Real-world emissions measurements of a GDI passenger car with and without a gasoline particulate filter

A new study aims to evaluate the effects of a gasoline particulate filter on NO_x and PN emissions from GDI passenger vehicles under real driving conditions.

Background

Emissions have been the focus of worldwide legislation for more than 25 years. Regulation initially concentrated on gaseous emissions of carbon monoxide, hydrocarbons and NO_x. However, particles emitted from vehicles and from other sources are now accepted as having an impact on air quality and on human health. Traditionally port fuel injected (PFI) gasoline vehicles generally emit very low levels of particulates because the fuel is well mixed with the intake air before combustion. Gasoline direct injection (GDI) vehicles have been increasing in market share due to their positive contribution to improving the average fleet fuel economy. GDI vehicles share some features with diesel vehicles in that the fuel is injected directly into the cylinder and has much less time to evaporate and mix before combustion starts, and this can lead to particulate formation [1].

Particle mass emissions are measured by collecting diluted exhaust gas on a filter paper which is then weighed to determine the amount of particulate. This method is effective even at the low Euro 5/6 levels, but the variability is such that small differences in emissions are difficult to detect. For this reason, a new particulate number (PN) test has been developed through the European Particle Measurement Programme (PMP) over the past decades and introduced from Euro 5 for both diesel and direct injection gasoline vehicles. A PN limit of 6×10^{11} particles/km became effective for diesel vehicles from November 2009, and this same limit will apply to direct injection gasoline cars from 2017 with an interim limit for the latter of 6×10^{12} particles/km which has been a requirement since 2014. Direct injection gasoline vehicles have so far met the limits through engine modifications [2] although the gasoline particulate filter (GPF) will be a practical approach to meeting future regulations as emission limits tighten further[3].

Emissions regulations for passenger vehicles have traditionally been based on the New European Driving Cycle (NEDC) run on the chassis dynamometer (rolling road). Amid concerns that this test cycle does not represent real road driving closely enough in terms of carbon dioxide (CO_2) and other emissions levels, two new test procedures are under development—the Worldwide harmonized Light duty Test Cycle (WLTC) for use on the chassis dynamometer and, for on-road use, the Real Driving Emissions (RDE) test procedure. Included in the RDE test is the use of portable equipment measurement systems (PEMS) which are able to measure gaseous and PN emissions under real driving conditions. The RDE test protocol was adopted in 2016 together with a not-to-exceed limit (NTE) for NO_x. (NTE = conformity factor x limit value). Two extra Euro 6 stages will be introduced as a consequence, a temporary one as of September 2017 with a NO_x conformity factor[1] (CF) of 2.1 and a permanent one as of January 2020 with a NO_x CF of 1.5.

In parallel with the developments in vehicle technology, emissions regulation, measurement equipment and test cycles, the European Renewable Energy Directive (RED, 2009/28/EC) will require 10% renewable energy in transport fuels by 2020 while the Fuel Quality Directive (FQD, 2009/30/EC) will also require reductions in GHG emissions intensities from transport fuels of 6%. Oxygenated biofuels such as ethanol and ETBE, for example, are already used in Europe and their use is expected to increase to meet these regulatory demands. Reference fuels used for certification purposes have recently changed from E5 to E10 in moving from Euro 6b to Euro 6c specifications, and it is planned that RDE testing will be carried out on market fuels meeting the gasoline EN228 specification.

In a previous study[4], the Association for Emissions Control by Catalyst (AECC) and Concawe investigated the emissions from commercially available vehicles fitted with gasoline particulate filters under standard conditions, which concluded that the GPF could successfully reduce gasoline particulate emissions below the proposed limits. It was decided that it would be useful to measure real driving emissions on-road as well as simulated RDE on the dynamometer designed to go

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[1] Conformity factor gives an indication of how close the measured value is to the limit value, i.e. CF = 1 means that the measured value = limit value.

