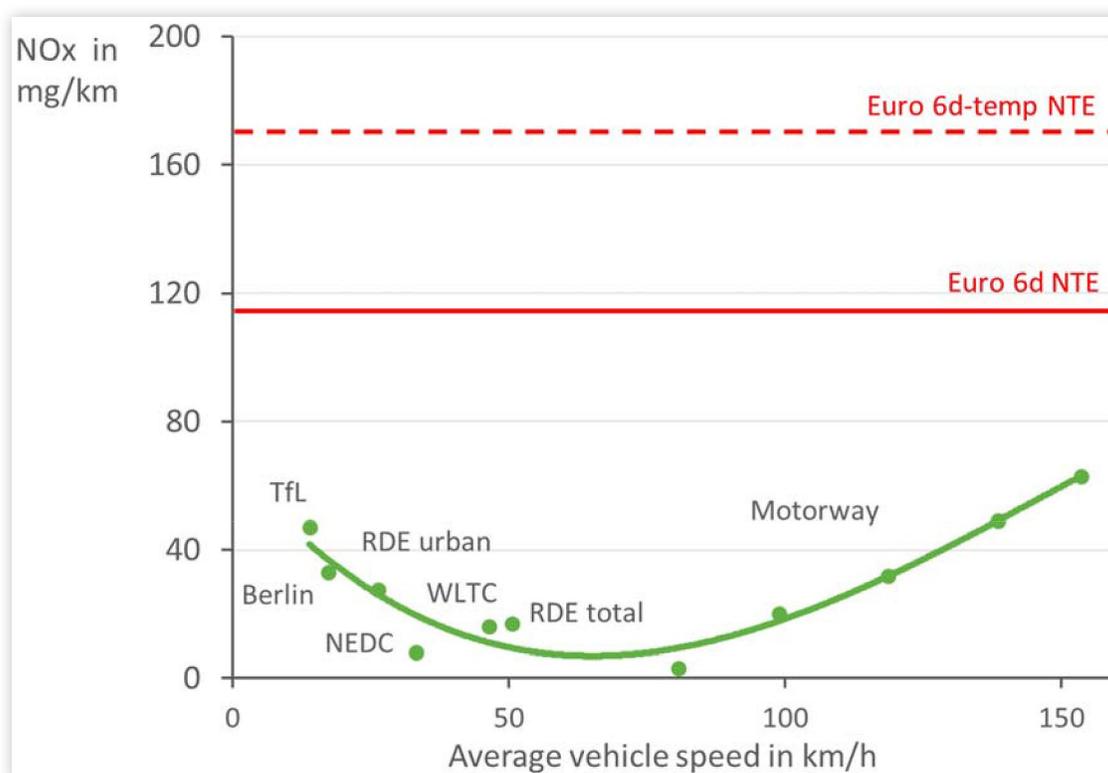
The increase in CO₂ emissions caused by the implementation of active thermal management remained

FIGURE 13 Breakdown of NO_x emissions during motorway driving conditions



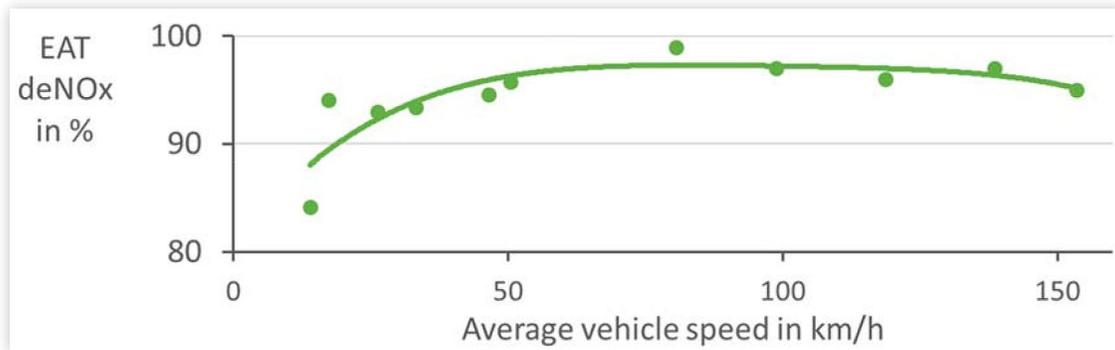
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FIGURE 14 Summary of tailpipe NO_x emissions achieved over the range of driving conditions covered in the programme

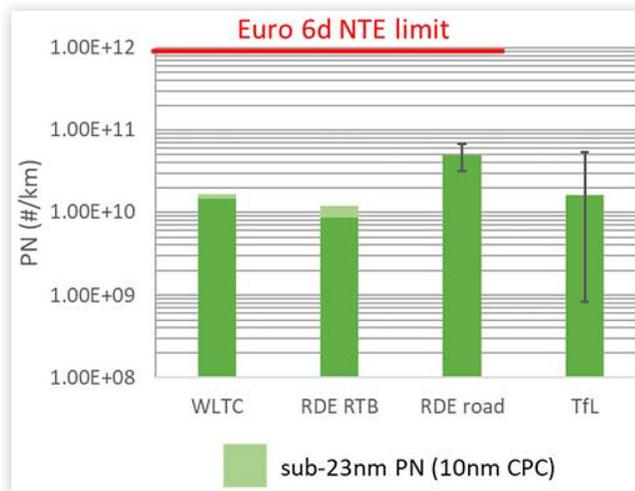


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FIGURE 15 Summary of total system deNOx efficiency achieved over the range of driving conditions covered in the programme

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FIGURE 16 PN emissions measured in the lab and on the road

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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 NH₃ slip remained below 10 ppm (peak) and 1 mg/km (total test result).

