Real-World Emissions Measurements of a Gasoline Direct Injection Vehicle without and with a Gasoline Particulate Filter

2017-01-0985

Published 03/28/2017

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CITATION: Demuynck, J., Favre, C., Bosteels, D., Hamje, H. et al., "Real-World Emissions Measurements of a Gasoline Direct Injection Vehicle without and with a Gasoline Particulate Filter," SAE Technical Paper 2017-01-0985, 2017, doi:10.4271/2017-01-0985.

Abstract

The market share of Gasoline Direct Injection (GDI) vehicles has been increasing, promoted by its positive contribution to the overall fleet fuel economy improvement. It has however been reported that this type of engine is emitting more ultrafine particles than the Euro 6c Particle Number (PN) limit of $6 \cdot 10^{11}$ particles/km that will be introduced in Europe as of September 2017 in parallel with the Real Driving Emission (RDE) procedure.

The emissions performance of a Euro 6b GDI passenger car was measured, first in the OEM build without a Gasoline Particulate Filter (GPF) and then as a demonstrator with a coated GPF in the underfloor position. Regulated emissions were measured on the European regulatory test cycles NEDC and WLTC and in real-world conditions with Portable Emissions Measurement Systems (PEMS) according to the published European RDE procedure (Commission Regulation (EU) 2016/427 and 2016/646). Finally, tests were conducted on the chassis dyno to explore the impact of going towards the RDE boundary conditions (driving dynamics and ambient temperature as defined in the RDE legislation).

PN results showed that the vehicle was a state-of-the-art GDI as values on the regulatory test cycles were below the Euro 6c limit of $6 \cdot 10^{11}$ particles/km in its original configuration using the reference E5 fuel. A maximum value of $9 \cdot 10^{11}$ particles/km was measured during the on-road tests, increasing to $2 \cdot 10^{12}$ particles/km when going towards the RDE boundary conditions. With the GPF, PN emissions were controlled well below $6 \cdot 10^{11}$ particles/km on NEDC, WLTC and on-road RDE. With GPF, emissions stayed well below $9 \cdot 10^{11}$ particles/km towards the RDE boundaries, demonstrating that the GPF enables well controlled real-world PN emissions.

No fuel penalty impact could be measured for the GPF during the tests and NOx emissions were always below the Euro 6d NTE (Not-to-exceed) limit that will apply from 2020 onwards.

Introduction

Emissions have been the focus of worldwide legislation for more than twenty-five years. Regulation initially concentrated on gaseous emissions of carbon monoxide, hydrocarbons and NOx. However, particles emitted from vehicles and from other sources are now accepted as having an impact on air quality and on human health [1, 2] and as a result European emissions legislation has set limits for particulate emissions from diesel vehicles since the early 1990's. For diesel passenger cars PM limits were first introduced with the Euro 1 standards in 1992. Since then the limits have become progressively tighter, reaching 5 mg/km for the Euro 5 (2009) and 4.5 mg/km for the Euro 6 (2014) standards. Similarly stringent standards have been introduced in other parts of the world. The introduction of these limits along with the introduction of clean fuels and advanced vehicle and after-treatment technologies has resulted in a substantial reduction in automotive particulate mass (PM) emissions [3, 4] with a corresponding improvement in air quality.

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. As a result, the focus of much research and legislation has remained on diesel vehicles which have historically had much higher emissions [5]. More recently, 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 [6]. There are a growing number of research studies on particle emissions from direct injection gasoline engines and the Euro 5 and 6 particulate emission limits now apply to DI gasoline vehicles as well as diesel vehicles. Direct injection gasoline vehicles have so far met the limits through engine modifications [7] although the Gasoline Particulate Filter (GPF) has been proven to be a practical approach to meeting future regulations as emission limits tighten further [8].

Apart from engine and vehicle technological advances needed, the reduction in particle emission levels has also introduced challenges for the measurement techniques used. 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 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 Particulate Measurement Programme (PMP) over the past decades [9, 10, 11] and introduced from Euro 5 for both diesel and DI gasoline vehicles. The PM measurement method was also improved as part of the same programme. A limit of $6\cdot10^{11}$ particles/km became effective for diesel vehicles from November 2009 and this same limit will apply to DI gasoline cars from 2017 (Euro 6c) [12, 13] with an interim limit for the latter of $6\cdot10^{12}$ particles/km which has been a requirement since 2014 (Euro 6b).

Another factor which is now becoming important is that emissions regulations for passenger vehicles have traditionally been based on the New European Driving Cycle (NEDC). Amid concerns that this test cycle does not represent closely enough real road driving in terms of CO_2 and other emissions levels, two new test procedures are under development - World harmonized Light duty Test Cycle (WLTC) for use on the chassis dynamometer and for on-road use the Real Driving Emissions (RDE) procedure. These tests will be used going forward to certify vehicles and there is much interest in how they will compare with the current NEDC certification test. Other recent developments are the use of Portable Equipment Measurement Systems (PEMS) which are able to measure gaseous and PN emissions under real driving conditions and which will be used for the RDE test. The RDE test protocol has been adopted in 2016 together with the Not-to-exceed limit (NTE) for NOx, published in the first two packages [14, 15]. Two extra Euro 6 stages will be introduced as a consequence, Euro 6d-Temp as of September 2017 with a NOx Conformity Factor (CF) of 2.1 and Euro 6d as of January 2020 with a NOx CF of 1.5. The test protocol defines limits for the environmental and driving dynamic boundary conditions. PEMS measurement data is post-processed with normalization tools (EMROAD and CLEAR) before the CF is calculated. Two more packages are expected for a PN NTE limit, cold-start provisions, hybrids, and in-service conformity testing among other things, these were not yet adopted at the time of writing.

In parallel to the developments on vehicle technology, emissions regulation, measurement equipment and test cycles, the European Renewable Energy Directive (RED, 2009/28/EC) [16] will require 10% renewable energy in transport fuels by 2020 while the Fuel Quality Directive (FQD, 2009/30/EC) [17] 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 and it is planned that RDE testing will be carried out on market fuels.

In a previous study [18], AECC and Concawe investigated the emissions from a commercially available vehicle fitted with a gasoline particulate filter which concluded that the GPF could successfully reduce gasoline particulate emissions below the proposed limits. The new real driving emissions protocol was used according to the draft procedure available at the time of testing, using the PEMS equipment and comparing the existing and future chassis dynamometer tests.

In the current study emissions were studied with and without GPF. Real driving emissions were measured on the dynamometer and road using the standard protocol as well as simulated RDE on the dynamometer designed to go towards the limits of the RDE boundary conditions from a dynamic and temperature perspective. Fuel effects were also studied which were not part of the previous study including fuels representing the market and those of a range of qualities including E5 and E10.

Experimental Set-Up

Vehicle

The test vehicle was a lambda 1 direct injection gasoline vehicle of Euro 6b specification, equipped with a 3-way catalyst for emissions control. An automatic vehicle was selected to remove driver influence on gear shift strategy for the RDE tests.

Maximum power for the vehicle was 92kW @ 5000 rpm, and the type approval emissions data is compliant with Euro 6b requirements (Table 1). PN emissions are ~25% above the $6\cdot10^{11}$ particles/km threshold for Euro 6c.

Table 1. Test Vehicle Certification Data

	Certification [mg/km]	Euro 6b [mg/km]
CO_2	116	-
CO	154.1	1000
THC	44.8	100
NOx	29.8	60
PM	0.0	4.5
PN [#/km]	$7.47\cdot10^{11}$	$6\cdot10^{12}$

Chassis dynamometer tests were performed in the Vehicle Emissions Research Centre (VERC) of Ricardo UK using load terms generated from published US EPA values for a similar vehicle (Table 2). These terms represent a greater road load than those used by the European OEM, so a higher CO_2 emission than shown in Table 1 was anticipated during NEDC tests in this programme.

Table 2. Dyno loads and inertia

Test Property	
Kerb weight (kg)	1275 kg
NEDC Test Inertia (kg)	1360 kg
WLTC Test Inertia (kg)	1470 kg
Dyno terms	
Highway term A (N)	133.497
Highway term B (N/(km/h))	0.359
Highway term C (N/(km/h)²)	0.0311

The vehicle was tested in both OEM (referred to as ‘without GPF’ in the results section) and retrofit GPF builds. To enable this, the baseline exhaust system of the vehicle was removed, a straight section downstream of the existing 3-way catalyst cut out and flanged and then replaced.

A 3-way catalytically-coated GPF (degreened on engine bench to match the vehicle mileage of around 5000km) was provided by AECC to Ricardo where it was canned, coned and flanged. The GPF canning was then extended to the length of the straight section removed from the baseline exhaust. To enable testing of the GPF build, the straight section was then replaced with the GPF section. Several swaps from OEM to GPF builds were conducted during the test programme. Figure 1 shows an underfloor view of the test vehicle, indicating the unmodified OEM exhaust. During the entire project, there has been no active regeneration of the filter. Passive regeneration occurred during each test, removing the built-up soot.

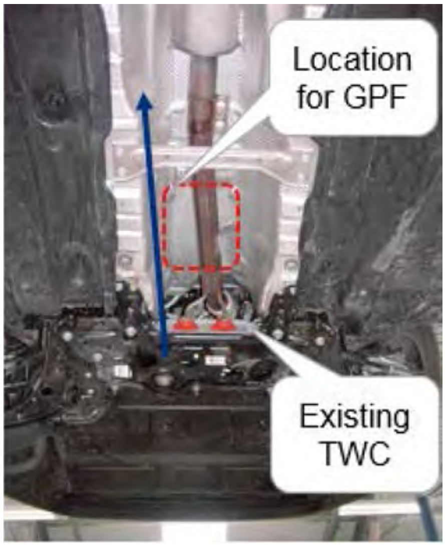

Figure 1. Underfloor view - unmodified exhaust

Figure 2 illustrates the impact of swapping the straight section for the GPF to achieve the GPF-build.

