Report

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Real Driving Emissions from Four Euro 6 Diesel Passenger Cars

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Real Driving Emissions from Four Euro 6 Diesel Passenger Cars

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ABSTRACT

In Europe, the development and implementation of new regulatory test procedures including the chassis dynamometer (CD) based World Harmonised Light Duty Test Procedure (WLTP) and the road-based Real Driving Emissions (RDE) procedure, has been driven by the close scrutiny that real driving emissions and fuel consumption from passenger cars have come under in recent times. This is due to a divergence between stated certification performance and measured on-road performance, and has been most pointed in the case of NOx (oxides of nitrogen) emissions from diesel cars. The RDE test is more relevant than CD test cycles, but currently certification RDE cycles will not necessarily include the most extreme low speed congested, low temperature or high speed highway conditions which are likely to be more challenging for NOx after-treatment systems. To build understanding of the emissions and fuel consumption performance of the latest available diesel passenger cars, Concawe has conducted a study of the performance of four vehicle types over a range of test cycles. The data generated provides insights into the emissions performance of Euro 6 diesel passenger cars, and their after-treatment systems, in extreme congested cold urban conditions including, and beyond, the most demanding likely to be encountered under regulatory RDE testing.

KEYWORDS

WLTC, real driving emissions, TfL

INTERNET

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SUMMARY

Certification RDE cycles cover a large proportion of normal European driving but RDE compliant vehicles may be challenged by the most extreme high speed, low speed congested or low temperature conditions which have historically been more demanding for diesel NOx control. Concawe has conducted a study of four diesel passenger vehicle types that span Euro 6b to Euro 6d-TEMP certification levels and represent different exhaust after-treatment technologies. The vehicles were tested over a range of different test cycles – New European Drive Cycle (NEDC) and Worldwide harmonized Light Duty Test Cycle (WLTC) conducted on the Chassis Dynamometer (CD). Tests were also conducted over a compliant moderate RDE (real driving emissions) on-road cycle, as well as CD testing of the Transport for London (TfL) Urban Inter Peak (UIP) cycle, developed directly from real-driving of buses in congested traffic in London, UK. The TfL UIP cycle is known to be more severe and in addition to increase the severity further, tests were run over some lower temperatures including ambient temperatures ranging from -15°C to 23°C. The results varied between the vehicles. Differences in NOx control were evident due to the different aftertreatment hardware but also due to different calibration applications. The Euro 6d-TEMP vehicle was also tested at a high speed steady state condition on the CD representing high speed autobahn driving. Under this condition NOx emissions were 12mg/km, signalling a step improvement in high speed NOx control from diesel passenger cars versus previous generations. In addition, fuels covering the density range of the EN590 diesel specification were tested using the RDE cycle (in three of the cars) and no differences between emissions produced from the two fuels tested were detected.

1. INTRODUCTION

European emissions legislation has set limits for particulate matter and NOx emissions from diesel vehicles since the early 1990's along with hydrocarbons (HC), which were initially included with NOx until 2000, and carbon monoxide (CO). NOx emissions limits have reduced steadily and for diesel Euro 6 vehicles the limit has reached 80mg/km. Similarly stringent standards have been introduced in other parts of the world. The introduction of these limits along with the introduction of low sulphur fuels and advanced vehicle and after-treatment technologies has resulted in a substantial reduction in automotive particulate mass (PM) and particle number (PN) emissions [1, 2] with a corresponding improvement in air quality [3]. However, ambient NOx levels have not been reduced to the same degree as the Euro tailpipe emissions standards [4-6]. Part of the reason 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 including NOx, two new test procedures have been developed: the WLTP featuring the WLTC (World-harmonized Light duty Test Cycle), for use on the chassis dynamometer (CD) and, for on-road use, the Real Driving Emissions (RDE) procedure. The WLTC is longer than the NEDC and is expected to be more severe as it covers a more realistic range of driving conditions, though the impact of cold starting is diminished. A further difference is that vehicle emissions are measured as NOx, whereas air quality standards are expressed as ambient NO_2 concentration. NO is typically the largest constituent of vehicle tailpipe NOx and oxidizes to form NO_2 in the atmosphere, but the rate at which this occurs is highly dependent on environmental factors such as abundance of ozone. The ultimate effect that vehicle-derived secondary NO_2 has on local air quality is dependent on both environmental factors and rate of atmospheric exchange as the latter impacts the residence time before the emissions are dispersed [7]. Therefore, the impact of vehicle derived primary and secondary (reacted) NO_2 on local air quality is difficult to generalize. In one study, NO and NO_2 were measured inside a road tunnel, which exemplified the variations in NO_2/NOx ratio depending on position in the tunnel due to different environmental factors, [8].