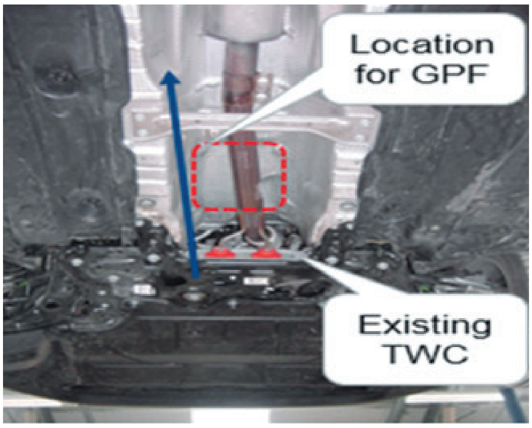
towards the limits of the RDE boundary conditions from a dynamic and temperature perspective (severitisation process). Fuel effects were also studied (this was not part of the previous study), and included tests on fuels representing the market and fuels with a range of qualities including E5 and E10. This article focuses on the dynamic (severity) test results. The low-temperature studies are described in a recently published SAE paper[5].

Test vehicle and modifications

The test vehicle was a direct injection 1.4 litre gasoline vehicle of Euro 6b specification, equipped with a three-way catalyst (TWC) for emissions control. This vehicle, as purchased, did not have a GPF but was retrofitted for the study so that GPF emissions could be measured before and after.

Chassis dynamometer tests were performed in the Vehicle Emissions Research Centre (VERC) of Ricardo UK. The vehicle was tested in both OEM build (without the GPF) and retrofitted with a GPF. To enable this, the baseline exhaust system of the vehicle was removed, and a straight section downstream of the existing TWC was cut out and replaced with the three-way catalytically-coated GPF.

Figure 1 Underfloor view of the test vehicle showing the unmodified exhaust system, and indicating the location for the GPF



Measurements and measurement systems

An important aspect of validating the performance of PEMS systems for on-road use is the correlation between PEMS and the laboratory-based analysers used during a WLTC test. This correlation must meet specified criteria that are laid down in the regulatory approach. All data shown in this paper are derived from compliant PEMS measurements, and validated not only during WLTC tests but also for dynamometer RDE tests.

By regulatory intent, on-road RDE tests are inherently variable, due to the unpredictable nature of traffic and the weather. However, to indicate the magnitude of this variability, three repeats of the on-road cycle were carried out, with testing occurring at the same time of day and using the same driver. The percentage variation in emissions levels, for all species of interest, derived from these three repeats were applied as error bars in the Figures presented in this article. For the on-dynamometer RDE tests, three repeats were conducted at one set of dynamometer loads (the loads most closely replicating the real road loads observed in the actual on-road RDE tests). With the elimination of traffic and weather variables, and despite the severitisation process, the on-dynamometer RDE tests showed improvement in repeatability when compared with the on-road tests. For example, the variation in CO_2 emissions from the baseline vehicle dropped from ~1.5% to nearer 1%.

Fuels and test matrix

Three fuels were tested, representing the certification fuel for Euro 6b (nominally RFE05), the certification fuel for Euro 6c (RFE10) and pump-grade gasoline currently available in the UK (EN228). Selected fuels data are shown in Table 1 on page 15.

The majority of the chassis dynamometer and RDE testing was conducted on the pump-grade fuel with a subset of tests conducted on the market EN228 (E5) fuel. Preliminary chassis dynamometer tests (NEDC and WLTC) were conducted on RFE05 for reference purposes and to relate emissions to those published from certification.

An overview of the tests, including chassis dynamometer, on-road and on-dynamometer RDE tests conducted after a 23°C soak and with a 23°C start temperature are given in Table 2.

The project commenced with an NEDC chassis dynamometer test, using the RFE05 fuel and the vehicle in standard build, to compare CO_2 and regulated emissions with certification levels and establish the effect of the road loads employed relative to the unknown certification loads. A WLTC test was also performed (without GPF) on this fuel. All tests were conducted at ~23°C including the overnight soak.

The vehicle was then equipped with a Horiba OBS-ONE PEMS system and the fuel was changed to pump-grade EN228. Single NEDC, WLTC and triplicate on-road RDE tests were conducted, both without and with the GPF. These tests were conducted at ~23°C including the overnight soak.

Following the chassis dynamometer and on-road tests on EN228, the fuel was changed to RFE10, and single NEDC, WLTC and triplicate on-road RDE tests, both without and with GPF, were carried out.