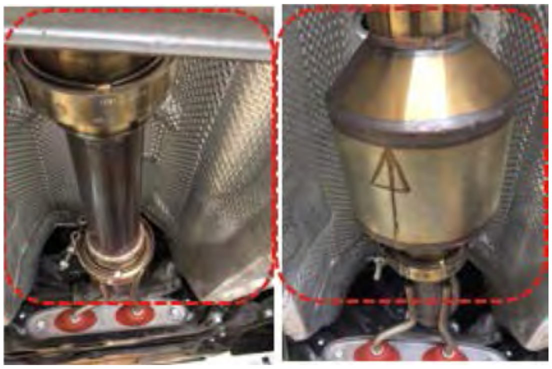

Figure 2. Underfloor view, with and without GPF installed

Fuels

Three fuels were tested in the work programme, 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 3, with further detail available in the appendices.

The majority of the chassis dyno and RDE testing was conducted on the pump-grade fuel with a subset of tests conducted on RFE10. Preliminary chassis dyno tests (NEDC and WLTC) were conducted on RFE05 for reference purposes and to relate emissions to those published from certification.

Table 3. Selected fuel property data

	RFE10	**RFE05**	**EN228**
Density 15°C kg/m3	747.7	749.5	736.5
I.B.Pt. °C	37.3	35.6	24.6
% Evaporated at 70°C, E70 %(V)	43.8	32.8	47.3
% Evaporated at 100°C, E100 %(V)	57.1	56.1	61.6
% Evaporated at 150°C, E150 % (V)	90.4	88.2	92.7
% Evaporated at 180°C, E180 % (V)	-	95.2	99.0
F.B.Pt. °C	181.2	193.4	179.8
R.O.N	97.4	95.5	96.8
M.O.N.	86.1	85.2	85.4
Aromatic content %(V)	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 %(V)	9.9	5	4.8

Measurements and Measurement Systems

During in-lab measurements, MEXA ONE analysers from Horiba were used to measure the continuous raw and bag emissions. A MEXA 2000 SPCS was used to measure dilute PN emissions.

A Horiba OBS-ONE PEMS unit was used to measure CO_2, CO and NOx during RDE measurements (on-road and on-dyno). The OBS-ONE PEMS-PN unit was not yet available on the market at the time the project started, but a prototype of this system was obtained for the tests from Horiba. An important aspect of validating the performance of the PEMS systems for on-road use, is the correlation between it and the lab-based analyzers during a WLTC test. This correlation must meet specified criteria that are laid down in the regulatory approach [14]. Correlations must comply within either absolute boundaries [± mg] or variable boundaries [± %], whichever is the higher. All data shown in this paper derives from compliant PEMS measurements, validated during not only WLTC tests, but also all on dynamometer RDE tests. As an example, the correlations for CO_2, along with the permissible boundaries [±10g/km] & [± 15%] are shown in Figure 3 for some on dynamometer RDE tests (the test labels are explained in the next section).

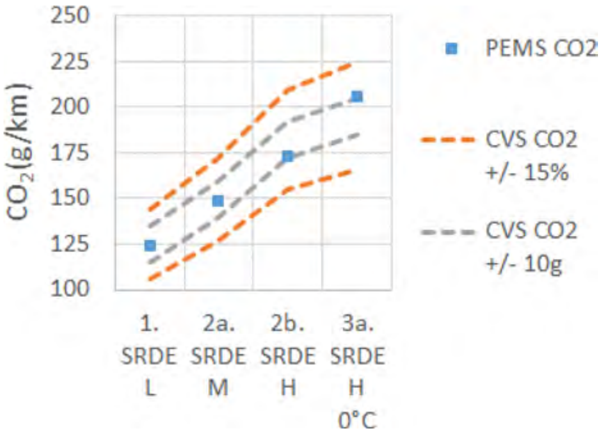

Figure 3. PEMS vs. CVS validation for on dynamometer RDE tests

PN results at 0°C and -7°C are an exception as the prototype device output in those conditions was outside the required tolerance. Consequently, CVS-PN results will be shown for those conditions.

By regulatory intent, on-road RDE tests are inherently variable, due to the unpredictable nature of traffic and the weather. However, in order to indicate the magnitude of this variability, three repeats on the on-road cycle were undertaken, with testing occurring at the same time of day and using the same driver. The percentage variation (CoV) in emissions levels, for all species of interest, derived from these 3 repeats were applied as error bars in the figures of this paper. For the on dynamometer RDE tests, 3 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 severitization process, the on-dyno SRDE tests showed improvement in repeatability when compared with the on-road tests. For example, with CO_2, variation in emissions from the baseline vehicle dropped from ~1.5% to nearer 1%. There is not enough data available to add error bars on each measurement point.

Vehicle data was logged through the OBD connector with a commercially available scanning tool.

Test Matrix

Tests on Euro 6b Reference Fuel

The test project commenced with an NEDC chassis dyno test on RFE05 in standard build, in order 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 over-night soak.

Tests on EN228

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 GPF. These tests were conducted at ~23°C including the over-night soak.

RDE Route

All on-road RDE tests were conducted on a route (Figure 4) known to be EMROAD [14] compliant with >10 vehicles. The RDE route commences from 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 rail-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 relatively flat and the motorway gradually ascending eastbound and descending on the westbound return trip.

Figure 4. RDE route

Tests on RFE10

Following the chassis dyno 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 undertaken.

On-Dyno RDE testing

Following completion of the NEDC, WLTC and on-road RDE tests on RFE10, the fuel was changed back to EN228 and a process undertaken to develop three on-dyno 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 [14, 15]. Together these create a multi-dimensional 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, the creation of more demanding RDE tests that can be conducted on a chassis dynamometer is desirable.

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

This process is described in brief by the steps and MAW diagrams below:

1. An on-road RDE test was selected as the basis for the on-dyno tests. The MAW-diagram is shown in Figure 5. 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 dotted green lines, with each representing at 25% change in the normal MAW levels. MAW outside this lines are corrected by the EMROAD analysis up to the 50% boundary (dotted red line). MAW outside this are not taken into account.
2. The speed vs. time trace for the on-road RDE was entered into the chassis dyno drivers-aid and the cycle driven. This result is described as the nominal-RDE (NRDE). The resulting MAW diagram is shown in Figure 6. This indicates that the MAW CO_2 has generally decreased with transposition of the cycle from road to dyno, due to the elimination of headwind and altitude gain from the cycle.
3. The two boundary conditions used to ensure the RDE cycle is not driven too aggressively (velocity x positive acceleration, $v \cdot a_{pos}$) or too moderately (relative positive acceleration, RPA) were quite distant from their respective limits from the on-road RDE cycle. This is visualised in Figure 7 for the $v \cdot a_{pos}$ values of all the on-road RDE trips with blue (w/o GPF) and green (with GPF) data points.

   $V \cdot a_{pos}$ was made more severe by taking the speed vs. time trace of the NRDE and modifying it to increase each acceleration within the cycle to near the maximum achievable by the vehicle (Figure 8). This process of increasing severity creates the severitized RDE (SRDE) trace which has considerably more aggressive $v \cdot a_{pos}$, see the red data points in Figure 7, similar RPA, but still relatively low MAW CO_2 (Figure 9).
4. The objective in creating three SRDE variants was to align the measured MAW CO_2 levels with the MAW validity limits of EMROAD. By good fortune, the development of the SRDE led to a MAW profile along the -25% validity line in Figure 9, so this was adopted as the mild / low load SRDE, or SRDE_L.
5. To generate SRDE cycles that matched the characteristic curve (moderate SRDE; SRDE_M) and the +25% boundary (high load SRDE; SRDE_H) it is necessary to increase the CO_2 of the MAW without impacting the vehicle speed. This was achieved by determining a relationship between dyno load and vehicle CO_2. Required increases in CO_2, as percentages, were then calculated, and increments in dyno loads required to uplift the MAW profiles to SRDE_M and SRDE_H identified in a short iterative study.
6. Dyno load changes, following those initially entered for urban, were applied between urban and rural, and rural and motorway phases and the resulting SRDE_M and SRDE_H profiles are shown in Figure 10 and Figure 11 respectively.

