Fuel Effects on Regulated and Unregulated Emissions from Three Light-Duty Euro 5 and Euro 6 Diesel Passenger Cars

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Abstract

Substantial advances in European road vehicle emissions have been achieved over the past 3 decades driven by strengthening revisions in emissions legislation and enabled by advances in fuel, vehicle engine and emissions control technologies. As both vehicle technology and emissions legislation in Europe continue to evolve, Concawe has conducted a study to examine the opportunities that fuels can provide to further reduce emissions from light-duty diesel passenger cars. Three European diesel cars spanning Euro 5, Euro 6b and Euro 6d-TEMP emissions certification levels have been tested over the cold-start WLTC (Worldwide harmonized Light-duty Test Cycle) with 6 fuels: an EN590-compliant B5 (petroleum diesel containing 5% biodiesel by volume), a bio-derived paraffinic diesel, a 50:50 blend of the aforementioned fuels, a low density petroleum-derived B5, a B30 and the same B30 additized with a high dose of cetane number improver. Results have shown that low density fuels with high hydrogen to carbon (H/C) ratio are capable of delivering benefits in tank-to-wheels CO_2 (carbon dioxide), CO (carbon monoxide), HC (hydrocarbons), other greenhouse gases and NO_x (oxides of nitrogen), whereas no further benefits were measured in NH_3 (ammonia) or in PN (particle number) at the low baseline levels produced by the vehicles. Compared to B5, B30 gave a significant increase in NO_x at the tailpipe from the Euro 5 car and engine-out from the Euro 6d-TEMP car but no tailpipe detriments in NOx were measurable in either of the Euro 6 cars, due to the good performance of their NOx aftertreatment devices. The latter results show that some fuel qualities previously important to control emissions such as PN or NOx have become less impactful with the latest engine technologies. The addition of cetane number improver to the B30 did not reduce NOx. The findings suggest that high H/C ratio diesel fuels could offer benefits to both emissions affecting local air quality and to greenhouse gas emissions on a tank-to-wheels basis. The addition of higher FAME (Fatty Acid Methyl Ester) levels to fuels can be used to increase renewable fuel contribution resulting in no penalty in NOx emissions from newer technology vehicles. Compatibility of these fuels with the existing vehicle fleet would require further specific consideration.

Introduction

The EN590 specification [1] is used to control automotive diesel fuel quality in Europe to ensure the reliable operation of road vehicles. The current specification is the culmination of 3 decades of development driven by and enabling the introduction of sophisticated emissions aftertreatment devices such as DPFs (Diesel Particulate Filters (DPF) Lean NOx Traps (LNT) and Selective Catalytic Reduction catalysts (SCR) to achieve low emissions performance of the incumbent vehicles. Going forward, fuels used in diesel engines are likely to develop further and diversify to help meet future targets for CO_2 (carbon dioxide) and other emissions associated with road vehicle use.

The current EN590 specification allows up to 7% v/v FAME (Fatty Acid Methyl Ester by volume) meeting the EN14214 specification to be blended into conventional

petroleum diesel fuel. In addition EN16709 provides a standard for B20 and B30 (petroleum diesel containing 20% and 30% biodiesel) fuels for use in captive fleets. It is anticipated that higher renewables levels will be needed in order to meet the future renewable energy targets mandated by the recast Renewable Energy Directive, (RED2) though the use of biofuels made from food and feed crops will be limited [2].

In this study, two fuels containing 30% v/v FAME (B30, one including cetane number improver, (CNI)) were tested and their results compared to a fuel containing 5% v/v FAME (B5). This was in order to determine the impact of using FAME at levels much higher than currently permissible in EN590 with those typical of current European diesel fuels. The addition of FAME into diesel fuel is well-known to decrease the engine-out PM (Particulate Matter) emissions of diesel engines [3, 4, 5]. This effect is largely attributed to the presence of oxygenated compounds in the fuel which increases the local oxygen concentration in the rich area of the diesel flame [6] and by diluting aromatic hydrocarbons and especially polycyclic aromatic hydrocarbons in the diesel fuel with an aromatics-free blending component where the FAME is splash-blended. Previous Concawe work confirmed that the addition of FAME in diesel fuel decreases the engine-out PM emissions and noted a reduction in fuel consumption penalty associated with reducing the frequency of DPF regenerations [7]. Another study showed that the vehicles' volumetric consumption increased due to the reduced energy content of FAME/diesel blends, which could not be compensated for through better engine efficiency on the oxygenated fuels [8]. In general, previous studies have showed that increasing FAME reduces HC (Hydrocarbon) and CO (Carbon Monoxide) and increases NO_x (Oxides of Nitrogen) emissions to a lesser degree. However, it should be remembered that these results are from a collection of published studies that predominantly focused on heavy-duty engines (and primarily on US market engines) that were not equipped with NO_x exhaust aftertreatment and tested only over hot start test cycles. It may not be reasonable to assume that these results will be representative of modern European light-duty vehicles that are equipped with a variety of aftertreatment technologies and are certified over a cold start test cycle. There are considerably fewer publications related to modern light-duty diesel vehicles and the results that have been reported are generally less consistent than those from the heavy-duty tests. One study on light duty engines [9] demonstrated that vehicle effects became stronger than fuel effects when emissions start to become very low. A latter Concawe study examined the consumption and emissions effects of 10% FAME vs FAME-free fuel on emissions and consumption in Euro 4, 5 and 6 vehicles. This showed that increasing FAME content had the expected effect of increasing volumetric fuel consumption whereas it had no consistent negative or positive effects on emissions and that NO_x penalties and PM benefits were only observed in the Euro 4 (non-DPF) vehicle, [10].

Studies sponsored by CARB (California Air Resources Board) showed that use of more paraffinic fuels as blending components and addition of cetane number improvers could mitigate the NO_x penalties experienced when using high FAME content fuels in US Heavy-Duty (HD) engines and trucks manufactured between 1998 and 2010 and subsequently

some blends and fuel additives were certified for use in California for NOx mitigation in high FAME content fuels [11].

There are a number of EN590 specification properties defined to be environmental parameters according to the European Fuel Quality Directive [12] and previous regulations. The aforementioned Concawe study [10] considered other fuel properties as well as FAME: density, PAH (Polycyclic Aromatic Hydrocarbons), cetane number. It showed that in diesel cars certified to Euro 4, 5 and 6 standards increasing density above the current EN590 specification limit increased tailpipe CO_2 emissions in all cases, with varied effects observed for other regulated emissions. Emissions effects of cetane number were inconsistent except for HC and CO benefits in NEDC (New European Driving Cycle), and not WLTC (Worldwide harmonized Light-duty Test Cycle) for all vehicles indicating CN (Cetane Number) effects are vehicle and test cycle dependent. Effects of higher PAH levels on tailpipe emissions were largely insignificant and a PM increase observed in the non-DPF car was not observed in the Euro 5 or Euro 6 vehicles. Overall the effect of vehicle calibration and test cycle clearly dominated fuel effects on emissions and efficiency.

Paraffinic diesel fuels (PDFs) can be derived from natural gas (Gas-To-Liquids, GTL), biological sources (such as so-called Hydrotreated Vegetable Oil (HVO), Biomass-To-Liquids, (BTL)) and Power-To-Liquids, (PTL). As some PDFs have become more abundant in the market (GTL, HVO) a European specification describing the quality for PDFs for use in automotive applications, EN15940, has been developed in recent years, [13]. PDFs have been proven to have beneficial effects on vehicle tailpipe emissions, including PM, NOx, CO and HC, [14, 15] although some studies have shown that PN can be increased, [16]. As well as the tailpipe or 'tank-to-wheels' benefits, these fuels can provide overall lifecycle CO_2 benefits when derived from renewable sources [17].

As both vehicle technology and emissions legislation in Europe continue to evolve, Concawe has conducted a study (in 2019) to examine the opportunities that fuels can provide to further reduce emissions from light-duty diesel passenger cars. Three European specification diesel cars spanning Euro 5, Euro 6b and Euro 6d-TEMP emissions certification levels have been tested over the cold-start WLTC with 6 fuels: EN590-compliant B5, bio-derived paraffinic diesel (HVO), a 50:50 blend of the aforementioned fuels, low density petroleum-derived B5, B30 and B30 including a high dose of cetane number improver.

Scope and Objectives

The objective of the study was to provide understanding of the benefits that diesel fuels operable in current automotive technology applications could offer to both emissions affecting local air quality and to greenhouse gas emissions, with the focus on Tank-To-Wheels (TTW) effects. The fuels tested do not necessarily comply with the current EN590 specification and therefore it is recognized that compatibility of these fuels with the existing vehicle fleet would require further specific consideration which is outside the scope of the study.

Tests over the WLTC rather than the RDE (Real Driving Emissions) protocol were appropriate to obtain the experimental repeatability required to analyse fuel effects, given that in a previous Concawe study fuel differences spanning EN590 in terms of density were undetectable over RDE [18].

Testing was limited to one example each of Euro 5, 6b and 6d-TEMP European passenger cars due to resource constraints.

Test Fuels

The test fuel set comprised commercially available fuels and fuel components already used in vehicles in demonstration fleets or commercial applications without modifications. The rationale for selecting such fuels was to consider fuel options that could be applied to and achieve benefits in the existing as well as future fleets. The fuels were selected for their potential to provide benefits to both emissions affecting local air quality and to greenhouse gas emissions, with the focus on TTW effects. The fuels, F1 - F6 (Fuel 1 - 6) are described in the following sub-sections, key fuel properties are listed in Table 1 and full properties are given in the appendix.

Fuel 1 - EN590 B5

The EN590 B5 fuel was selected to represent a current European diesel road fuel complying with EN590 and provided a reference fuel for some of the other fuels in the set. This fuel comprised crude-derived petroleum diesel (95%v/v) and FAME type biodiesel derived from used cooking oil (UCOME, 5%v/v) which complied with EN14214. Density for this fuel was at the top of the density range permitted in the EN590

specification: 845g/L and cetane number was close to the EN590 minimum at 52.

Fuel 2 - Low Density B5 (LD B5)

The Low Density B5 (LD B5) was selected to represent a lower than EN590 specification density fuel derived from refinery streams normally used for jet and diesel fuel to enable the impact of reduced density and higher hydrogen-to-carbon (H/C) ratio on emissions to be evaluated while still using conventional refinery streams. The LD B5 fuel also acted as a reference fuel for some other fuels in the set and the biodiesel component was UCOME complying with EN14214.

Fuel 3 - Paraffinic Diesel Fuel (PDF)

The PDF was chosen to represent paraffinic fuels derived from natural gas (GTL), biological sources (such as HVO, BTL) and PTL fuels. In this case, Fuel 3 was HVO targeted at the lower end of the EN15940, class A specification in terms of density and as such enabled the impact of low density, high H/C ratio, low aromatics and high cetane number on emissions to be evaluated.

Fuel 4 - 50:50 Blend of Fuels 1 and 3 (PDF50)

The 50:50 blend of PDF and EN590 B5 (PDF50) enabled the impact of a paraffinic blend component on emissions to be evaluated. This fuel was included to represent scenarios in which availability of paraffinic fuels are limited, to cater for scenarios where vehicles are not compatible with pure PDF fuel, and to determine in these cases whether or not emissions benefits can be expected to be proportional to the paraffinic

TABLE 1 Key properties of test fuels, (see full data in Appendix for measurement methods)

	Units	F1 - EN590 B5	F2 - LD B5	F3 - PDF	F4 - PDF50	F5 - B30	F6 - B30 + CNI
Density	kg/l	0.845	0.805	0.764	0.805	0.825	0.826
Cetane number	-	52.0	51.4	79.6	67.0	52.4	65.8
Viscosity at 40°C	mm²/s	2.57	1.66	1.95	2.18	2.09	2.10
FAME content	%v/v	4.6	5.1	<0.1	2.4	30.5	30.3
PAH content	%m/m	3.6	0.8	<0.1	1.9	0.7	0.4
Total aromatics	%m/m	34.0	7.0	0.1	17.9	5.1	4.5
Carbon content	%m/m	86.45	85.33	84.62	85.66	83.59	83.60
Hydrogen content	%m/m	13.05	14.12	15.38	14.08	13.12	13.12
Oxygen content	%m/m	0.50	0.55	0.00	0.26	3.29	3.27
Net heating value (m)	MJ/kg	42.69	43.23	44.17	43.38	41.69	41.69
Net heating value (v)	MJ/l	36.07	34.80	33.75	34.92	34.39	34.44
IBP	°C	162.1	171.2	192.5	176.8	173.7	169.3
T50	°C	277.4	209.4	238.3	251.9	230.7	233.4
T95	°C	355.8	351.4	288.8	338.1	347.8	350.3
FBP	°C	366.7	362.7	301.5	354.1	354.5	354.9

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fuel content. It was also postulated that paraffinic fuel blends could offer the opportunity to provide emissions benefits while remaining nearer to the existing EN590 specification.