One of the key enablers for the testing of more real-world driving on the road is the use of Portable Emissions Measurement Systems (PEMS) which are able to verify the proper operation of emission control technologies as well as measure gaseous and PN emissions under a wide variety of normal operating conditions. The RDE test protocol defines limits for the environmental and driving dynamic boundary conditions, [9]. The Not-to-exceed (NTE) limit is expressed as a Conformity Factor (CF), defined as the permitted emission on the RDE test divided by the certification limit on the CD-based WLTC.

The RDE is being developed in stages called 'packages' to include CFs for PN and NOx, cold-start provisions, hybrids, and in-service conformity testing among other things. The RDE test protocol was adopted in 2016 and published in the first two packages [9,10]. Package 3 was published in July of 2017 [11]. This package included PN requirements including a CF of 1.5 applying to both the urban part and the complete RDE trip and cold start emissions (both gaseous and PN) including in the EMROAD and CLEAR post-processing analyses.

PEMS measurement data is post-processed to check that RDE test CO_2 is within an acceptable range of that expected from WLTP testing before the CF is calculated.
In November 2018 the final RDE4 package was published, including changes to the validation and normalisation procedure to reduce the two procedures EMROAD and CLEAR implemented in package 3 to one simple evaluation method and reduce NOx

CF from 1.5 to 1.43 [12] from 2020 onwards. New methods for in-service conformity (checking the performance of vehicles taken from the field introduced in package 3) are also included in package 4.

Two extra Euro 6 vehicle stages will be introduced as a consequence of the evolution of the regulations in addition to Euro 6b and Euro 6c: Euro 6d-TEMP beginning for new models in September 2017 with a NOx CF of 2.1 and Euro 6d as of January 2020 with a NOx CF of ≤ 1.43 [12].

Another test cycle which is being increasingly used as a more severe test cycle is the Transport for London (TfL) Urban Inter Peak (UIP) cycle, developed directly from real-driving of buses in congested traffic in London, UK.

This study was conducted by Concawe to build understanding of the emissions performance of Euro 6 diesel passenger cars. The CD and RDE performance of four vehicles of different manufacturers and models were tested. The vehicle types were chosen to be representative of the most significant exhaust after-treatment technologies for Euro 6. For three vehicles, three tests each were conducted on the CD using NEDC and WLTC as well as using the RDE test protocol. Although fuel effects were expected to be small compared to the differences between the test cycles [12], two fuels which cover the range of densities encompassed by the current EN590 diesel specification were also tested in the RDE cycle. Finally, the RDE and TfL UIP results were compared for the fourth vehicle, an early example of a Euro 6d-TEMP, once vehicles of this certification level became available.

Currently, certification RDE cycles do not include the most extreme low speed congested or low temperature conditions which are likely to be more challenging for NOx aftertreatment systems. Concawe explored some of these conditions using all four vehicles in the more severe CD test: the TfL UIP cycle, at temperatures down to below those proposed to be included in future RDE tests.

2. EXPERIMENTAL

2.1. DESCRIPTION OF VEHICLES

Three Euro 6b-c cars were included for the bulk of the study. These vehicles were chosen to represent a range of size categories in the M1 emissions class and different aftertreatment systems. A fourth, Euro 6d-TEMP car, was sourced once vehicles certified to this standard became available (late in 2017). Vehicle details are summarized in Table 1.