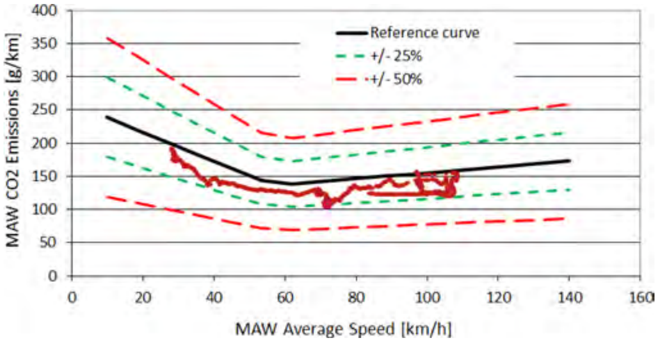

Figure 5. On-road RDE MAW-diagram

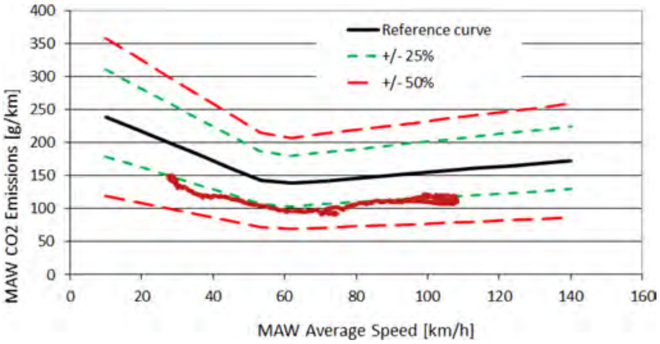

Figure 6. NRDE MAW-diagram

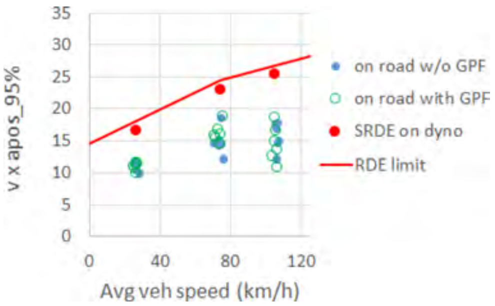

Figure 7. Visualisation where the data are within the dynamic boundary condition ($v \cdot a_{pos}$)

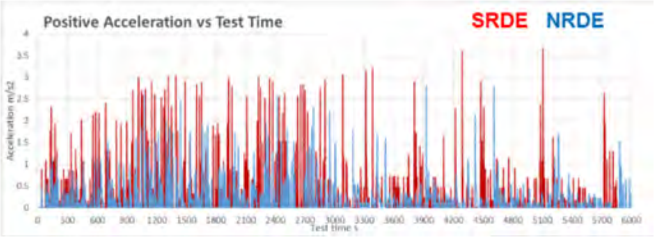

Figure 8. Increase of positive acceleration creates SRDE

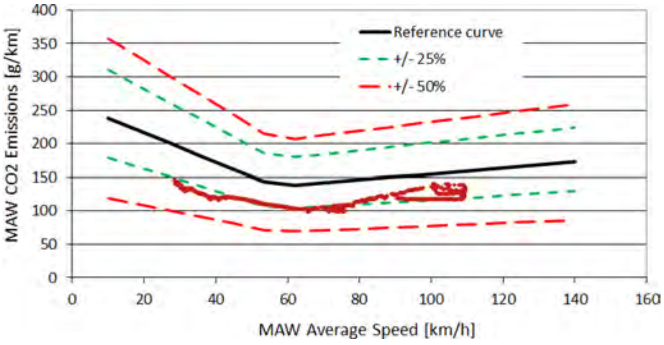

Figure 9. SRDE MAW diagram (on the -25% boundary)

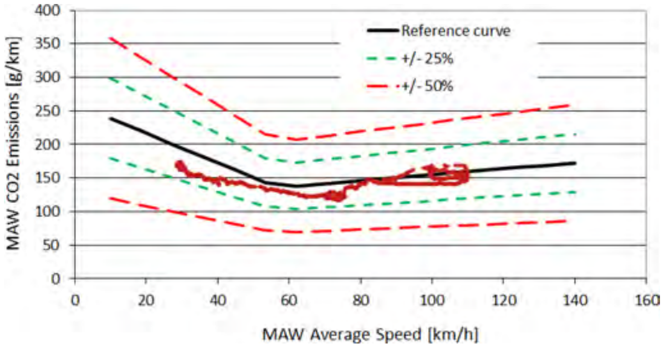

Figure 10. MAW-diagram showing SRDE_M on the midpoint line

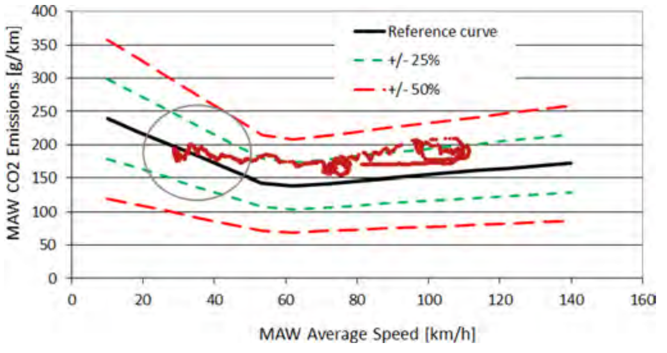

Figure 11. MAW-diagram showing SRDE_H on the +25% boundary

The test vehicle was a relatively low-powered application, and power / CO_2 was limited in the urban section. It was not possible to reach the "+25%" boundary in the urban section (<50km/h; Figure 11) even though the vehicle was at full load, however it's clear that the most severe condition in urban, for CO_2 production, is being achieved in this case.

Summary of Initial Tests

An overview of the initial tests above, including chassis dyno, on-road and on-dyno RDE tests conducted after 23°C soak and with 23°C start temperature are given in Table 4.

Table 4. Summary of 23°C Start Dyno and On-road Tests

	GPF (Y/N)	RFE05	RFE10	EN228
NEDC	N	1	1	1
	Y	-	1	1
WLTC	N	1	1	1
	Y	-	1	1
On-road RDE	N	-	3	3
	Y	-	3	3
On-dyno RDE Low load "SRDE_L"	N	-	1	-
	Y	-	1	-
On-dyno RDE Moderate load "SRDE_M"	N	-	3	-
	Y	-	3	-
On-dyno RDE High load "SRDE_H"	N	-	1	-
	Y	-	1	-

Further Testing of Boundary Conditions

In addition to the dynamic boundary conditions tested by the SRDE process, the project also investigated the impacts of low temperature operation for the on-dyno RDE cycles, with the aim of identifying emissions control system, including GPF, impacts.

- SRDE_H was tested at 0°C both with and without GPF - nominally SRDE_H0_Y and SRDE_H0_N respectively
- SRDE_H and SRDE_L were also tested at -7°C both with and without GPF

These additional tests are summarised in Table 5.

Table 5. Low temperature chassis dyno and on-dyno RDE tests

	GPF (Y/N)	EN228 at -7°C	EN228 at 0°C
WLTC	N	1	-
	Y	1	-
On-dyno RDE Low load "SRDE_L-7"	N	1	-
	Y	1	-
On-dyno RDE High load "SRDE_H0"	N	-	1
	Y	-	1
On-dyno RDE High load "SRDE_H-7"	N	1	-
	Y	1	-

Results and Discussion

First, an overview is given of where the data fit within the boundaries defined in the RDE legislation for ambient conditions and driving dynamics.

The results of the entire test matrix (NEDC, WLTC, RDE on the road and RDE on the dyno) are then discussed per pollutant in separate sections. The raw PEMS data is discussed first, i.e. no exclusions or normalization applied. The impact of the post-processing done with the normalization tools mentioned in the introduction is discussed at the end.

The results of the original vehicle configuration (without GPF) are each time plotted on the left side of the graphs in blue, those with GPF on the right, in green. A different filling pattern is used to indicate the fuel that was used. A red line indicates the Euro 6 emission limit on test cycle results. Euro 6d is mentioned as this is described in the legislation as "the full Euro 6 emission requirement, i.e. Euro 6b emission standard, final PN standard for PI vehicles, use of E10 and B7 reference fuel (where applicable) assessed on regulatory lab test cycle and RDE testing against final conformity factors." The figures with RDE results contain a dashed line with the Euro 6d NTE limit. At the time of writing, an NTE limit has not yet been adopted for PN. The proposal of the European Commission of September 2016 is indicated (CF=1.5) in this case.

Data within RDE BoundaryConditions

All measured data are within the RDE boundary conditions defined by the legislative test protocol. As explained above, the on-dyno RDE work investigated the impact of going towards these boundary conditions.

Figure 12 illustrates where the measured RDE data fit within the environmental boundary conditions. The blue dots represent the average temperature and altitude during each on-road RDE test without GPF, the green ones those with GPF. The blue and green box visualise all the conditions observed during the tests without and with GPF respectively, showing that similar conditions were covered. The red dots show the conditions used during the on-dyno RDE work (23°C, 0°C and -7°C). There is also an upper limit for the altitude accumulation throughout the RDE trip (1200m/100km). Although the tests are done near sea level, severity from altitude accumulation during the RDE route on the road reaches 800m/100km.

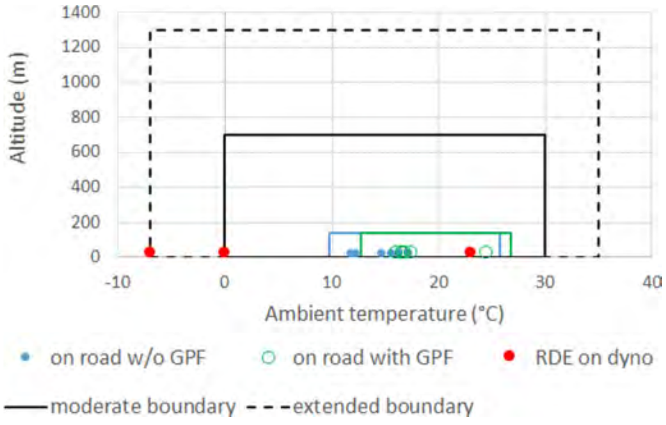

Figure 12. Visualisation where the data fit within the environmental boundary conditions.

Figure 7 showed that similar driving severity, characterized by $v \cdot a_{pos}$, was covered with and without GPF within the RDE boundaries on the road. It also showed that near boundary conditions were covered with the severitized driving trace (SRDE) on the dyno. The lower cut-off limit for driving severity, represented by RPA (Relative Positive Acceleration), was always within the limit and not much different for the NRDE and SRDE trace.