Fuel 5 - B30 based on LD B5 (B30)

The B30 fuel was configured from an altered ratio of the components in Fuel 2, low density petroleum-based diesel (70%v/v) and UCOME (30%v/v). This fuel was designed to enable the impact of high FAME content levels, so far only used in captive fleets, on emissions. It was postulated that the increased NOx emissions historically associated with the use of high FAME fuels could be mitigated by the sophisticated exhaust aftertreatment used in the latest vehicles.

Fuel 6 - B30 + Cetane Number Improver (B30+CNI)

Fuel 6 comprised Fuel 5 with a high dose of 2-Ethyl Hexyl Nitrate (2-EHN) CNI of 0.52%v/v, (B30+CNI). The rationale was that the addition of CNI was found to be effective at mitigating NOx penalties associated with the use of high biodiesel blends used in HD trucks in California, [11] and could also yield some other emission benefits.

Key Fuel Properties

Key properties of the test fuels are summarized in Table 1 and full properties are listed in the Appendix. It is notable that there is an anomalous measured difference in PAH and total aromatics between F5 and F6, which is in fact within the reproducibility of the measurement method.

Test Vehicles

The test vehicles were chosen based on representation of:

- vehicle types currently common in the European market;
- engine and emission control technologies currently common in the European market;
- vehicles certified to Euro 5, Euro 6b and Euro 6d-TEMP standards;
- different parent OEMs (Original Equipment Manufacturers);
- common passenger car segments and engine sizes.

The two Euro 6 vehicles had been used on previous Concawe test programmes and had low mileage. The Euro 5 car was purchased second hand from the UK market for this study and had a representative mileage for a 2013 car of 91,000km at start of test.

Key test vehicle details are given Table 2 and schematics of their exhaust aftertreatment systems are shown in Figure 1.

TABLE 2 Key test vehicle details

	Car A	Car B	Car C
Emissions class	M1	M1	M1
Size category	C - SUV	C	C
Emissions certification	Euro 5b	Euro 6b	Euro 6d-TEMP
Year of registration	2013	2016	2017
Swept volume (l)	1.6	1.5	1.5
Exhaust after-treatment	HP EGR, DOC, DPF	HP EGR, LNT, DPF, passive SCR	HP EGR, PNA, urea-SCR, SCRF
Transmission	DCT6	M6	M6
SOT mileage (km)	91,000	10,000	6,000
Mass in running order (kg)	1365	1420	1355

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FIGURE 1 Schematics of exhaust aftertreatment systems of the test vehicles.
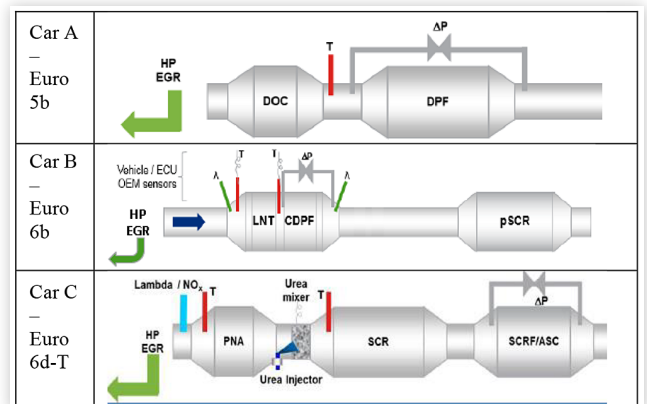
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Experimental Programme

Vehicle Preparation

Ahead of testing, the serviceability of each vehicle and OBD were checked for existing faults and identified faults were rectified. The vehicles were within their recommended service intervals for the duration of the test programme, therefore avoiding the need for servicing mid-programme and they were each filled with the OEM recommended lubricant. An oil analysis prior to the start of testing did not indicate significant historical fuel ingress to the lubricant. Road load models were derived from track-based coastdowns. Access to key OBD data channels was checked and data was accessible from the three vehicles using a DiagRA tool. However EGR activity which was deemed to be a critical parameter was not readable from the Euro 5 car via OBD and the car's EGR valve position was instrumented to enable EGR valve activity data to be monitored during testing and ensure consistency between tests. Static DPF regenerations were carried out on the vehicles via the relevant main-dealer networks to ensure a consistent starting point in terms of DPF fill, given that data pertaining to the fill state of the DPFs was not obtainable.

Engine lubricant levels were monitored throughout the test programme and top-ups were not required.

Test Facility and Measurements

Tests were carried out over the WLTC in a temperature controlled chassis dynamometer facility. Gaseous emissions were measured using Horiba OBS-ONE analysers, recording both bagged and continuous emissions from a CVS (Constant Volume Sampling) system with emissions from the WLTC low sub-cycle being captured in bag 1, from the medium sub-cycle - bag 2, high sub-cycle - bag 3, extra-high sub-cycle - bag 4.

In addition to the tailpipe emissions measurement, engine-out (post turbocharger, pre-exhaust aftertreatment) measurements of CO_2, NOx, HC and CO were carried out on the Euro 6d-TEMP vehicle only, to determine if any fuel effects on emissions were suppressed or amplified in the exhaust aftertreatment system, and also provide further understanding of the potential effects of the fuel properties investigated in vehicles with less sophisticated exhaust aftertreatment systems, through interrogation of the engine-out emissions. Measurements are summarized in Table 3.

Test Protocol

Ahead of each WLTC the fuel was changed to the next fuel:

- the vehicle fuel tank was completely drained using an external pump;
- 5 litres of the new fuel was added and the vehicle run at idle for 10 minutes to flush the old fuel from the fuel system;
- the tank was drained again and the tank was filled with 20 litres of the new test fuel ready for test.

TABLE 3 Measurements and measuring systems

Measuring system	Metrics
Chassis dynamometer control computer	Speed, load, test cell air temperature, EGR valve voltage (Euro 5 car only)
Horiba OBS-ONE (dilute gas systems)	Dilute bagged and continuous tailpipe NOx, NO, CO_2, CO, HC, gravimetric PM
DiagRA	OBD (On-Board Diagnostics) parameters
Quantum Cascade Laser (QCL)	NH_3, N_2O (Nitrous Oxide) (tailpipe)
Cambustion Differential Mobility Particle Sizer DMS500	Particle size distribution (tailpipe)
SPCS (Solid Particle Counting System) PMP method	PN > 23nm d50 (median particle size) (tailpipe)
Particle number down to ten (DTT) system	PN > 4nm d50, PN > 10nm d50, PN >23nm d50 (tailpipe)
Horiba OBS-ONE (raw gas systems)	Euro 6d-TEMP car only: Engine out HC, CO, CO_2, NOx

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A full WLTC was run as a pre-conditioning ahead of the measured test run. Vehicles were stored at the ambient test temperature of 23°C for a minimum of 6 hours, typically 8 hours, prior to the measured cold start WLTC. OBD measurements of engine oil and coolant temperature were used to check that they did not differ substantially from the target test temperature of 23°C at start of test.

Following each test, the test data were examined and the test was repeated if it was deemed that the test had been affected by a DPF regeneration or abnormal application of the start-stop system.

Test Execution

The test order was designed so that the repeats on each fuel were positioned approximately symmetrically about the mid-point of the test sequence. This ensures that the fuel means would have experienced minimal adjustment had (linear) drift been present in the data and a correction applied. Each fuel was followed by a test on a different fuel and repeated pairings of the same fuels were also avoided so that, in the very unlikely event that the effects of a fuel carried over into the following test, any impact would be distributed across multiple fuels. As Fuel 1 and Fuel 2 were used as references for the other fuels, more tests were carried out on these fuels to increase the statistical power of the fuel comparisons. Tests identified as invalid at the time of running were repeated in-sequence whereas those identified later as non-conforming were repeated in a position in the sequence subject to the constraint of avoiding successive tests on the same fuel. The detailed formulation of the fuels was not disclosed to the test facility until after the test programme was complete, (details required for the correct calculation of fuel and energy consumption were disclosed). This ensured that all testing was blind and that the decision to omit any test as invalid on operational grounds and repeat it was made without any knowledge of expected performance.

Part way through the test programme it was noticed that the results from the Euro 6d-TEMP car (C) were less repeatable than the other vehicles despite the same rigorous approach to preparation and testing. This was attributed to a malfunctioning battery causing poor start / stop repeatability and possibly varying levels of battery charging/discharging between tests. The series of tests was restarted on this vehicle after a new battery was fitted, and the repeatability observed substantially improved. The actual test order deviated from the planned test order due to operational requirements and the actual order for valid tests for each vehicle is shown in Table 4.

Data Analysis

Data Quality

PN measurements were seen to increase by an order of magnitude in tests where a DPF regeneration had occurred, not in the test itself but in the pre-conditioning stage, this is thought to be due to the filtration efficiency being lowest immediately

TABLE 4 Fuels test order applied to the three test vehicles

Test No.	Car A	Car B	Car C
Test 1	F1	F1	F1
Test 2	F4	F2	F4
Test 3	F2	F5	F2
Test 4	F5	F1	F6
Test 5	F1	F3	F1
Test 6	F3	F6	F5
Test 7	F2	F2	F2
Test 8	F6	F6	F3
Test 9	F1	F1	F1
Test 10	F5	F5	F3
Test 11	F2	F2	F5
Test 12	F4	F4	F2
Test 13	F3	F3	F4
Test 14	F1	F1	F6
Test 15	F6	F4	F1

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after a regeneration until a soot cake has reformed. As no other measurements were affected, the test was not rejected or repeated. However, these inflated PN measurements were omitted from the analysis of the Euro 5 car (Test 5 - F1 and Test 13 - F3) and Euro 6d-TEMP car (Test 4 - F6 and Test 9 - F1). The Euro 6b car had unusually variable PN measurements, which appeared to follow a cycle between the DPF regenerations and, as all tests appeared to be affected in one way or another, it was not possible to identify individual tests for omission and all PN data have been included for this car.

In the Euro 6d-TEMP car, the test immediately following the first DPF regeneration (Test 4 - F6) showed abnormally high NO_2 (Nitrogen dioxide) and, to a lesser extent, high NO & NOx. Although not technically a statistical outlier, engineering advice was that it was a direct consequence of the DPF regeneration and this test should be omitted from the analysis of all NOx-related variables i.e. NOx, NO and NO_2.

The statistical analysis was carried out on all remaining data declared valid by the test facility. Although statistical outlier testing was applied, no significant outliers were identified for further omission. Visual analysis of the data identified a few isolated occurrences of linear drift but this was not consistent across the majority of measured responses in any car and hence no adjustments for drift have been made. There was evidence of a (statistically significant) step change in WLTC CO_2 levels following the first DPF regeneration in the Euro 6b car. This step change was credited to the effect of the regeneration and additionally significant in the related measurements of fuel consumption, GHG (Greenhouse Gas) emissions and energy consumption. Since only three fuels (F1, F2 & F5) had been run before the regeneration, the means for these fuels would be unfairly inflated relative to Fuels F3, F4 & F6 and would have yielded misleading results. Hence, in these instances, for the Euro 6b car, the test sequence was divided into blocks between DPF regenerations and a block effect has been fitted in the analysis. This adjusts the fuel means to place them all on an equivalent footing for comparison as well as removing the abnormal step change from the estimate of random variation.

Statistical Analysis

The statistical analysis was carried out separately for each car and is based on a simple one-way Analysis of Variance (ANOVA) with Fuel as the factor. Standard statistical methods such as ANOVA assume that the variation in the data is constant regardless of the level of the mean but many emissions measurements exhibit proportional variation where the variability of the measurements increases with its mean level. This is not a concern for CO_2 emissions, fuel consumption and the related GHG CO_2 equivalent and energy consumption measurements as these are predominantly determined by the vehicle and fuel effects are small in relative terms. However, for other emissions where large proportional differences can arise between fuels, a weighted analysis has been applied where the weights correspond to $1/(Mean^2)$. This weighting has no effect on the fuel means but gives more weight to smaller measurements, which are more precise, and smaller fuel means will therefore have smaller confidence intervals than larger fuel means.

The study was designed to evaluate the impact of fuel properties, namely density, paraffinic fuel content, B30 and B30 with CNI via a small fuel matrix using a pre-defined set of fuel comparisons. With more than one reference fuel involved, fuel differences have been assessed for significance using the Holm-Bonferroni method which protects the family-wise error to provide protection against the risk of false positives but offers greater statistical power than other, more severe, multiple comparison tests.

Results

Key results from the WLTC are described in this section and the full results are tabulated in the Appendix. Where shown on charts, error bars denote the 95% confidence intervals about the mean. Differences between fuel means that are statistically significant at the 95% confidence level from the comparator fuel are marked with patterned bars. Fuel comparisons follow logic based on blend similarity, as follows: -

- EN590 B5 vs LD B5, PDF and PDF50
- LD B5 vs B30 and B30 + CNI

Carbon Dioxide

CO_2 emissions differences between the EN590 B5 reference fuel, the LD B5, PDF and PDF50 are shown in Figure 2. These fuels with lower density and higher H/C ratio tend to give lower CO_2 emissions than the EN590 B5.