Table 1 Test vehicle overview

	V1	V2	V3	V4
Emissions class	M1	M1	M1	M1
Size category	D	E	C	C
Emissions certification	Euro 6b	Euro 6c	Euro 6b	Euro 6d-TEMP
Year of registration	2015	2016	2016	2017
Displacement (l)	2.0	2.0	1.5	1.5
Exhaust after-treatment	HP&LP EGR, urea-SCRF, ASC	HP&LP EGR, urea-SCRF, SCR/ASC	HP EGR, LNT, DPF, passive SCR	HP EGR, PNA, urea-SCR, SCRF
Transmission	DCT6	DCT9	M6	M6
SOT mileage (km)	5969	10025	6514	6000
Mass in running order from CoC (kg)	1581	1700	1420	1255
Mass as tested including PEMS (kg)	1897	2067	1724	1534
Certification combined cycle CO_2 (g/km) (NEDC)	119	112	109	93

2.2. DESCRIPTION OF FUELS

Two fuels were tested over the RDE to determine the scope for detecting fuel effects over the new regulatory cycle. Fuels were chosen which differed substantially in terms of density, one being near the EN590 density minimum and one being near the EN590 density maximum. The fuels also differed substantially in terms of Polycyclic Aromatic Hydrocarbon (PAH) content and distillation properties. The low density fuel number 2 was fully EN590 compliant whereas Fuel 1 was EN590 compliant except for T95 which was 10°C over the EN590 limit. Apart from shakedown tests, only Fuel 2 was tested over the CD cycles given that the key objective for those tests was to compare CD and RDE emissions on the same fuel. Fuel 2 was also used for the TfL tests under all temperature conditions. The full fuel properties are shown in Appendix 1 for the low density (LD) and high density (HD) fuels respectively.

Table 2 Test fuel properties

Property	Method	EN590 min	EN590 max	Fuel 1	Fuel 2
CN	EN ISO 5165	51.0	-	52.2	53.0
Density kg/m^3	EN ISO 12185	820.0	845.0	843.5	821.8
Sulfur mg/kg	EN ISO 20846	-	10	7.1	7.9
Viscosity at 40°C mm^2/s	ASTM D445	2.000	4.500	2.099	2.278
FAME v/v%	EN 14078	-	7.0	4.0	4.1
PAH %m/m	IP 391 mod	-	8.0	7.5	1.2
Total aromatics %m/m	IP 391 mod	-	-	27.0	11.5
C %m/m	ASTM D3343	-	-	86.32	85.72
H %m/m	ASTM D3343	-	-	13.25	13.84
O %m/m	EN 14078	-	-	0.43	0.44
NCV MJ/kg	ASTM D3338	-	-	42.82	43.12
IBP °C	ASTM D86	-	-	176	160
T50 °C	ASTM D86	-	-	274	255
T95 °C	ASTM D86	-	360	370	344
FBP °C	ASTM D86	-	-	382	355

2.3. EMISSIONS MEASUREMENT

On road emissions were measured using a Horiba PEMS OBS-ONE unit with a pitot flow tube for exhaust flow determination and CD emissions measured using Horiba MEXA ONE analysers as outlined in Table 3. Focus was given to those pollutants available from both the CD and PEMS testing platforms, i.e. CO_2, CO, PN and NOx. Dilute bagged emissions were measured via CVS (Constant Volume Sampling) on the CD. HC is not required for light-duty RDE testing and is not usually measured because the heated FID (Flame Ionisation Detector) requires substantial electrical power and consequently additional batteries and space as well as additional safety considerations.

PEMS and lab-based emissions measurements must correlate within defined limits. Tests were completed to check this correlation and all measurements subject to the correlation criteria were within the specified limits [13].

Table 3 Overview of emissions measurement via PEMS and on CD

	MEXA ONE (CD)	OBS-ONE (PEMS)
CO	NDIR (Non-dispersive Infra Red)	NDIR
CO_2	NDIR	NDIR
NOx	CLD (Chemi-Luminescence Detector)	CLD
PN	MEXA 2000SPCS	OBS-ONE PN
	condensation particle counter (CPC) with primary diluter, volatile particle removal and secondary dilution. 23nm d50 cut-off as per PMP (Particulate Measurement Programme) protocol [16]	

2.4. DRIVECYCLES AND TESTING PROTOCOLS

2.4.1. Chassis dynamometer test cycles (NEDC and WLTC)

For the purposes of this study, two driving cycles were tested. The first, the New European Driving Cycle (NEDC), was at the time of testing, the current type approval procedure in Europe, while the second, the Worldwide harmonised Light duty Test Cycle (WLTC), will succeed the NEDC and is considered more representative of real world driving conditions. WLTC was introduced in 2017, and after a 3-year transition period when both cycles will be used, will finally replace the NEDC in 2020.