Particulate Emissions

Figure 13 and Figure 14 show the PN measurements on the regulatory test cycles NEDC and WLTC. PN emissions on both cycles are just below the Euro 6c/d limit of $6 \cdot 10^{11}$ particles/km for the reference E5 fuel. This confirms that, although the vehicle is type-approved according to the higher Euro 6b limit of $6 \cdot 10^{12}$ 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/d limit, when considering tests on the other fuels as well, the variation is between 5.4 and $7.9 \cdot 10^{11}$ particles/km. For these tests it is difficult to make conclusions on fuel to fuel differences due to the limited number of repeats. All PN results with the GPF are significantly below the limit, between 1.5 and $2.3 \cdot 10^{11}$ particles/km.

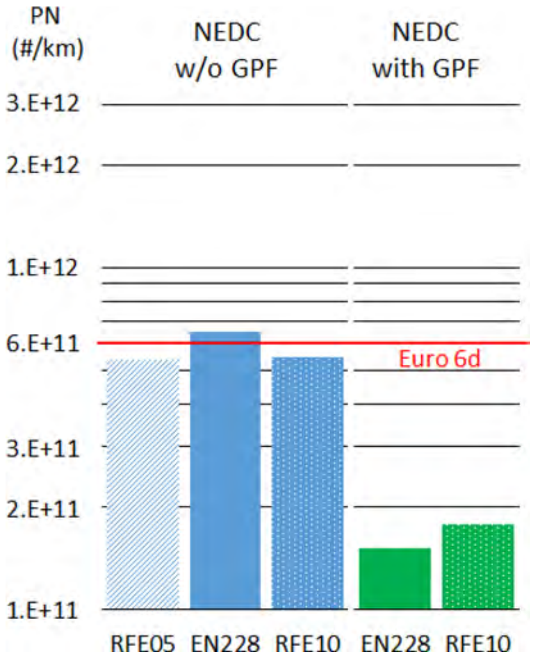

Figure 13. PN emissions measured on the NEDC.

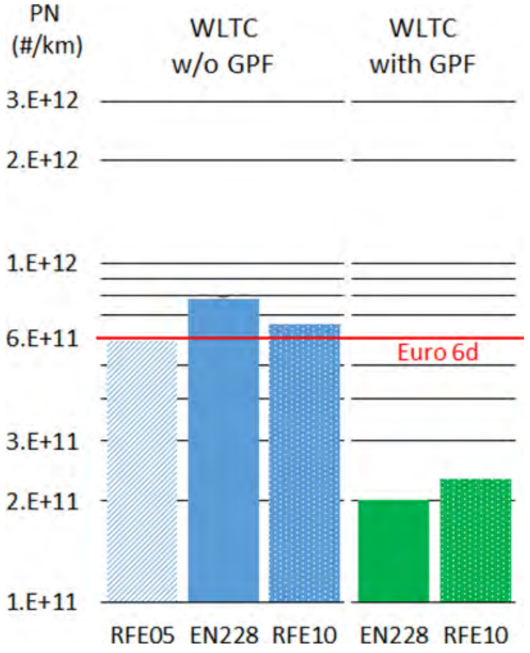

Figure 14. PN emissions measured on the WLTC

PN emissions of the total RDE trip are plotted in Figure 15, those of the urban part in Figure 16. Both graphs show a similar trend for the original configuration, but with different absolute levels. The highest PN emissions are observed for the urban part without GPF, being between 6.6 and $8.9 \cdot 10^{11}$ particles/km. The results are just within the proposed Euro 6d NTE limit at the time of writing this paper. This further confirms that the vehicle uses state-of-the-art GDI technology. With the GPF fitted, the PN results are below $6 \cdot 10^{11}$ particles/km, varying between 1.6 and $2.2 \cdot 10^{11}$ particles/km. There were some indications without the GPF fitted that PN emissions for the ethanol containing fuel were lower with the E5 market fuel. This was also reflected in the total RDE emissions with the GPF but not in the Urban RDE PN emissions.

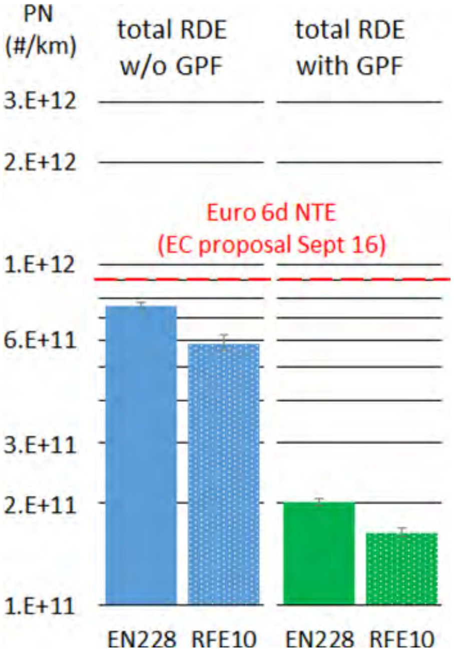

Figure 15. Total RDE PN emissions measured on the road.

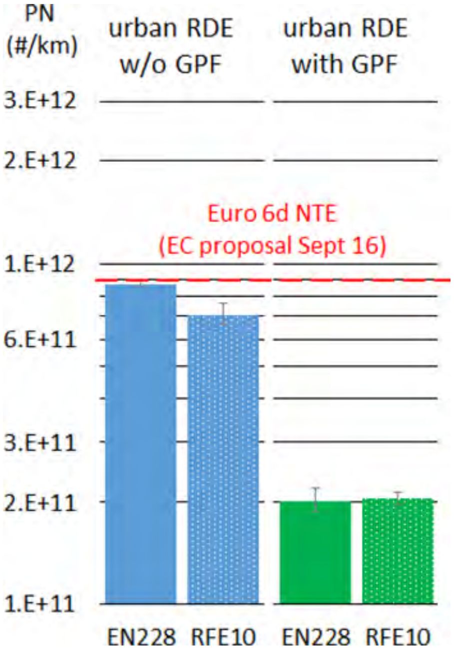

Figure 16. Urban RDE PN emissions measured on the road.

On the market E5 fuel, further RDE tests were carried out on the chassis dyno to explore the impact of the boundary conditions as described above in the section on the experimental set-up. 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, so these are plotted in the following graphs.

In Figure 17, the impact of the driving dynamics is plotted (vehicle acceleration and road load). The first bar in the graph gives the reference on-road result (‘RDE road’). The second bar shows the on-dyno result of the same vehicle speed trace (‘NRDE’), hence the difference between the first two shows the impact of going from the road back to the dyno. PN emissions drop as there is e.g. no road gradient when testing on the dyno. The following bars then show the results when a stepwise increase towards the RDE boundary conditions is taken. Comparing the bars labelled with ‘1. SRDE L’ and ‘NRDE’ shows the impact of increasing the accelerations towards the upper v·a_{pos} limit with the severitized drive cycle. Then, the dyno load is increased towards the +25% CO_2-line in EMROAD in two steps (labeled as. ‘2a. SRDE M’ and ‘2b. SRDE H’), keeping the severitized drive cycle. The impact of the dyno load is higher than that of the severitized drive cycle. Without a GPF, PN emissions increase towards $2 \cdot 10^{12}$ particles/km. With the GPF, the highest value is $2.5 \cdot 10^{11}$ particles/km, remaining significantly below the NTE limit and also below $6 \cdot 10^{11}$ particles/km.

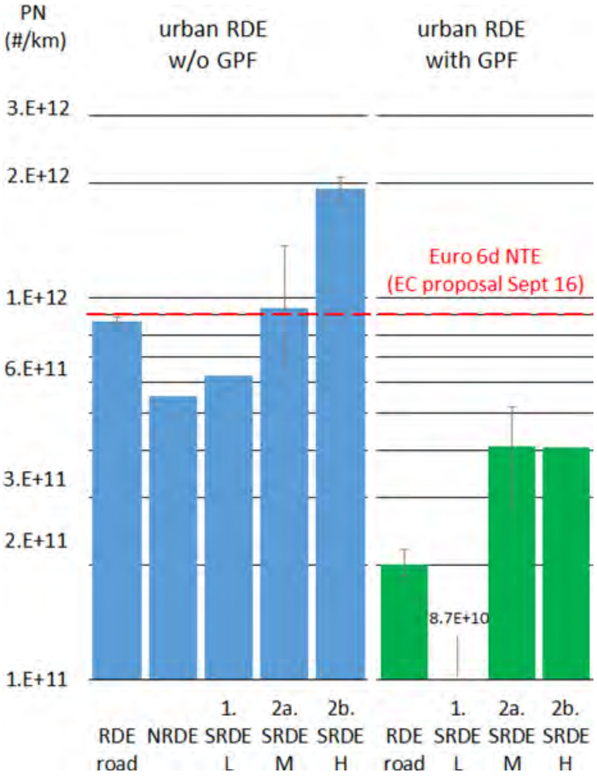

Figure 17. Urban RDE PN emissions measured on the dyno with increased vehicle accelerations and dyno load.

In the following measurements, the impact of ambient temperature was investigated. Tests were done at 0°C and -7°C, keeping the severitized drive cycle and highest dyno load from the previous section (labeled as ‘3a. SRDE H 0°C’ and ‘3b. SRDE H -7°C’). Consequently, these tests investigate a combination of the extremes within the RDE boundary where little test experience exists. As explained in the section on the experimental set-up, the results shown here are from the CVS.

The RDE legislation prescribes that the test results in the extended environmental conditions are divided by a factor of 1.6. Figure 12 showed the situation as of Euro 6d, 0°C being the border between moderate and extended conditions. For Euro 6d-Temp that goes into force as of September 2017, the border is at 3°C. Hence, the 1.6 factor is applied here for the results at 0°C and -7°C.