On-road Real Driving Emissions route

All on-road RDE tests were conducted on a route known to be EMROAD compliant with >10 vehicles (see Figure 2). EMROAD is the RDE validation tool which is used a part of the test procedure. Compliant routes contain equal amounts of urban, rural and motorway driving. This RDE route commences at the Ricardo site with immediate urban operation that is conducted wholly in 30 and 50 km/h zones within Shoreham-by-Sea. Increased urban severity is achieved through moderate hill climbs, inclusion of multiple T-junctions, traffic lights and a railway crossing so that no artificial stop periods are required. Rural and motorway sections are both out-and-back routes using roundabouts for the turn, with the rural section relatively flat and the motorway gradually ascending eastbound and descending on the westbound return trip.

Table 1 Selected fuel property data

	RFE10	RFE05	EN228
Density, 15°C (kg/m^3)	747.7	749.5	736.5
I.B.Pt. (°C)	37.3	35.6	24.6
% evaporated at 70°C, E70 (% volume)	43.8	32.8	47.3
% evaporated at 100°C, E100 (% volume)	57.1	56.1	61.6
% evaporated at 150°C, E150 (% volume)	90.4	88.2	92.7
% evaporated at 180°C, E180 (% volume)	-	95.2	99.0
F.B.Pt. (°C)	181.2	193.4	179.8
RON	97.4	95.5	96.8
MON	86.1	85.2	85.4
Aromatic content (% volume)	28.3	33.5	32.6
Sulphur content (mg/kg)	4.5	3.5	4.9
Atomic H/C ratio	1.799	1.845	1.861
Ethanol (% volume)	9.9	5	4.8

Table 2 Summary of 23°C start dynamometer and on-road tests

Exhaust	Fuel	NEDC + WLTC	RDE on road	RDE on dyno
Original (without GPF)	Ref E5	1x	-	-
	Ref E10	1x	3x	-
	Market E5	1x	3x	6x
With coated DPF	Ref E10	1x	3x	-
	Market E5	1x	3x	6x

Figure 2 Real Driving Emissions test route

Figure 3 PN emissions measured on the NEDC test cycle

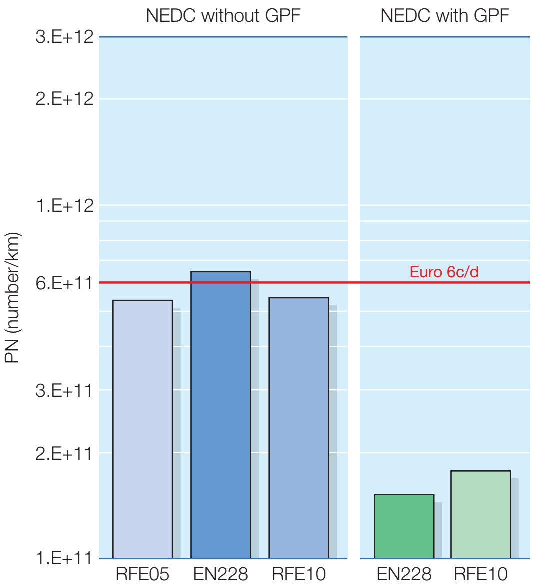
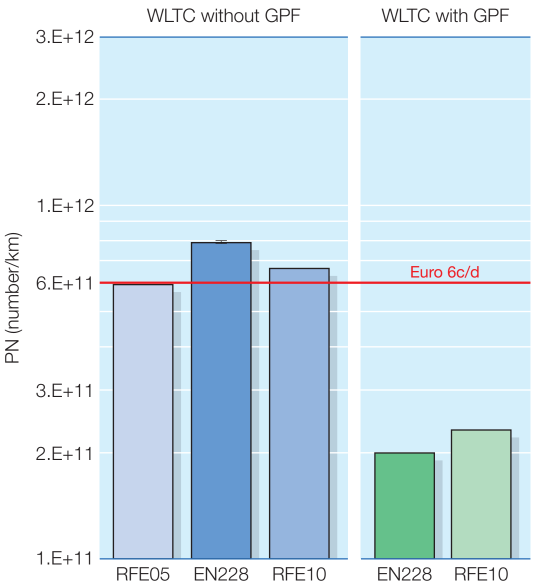