The vehicle speed profiles of the two cycles considered in this study are shown in Figure 5. The WLTC represents the test cycle of the new regulation, the so called WLTP (Worldwide harmonized Light vehicles Test Procedure), which is different from NEDC in many aspects (vehicle mass, road load, test temperature etc.). However, it was not feasible to consider all these different aspects of the two cycles in the context of this testing activity,

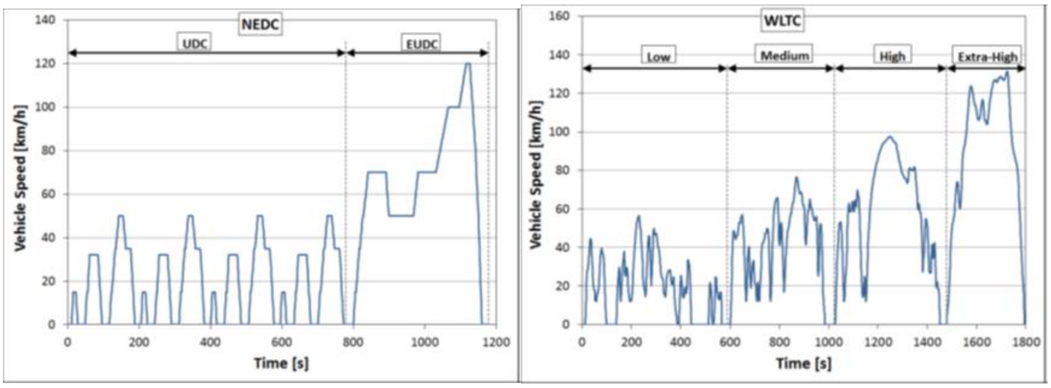


Figure 1 Speed profiles of the two driving cycles considered in this study (left: NEDC, right: WLTC).

2.4.2. RDE

The RDE route used is illustrated in Figure 2. The route commences with urban operation wholly in 20 and 30m/hr (32 & 48km/h) zones. Rural and motorway phases are conducted on major roads to the west and east of Ricardo's site respectively. The requirements of the test are achieved without introducing artificial stop periods and urban severity is achieved through moderate hill climbs and multiple T-junctions. Hill climbs and descents are also present in both rural and motorway sections. Total test time is around 105 minutes and cold start emissions were included in the analysis. Triplicate RDE tests were carried out per vehicle and complied with the regulation in terms of urban/rural/motorway split and CO_2 moving average window matching to WLTC tests. Ambient temperature at start of test ranged from 6 – 29°C and no attempt was made to limit this by testing on selected days in the spirit of representing real-world conditions.