Figure 18 shows that the results without GPF are between 1.2 and $1.7 \cdot 10^{12}$ particles/km. With GPF, the emissions are between 2.0 and $6.7 \cdot 10^{11}$ particles/km. PN emissions with GPF at -7°C were unexpectedly lower than those at 0°C. This could be within the test-to-test variability that increased under these conditions as observed by repeating the test with GPF at 0°C three times.

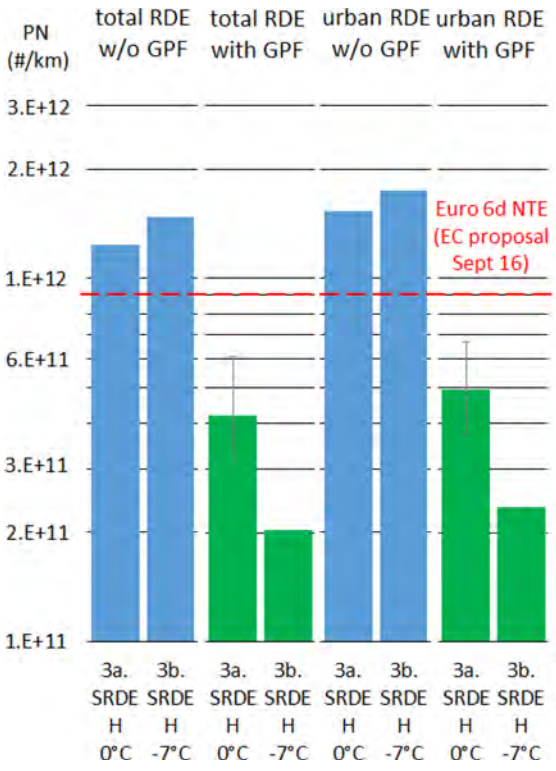

Figure 18. Total and urban RDE PN emissions measured on the dyno at low ambient temperatures.

During tests on the dyno, PM mass emissions have been measured as well. The PM results on NEDC and WLTC are plotted in Figure 19 for the E5 market and E10 reference fuel. PM results are below 0.5 mg/km for both configurations, being significantly below the Euro 6c limit of 4.5 mg/km. In contrast to PN, no measurable difference is observed between the two configurations, without and with GPF. As with PN, no conclusions could be made on fuel differences due to limited numbers of repeats. All differences are within the test-to-test variability observed on those tests that were repeated. The PN metric allows differentiation between gasoline vehicle particulate emissions with significantly higher resolution than PM.

NOx Emissions

The NOx emissions on NEDC and WLTC are presented in Figure 20 and Figure 21. The graphs show that NOx emissions are significantly below the Euro 6d limit on all fuels, for these laboratory cycles, without or with a GPF. No further NOx reduction can be observed from the coated GPF to that done by the TWC.

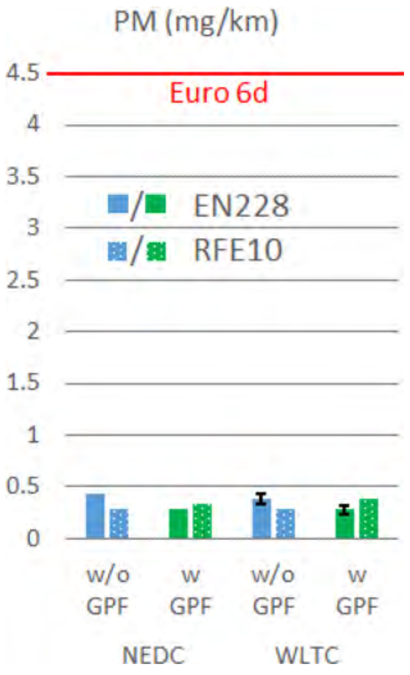

Figure 19. The PM mass emissions measured on NEDC and WLTC.

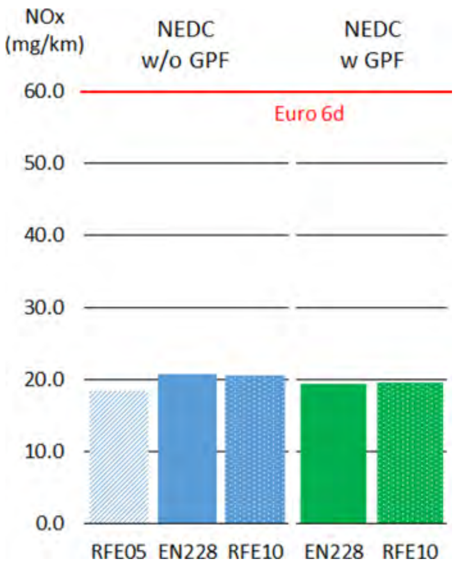

Figure 20. The NOx emissions measured on NEDC.

The NOx emissions measured over the total RDE trip and the urban part are plotted in Figure 22 and Figure 23. They are below the laboratory cycle based Euro 6 limit of 60 mg/km for all tests. NOx emissions during the urban part are higher than those over the entire trip. One test on E10 resulted in urban NOx emissions of 59.7mg/km, however statistically there were no differences between the two fuels tested overall. The spread in NOx 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 NOx between 27 and 60 mg/km without GPF and between 22 and 30 with the GPF. Unlike on the regulatory cycles, the coated GPF brings additional NOx reductions in real-driving conditions.

Figure 24 and Figure 25 show the impact of going towards the RDE boundary. The effect of the severitized drive cycle (SRDE L) and increase in dyno load (SRDE M and SRDE H) on the urban NOx emissions is plotted in the first graph. The bars correspond to the same conditions explained during the discussion of the PN emissions. Without GPF, NOx emissions increase above 60 mg/km.

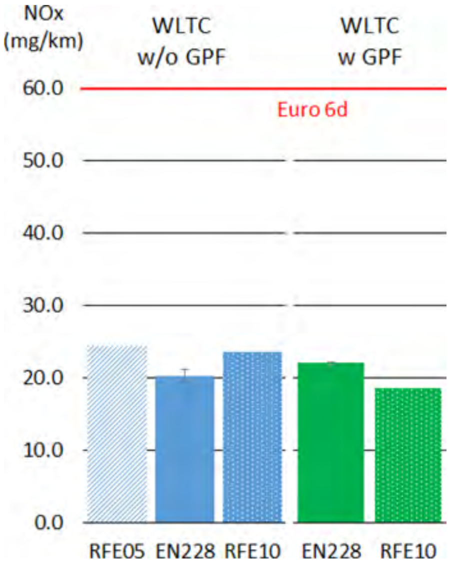

Figure 21. The NOx emissions measured on WLTC.

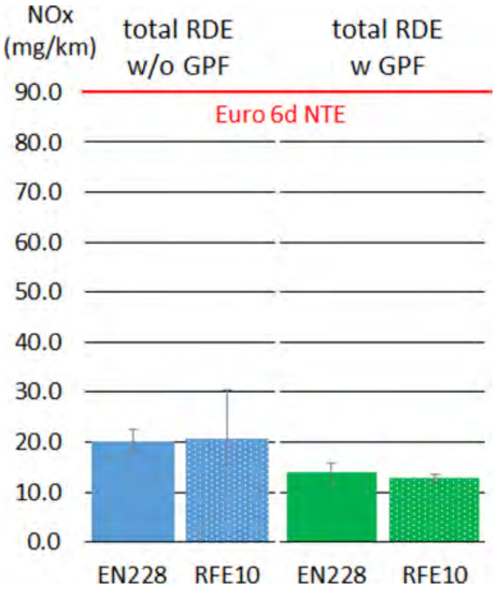

Figure 22. The NOx emissions over the total RDE trip.

With the GPF, the results stay below 60 mg/km. The total RDE NOx results that are not plotted here all stay below 60 mg/km, test 2b being the highest at 40 mg/km without GPF and 20 mg/km with the GPF.

When the ambient temperature is lowered, see Figure 25, total RDE NOx emissions stay below 60 mg/km in both vehicle configurations. The urban emissions are similar to those at 23°C when the 1.6 factor is taken into account, all results stay below the Euro 6d NTE limit. In this case, both emissions without and with GPF at -7°C are lower than at 0°C, but this might be within test-to-test variability as well.

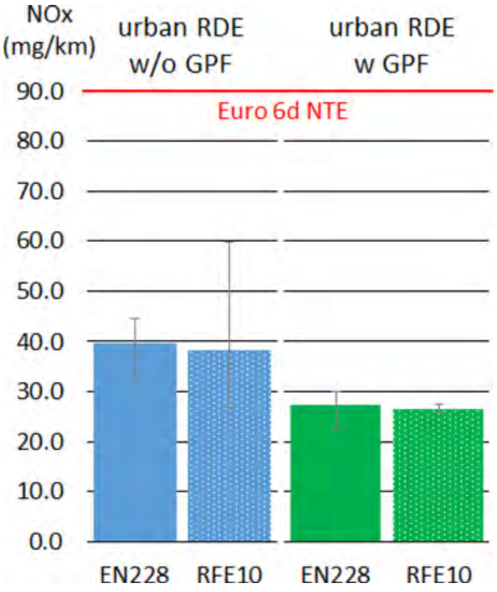

Figure 23. The NOx emissions over the urban part of the RDE trip.