CO_2 differences between the Low Density B5 fuel, the B30 and B30 with CNI are shown in Figure 3. Results are inconsistent between vehicles with CO_2 being significantly higher with B30 in the Euro 5 car and with B30 + CNI in the Euro 6b car, whereas in the other four cases differences were insignificant. It is possible that the high cetane number resulting from the addition of the CNI could over-advance start of combustion leading to lower thermal efficiency for vehicles

FIGURE 2 CO_2 from the EN590 B5, Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend with error bars denoting the 95% confidence interval about the mean. Results which are significantly different from the EN590 B5 fuel are shown with patterned bars.
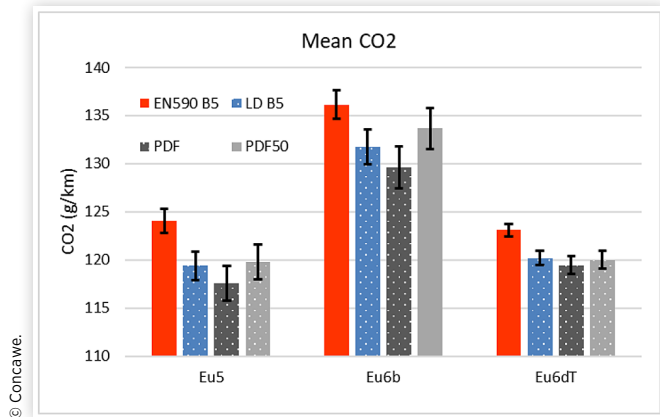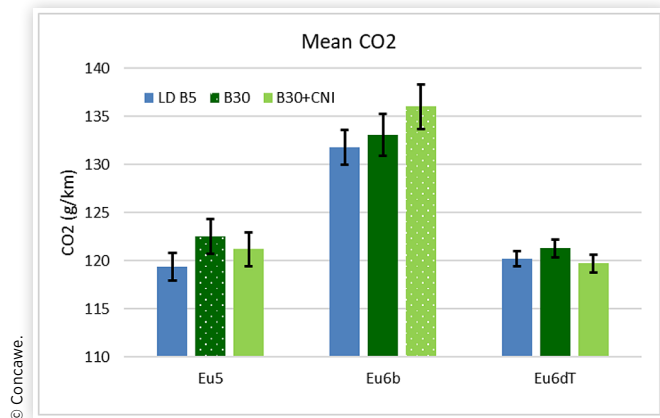

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FIGURE 3 CO_2 between the Low Density B5, B30 and B30 with CNI with error bars denoting the 95% confidence interval about the mean. Results which are significantly different from the EN590 B5 fuel are shown with patterned bars.

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FIGURE 4 Volumetric fuel consumption from the EN590 B5, Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend.
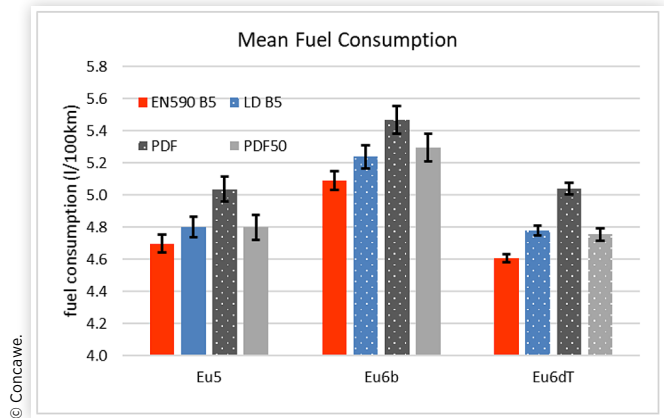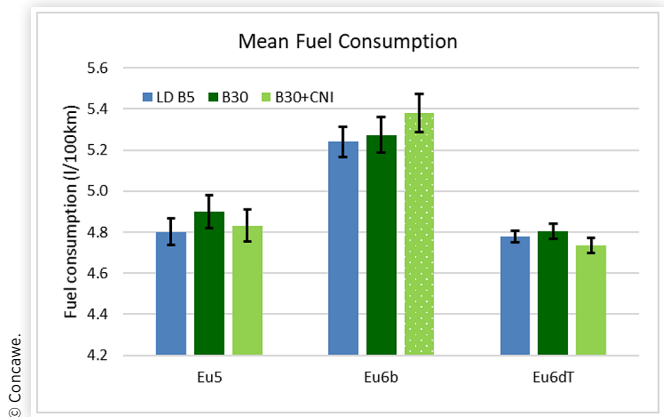

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FIGURE 5 Volumetric fuel consumption from the Low Density B5, B30 and B30 with CNI.

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Volumetric fuel consumption for the B30 fuel was not significantly different from the LD B5 fuel in any of the cars. The B30 treated with CNI gave significantly higher fuel consumption in the Euro 6b car only, Figure 5.

calibrated to have optimal combustion phasing with fuels of cetane numbers typical in the European market, (around 51-55). This is dependent on the calibration of the individual vehicle type and could explain why CO_2 (Figure 3) and volumetric fuel consumption (Figure 5) is higher with B30+CNI in only one of the three test vehicles. Higher CO2 with B30 in the Euro 5 car could be due to de-optimization of fuel metering with the high oxygen-content fuel which would require higher injected fuel volumes compared to B5 fuel.

Volumetric Fuel Consumption

Volumetric fuel consumption calculated from the carbon balance of emissions, the fuel H/C, O/C (Oxygen/Carbon) ratios, energy content and density, was dominated by fuel volumetric energy density and was therefore higher for the low density fuels than the comparator EN590 B5 fuel, see Figure 4.

Energy Consumption

Energy consumption (MJ/100km) was calculated by multiplying the fuel net heating value (MJ/kg) by the volumetric fuel consumption (l/100km) and the fuel density (kg/l).

There was only one significant fuel effect on energy consumption for the low density fuels compared to the EN590 B5, which was in the Euro 6d-TEMP car with PDF which was significantly higher, Figure 6. It is postulated that this may be due to the vehicle responding to the longer injection duration required with low density fuel which has resulted in a different, less energy efficient operating region on the engine map being applied.

Energy consumption for the B30 fuel was not significantly different from the LD B5 fuel in any of the cars. The B30

FIGURE 6   Energy consumption from the EN590 B5, Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend.
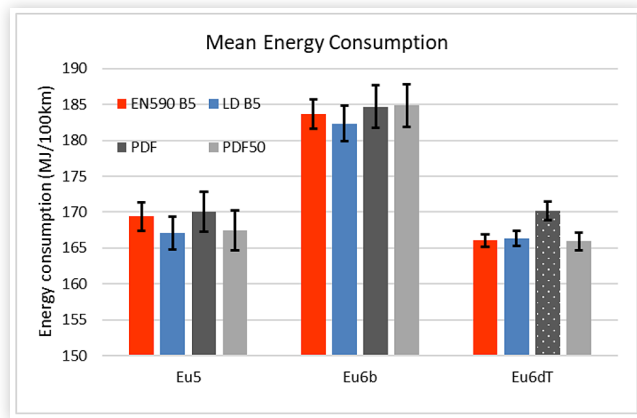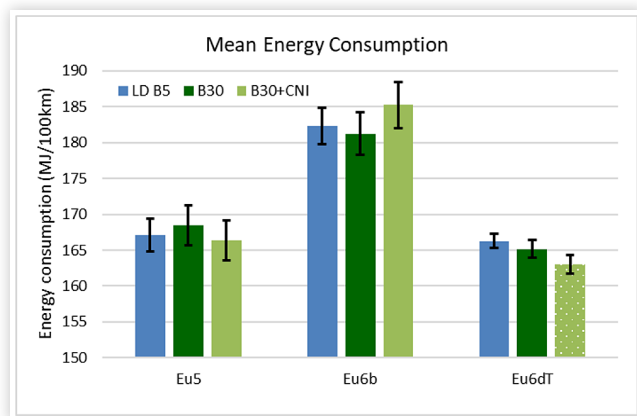

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**FIGURE 7**   Energy consumption from the Low Density B5, B30 and B30 with CNI.

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treated with CNI gave significantly lower energy consumption in the Euro 6d-TEMP car only, Figure 7.

Oxides of Nitrogen (NOx)

NO_x over the WLTC was substantially higher than the Euro 5 limit (180mg/km) from the Euro 5 car, (which was certified over the NEDC), whereas WLTC NO_x from the Euro 6b car (also certified over the NEDC) was close to the Euro 6 limit (80mg/km). NO_x from the Euro 6d-TEMP car over the WLTC was under the Euro 6 limit in all cases. NO_x was directionally lower for all low-density fuels in all cars compared to the EN590 B5, however none of the individual results were statistically significant at the 95% confidence limit, although LD B5 and PDF were significantly lower than the EN590 B5 at the 90% confidence level, Figure 8. Furthermore, PDF gave a statistically significant benefit for NO_x on a fleet average basis, (i.e. when the fuel effects on NOx are pooled across the three vehicles).

NO_x was significantly higher with B30 fuel and with B30 + CNI than with LD B5 in the Euro 5 car which emitted high absolute NO_x levels and is not fitted with catalytic NOx

FIGURE 8   NOx from the EN590 B5, Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend.

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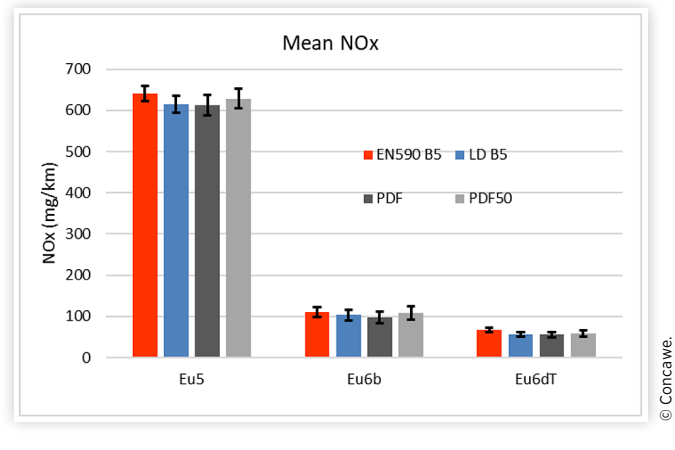
exhaust aftertreatment. NO_x differences were not significant between the LD B5 and B30 fuels in the Euro 6 cars. The addition of CNI to B30 did not reduce the NO_x values in any car, Figure 9. Traditionally, the addition of CNI may have been expected to reduce the NOx increase sometimes observed with the use of high FAME fuel concentrations. The explanation why this is not observed here may be twofold. Firstly there is the direct nitrogen contribution of the CNI which could contribute to NOx and secondly, modern diesel vehicles systematically employ multiple injection strategies to control the auto-ignition delay with pilot injections and may be less sensitive to CN for the control of the premixed flame; hence less sensitive to CNI for NOx emissions reduction. This could explain the trend seen in tailpipe NOx for the Euro 5 car (Figure 9) and the trend in engine-out NOx for the Euro 6d-TEMP car (Figure 29).

There were no significant differences in the fraction of NO_2 contained in the NOx emissions between any of the fuels, see Appendix for data.

FIGURE 9   NOx from the Low Density B5, B30 and B30 with CNI.

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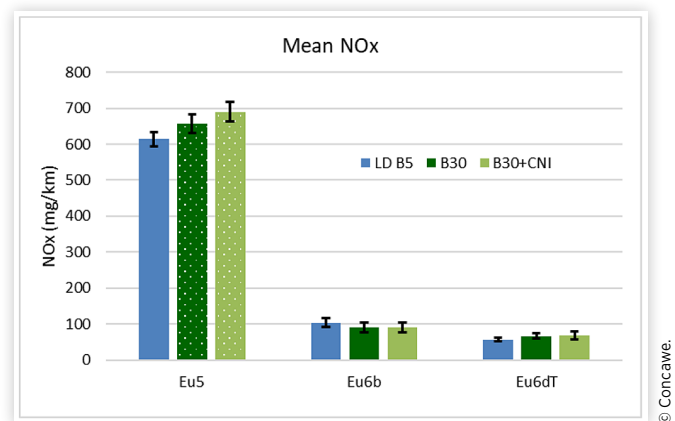
Particulate Mass and Particle Number

Mean particulate mass measured gravimetrically was less than 0.4mg/km for all fuels and there were no significant differences between fuels, see Appendix for data.