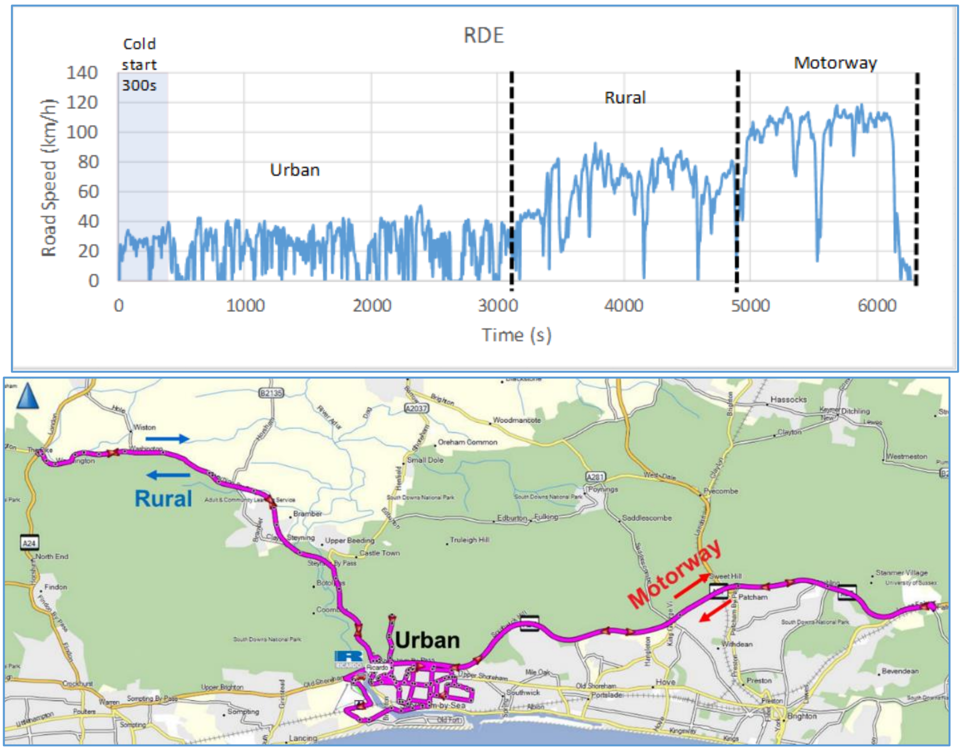


Figure 2 Speed/time and map plot of Ricardo RDE route

2.4.3. Testing overview for NEDC, WLTC and RDE

Initial NEDC and WLTC check tests were performed on the vehicles in duplicate to ensure that there were no obvious problems and checks were done to ensure there were no faults recorded in the OBD. All tests were executed in accordance with the latest relevant protocols including pre-conditioning.
The test sequence for each car was designed to facilitate a valid statistical comparison between the fuels Fuel 1 (F1) & Fuel 2 (F2) in the on road RDE test. Thus, the RDE test sequence was comprised of an alternating sequence of F1 & F2. In addition, to facilitate a direct comparison of the emissions from the RDE, NEDC and WLTC on F2, the CD cycles were carried out each time the car was running on F2 with the order of the three cycles varying each time. The designed sequence is shown in Table 4. This was departed from in some instances as some tests, in particular RDE tests, were deemed non-compliant and were repeated out of sequence due to logistical requirements.

Table 4 Showing the designed test sequence for vehicles V1-V3.

Fuel change to			
F1	RDE # 1		
F2	RDE # 1	NEDC # 1	WLTC # 1
F1	RDE # 2		
F2	NEDC # 2	WLTC # 2	RDE # 2
F1	RDE # 3		
F2	WLTC # 3	RDE # 3	NEDC # 3

Preconditioning consisted of a full RDE cycle to help manage battery state of charge and DPF loading. The repeat NEDC and WLTC CD cycles were therefore carried out some days apart and interspersed with fuel changes and several RDE cycles (test and preconditioning). Thus, the variability of these NEDC and WLTC tests was expected to be somewhat higher than that typically achieved in back-to-back repeats on the same test procedure and fuel combination. Vehicle fuel systems were drained and flushed to effect fuel changes. In practice, the test order varied from the designed programme, because some of the road tests had to be repeated to generate results which were fully validated in the RDE procedure. The actual test order can be found in Appendix 3 along with the results.

2.4.4. TfL UIP testing

Tests were carried out on CD according to the Transport for London Urban Inter-Peak (TfL UIP) cycle. This cycle was one of those developed by TfL to assess vehicle emissions in congested London traffic where local air quality is below target. The Urban Inter-Peak was selected for this work as the cycle that would be most demanding for NOx control, given that it combines very low average speed (14km/h), stationary periods and many rapid transients. These cycle characteristics result in generally low exhaust temperatures with sudden excursions to high pollutant throughput which is challenging for the exhaust after-treatment - especially deNOx devices – to deal with. Road load models for the TfL testing were derived from track-based coast-down times in which the vehicles were loaded with ballast to simulate the additional mass of the PEMS equipment used for RDE to ensure valid read-across from the CD to road testing. Profiles of the test cycle are illustrated in Figure 3.