Figure 4 PN emissions measured on the WLTC test cycle

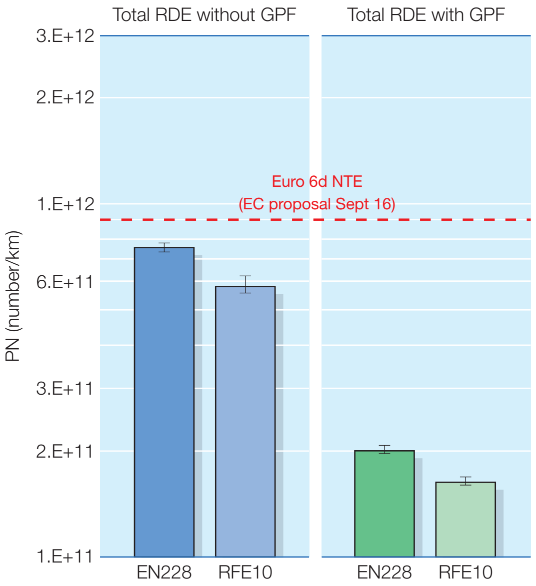


Particulate emissions under standard conditions

The PN measurements on the regulatory test cycles NEDC and WLTC (Figures 3 and 4, respectively) show that PN emissions on both cycles are just below the Euro 6c limit of 6x10^{11} particles/km for the reference E5 fuel. This confirms that, although the vehicle is type-approved according to the higher Euro 6b limit of 6x10^{12} particles/km, it is close to meeting the Euro 6c limit and it can be considered as state-of-the-art technology. PN emissions in the original configuration fluctuate around the Euro 6c limit; when considering tests on the other fuels as well, the variation is between 5.4x10^{11} and 7.9x10^{11} particles/km. For these tests it is difficult to draw conclusions on the differences between fuels due to the limited number of repeats, although directionally the WLTC results are higher than the NEDC results. All PN results with the GPF are significantly below the limit, between 1.5x10^{11} and 2.3x10^{11} particles/km across the two cycles.

PN emissions of the total RDE trip are plotted in Figure 5. PN limits need to be met, both for total PN emissions, as well as for PN emissions measured during the urban portion of the test cycle. Both total and urban results show a similar trend for the original vehicle configuration, but with different absolute levels. The highest PN emissions are observed for the urban part without GPF, being between 6.6x10^{11} and 8.9x10^{11} particles/km. The results are just within the Euro 6d NTE limit. This further confirms that the vehicle uses state-of-the-art GDI technology. With the GPF fitted,

Figure 5 PN emissions measured under total RDE

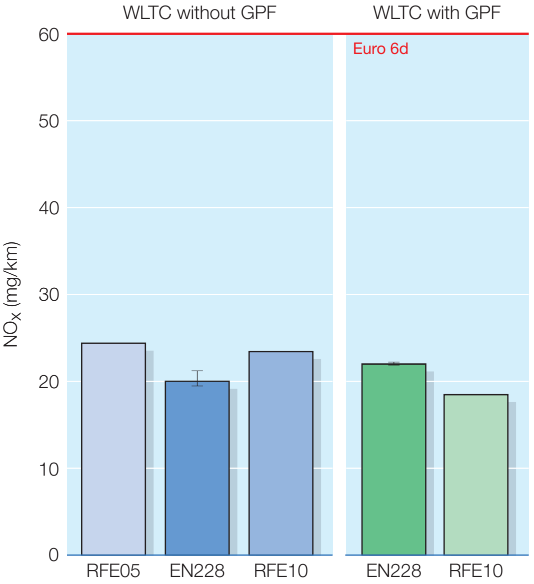


the PN results are below 6x10^{11} particles/km, varying between 1.6x10^{11} and 2.2x10^{11} particles/km. There were some indications that, without the GPF fitted, PN emissions for the fuel containing 10% ethanol were lower than with the EN228 E5 market fuel. This was also reflected in the total RDE emissions with the GPF but not in the urban RDE PN emissions.

NO_x emissions under standard conditions

The NO_x emissions on the NEDC and WLTC test cycles were significantly below the Euro 6d limit on all fuels, for these laboratory cycles, without or with a GPF. No further NO_x reductions were observed from the coated GPF compared with those achieved with the TWC. The WLTC NO_x results are shown in Figure 6.

Figure 6 NO_x emissions measured on the WLTC test cycle



The NO_x emissions measured over the total RDE trip and the urban portion of the cycle are plotted in Figures 7 and 8. They are below the Euro 6 limit of 60 mg/km for all laboratory-based test cycles and well below the NTE limit for Euro 6d (shown). NO_x emissions during the urban part are higher than those over the entire trip. One test using the E10 fuel resulted in urban NO_x emissions of 59.7 mg/km, however, statistically there were no differences between the two fuels tested overall. The spread in NO_x emissions is lower with the GPF compared to the original vehicle configuration. Repeating the RDE test three times results in a spread for the urban NO_x emissions of between 27 and 60 mg/km without the GPF, and between 22 and 30 mg/km with the GPF. In contrast with the results of the regulatory test cycles, the coated GPF brings additional NO_x reductions in real-driving conditions.