Particle number measurements were carried out in the >23nm size range using the official PMP measurement method and using the revised methodology and equipment developed in 'Down To Ten' (DTT) [19] for >23nm, >10nm and >4nm size ranges. Within the DTT measurements, approximately 5% fewer particles were reported in the >4nm range than in the >10nm range indicating a lack of particles in the 4nm -10nm range with the difference possibly due to particle counter dissimilarities. Around 22% more particles were counted in the >10nm range than in the >23nm range using the DTT method. This is consistent with the data generated by the DTT project for the diesel vehicles equipped with a DPF [20]. The DTT measurements in the > 23nm range are also globally consistent with PMP measurements, with an absolute count which differs between 30% and 40% on average (with the exception of one bigger relative difference, obtained with the lowest absolute count measured). The difference between the 23nm PMP measurement and the 23nm DTT measurement is due to the difference in data correction: PMP data are corrected for both dilution and losses, while DTT data are only corrected for dilution. Except at the lowest emissions levels (less than ~10^9#/km) where the DTT system is sensitive but levels are at the limit of detection for the PMP equipment, the DTT and PMP systems are highly correlated. This indicates that losses in the DTT system at 23nm are proportional to those in the PMP system.

Particle number means for all fuels, cars, measurement methods and particle size classes were below the 6 x 10^{11} Euro 6 PN limit. In most cases means fell one or two orders of magnitude below the Euro 6 limit showing the effectiveness of modern DPFs.

Where there were valid repeat measurements, there were no significant differences in mean particulate number between fuels, Figures 10-11.
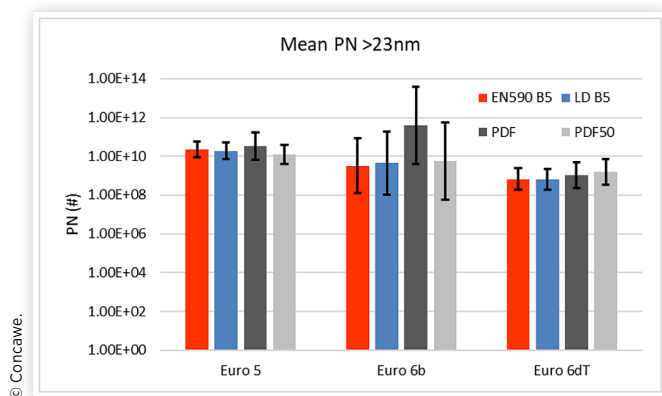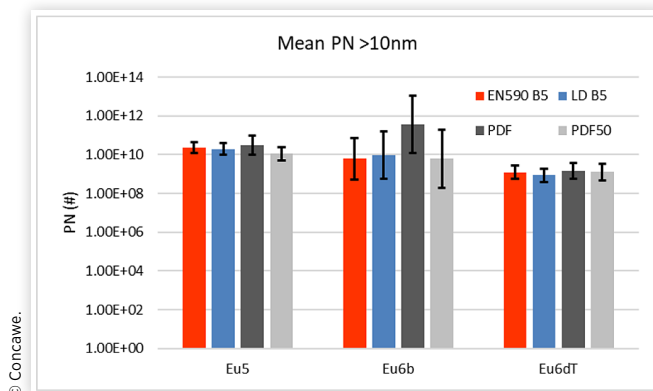
FIGURE 11 Particle number in the >10nm range using the DTT method from the EN590 B5, Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend fuels.

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The B30 + CNI fuel produced higher PN than the comparator LD B5 fuel in the Euro 6d-TEMP car in all size ranges and both measurement methodologies, however this was based on a single valid test with the B30 + CNI fuel, Figures 12-13. The difference between LD B5 and B30 + CNI was smaller in the >10nm range than in the >23nm range, therefore the extended PN measuring size range would not lead to a worsening effect on PN of this fuel. PN data is listed in the Appendix.

Carbon Monoxide

CO over the WLTC was much higher than the Euro 5/6 limit in the Euro 5 car in all cases and it is postulated that this is due to low catalyst volume, or precious metal loading to deal with the CO instead of a difference due to the use of the WLTC instead of the NEDC over which the car would have been certified. CO was around an order of magnitude below the Euro 5/6 limit from the Euro 6b and Euro 6d-TEMP cars. CO was significantly lower for LD B5, PDF and PDF50 than for EN590 B5 in both Euro 6 cars, whereas there were no significant fuel differences in the Euro 5 car, Figure 14.

FIGURE 10 Particle number in the >23nm range using the PMP method from the EN590 B5, Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend fuels.

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FIGURE 12 Particle number in the >23nm range using the PMP method from the LD B5 B30 and B30 + CNI.
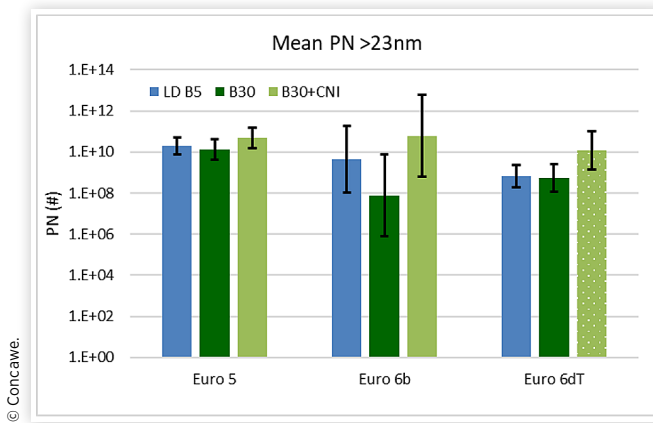

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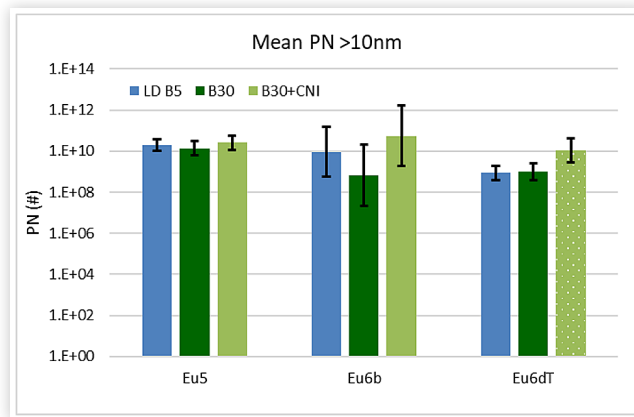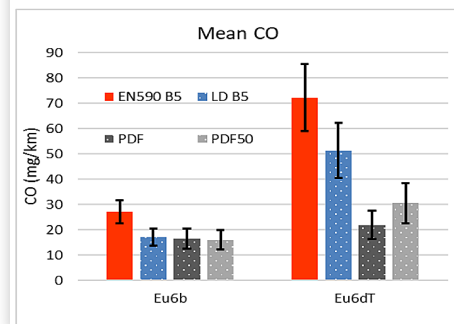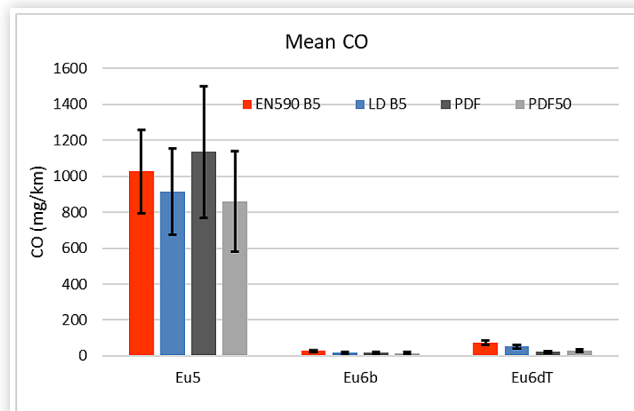**FIGURE 13**   Particle number in the >10nm range using the DTT method from the LD B5 B30 and B30 + CNI.

FIGURE 14   CO from the EN590 B5, Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend.

FIGURE 15   CO from the Low Density B5, B30 and B30 + CNI.

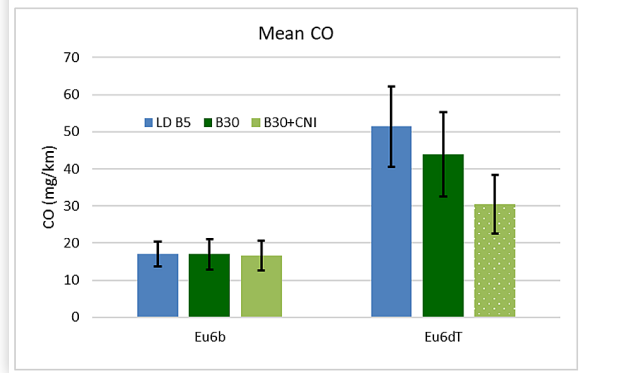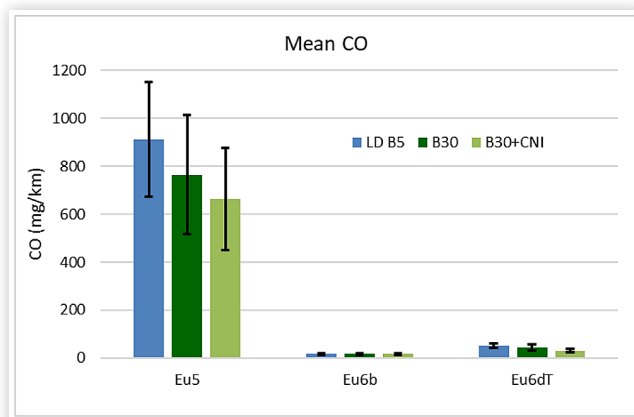**FIGURE 16**   HC from the EN590 B5, Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend.

CO was lower for the B30 and B30 + CNI fuels in the Euro 5 and Euro 6d-TEMP cars, but the difference was only statistically significant in the Euro 6d-TEMP car with B30 + CNI, Figure 15.
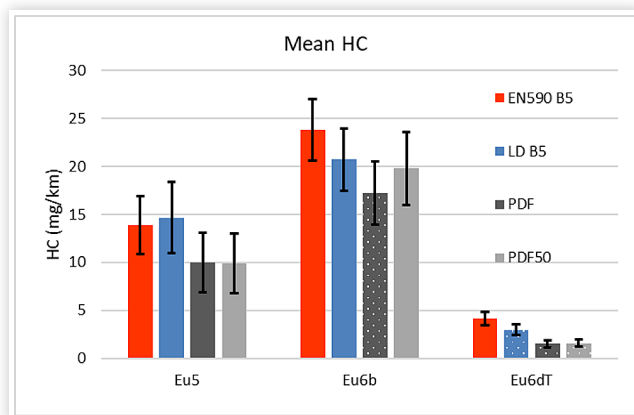
Hydrocarbons

Hydrocarbon emissions were very low for all fuels and cars. HC was directionally lower for LD B5, PDF and PDF50 than for EN590 B5 in most cases and the differences were significant in all cases in the Euro 6d-TEMP car and in the Euro 6b car with PDF fuel, Figure 16.

There was no impact on HC with B30 or B30 + CNI compared to LD B5 that was consistent between vehicles or statistically significant, Figure 17.

Greenhouse Gases

Methane   Methane emissions were generally very low, though were substantially higher from the Euro 6b car than the others. This is thought to be due to the aftertreatment

FIGURE 17 HC from the Low Density B5, B30 and B30 + CNI.

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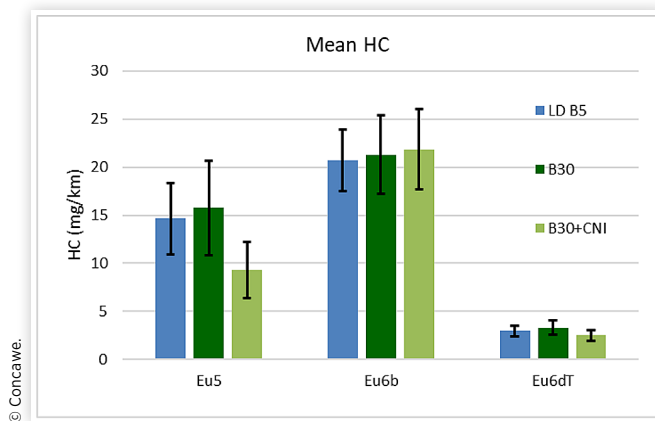
system of the vehicle which includes a lean NO_x trap that relies on periodic rich spikes for regeneration and some of the exhaust methane could be from this source. Comparing the data in Figures 16 and 18 shows that most of the HC emissions from the Euro 6b car are attributable to methane, whereas the proportion of methane in the HC emissions from the other cars is much lower.

The effect of LD B5, PDF and PDF50 on methane was directionally similar to that on total hydrocarbons, with reductions in most cases, albeit with the magnitude and statistical significance of the effects tending to be lower, Figure 18.

Similarly to HC, there was no statistically significant impact on methane with B30 or B30 + CNI compared to LD B5, except in the Euro 5 car where methane for B30 + CNI was significantly lower than for LD B5, Figure 19.