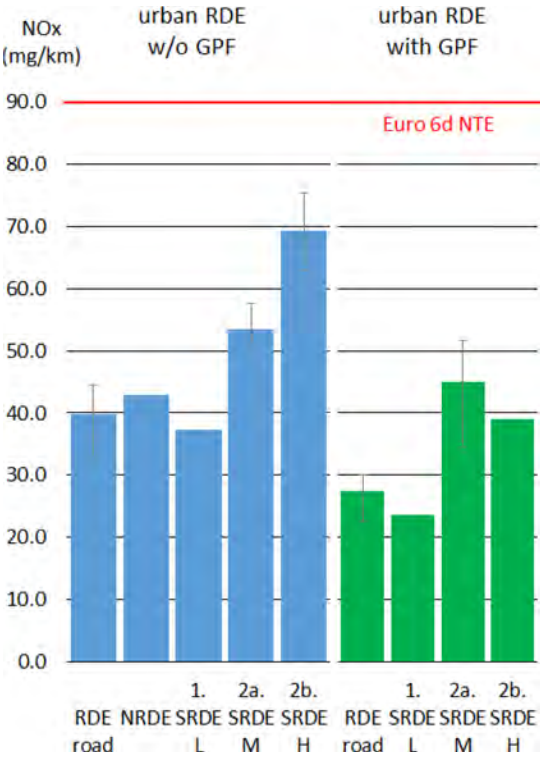

Figure 24. NOx emissions during the urban part of the RDE trip measured on the chassis dyno.

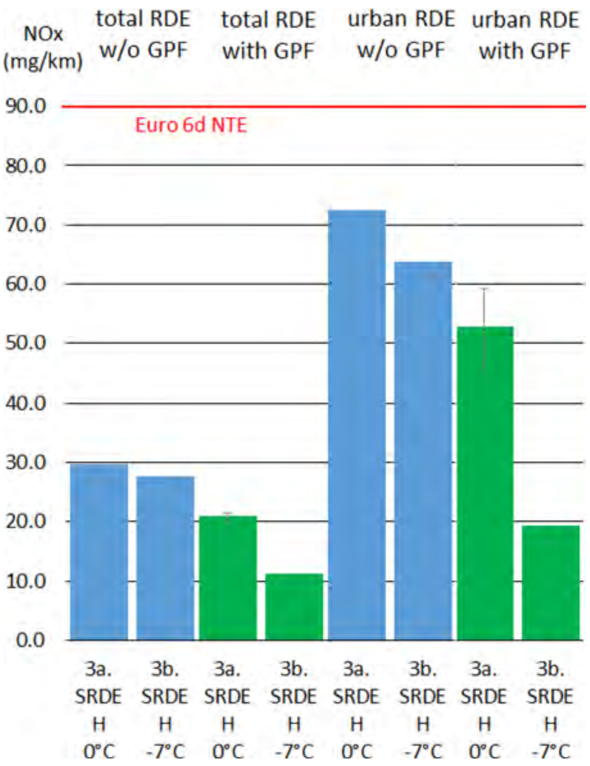

Figure 25. Total and urban RDE NOx emissions measured on the dyno at low ambient temperatures.

Other Emissions

This section discusses CO_2 and CO emissions for which there are currently no NTE limits foreseen in the RDE legislation.

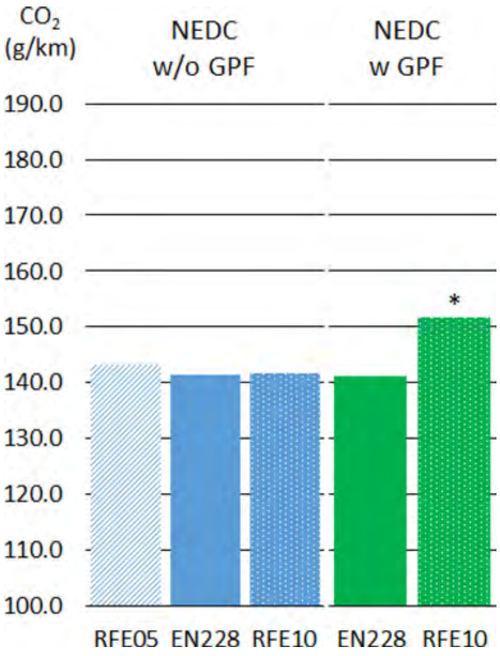

Figure 26. CO_2 emissions measured on NEDC.(*) impact of inactive start-stop system.

CO_2 emissions on the NEDC and WLTC are plotted in Figure 26 and Figure 27. Different observations can be made. First, the NEDC CO_2 emissions on the reference E5 fuel are 23% higher than the type approval data (116 g/km) when the road load coefficients from the US EPA database are used. Emissions are not impacted by the test fuel or cycle. Second, some measurements resulted in an unexpected high amount of CO_2 (on both cycles and in both configurations, see the bars marked by an asterisk symbol). This happened if the start-stop system of the vehicle was not active during all idling conditions. Third, the data does not indicate a measurable impact of the addition of the GPF on CO_2 emissions on regulatory test cycles.

CO_2 emissions measured during the on-road RDE tests are shown in Figure 28. All differences between fuels and configurations are within the measurements spread, so again no measurable impact can be seen for the GPF, both in the urban part and the total RDE trip. The total RDE CO_2 values match those on NEDC and WLTC, demonstrating that the US EPA road load coefficients are realistic values for this vehicle.

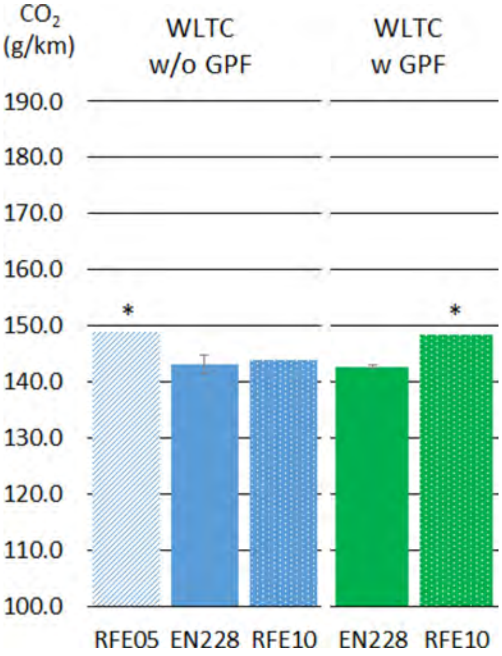

Figure 27. CO_2 emissions measured on WLTC.(*) impact of inactive start-stop system.

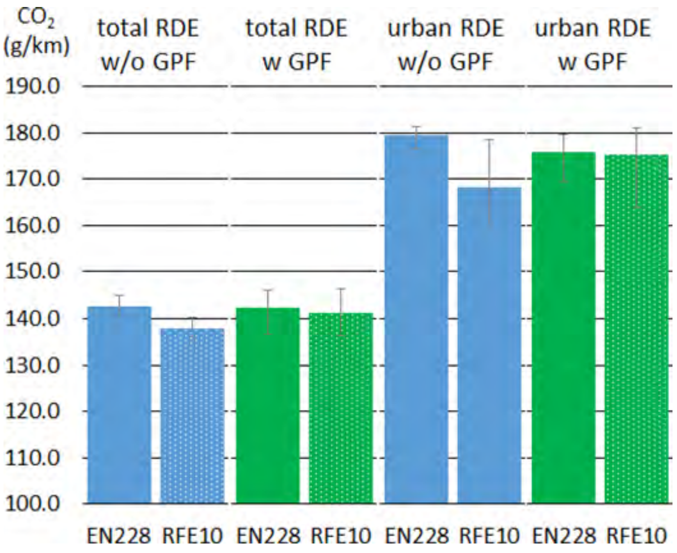

Figure 28. CO_2 emissions measured on the road during the total RDE trip and the urban part.

CO emissions are significantly below the Euro 6d limit during the NEDC, WLTC and RDE on the road. The last two results are plotted in Figure 29 and Figure 30. All on-road RDE results are significantly below 1000 mg/km in both vehicle configurations. As was the case for NOx emissions, the coated GPF lowers CO tailpipe emissions during the RDE tests.

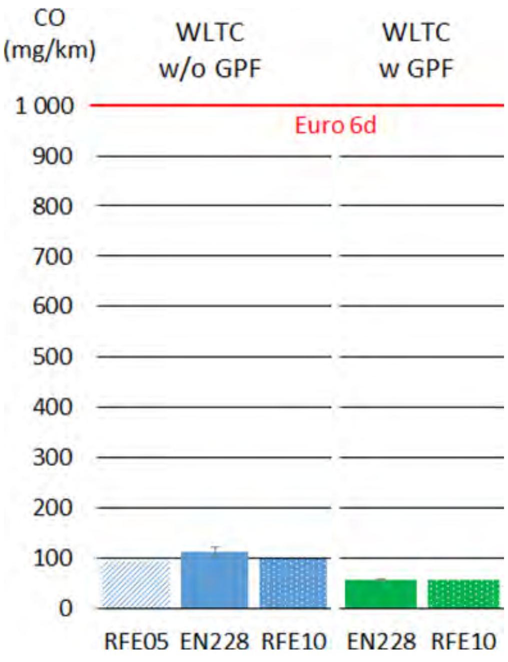

Figure 29. CO emissions measured on WLTC.

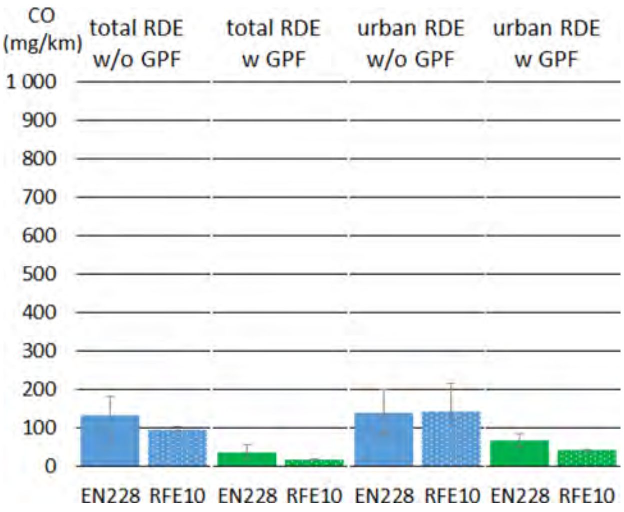

Figure 30. CO emissions measured on the road during the total RDE trip and the urban part.