Figure 7 NO_x emissions over the RDE trip

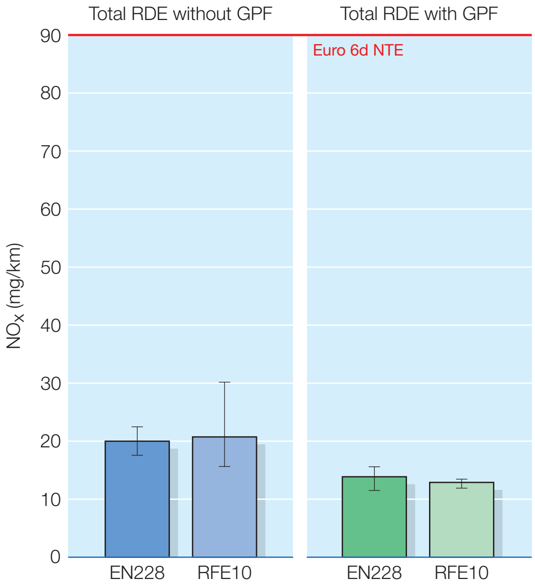
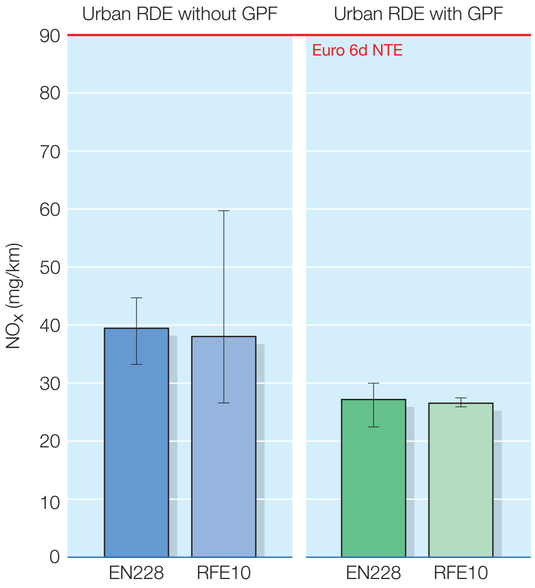


Figure 8 NO_x emissions over the urban part of the RDE trip



On-dynamometer RDE testing and results

Following completion of the NEDC, WLTC and on-road RDE tests using RFE10, the fuel was changed back to the EN228 market fuel and a process undertaken to develop three on-dynamometer RDE cycles with the aim of expanding the range of RDE test severities experienced by the test vehicle.

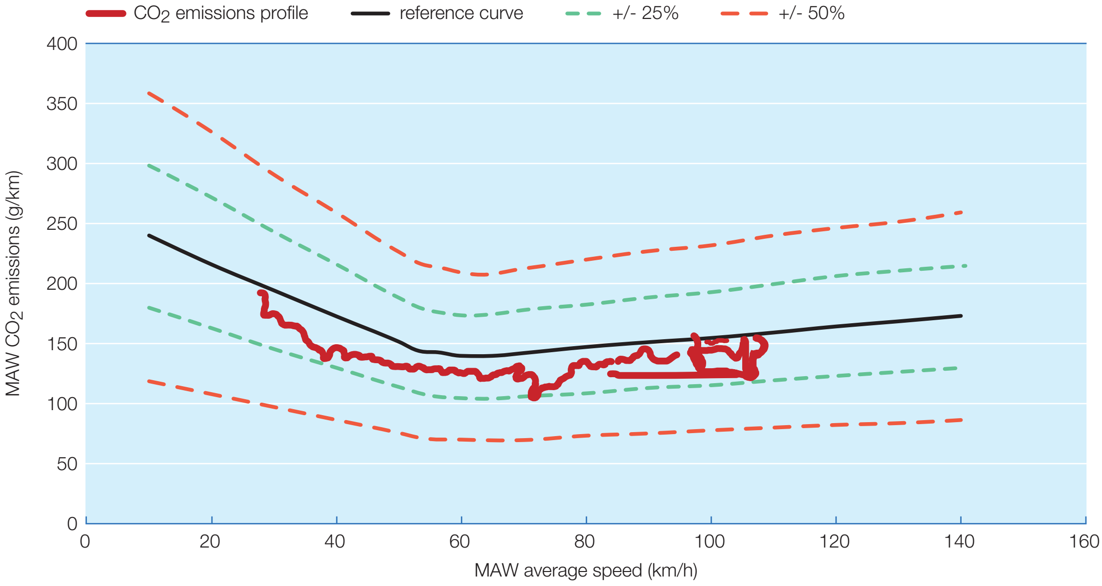
An RDE trip is defined by a number of boundary conditions defined within the regulation. Together these create a multidimensional RDE space within which a huge number of possible valid RDE routes exist. For certification purposes, a valid test is required on a single route only, but since this route may not present the most severe challenge possible within the RDE space, it was considered helpful to understand whether or not the GPF remains effective at higher RDE severities.