Nitrous Oxide Nitrous oxide emissions were below 10mg/km in all cases from all three cars. Higher N_2O emissions would have been expected from vehicles with catalytic de-NOx systems. It is speculated that N_2O from the air (at ~350ppb) might survive combustion and contribute to exhaust N_2O levels. In this case it could be the dominant source in the exhaust. N_2O was measured raw, so no background correction for N_2O was applied.

FIGURE 18 Methane from the EN590 B5, Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend.
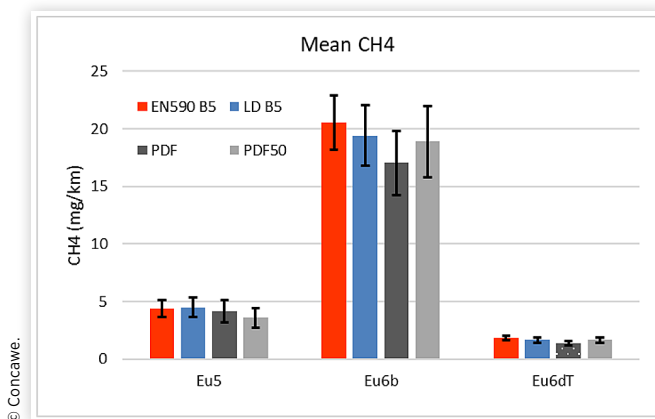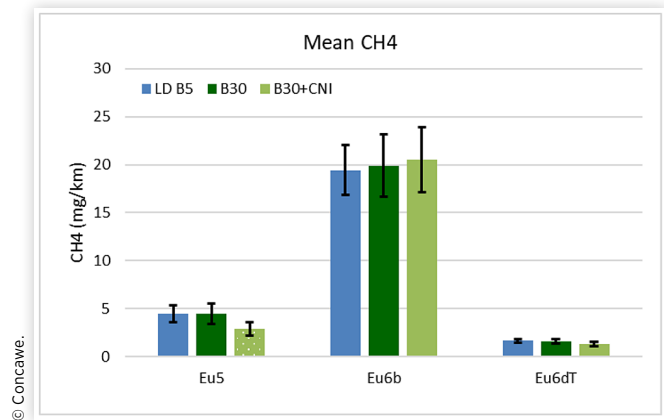

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FIGURE 19 Methane from the Low Density B5, B30 and B30 with CNI with error bars denoting the 95% confidence interval.

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N_2O is generally lower for LD B5, PDF and PDF50 than for EN590 B5, differences are significant in the Euro 5 car for PDF and PDF50 and in the Euro 6d-TEMP car for LD B5 and PDF50, Figure 20.

There were no differences in nitrous oxide between LD B5, B30 and B30 + CNI that were consistent between vehicles, Figure 21.

Total Greenhouse Gas The emissions of CO_2, methane and nitrous oxide were added to determine a total GHG emissions figure for each fuel and car combination in terms of global warming potential (GWP) 100 year figures for CO_2e (CO_2 equivalent) using the GREET model [21].

The GWP of the methane emissions measured in terms of CO_2 equivalent (CO_2e) lie between 0.06 - 0.6g/km and the GWP of the nitrous oxide emissions measured in terms of CO_2e lie between 1.6 - 2.3g/km.

The results showed significantly lower GHG for LD B5, PDF and PDF50 except for PDF50 in the Euro 6b car which was significant at the 90% confidence limit. In 8 out of the 9 cases total GHG differences were larger than CO_2 differences

FIGURE 20 Nitrous oxide from the EN590 B5, Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend with error bars denoting the 95% confidence interval.
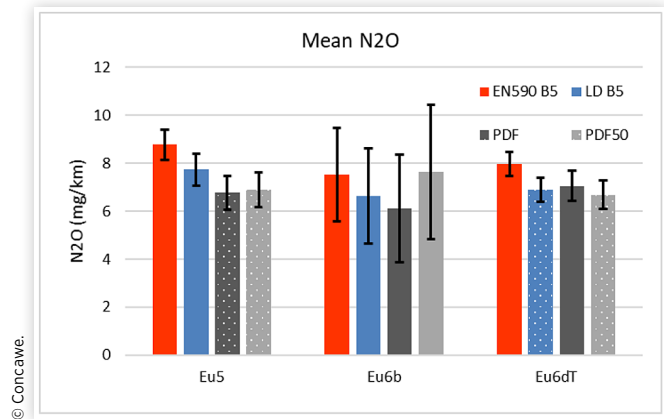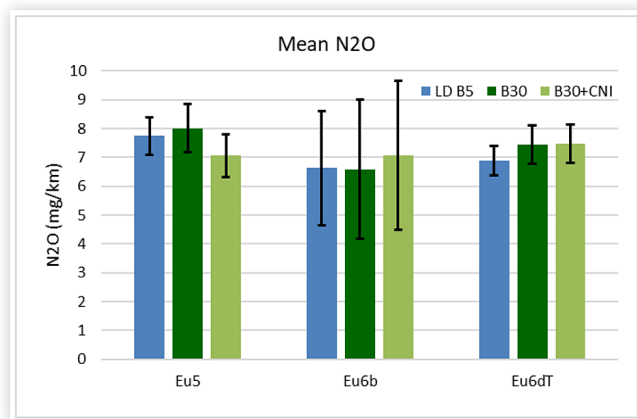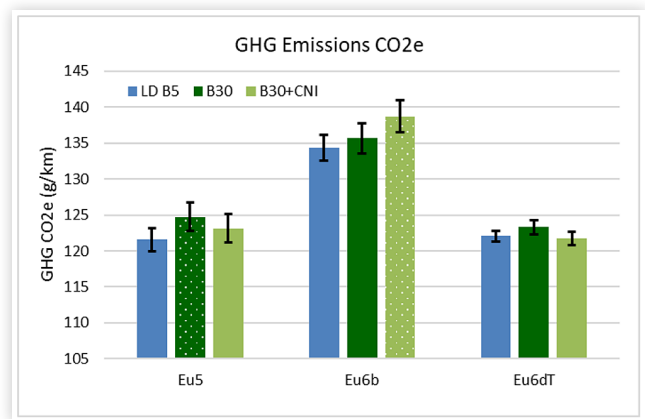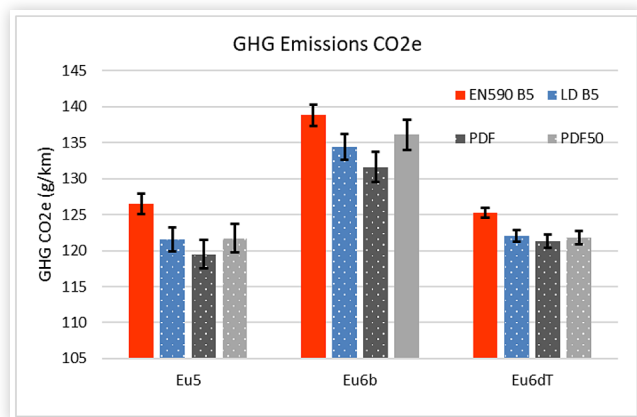

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**FIGURE 21** Nitrous oxide from the Low Density B5, B30 and B30 + CNI.

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FIGURE 23 Total GHG emissions (CO_2, CH_4 and N_2O) from the Low Density B5, B30 and B30 + CNI.

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FIGURE 22 Total GHG emissions (CO_2, CH_4 and N_2O) from the EN590 B5, Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend.

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FIGURE 24 Ammonia emissions from the EN590 B5, Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend.
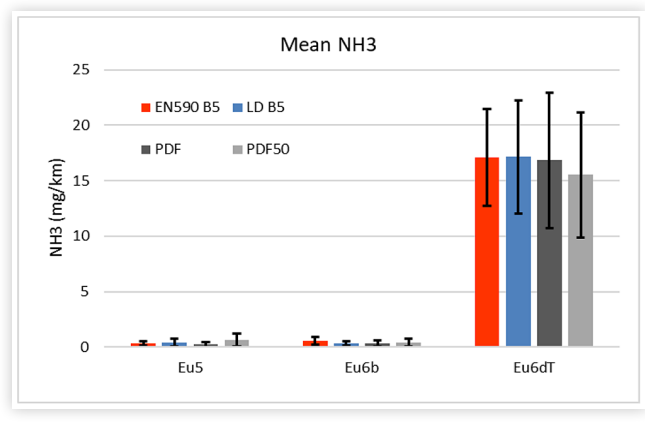
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(and in the ninth case equal), due to benefits in both nitrous oxide and methane (CH_4), Figure 22.

GHG emissions on a CO_2e basis showed little difference from the CO_2 results for the B30 and B30 + CNI fuels compared to the LD B5 fuel, Figure 23.

Ammonia

Ammonia emissions were very low in the Euro 5 and Euro 6b cars (<1 mg/km) which were not equipped with urea-SCR and considerably higher in the Euro 6d-TEMP car (with urea-SCR), despite the presence of an ASC. No fuel related differences were detected in either the low density or B30 fuel set, Figures 24 and 25.

Comparison of Engine-out and Tailpipe Emissions

Engine-out (post turbocharger, pre-exhaust aftertreatment) measurements of CO_2, NO_x, HC and CO were carried out on the Euro 6d-TEMP vehicle to determine if any fuel effects on

emissions were suppressed or amplified in the exhaust aftertreatment system. This also provides further understanding of the potential effects of the fuel properties in vehicles with less sophisticated exhaust aftertreatment systems, though it is accepted that other differences exist between modern and older technology vehicles, such as differences in engine management and hardware, calibration and fuel injection system sophistication, which could lead to different fuel effects on emissions.

Carbon Dioxide Raw, time-resolved (modal) engine-out emissions, were measured versus bagged emissions via a CVS, together with the tailpipe sampling with the latter method being of accepted higher accuracy. This difference in accuracy is postulated as being the reason for the consistently lower tailpipe CO_2 levels versus engine-out. The expectation would be that CO_2 would be very similar, or slightly higher in the tailpipe sample due to the oxidation of carbon-containing species (CO, HC, PM) in the exhaust oxidizing catalysts. Trends in engine-out CO_2 were similar to those of tailpipe CO_2, though engine-out results are more variable, Figures 26-27.

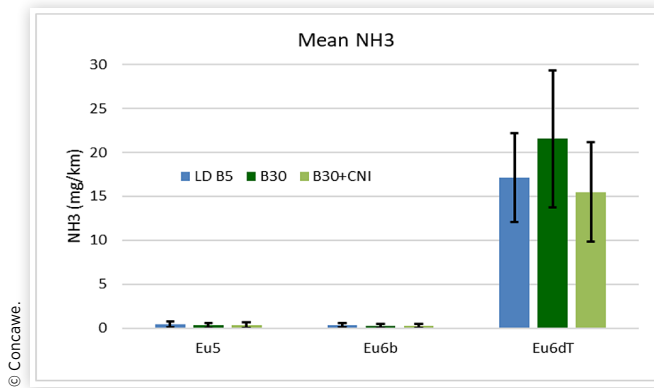**FIGURE 25** Ammonia emissions from the Low Density B5, B30 and B30 + CNI.

FIGURE 26 Engine-out and tailpipe CO_2 from the EN590 B5 and Low Density B5, Paraffinic Diesel Fuel and EN590 B5/ PDF 50:50 blend.
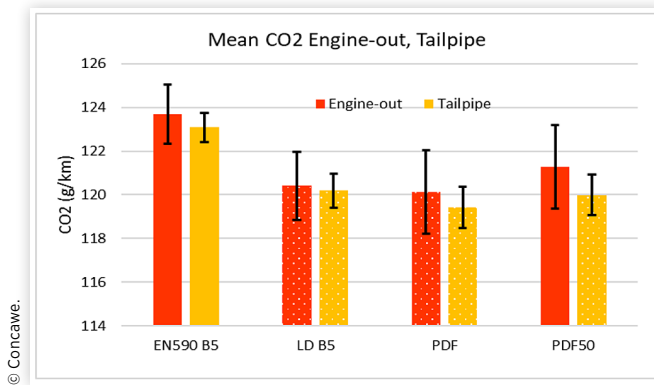
FIGURE 27 Engine-out and tailpipe CO_2 from the Low Density B5, B30 and B30 + CNI.

FIGURE 28 Engine-out and tailpipe NOx from the EN590 B5 and Low Density B5, Paraffinic Diesel Fuel and EN590 B5/ PDF 50:50 blend.

FIGURE 29 Engine-out and tailpipe NOx from the Low Density B5, B30 and B30 + CNI.

NOx Engine-out NO_x is substantially reduced across the exhaust aftertreatment system and there are statistically significant benefits in engine-out NO_x for LD B5 and PDF50 versus EN590 B5, requiring less conversion efforts from the aftertreatment system, Figure 28. It is somewhat surprising that larger engine out NOx benefits are not observed for the PDF, presuming that the lack of aromatics in the fuel is the reason for the NOx benefit in the PDF50 fuel relative to the EN590 B5. Engine-out emissions from the low sub-cycle of the WLTC including the cold start are similar to those from the whole WLTC, though tailpipe emissions are substantially higher due to aftertreatment efficiency related to temperature. Fuel effects are similar between the low sub-cycle and whole WLTC, see Appendix for data.