Figure 31 shows CO emissions during the on-dyno RDE tests. For CO, the highest emissions are observed for the total RDE trip, so these are plotted here. The graph demonstrates the strong impact of the driving dynamics on CO emissions, which significantly increase when the vehicle is driven towards the RDE boundary. For the urban part (not plotted), similar trends can be observed and a maximum value of 876 mg/km is measured. The impact of the ambient temperature on the total and urban RDE CO emissions is shown in Figure 32. CO emissions at 0°C and -7°C are comparable to those at 23°C when the 1.6 factor is applied, similarly to NOx and PN. CO emissions at -7°C are also lower than those at 0°C. In all of these tests there were no strong fuel effects observed.

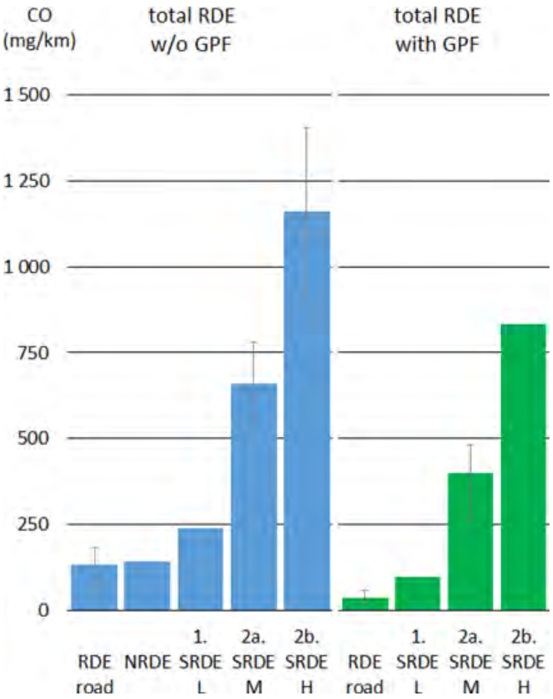

Figure 31. Total RDE CO emissions measured during the RDE on dyno tests.

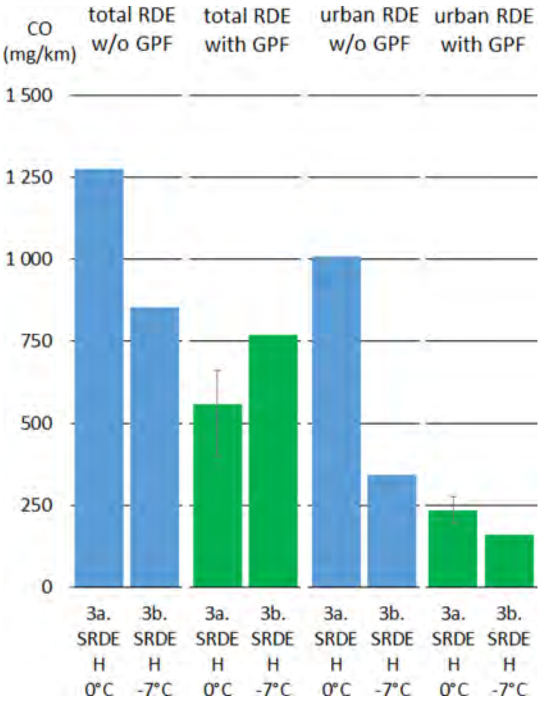

Figure 32. Total and urban RDE CO emissions measured during the RDE on dyno tests at low ambient temperature.

Normalization Tool Impact

In the previous sections, the raw results measured by the PEMS equipment were presented. As described above, the RDE legislation prescribes data post-processing with the normalization tools EMROAD and CLEAR before the CF is calculated. The impact of this post-processing on the results is discussed here.

Besides the normalization, the adopted RDE procedure at time of writing also excludes the first 5 minutes of the measured emissions (or up to the point of reaching 70°C coolant temperature if this is reached earlier). Different options to include the 5 minutes in the post-processing were considered. Here, the 5 minutes are included in the post-processing with the normalization tools without further weighing as this was the proposal for the 3rd RDE package released by the European Commission in September 2016.

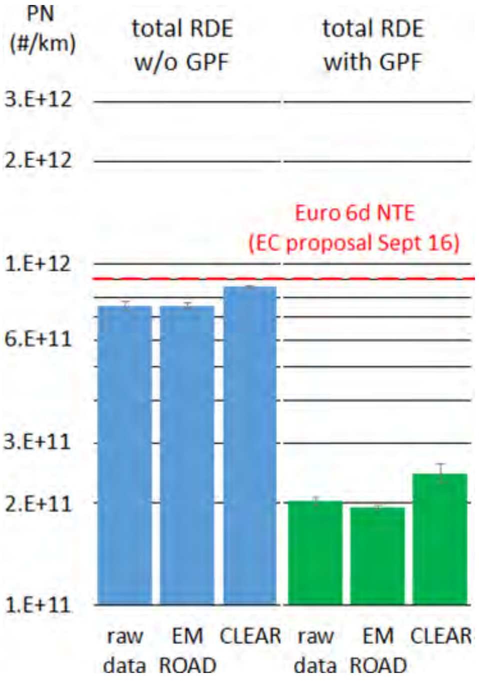

Figure 33. EMROAD and CLEAR impact on total RDE PN emissions (EN228 fuel).

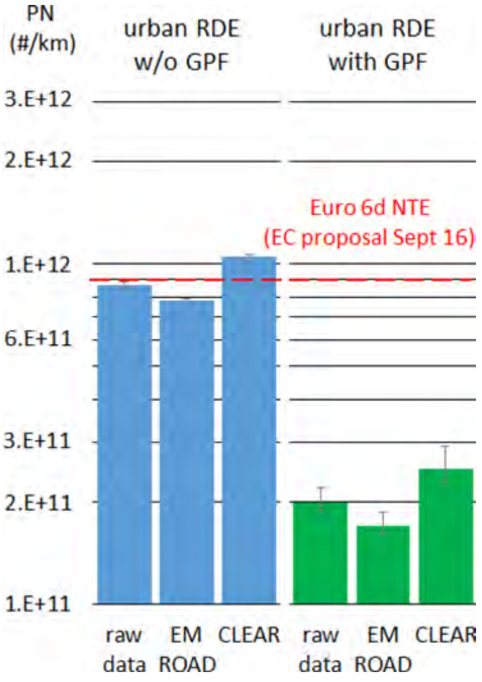

Figure 34. EMROAD and CLEAR impact on urban RDE PN emissions (EN228 fuel).

In general, conclusions made before based on the raw data are not impacted if results are significantly below or above the Euro 6d NTE limit. When results are closer to the limit, the results might go above or under after the normalization. Furthermore, the impact of the normalization tools is difficult to grasp as EMROAD and CLEAR sometimes have an opposite impact. This is illustrated in Figure 33 and Figure 34 for the total and urban RDE PN emissions measured on EN228 fuel. CLEAR results are higher than the raw ones whereas EMROAD output is lower.

Summary/Conclusions

The paper presents the results of a test campaign on a Euro 6b GDI vehicle. The test matrix included measurements on NEDC, WLTC and RDE on the road. RDE measurements were also performed on the chassis dyno to explore the impact of going towards the RDE boundary conditions (driving dynamics and ambient temperature as defined in the RDE procedure). Different fuels were used and the test matrix was repeated in the original configuration without a GPF and with a coated GPF mounted in an underfloor position.

PN results showed that the vehicle was a state-of-the-art GDI. PN emissions met the Euro 6c limit of $6 \cdot 10^{11}$ particles/km on the regulatory test cycles NEDC and WLTC using the reference E5 fuel. During the on-road RDE campaign, PN emissions were below $9 \cdot 10^{11}$ particles/km. PN emissions of the vehicle without GPF increased to $2 \cdot 10^{12}$ particles/km when vehicle accelerations, dyno load and ambient temperature were varied towards the boundary conditions defined within the RDE procedure. With the GPF, PN emissions stayed below $9 \cdot 10^{11}$ particles/km, even towards the RDE boundary.

NOx emissions were always below the Euro 6d NTE limit of 90 mg/km in the original configuration throughout the tests. Further NOx reduction was achieved with the coated GPF during real-world driving.

CO emissions were significantly below the Euro 6d limit on the regulatory test cycles NEDC and WLTC in both vehicle configurations. They increased during the RDE on dyno tests. Similarly to the NOx emissions, the coated GPF allowed lowering of CO tailpipe emissions under real-world driving.