Within this programme, the CO_2 vs speed diagrams generated by EMROAD were used as the basis for defining severity, and an approach was developed to generate low, moderate and high CO_2 emissions for nominally the same vehicle speeds.

An on-road RDE test was selected as the basis for the on-dynamometer tests. The CO_2 speed diagram is shown in Figure 9. The 'characteristic' curve, which is generated from WLTC test data, increased to account for differences between certification road and real road loads, represents 'normal' operation. Low and high CO_2 validity limits are indicated by the dashed green lines, with each representing a 25% change in the normal levels. CO_2 emissions outside these levels are corrected by the EMROAD analysis up to the 50% boundary (dashed red line). Emissions beyond these levels are not taken into account. The objective was to create three RDE variants by aligning the measured CO_2 levels with the validity limits of EMROAD.

The speed vs time trace for the on-road RDE was entered into the chassis dynamometer driver's aid and the cycle driven. Luckily, the development of the RDE led to a CO_2 profile along the -25% validity line so this was adopted as the mild/low severity RDE (SRDE L). To generate RDE cycles that matched the characteristic curve (moderately severe RDE, SRDE M) and the +25% boundary (high severity RDE, SRDE H) it was necessary to increase the CO_2 without impacting the vehicle speed. This was achieved by determining a relationship between dynamometer load and vehicle CO_2. Required increases in CO_2, as percentages, were then calculated, and increments in acceleration and dynamometer loads required to move the CO_2 profiles up to SRDE M and SRDE H (see Figure 10).

Figure 9 CO_2 vs speed for the on-road RDE test cycle



The test vehicle was relatively low-powered, meaning that power/CO_2 was limited in the urban section. It was not possible to reach the '+25%' boundary in the urban section even though the vehicle was at full load, however it is clear that the most severe condition for CO_2 production in urban driving is being achieved in this case.

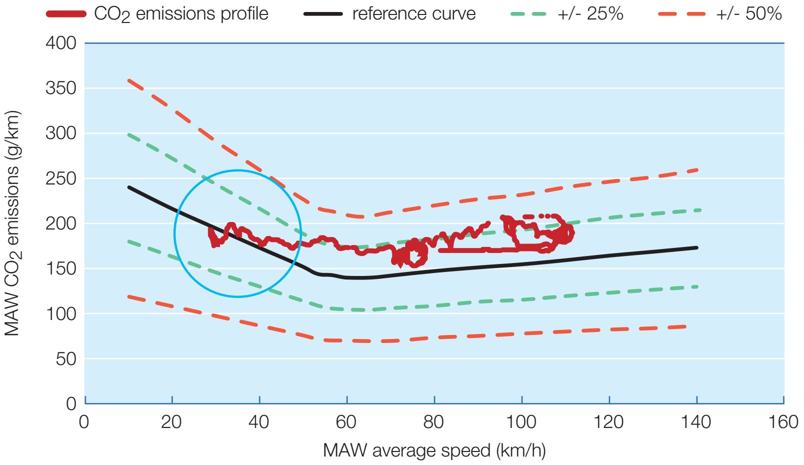
Using the EN228 market fuel, further RDE tests were carried out on the chassis dynamometer to explore the impact of the boundary conditions described above. The same trends can be observed for the evaluation of the total RDE trip or only the urban part. The highest absolute PN emissions are observed for the urban part.