Engine-out NOx from B30 and B30 + CNI is significantly higher than from LD B5, however these differences are not significant in the tailpipe emissions, meaning that these fuels may require more conversion from the aftertreatment system, which is actually achieved, Figure 29.

Carbon Monoxide Tailpipe CO levels are much lower than engine-out levels due to the oxidizing activity of the exhaust aftertreatment system. Reduction of engine-out CO is evident for the PDF and PDF50 fuels relative to the EN590 B5, however this is only significant in the PDF50 results due to the relatively high variability in the engine-out data. Furthermore, there is no benefit in engine-out CO evident for the LD B5 vs EN590 B5 despite there being a significant difference in the tailpipe data. This appears to indicate that a fuel benefit manifests within the aftertreatment system to

FIGURE 35 WLTC low sub-cycle engine-out and tailpipe HC from the EN590 B5 and Low Density B5, Paraffinic Diesel Fuel and EN590 B5/PDF 50:50 blend. (Tailpipe results for LD B5, PDF and PDF50 are all significantly lower than for EN590 B5).
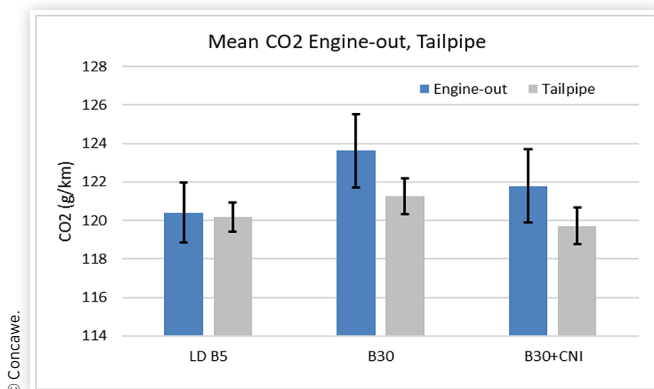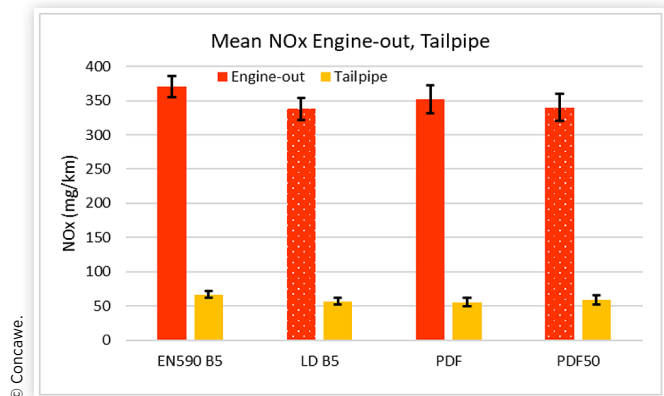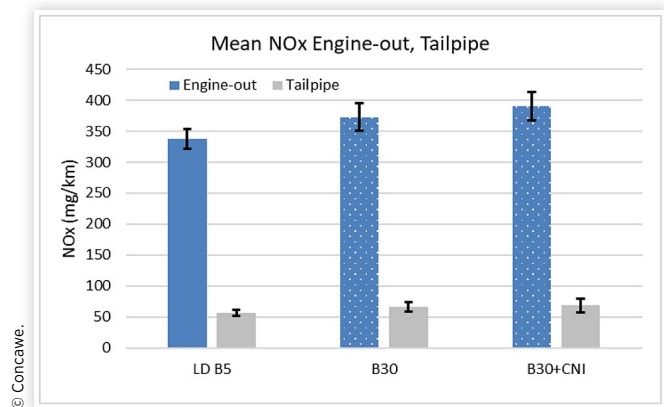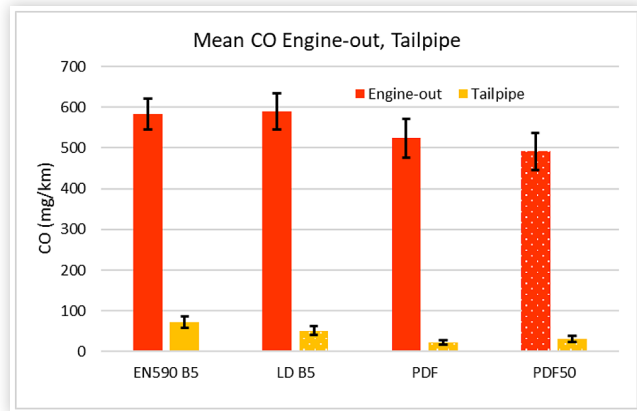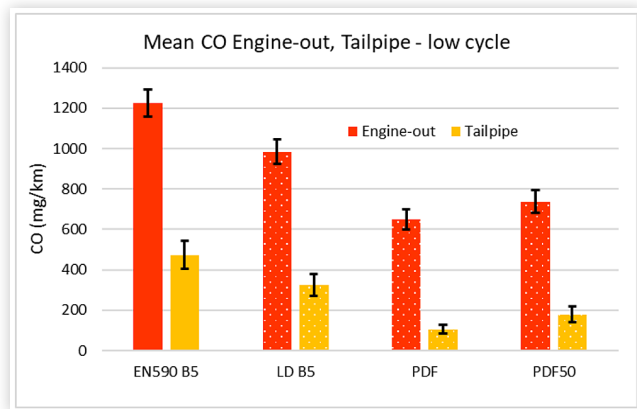

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FIGURE 36 Engine-out and tailpipe HC from the LD B5, B30 and B30 + CNI.

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FIGURE 37 WLTC low sub-cycle engine-out and tailpipe HC from the LD B5, B30 and B30 + CNI.

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the fuels tested have potential to provide renewability benefits as well as the TTW effects studied, but in many cases additional OEM certification would be required to deploy such fuels for general automotive use in the European market. The scope of the study was limited to one example each of Euro 5, 6b and 6d-TEMP European passenger cars due to resource constraints and this limitation should be taken into account when considering the applicability of the findings.

Results showed that low-density hydrocarbon fuels can offer TTW CO_2 benefits, but with an accompanying increase in volumetric fuel consumption. When combining CO_2, CH_4 and N_2O emissions, these fuels also offer total TTW GHG benefits. In terms of emissions that could affect local air quality, the low-density hydrocarbon fuels provided benefits in CO, HC, and some directional benefits in NO_x. The engine-out versus tailpipe data available for the Euro 6d-TEMP vehicle tested are a clear example of the major positive impact that advanced aftertreatment systems have on emissions control. The effectiveness of the aftertreatment system greatly reduced emissions, in turn leading to the reduction of emissions benefits engine-out to much lower margins for NO_x, THC and CO. These effects were particularly evident in the cold start phase for HC and CO. More than 50% of the benefits observed from using the PDF (in some cases of CO_2, HC, CO, NO_x) arose from using a 50% blend of paraffinic diesel (combined with an EN590 B5) as well as having less than 50% of the volumetric fuel consumption penalty of using neat PDF.

Another positive effect on fuel-related emissions was evident in the B30 fuel set, where large statistically significant NO_x penalties observed in the engine-out emissions of the Euro 6d-TEMP vehicle from B30 were greatly reduced to insignificant levels in the tailpipe data. This trend of NO_x aftertreatment suppressing NO_x penalties associated with high FAME fuels was echoed in the data produced from the Euro 5 vehicle, which having no NO_x aftertreatment, presented a penalty in NO_x for the B30 fuel both with and without CNI. On the other hand, comparing the engine-out and tailpipe B30 fuel set data from the Euro 6d-TEMP vehicle shows that the benefits in HC (and CO in the case of B30 + CNI) present in the engine-out data are deleted in the tailpipe data where absolute emission levels are greatly reduced.

The B30 + CNI fuel was included primarily to determine if the addition of CNI could mitigate any NO_x penalties arising

WLTC. Tailpipe emissions were also much higher due to part of this period being before the oxidation catalyst light-off temperature being reached. Fuel effects were larger in both engine-out and tailpipe HC emissions for this sub-cycle, being significantly lower for LD B5, PDF and PDF50 than for EN590 B5, Figure 35.

Over the whole WLTC, B30 and B30 + CNI both produced significantly lower engine-out HC than LD B5, whereas these differences were not significant in the much lower tailpipe data, Figure 36. In the WLTC low sub-cycle data only the B30 + CNI gives a significant reduction in HC versus LD B5 which is only observed in the engine-out data, Figure 37.

Summary

The emissions and fuel consumption performance of six diesel fuels have been tested over the WLTC in three European passenger cars to determine their potential benefits. Most of

from the high FAME level in B30 (as is practiced for HD vehicles in California, [11]). In these LD vehicles, where there was a significant difference between NO_x produced with B30 and B30 + CNI, this was to the disadvantage of the CNI-treated fuel (in the Euro 6d-TEMP engine-out data and in the case of the Euro 5 car which does not have NO_x aftertreatment). This could possibly be contributed to by the direct nitrogen-addition of the additive, nevertheless a benefit was certainly not present. Furthermore, the only significant fuel effect on PN in the programme was a detriment for B30 + CNI versus the comparator LD B5, although this was based on a single valid test measurement on the B30 + CNI fuel. In this case the difference in PN between the B30 + CNI and LD B5 comparator fuel was smaller in the >10nm range than in the >23nm range indicating that future legislation extending the PN size range would not result in additional disadvantages in PN for this fuel formulation. The only positive effect of the CNI appeared to be in HC and CO (observed in the engine out and tailpipe CO and engine out HC of the Euro 6d-TEMP car only, and in particular in the cold start phase). These effects could be attributable to reduced premixing associated with higher CN fuels, [10].

There are a number of new motor vehicle pollutants on the horizon for future regulation, some of which were measured in this programme. Within these, primary observations are that the greenhouse gases N_2O and CH_4 can be positively influenced by low density hydrocarbon fuels, whereas there were no additional fuel effects on PN in the sub-23nm range, nor in NH_3 emissions, with measurement of the latter illustrating that NH_3 emissions are almost unmeasurable unless a urea-activated SCR catalyst is employed.

Conclusions

The emissions and fuel consumption performance of six 'drop-in' diesel fuels has been tested over short duration WLTCs in single examples of European passenger cars representing Euro 5, Euro 6b and Euro 6d-TEMP certification levels. Bearing in mind the limitations of the study in terms of vehicles and test scenarios, it can be concluded that: -

- Low-density hydrocarbon fuels can offer benefits in TTW CO_2, other GHG emissions and emissions impacting local air quality. Using paraffinic diesel as a blend component can give disproportionally large benefits in these emissions which bodes well for cases where PDFs are in short supply and in the future when HVO, BTL and PTL fuels become more widely available.

- Advanced exhaust aftertreatment suppresses the negative NO_x effects associated with the use of high FAME content fuels, opening the door to the use of such fuels in markets dominated by advanced vehicles, therefore enabling increased use of such renewables without local air quality drawbacks.

- In the European passenger cars tested, the use of high levels of CNI did not mitigate the NO_x penalty traditionally associated with the use of high FAME content fuels.

- Deleterious fuel effects were not evident in the emissions slated for future regulation (<23nm PN, NH_3) however,

some additional benefits may be achieved from application of specific fuel qualities (CH_4, N_2O).

- Some traditional benefits of fuel quality on emissions are reduced or even deleted in the tailpipe emissions of cars using advanced aftertreatment.

- Most of the fuels tested have potential to provide renewability benefits as well as the TTW effects studied, but in many cases additional OEM certification would be required to deploy such fuels for general automotive use in the European market.