References

1. "The health effects of PM2.5 (including ultrafine particles)", Concawe Report No. 99/60. Brussels (1999).
2. HEI (2002), "Understanding the health effects of components of the particulate matter mix: progress and next steps". HEI Perspectives April 2002. Boston MA: Health Effects Institute
3. EU (1998) "Directive 98/69/EC of the European Parliament and of the Council of 13 October 1998 relating to measures to be taken against air pollution by emissions from motor vehicles and amending Council Directive 70/220/EEC". Official Journal of the European Communities No. L350, 28.12.1998
4. EU (2000) "Directive 1999/96/EC of the European Parliament and of the Council of 13 December 1999 on the approximation of the laws of the Member States relating to measures to be taken against the emission of gaseous and particulate pollutants from compression ignition engines for use in vehicles, and the emission of gaseous pollutants from positive ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles and amending Council Directive 88/77/EEC". Official Journal of the European Communities No. L44, 16.02.2000

5. "Fuel effects on the characteristics of particle emissions from advanced engines and vehicles". Report No. 1/05. Brussels: Concawe (2005).
6. Kittleson, D & Kraft, M, "Particle Formation and Models in Internal Combustion Engines". Cambridge Centre for Computational Chemical Engineering. University of Cambridge (England) preprint No 142, (2014).
7. Bulander R., "Powertrain optimization using a comprehensive systems approach", 36th International Vienna Motor Symposium proceedings, 2015.
8. Mamakos, A et al, Feasability of introducing Gasoline Particulate Filters on Gasoline direct injection vehicles. European Commission Joint Research Centre Institute for Energy and Transport, EUR 25297 EN, 2011.
9. Andersson, J. and Wedekind, B. (2001), "DETR/SMMT/CONCAWE Particulate research programme 1998-2001 - Summary report". Report No. DP01/0515, Shoreham-by-Sea: Ricardo Consulting Engineers Ltd.
10. Andersson, J. et al (2007) "Particle Measurement Programme (PMP) Light-duty interlaboratory correlation exercise (ILCE_LD)". European Commission, JRC, Institute for Environment and Sustainability, Final Report No. EUR 22775 EN. Ispra.
11. "Comparison of particle emissions from advanced vehicles using DG TREN and PMP measurement protocols", Report No. 2/09. Brussels: Concawe (2009).
12. EU (2012) "Commission Regulation (EU) No 459/2012 of 29 May 2012 amending Regulation (EC) No 715/2007 of the European Parliament and of the Council and Commission Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6)". Official Journal of the European Communities No. L142, 01.06.2012.
13. Mamakos, A et al, Assessment of particle number limits for petrol vehicles EUR 25592 EN, 2012.
14. Commission Regulation (EU) 2016/427 of 10 March 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6).
15. Commission Regulation (EU) 2016/646 of 20 April 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6).
16. European Renewable Energy Directive, "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources". Official Journal of the European Communities No. L140, 05.06.2009.
17. European Fuel Quality Directive, "Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions" Official Journal of the European Communities No. L140, 05.06.2009.
18. Bosteels, D. "Real Driving Emissions of a GPF-equipped production car", 3rd International conference on Real Driving Emissions, Berlin, October 2015.

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Acknowledgments

The authors wish to thank the members of AECC and Concawe who funded the program.

Definitions/Abbreviations

CO - carbon monoxide

CO$_2$ - carbon dioxide

CF - Conformity factor

CVS - Constant Volume Sampling

DI - Direct Injection

DSG - Direct Shift Gearbox

EN228 - European motor gasoline standard

ETBE - Ethyl Tertiary Butyl Ether

EX - Fossil fuel with X% ethanol

GDI - Gasoline Direct Injection

GPF - Gasoline Particulate Filter

MAW - Moving Average Window

NEDC - New European driving cycle

NOx - nitrogen oxides (NO+NO$_2$)

NRDE - Normal RDE

NTE - Not-to exceed

OBD - On-Board Diagnostics

PEMS - Portable Emissions Measurement System

PFI - Port Fuel Injected

PM - Particulate Mass

PN - Particle Number

RDE - Real Driving Emissions

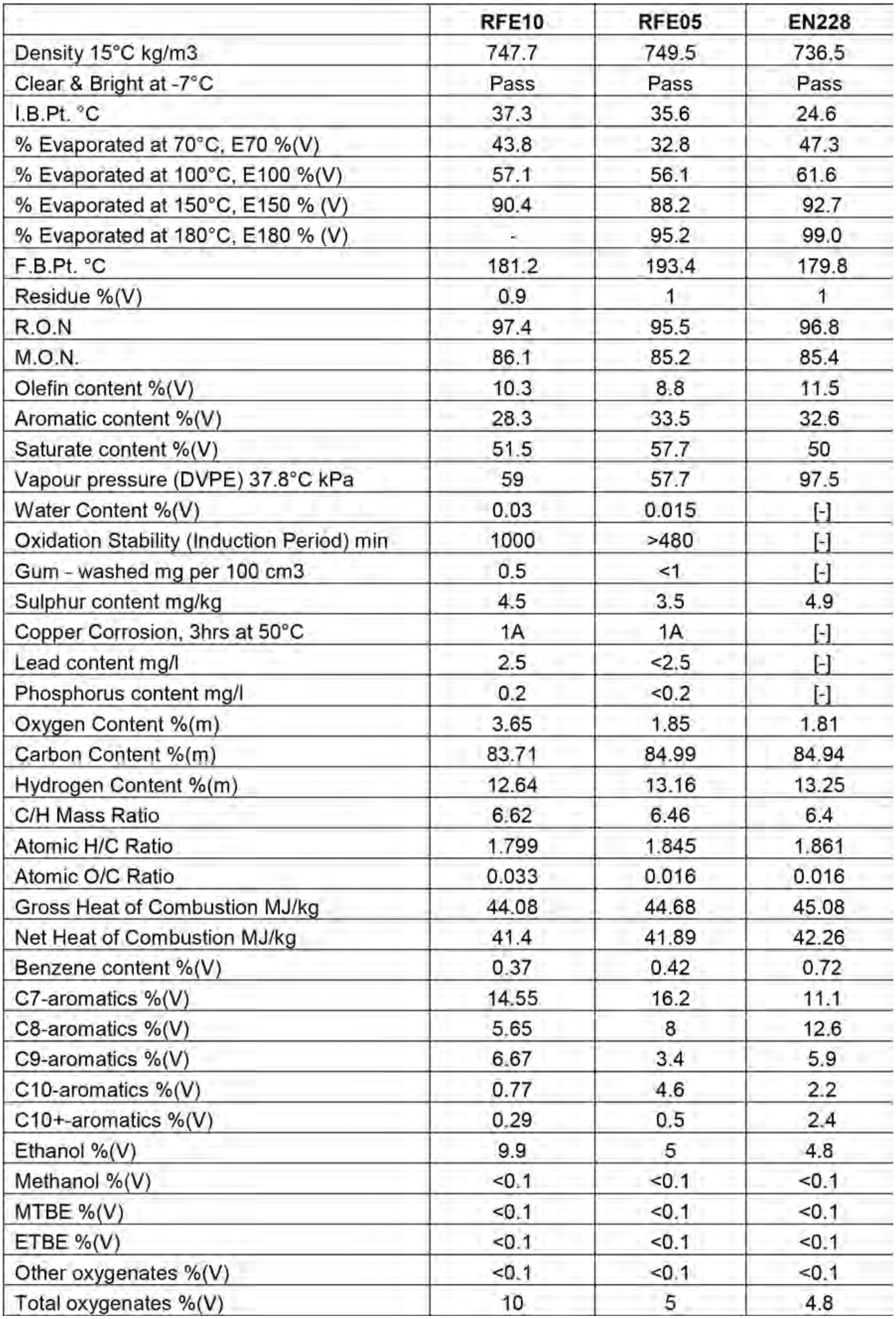
SPCS - Solid Particle Counting System

SRDE - Severitized RDE

TWC - Three-way catalyst

WLTC - World harmonized Light duty Testing Cycle

APPENDIX



	RFE10	RFE05	EN228
Density 15°C kg/m3	747.7	749.5	736.5
Clear & Bright at -7°C	Pass	Pass	Pass
I.B.Pt. °C	37.3	35.6	24.6
% Evaporated at 70°C, E70 %(V)	43.8	32.8	47.3
% Evaporated at 100°C, E100 %(V)	57.1	56.1	61.6
% Evaporated at 150°C, E150 % (V)	90.4	88.2	92.7
% Evaporated at 180°C, E180 % (V)	-	95.2	99.0
F.B.Pt. °C	181.2	193.4	179.8
Residue %(V)	0.9	1	1
R.O.N	97.4	95.5	96.8
M.O.N.	86.1	85.2	85.4
Olefin content %(V)	10.3	8.8	11.5
Aromatic content %(V)	28.3	33.5	32.6
Saturate content %(V)	51.5	57.7	50
Vapour pressure (DVPE) 37.8°C kPa	59	57.7	97.5
Water Content %(V)	0.03	0.015	[-]
Oxidation Stability (Induction Period) min	1000	>480	[-]
Gum - washed mg per 100 cm3	0.5	<1	[-]
Sulphur content mg/kg	4.5	3.5	4.9
Copper Corrosion, 3hrs at 50°C	1A	1A	[-]
Lead content mg/l	2.5	<2.5	[-]
Phosphorus content mg/l	0.2	<0.2	[-]
Oxygen Content %(m)	3.65	1.85	1.81
Carbon Content %(m)	83.71	84.99	84.94
Hydrogen Content %(m)	12.64	13.16	13.25
C/H Mass Ratio	6.62	6.46	6.4
Atomic H/C Ratio	1.799	1.845	1.861
Atomic O/C Ratio	0.033	0.016	0.016
Gross Heat of Combustion MJ/kg	44.08	44.68	45.08
Net Heat of Combustion MJ/kg	41.4	41.89	42.26
Benzene content %(V)	0.37	0.42	0.72
C7-aromatics %(V)	14.55	16.2	11.1
C8-aromatics %(V)	5.65	8	12.6
C9-aromatics %(V)	6.67	3.4	5.9
C10-aromatics %(V)	0.77	4.6	2.2
C10+-aromatics %(V)	0.29	0.5	2.4
Ethanol %(V)	9.9	5	4.8
Methanol %(V)	<0.1	<0.1	<0.1
MTBE %(V)	<0.1	<0.1	<0.1
ETBE %(V)	<0.1	<0.1	<0.1
Other oxygenates %(V)	<0.1	<0.1	<0.1
Total oxygenates %(V)	10	5	4.8