The impact of vehicle acceleration and road load is shown in Figure 11 on page 20. The first bar in the graph gives the reference on-road result ('RDE road'). The second bar shows the on-dynamometer result of the same vehicle speed trace ('NRDE'), hence the difference between the first two bars indicates the impact of going from the road back to the dynamometer. PN emissions drop, as there is, for example, no road gradient when testing on the dynamometer. The following bars then show the results when a stepwise increase towards the RDE boundary conditions is taken. Comparing the bars labelled '1. SRDE L' and 'NRDE' shows the impact of increasing the acceleration with the severitised drive cycle. Without a GPF, PN emissions increase towards 2×10^{12} particles/km. With the GPF, the highest value is just above 5×10^{11} particles/km, remaining significantly below the NTE limit and also below 6×10^{11} particles/km.

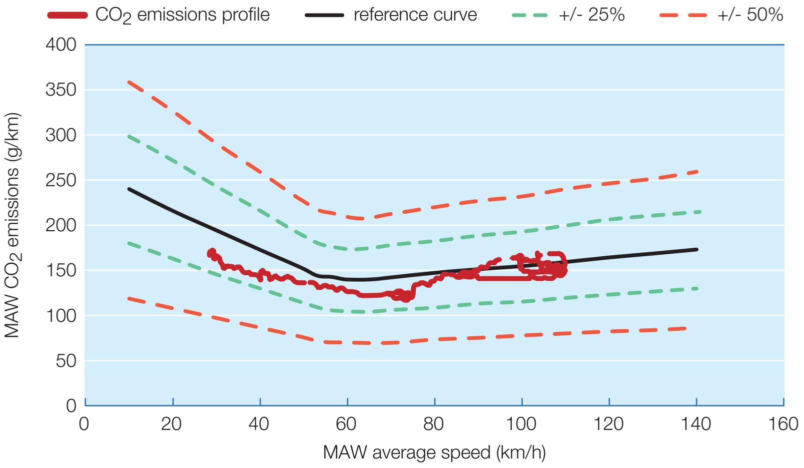
Figure 12 shows the impact of going towards the RDE boundary, and the effect of the severitised drive cycle (SRDE L) and increase in dynamometer load (SRDE M and SRDE H) on urban NO_x emissions. Without the GPF, NO_x emissions increase above 60 mg/km while with the GPF, the results stay below 60 mg/km. The total RDE NO_x results (not shown) also stay below 60 mg/km, test 2b being the highest at 40 mg/km without the GPF and 20 mg/km with the GPF.

Figure 10 CO_2 vs speed diagram showing SRDE on the +25% boundary, mid point and -25% boundaries respectively (SRDE H, M and L)

a) SRDE H (high severity)



b) SRDE M (medium severity)



c) SRDE L (low severity)

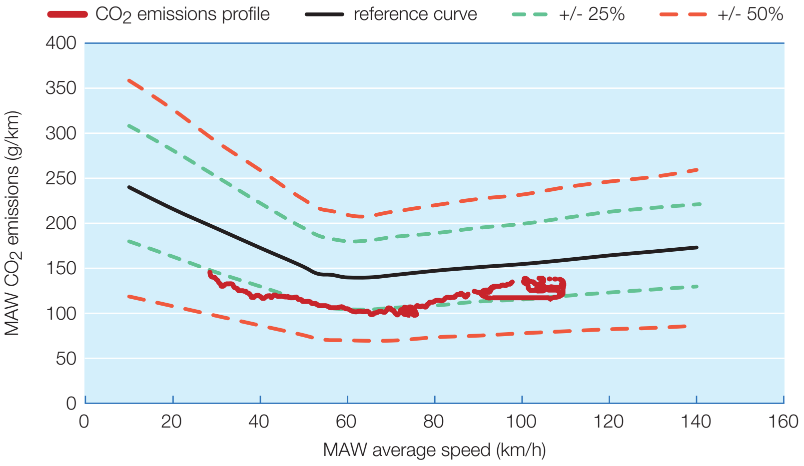


Figure 11 Urban RDE PN emissions measured on the dynamometer with increased vehicle acceleration and dynamometer load