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Acknowledgments

Definitions/Abbreviations

ASC - Ammonia Slip Catalyst

B5, B30 - Diesel containing 5% or 30% Biodiesel by volume

BTL - Biomass-To-Liquid

CARB - California Air Resources Board

CH₄ - Methane

CNI - Cetane Number Improver

CO - Carbon monoxide

CO₂(e) - Carbon dioxide (equivalent)

CVS - Constant Volume Sampling

d50 - Median particle diameter

DCT - Dual Clutch Transmission

DiagRA - OBD data reader

DMS - Differential Mobility particle Sizer

DOC - Diesel Oxidation Catalyst

DPF - Diesel Particulate Filter

DTT - Down To Ten (10 nanometer particle counting)

2-EHN - 2-Ethyl Hexyl Nitrate

EPA - Environmental Protection Agency (US)

FBP - Final Boiling Point

FAME - Fatty Acid Methyl Ester

GHG - Greenhouse Gas(es)

GTL - Gas-To-Liquids

GWP - Global Warming Potential

HC - Hydrocarbons

H/C ratio - Hydrogen to Carbon ratio

HD - Heavy Duty

HP EGR - High Pressure Exhaust Gas Recirculation

HVO - Hydrotreated Vegetable Oil

IBP - Initial Boiling Point

LD - Light Duty

LD B5 - Low Density B5

LNT - Lean NOx Trap

M6 - 6-speed manual transmission

NEDC - New European Drive Cycle

NH₃ - Ammonia

NO₂ - Nitrogen dioxide

NOₓ - Oxides of Nitrogen

OBD - On-board Diagnostics

O/C - Oxygen to carbon ratio

OEM - Original Equipment Manufacturer

PAH - Polycyclic Aromatic Hydrocarbons

PDF(50) - Paraffinic Diesel Fuel (50% by volume)

PM - Particulate Matter/Mass

PMP - Particle Measurement Programme

PN - Particle Number

PNA - Passive NOx Adsorber

PTL - Power-To-Liquids

QCL - Quantum Cascade Laser

RDE - Real Driving Emissions

RME - Rapeseed Methyl Ester

SCR(F) - Selective Catalytic Reduction (on Filter)

SOT - Start of Test

SPCS - Solid Particle Counting System

SUV - Sports Utility Vehicle

T50 - Temperature for 50%v evaporations

TTW - Tank To Wheels

UCOME - Used Cooking Oil Methyl Ester

WLTC - Worldwide harmonized Light-duty Test Cycle

Appendix A: Fuel Properties

TABLE A1 Fuel properties

Property	Units	Method	EN590 min	EN590 max.	F1 - EN590 B5	F2 - LD B5	F3 - PDF	F4 - PDF50	F5 - B30	F6 - B30 + CNI
Appearance		visual			C&B	C&B	C&B	C&B	C&B	C&B
Density at 15°C	kg/l	EN ISO 12185	820	845	0.845	0.805	0.764	0.805	0.825	0.826
Cetane number	-	EN ISO 5165	51		52.0	51.4	79.6	67.0	52.4	65.8
Carbon residue	%m/m	EN ISO 10370		0.3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Flashpoint	°C	EN ISO 2719	55		58.5	56.5	73.0	65.5	62.0	
Lubricity, WSD at 60°C	um	EN ISO 12156-1		460	n/a	194	400	247	n/a	
Sulphur	mg/kg	ASTM D5453		10	10	1.5	1.0	5.9	1.8	
Viscosity at 40°C	mm^2/s	EN ISO 3104			2.57	1.66	1.95	2.18	2.09	2.10
Water content	Mg/kg	EN ISO 12937		200	50		30	40	120	
FAME content	%v/v	EN 14078		7	4.6	5.1	<0.1	2.4	30.5	30.3
Mono-aromatics	%m/m	IP 391 mod			30.4	6.2	0.1	16.0	4.4	
Di-aromatics	%m/m	IP 391 mod			3.6	0.8	<0.1	1.9	0.7	
Tri+ aromatics	%m/m	IP 391 mod			0.0	0.0	<0.1	0.0	0.0	
PAH content	%m/m	IP 391 mod		8.0	3.6	0.8	<0.1	1.9	0.7	0.4
Total aromatics	%m/m	IP 391 mod			34.0	7.0	0.1	17.9	5.1	4.5
Carbon content	%m/m	ASTM D3343 mod			86.45	85.33	84.62	85.66	83.59	83.60
Hydrogen content	%m/m	ASTM D3343 mod			13.05	14.12	15.38	14.08	13.12	13.12
Oxygen content	%m/m	EN 14078			0.50	0.55	0.00	0.26	3.29	3.27
Net heating value	MJ/kg	ASTM D3338			42.69	43.23	44.17	43.38	41.69	41.69
E250	%v/v	EN ISO 3405		65	36.7	n/a	62.1	48.8	57.5	
E350	%v/v	EN ISO 3405	85		93.4	n/a	98.7	97.0	95.7	
IBP	°C	EN ISO 3405			162.1	171.2	192.5	176.8	173.7	169.3
T50	°C	EN ISO 3405			277.4	209.4	238.3	251.9	230.7	233.4
T95	°C	EN ISO 3405			355.8	351.4	288.8	338.1	347.8	350.3
FBP	°C	EN ISO 3405			366.7	362.7	301.5	354.1	354.5	354.9

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Appendix B: Emissions Test Data

TABLE B1 Test data Euro 5 WLTC

Test No	Fuel	CO2 g/km	CO mg/km	THC mg/km	NOx mg/km	NO mg/km	CH4 mg/km	NO2 mg/km	PM mg/km	PN >23nm #	Fuel_Cons l/100km	Distance km	QCL_N2O mg/km	QCL_NH3 mg/km	DTT_4nm #	DTT_10nm #	GHG g/km	NO2_Frac	NHV MJ/kg	Density kg/l	EC MJ/100km
1	Fuel#1	125.7	991.6	14.03	662.2	315.3	4.776	178.5	0.152	1.256E+10	4.757	23.26	9.158	0.1950	1.314E+10	1.415E+10	128.27	0.2695	42.69	0.8447	171.56
2	Fuel#4	120.2	932.8	10.20	629.3	305.2	3.338	160.5	0.188	1.239E+10	4.818	23.26	7.194	0.1756	1.190E+10	1.254E+10	122.16	0.2550	43.38	0.8045	168.13
3	Fuel#2	120.6	1062.0	16.40	598.2	294.5	4.725	147.0	0.199	1.479E+10	4.860	23.25	8.450	0.5104	1.564E+10	1.645E+10	122.98	0.2458	43.23	0.805	169.12
4	Fuel#5	121.7	768.6	17.14	665.4	320.9	4.631	173.6	0.158	1.024E+10	4.867	23.26	7.657	0.1656	1.026E+10	1.069E+10	123.85	0.2609	41.69	0.8247	167.34
5	Fuel#1	123.0	1093.4	17.05	612.0	288.3	4.843	169.9	0.587	2.238E+11	4.664	23.25	8.689	0.3510	2.299E+11	2.475E+11	125.47	0.2776	42.69	0.8447	168.18
6	Fuel#3	117.4	1083.5	12.79	617.8	292.2	4.623	168.9	0.179	3.281E+10	5.025	23.25	6.707	0.1555	2.962E+10	3.102E+10	119.27	0.2733	44.17	0.7644	169.66
8	Fuel#2	119.5	1107.0	14.10	626.2	297.9	5.056	169.6	0.201	3.846E+10	4.818	23.26	7.804	0.2952	6.254E+10	3.545E+10	121.71	0.2708	43.23	0.805	167.67
9	Fuel#6	121.0	800.4	10.87	677.0	320.6	3.516	185.2	0.089	1.823E+10	4.835	23.28	7.279	0.2850	1.796E+10	1.869E+10	123.07	0.2736	41.69	0.8259	166.46
10	Fuel#5	122.7	860.3	13.10	645.3	301.1	3.891	184.3	0.322	4.211E+10	4.637	23.25	8.077	0.1231	3.941E+10	4.235E+10	124.93	0.2856	42.69	0.8447	167.21
11	Fuel#2	123.3	761.8	14.40	649.1	305.0	4.365	181.5	0.326	1.668E+10	4.931	23.25	8.374	0.4305	1.570E+10	1.653E+10	125.67	0.2796	41.69	0.8247	169.54
12	Fuel#4	118.0	568.0	13.52	619.5	297.5	3.693	163.4	0.000	1.273E+10	4.727	23.27	6.963	0.4252	1.221E+10	1.271E+10	120.00	0.2638	43.23	0.805	164.51
13	Fuel#3	119.4	788.3	9.59	628.4	299.5	3.817	168.6	0.191	1.272E+10	4.779	23.27	6.606	1.1000	9.714E+09	1.015E+10	121.28	0.2682	43.38	0.8045	166.79
14	Fuel#1	117.8	1187.1	7.19	608.1	272.7	3.710	189.7	0.358	2.801E+11	5.049	23.24	6.840	0.2687	1.715E+11	1.776E+11	119.70	0.3119	44.17	0.7644	170.47
15	Fuel#1	124.8	1157.2	11.34	644.3	302.5	4.091	180.4	0.118	2.159E+10	4.732	23.24	9.147	0.6234	1.670E+10	1.765E+10	127.31	0.2801	42.69	0.8447	170.64
16	Fuel#6	121.3	526.2	7.76	702.5	326.7	2.358	200.7	0.204	1.195E+11	4.829	23.27	6.847	0.4039	4.850E+10	3.636E+10	123.22	0.2858	41.69	0.8259	166.28

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TABLE B2 Test data Euro 5 WLTC low cycle

TestNo	Fuel	CO2	CO	THC	NOx	NO	CH4	NO2	PN	Fuel_Cons	Distance	NO2_Frac
		g/km	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	#	l/100km	km	
1	Fuel#1	150.9	2341.9	49.65	536.9	305.8	14.431	73.09	1.986E+10	5.784	3.099	0.1361
2	Fuel#4	147.0	2378.1	35.10	519.8	294.8	7.457	72.68	1.808E+10	5.975	3.096	0.1398
3	Fuel#2	148.2	2855.8	53.68	531.1	305.0	13.754	70.27	2.417E+10	6.071	3.088	0.1323
4	Fuel#5	149.3	2434.2	62.73	528.6	304.1	16.648	69.38	2.168E+10	6.070	3.087	0.1312
5	Fuel#1	151.2	2960.2	72.56	495.6	278.3	14.218	74.87	1.483E+12	5.832	3.093	0.1511
6	Fuel#3	142.6	1454.4	40.74	523.7	289.0	12.173	83.73	1.175E+11	6.116	3.094	0.1599
8	Fuel#2	147.1	1689.3	39.00	487.3	276.8	10.209	68.58	2.013E+11	5.953	3.109	0.1407
9	Fuel#6	149.9	1504.6	30.52	573.7	322.4	8.015	87.85	3.804E+10	6.021	3.094	0.1531
10	Fuel#1	153.7	1558.3	44.40	538.7	300.8	10.841	85.36	2.549E+11	5.841	3.073	0.1584
11	Fuel#5	161.2	1861.7	49.18	557.6	311.7	14.801	85.50	7.137E+10	6.505	3.078	0.1533
12	Fuel#2	141.2	558.8	36.22	480.6	276.5	6.587	64.98	2.992E+10	5.649	3.098	0.1352
13	Fuel#4	146.4	1296.5	24.55	487.1	276.8	6.794	68.08	2.792E+10	5.882	3.097	0.1398
14	Fuel#3	148.8	2034.9	21.38	549.4	294.3	8.408	103.73	1.943E+12	6.414	3.092	0.1888
15	Fuel#1	157.9	2487.3	36.09	537.1	301.0	9.273	81.55	3.604E+10	6.053	3.091	0.1518
16	Fuel#6	152.1	1119.7	21.79	619.1	339.7	5.382	104.65	8.548E+11	6.083	3.108	0.1690

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TABLE B3 Test data Euro 6b WLTC