Particulate Emissions

PN and PM emissions measured are plotted in [Figure 16](#) and [Figure 17](#). PM emissions are only available from tests in the lab: WLTC, RDE RTB (Roller Test Bench) and TfL. PN emissions are also available from on-road RDE testing. PN emissions are between 8×10^9 and 7×10^{10} #/km. Sub-23nm PN was measured on WLTC and RDE RTB tests in the lab as well, but no significant contribution is observed. PM emissions are below 0.5 mg/km. These results confirm that particulate emissions are controlled effectively under all driving conditions by the Diesel Particulate Filter (DPF).

Other Emissions

CO emissions are plotted in [Figure 18](#). CO is below 50 mg/km on WLTC and RDE tests. An increase can be observed on the Transport for London cycle due to the impact of the

FIGURE 17 PM emissions measured in the lab

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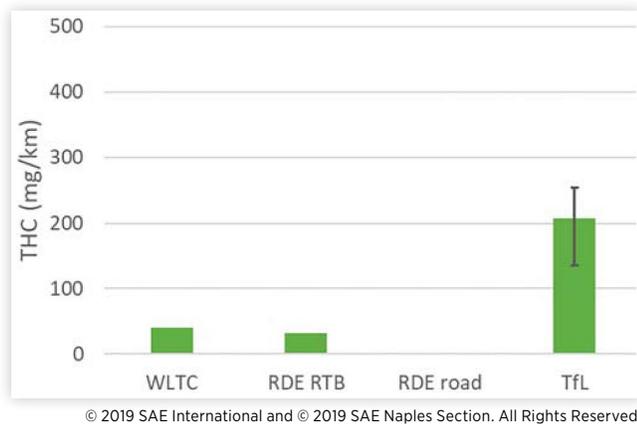
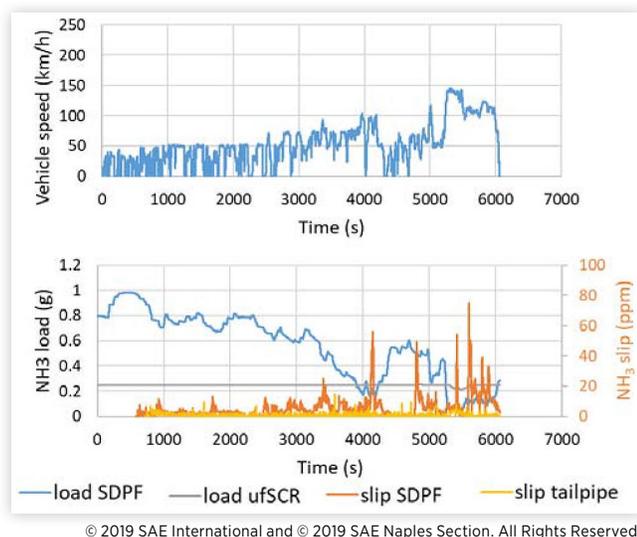
FIGURE 18 CO emissions measured on the road and in the lab

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post-injection within the active thermal management. Similar results can be observed for THC ([Figure 19](#)).

Further optimisation of the CO and THC emissions on TfL is possible. This would require fine-tuning the post-injection fuel quantity depending on the LNT temperature, but this was outside of the programme scope.

Different mechanisms are built-in to prevent NH₃-slip at the tailpipe. A model-based SCR control is implemented to have an optimum NH₃ load without slip. The benefit of the

FIGURE 19 THC emissions measured in the lab**FIGURE 20** NH₃ load and slip on the close-coupled SCR+SDPF and underfloor SCR during an RDE test

dual-SCR with twin-urea injection is that the NH₃ load can be controlled separately for the close-coupled SCR+SDPF and underfloor SCR. Additionally, the presence of the underfloor SCR allows to use a higher target NH₃ load for the close-coupled SCR+SDPF. Finally, an Ammonia Slip Catalyst is added to convert remaining NH₃.

Figure 20 illustrates the NH₃ load and slip on the close-coupled SCR+SDPF and underfloor SCR during an RDE test on the road. Tailpipe NH₃ was controlled below 10 ppm on RDE.

Summary/Conclusions

This demonstrator vehicle shows that diesel NO_x emissions can be consistently kept at a very low level 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 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 NO_x control (stabilisation of LNT regeneration, contribution to active thermal management and support of engine-out NO_x control). Model-based control of the SCR components was used to achieve high deNO_x efficiencies without NH₃ slip.

A multitude of emission tests were conducted to check the robustness of the NO_x control over a wide range of driving conditions, focussing on urban and motorway driving. Ultra-low NO_x levels of 8-40 mg/km were achieved on the WLTC and RDE tests. The integrated approach to optimise the contribution from each emission control component allowed the system to maintain a high deNO_x 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 NO_x emissions. Particulate emissions are effectively controlled by the DPF.

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Definitions/Abbreviations

CO - carbon monoxide
CO₂ - carbon dioxide
DPF - Diesel Particulate Filter
LNT - Lean NOx Trap
NOx - nitrogen oxides (NO+NO₂)
NTE - Not-to exceed
PEMS - Portable Emissions Measurement System
PM - Particulate Mass
PN - Particle Number
RDE - Real Driving Emissions
RTB - Roller Test Bench
SCR - Selective Catalytic Reduction
SDPF - SCR coated on a DPF
TfL - Transport for London
THC - Total Hydrocarbons
WLTC - World harmonized Light duty Testing Cycle