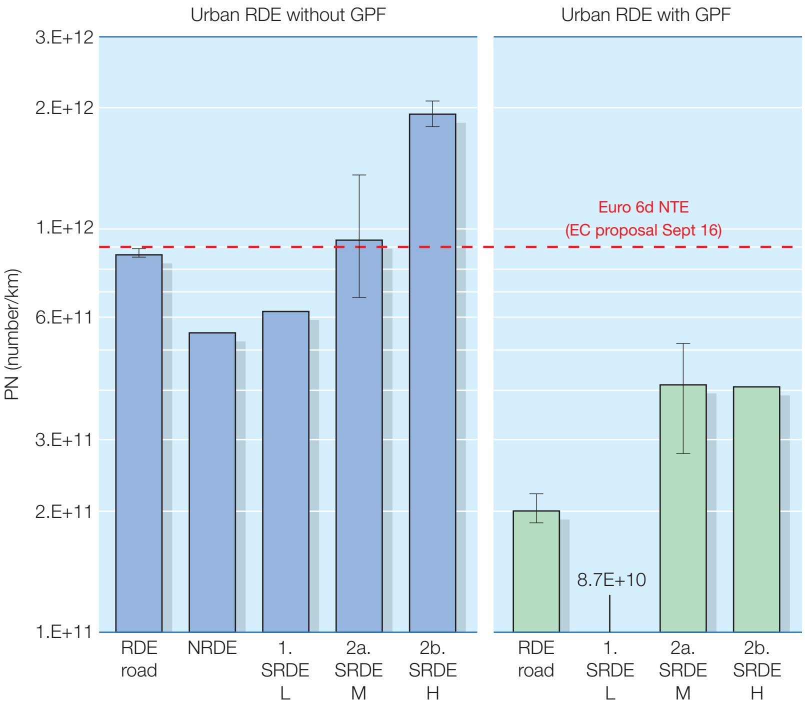
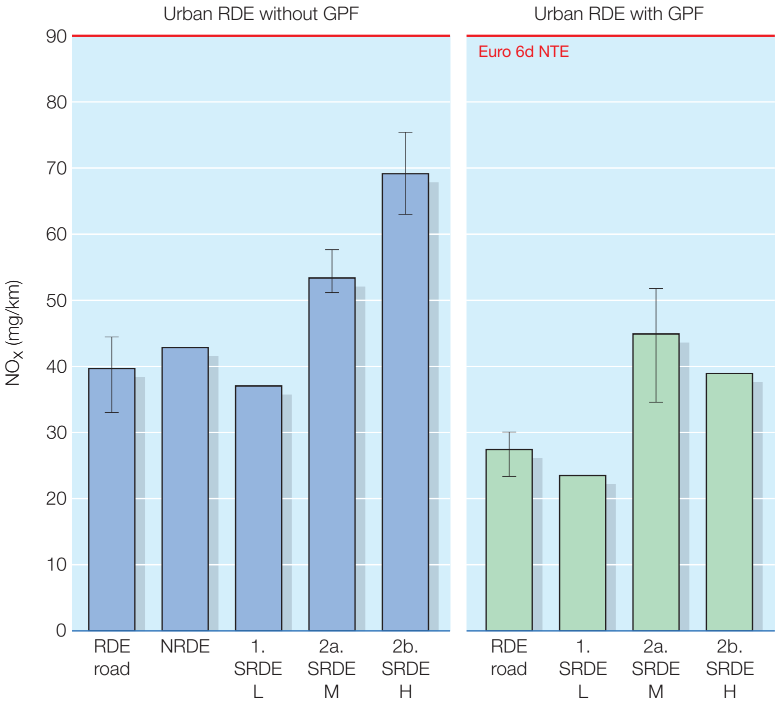


Figure 12 NO_x emissions during the urban part of the RDE trip measured on the chassis dynamometer



The use of a GPF reduces PN and NO_x

The study showed that, for a state-of-the-art GDI engine, PN emissions met the Euro 6c limit on the NEDC and WLTC regulatory test cycles. During the on-road RDE campaign, PN emissions were below the NTE limit. PN emissions of the vehicle without the GPF increased when vehicle acceleration, dynamometer load and ambient temperature were varied towards the boundary conditions defined within the RDE procedure. With the use of the GPF, PN emissions stayed below the NTE limit, even towards the RDE boundary.

NO_x emissions were always below the Euro 6d NTE limit in the original configuration throughout the tests. A further reduction in NO_x emissions was achieved with the coated GPF during real-world driving.

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