Test No	Fuel	CO2	CO	THC	NOx	NO	CH4	NO2	PM	PN >23nm	Fuel_Cons	Distance	QCL_N2O	QCL_NH3	DTT_4nm	DTT_10nm	GHG	NO2_Frac	NHV	Density	EC
		g/km	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	#	l/100km	km	mg/km	mg/km	#	#	g/km		MJ/kg	kg/l	MJ/100km
1	Fuel#1	137.09	25.61	21.78	99.68	42.89	19.50	33.83	0.0813	5.851E+09	5.128	23.25	7.137	0.9165	5.202E+09	5.503E+09	139.57	0.3394	42.69	0.8447	184.90
3	Fuel#2	134.38	14.10	20.52	104.19	48.10	19.17	30.39	0.1506	6.911E+07	5.343	23.27	5.393	0.2220	6.954E+08	7.258E+08	136.39	0.2917	43.23	0.805	185.92
4	Fuel#5	135.60	18.15	21.94	92.48	43.49	20.42	25.83	0.1254	7.887E+07	5.372	23.26	7.012	0.3771	7.123E+08	7.170E+08	138.08	0.2793	41.69	0.8247	184.71
5	Fuel#1	138.32	24.71	22.66	126.80	59.93	19.37	34.89	0.0768	4.689E+10	5.173	23.25	6.621	0.1977	4.750E+10	5.166E+10	140.65	0.2752	42.69	0.8447	186.56
6	Fuel#3	128.85	19.43	18.20	98.45	43.68	17.45	31.55	0.2640	2.713E+11	5.440	23.28	6.349	0.2991	2.510E+11	2.639E+11	131.06	0.3205	44.17	0.7644	183.68
7	Fuel#6	134.84	14.06	19.58	81.40	34.48	18.49	28.48	0.4166	1.183E+12	5.332	23.26	6.275	0.2673	1.023E+12	1.071E+12	137.05	0.3498	41.69	0.8259	183.60
8	Fuel#2	132.23	18.75	20.26	98.77	41.43	19.23	35.09	0.1303	4.196E+10	5.257	23.26	6.144	0.4286	3.426E+10	3.607E+10	134.44	0.3553	43.23	0.805	182.95
9	Fuel#6	135.21	19.38	24.11	97.87	43.44	22.55	31.23	0.1082	3.155E+09	5.348	23.26	7.880	0.2878	2.763E+09	2.932E+09	137.98	0.3190	41.69	0.8259	184.14
10	Fuel#1	136.36	27.75	22.62	117.39	52.72	19.33	36.57	0.3343	6.294E+07	5.100	23.25	6.501	0.2768	6.198E+08	6.615E+08	138.66	0.3116	42.69	0.8447	183.92
11	Fuel#5	131.58	15.75	20.65	90.03	41.02	19.40	27.10	0.2455	6.976E+07	5.213	23.30	6.158	0.1676	6.300E+08	6.327E+08	133.80	0.3011	41.69	0.8247	179.22
12	Fuel#2	128.79	18.36	21.37	106.78	50.04	19.86	30.02	0.2420	3.262E+10	5.121	23.26	8.345	0.2767	2.826E+10	2.962E+10	131.60	0.2811	43.23	0.805	178.20
13	Fuel#4	132.17	14.61	16.59	100.08	47.39	16.45	27.48	0.2704	3.227E+10	5.237	23.27	5.240	0.1667	2.701E+10	2.829E+10	134.05	0.2745	43.38	0.8045	182.77
14	Fuel#3	128.32	13.75	16.26	95.89	38.13	16.60	37.19	0.3893	5.718E+11	5.417	23.26	5.880	0.3319	4.573E+11	4.783E+11	130.37	0.3879	44.17	0.7644	182.90
15	Fuel#1	134.78	29.97	28.08	98.13	43.10	23.99	31.98	0.1144	6.415E+09	5.042	23.28	9.837	0.8725	6.458E+09	7.081E+09	138.11	0.3259	42.69	0.8447	181.83
16	Fuel#4	133.12	17.34	23.02	116.35	50.92	21.36	38.44	0.0568	9.534E+08	5.276	23.11	10.021	0.6028	1.248E+09	1.331E+09	136.42	0.3304	43.38	0.8045	184.12

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TABLE B4 Test data Euro 6b WLTC low cycle

TestNo	Fuel	CO2	CO	THC	NOx	NO	CH4	NO2	PN	Fuel_Cons	Distance	NO2_Frac
		g/km	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	#	l/100km	km	
1	Fuel#1	169.55	78.80	5.216	43.31	26.59	4.319	3.214	4.200E+10	6.342	3.092	0.0742
3	Fuel#2	168.75	45.92	5.120	38.81	23.72	4.390	2.643	2.962E+08	6.708	3.096	0.0681
4	Fuel#5	168.53	57.50	4.285	47.70	28.74	4.952	4.161	4.232E+08	6.676	3.096	0.0872
5	Fuel#1	171.39	78.24	6.370	43.66	26.97	4.428	2.881	2.669E+11	6.411	3.096	0.0660
6	Fuel#3	161.27	59.38	0.798	49.52	29.84	1.967	4.493	1.500E+12	6.809	3.102	0.0907
7	Fuel#6	170.17	36.46	3.039	40.51	24.64	1.913	3.259	7.961E+12	6.728	3.094	0.0805
8	Fuel#2	167.31	56.06	4.537	47.34	28.17	6.992	4.779	3.136E+11	6.651	3.096	0.1010
9	Fuel#6	166.67	35.78	2.061	61.34	36.53	3.355	6.225	2.321E+10	6.590	3.102	0.1015
10	Fuel#1	172.45	102.98	5.775	43.57	26.25	3.036	3.792	2.786E+08	6.452	3.092	0.0870
11	Fuel#5	164.81	58.44	4.313	43.31	25.70	2.993	4.126	4.012E+08	6.529	3.104	0.0953
12	Fuel#2	158.91	69.09	7.533	48.86	29.38	3.365	4.303	1.681E+11	6.319	3.092	0.0881
13	Fuel#4	167.88	25.82	2.707	36.90	22.22	4.064	3.338	1.613E+11	6.650	3.097	0.0905
14	Fuel#3	161.90	35.39	1.643	48.34	28.26	3.605	5.709	4.170E+12	6.834	3.092	0.1181
15	Fuel#1	165.28	98.25	9.684	57.95	34.37	3.756	6.118	4.730E+10	6.184	3.093	0.1056
16	Fuel#4	170.32	35.97	2.243	54.90	32.09	1.951	6.427	6.776E+09	6.747	3.082	0.1171

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TABLE B5 Test data Euro 6d-TEMP WLTC

TestNo	Fuel	CO2	CO	THC	NOx	NO	CH4	NO2	PM	PN >23nm	Fuel_Cons	Distance	QCL_N2O	QCL_NH3	DTT_4nm	DTT_10nm	GHG	NO2_Frac	NHV	Density	EC
		g/km	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	#	l/100km	km	mg/km	mg/km	#	#	g/km		MJ/kg	kg/l	MJ/100km
1	Fuel #1	123.60	81.14	4.157	68.40	42.58	1.87	5.88	0.000	1.495E+09	4.624	23.18	7.71	20.06	1.526E+09	1.624E+09	125.70	0.0860	42.69	0.8447	166.76
2	Fuel#4	119.40	34.50	1.781	63.73	39.28	1.77	5.53	0.078	9.003E+08	4.731	23.27	6.57	15.84	6.380E+08	6.706E+08	121.20	0.0868	43.38	0.8045	165.11
3	Fuel#2	119.82	56.84	2.896	57.94	35.80	1.74	5.21	0.069	3.260E+08	4.764	23.24	6.75	18.74	5.340E+08	5.585E+08	121.66	0.0899	43.23	0.805	165.80
4	Fuel#6	119.81	27.61	2.584	88.35	49.65	1.39	14.35	0.279	5.241E+11	4.737	23.25	7.86	9.34	3.333E+11	3.498E+11	121.94	0.1624	41.69	0.8259	163.11
5	Fuel#1	123.03	72.15	3.783	61.68	38.08	1.69	5.54	0.096	7.116E+08	4.603	23.27	7.48	16.20	1.148E+09	1.232E+09	125.07	0.0899	42.69	0.8447	165.98
6	Fuel#5	121.08	48.78	3.820	69.11	43.52	1.83	5.02	0.214	3.429E+08	4.797	23.24	7.55	22.71	8.215E+08	7.943E+08	123.14	0.0726	41.69	0.8247	164.93
7	Fuel#2	119.45	50.70	3.466	56.75	35.76	1.56	4.17	0.189	4.731E+08	4.749	23.24	6.82	15.80	7.915E+08	8.279E+08	121.31	0.0735	43.23	0.805	165.28
8	Fuel#3	119.57	19.04	1.316	52.08	31.82	1.34	5.01	0.130	3.829E+08	5.046	23.26	6.82	17.60	7.421E+08	7.545E+08	121.42	0.0963	44.17	0.7644	170.38
9	Fuel#1	122.86	53.21	4.163	66.29	40.09	2.08	6.94	0.000	4.508E+11	4.595	23.26	8.88	12.61	4.617E+11	5.044E+11	125.28	0.1047	42.69	0.8447	165.71
10	Fuel#3	119.27	24.78	1.702	59.18	36.75	1.42	4.87	0.000	2.909E+09	5.034	23.27	7.29	16.06	2.496E+09	2.664E+09	121.25	0.0823	44.17	0.7644	169.98
11	Fuel#5	121.46	39.16	2.768	62.79	38.98	1.39	5.16	0.109	8.543E+08	4.811	23.24	7.37	20.35	1.200E+09	1.278E+09	123.45	0.0822	41.69	0.8247	165.42
12	Fuel#2	121.29	46.58	2.534	55.57	34.39	1.65	4.97	0.163	1.650E+09	4.822	23.24	7.09	16.89	1.332E+09	1.406E+09	123.22	0.0894	43.23	0.805	167.81
13	Fuel#4	120.57	26.62	1.366	53.71	32.05	1.54	6.27	0.100	2.641E+09	4.777	23.21	6.78	15.24	2.186E+09	2.293E+09	122.42	0.1168	43.38	0.8045	166.71
14	Fuel#6	119.63	33.37	2.395	68.41	41.87	1.25	6.21	0.000	1.156E+10	4.731	23.26	7.07	21.65	1.028E+10	1.087E+10	121.54	0.0908	41.69	0.8259	162.88
15	Fuel#1	122.85	82.56	4.435	70.10	44.17	1.81	5.05	0.028	2.921E+08	4.597	23.26	7.82	19.47	7.864E+08	8.329E+08	124.98	0.0720	42.69	0.8447	165.76

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TABLE B6 Test data Euro 6d-TEMP WLTC low cycle

TestNo	Fuel	CO2	CO	THC	NOx	NO	CH4	NO2	PN	Fuel_Cons	Distance	NO2_Frac
		g/km	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	#	l/100km	km	
1	Fuel#1	129.85	512.47	23.956	281.6	175.8	7.362	25.97	3.158E+09	4.886	3.051	0.0922
2	Fuel#4	125.02	183.32	8.790	257.3	159.3	3.174	23.25	3.319E+09	4.963	3.076	0.0903
3	Fuel#2	126.19	368.21	14.294	265.2	164.5	4.981	24.14	1.266E+09	5.038	3.082	0.0910
4	Fuel#6	126.38	190.70	15.230	324.3	188.1	3.859	46.33	3.607E+12	5.009	3.074	0.1428
5	Fuel#1	132.46	474.07	22.583	250.7	155.1	6.089	23.48	8.626E+08	4.981	3.081	0.0937
6	Fuel#5	129.57	299.79	17.372	272.5	171.9	5.035	21.34	1.977E+08	5.150	3.08	0.0783
7	Fuel#2	125.51	314.06	15.959	239.6	151.2	4.297	18.67	6.031E+08	5.008	3.08	0.0779
8	Fuel#3	128.98	93.39	5.747	255.7	157.9	2.876	23.07	1.010E+09	5.449	3.085	0.0902
9	Fuel#1	130.93	368.39	26.277	297.0	180.9	9.972	30.85	3.162E+12	4.918	3.092	0.1039
10	Fuel#3	129.11	117.48	7.047	266.3	165.9	3.562	22.51	1.863E+09	5.456	3.093	0.0845
11	Fuel#5	132.34	256.53	14.777	283.4	175.7	4.347	24.77	4.267E+09	5.257	3.082	0.0874
12	Fuel#2	130.90	294.28	11.548	260.4	163.0	4.589	22.20	1.832E+09	5.221	3.088	0.0853
13	Fuel#4	130.31	175.62	7.924	249.6	152.4	5.240	25.09	6.306E+09	5.172	3.078	0.1005
14	Fuel#6	127.02	221.29	12.016	301.6	185.1	3.145	28.03	8.408E+10	5.035	3.088	0.0929
15	Fuel#1	131.29	540.75	26.273	293.0	184.2	6.276	23.42	4.892E+08	4.941	3.081	0.0799

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TABLE B7 Test data Euro 6d-TEMP engine-out

Date	Fuel	EO_CO2_WLTC	EO_CO_WLTC	EO_THC_WLTC	EO_NOx_WLTC	EO_CO2_Bag1	EO_CO_Bag1	EO_THC_Bag1	EO_NOx_Bag1
16/08/2019	Fuel#1	122.94	581.78	110.04	371.84	128.62	1230.75	297.04	326.67
20/08/2019	Fuel#4	119.45	485.09	76.81	333.95	124.31	680.53	122.62	298.61
28/08/2019	Fuel#2	119.87	606.99	103.52	343.68	126.79	1021.97	235.43	321.27
03/09/2019	Fuel#6	120.86	381.4	75.13	387.82	128.49	738.28	159.18	377.48
06/09/2019	Fuel#1	124.21	577.66	104.2	343.67	134.91	1205.17	275.82	305.75
19/09/2019	Fuel#2	121.16	532.21	99.29	321.4	129.53	948.22	224.97	298.95
23/09/2019	Fuel#3	120.53	529.53	70	348.19	131.07	628.79	95.36	333.83
25/09/2019	Fuel#1	123.5	557.04	116.33	382.97	131.62	1187.09	314.77	368.07
27/09/2019	Fuel#3	119.71	518.04	73.72	355.08	131.84	668.08	112.85	338.79
04/10/2019	Fuel#2	120.21	629.2	93.99	348.5	130.52	985.12	191.19	330.25
10/10/2019	Fuel#4	123.11	497.48	75.7	346.3	135.2	792.75	120.16	325.51
15/10/2019	Fuel#6	122.74	434.76	71.97	392.95	132.35	756.7	140.71	379.39
18/10/2019	Fuel#1	124.14	616.71	106.02	382.25	134.97	1277.14	296.74	362.79

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