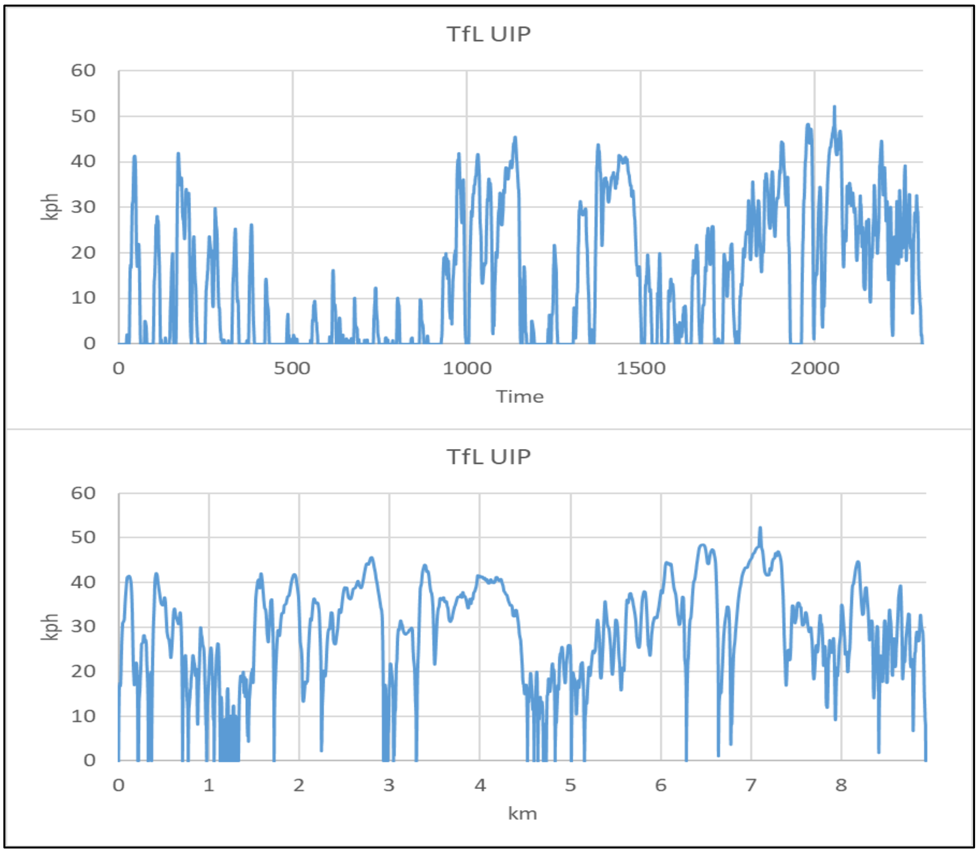


Figure 3 Road speed versus time and distance for the TfL UIP cycle

TfL UIP tests were run over a range of temperatures to explore the impact of low ambient temperature on NOx control. Single TfL UIP tests on each vehicle were run at: -15, -6, 0, 6, 14 and 23°C. Test order was randomised to avoid the possibility of systematic drift effects being misinterpreted as temperature effects. Test order for each car was:

23°C, -6°C, 14°C, -15°C, 6°C and 0°C

2.4.5. High speed test

A single test was run on the Euro 6d-TEMP car at 160km/h on the CD to check NOx control over the higher speed 'autobahn' conditions at which the RDE has also been accused of under-representing (in addition to congested urban conditions). High NOx here could be due to calibration or insufficient SCR catalyst capacity. The test started with a warm engine and speed was ramped up to 160km/h and held for 5 minutes, after which emissions had stabilised. Various temperatures as well as emissions were measured.

2.5. DATA TREATMENT AND STATISTICAL ANALYSIS

CD tests were considered valid if they were conducted to the relevant regulation and did not include a DPF regeneration or obvious vehicle or test equipment irregularities. However, results of TfL UIP tests including DPF regenerations are included in some results plots to illustrate the impact of these events. RDE tests were considered to be valid for statistical analysis if they met the RDE criteria, did not contain DPF regenerations and also validated in EMROAD. However, for transparency, raw not normalized results are quoted for the RDE.

Arithmetic means are given for gaseous emissions and geometric means for PN. Error bars on these charts correspond to 95% confidence intervals on the means and their purpose is to illustrate the observed level of variability between the repeats within each method. As these are 95% confidence intervals on the mean and not ranges of data, in some cases the bars are large and may extend into negative areas of the chart. This could be as a result of the fully randomized test matrix which fully represents the repeatability of the testing, and greater than if the tests on the same fuel were repeated consecutively. In the case of RDE this testing also includes the variability which is an intrinsic part of on-road testing. There are no error bars for the TfL UIP cycle as only a single test was conducted on each vehicle at each temperature.

3. RESULTS AND DISCUSSION

3.1. COMPARISON OF THREE VEHICLES RUN IN ALL TEST CYCLES

This section compares all the test cycles for Vehicles 1-3. All of the CD tests in this section were run with ambient temperature set at 23°C. The ambient temperature ranged from 13°C to 29°C for the RDE tests. In the charts in Figures 4 - 9, where repeats were run, error bars represent 95% confidence intervals on the mean. There was only a single TfL UIP test at 23°C on each vehicle and hence there are no error bars for this test cycle.

3.1.1. NOx

Figure 4 illustrates the NOx emissions for all three vehicles. It should be noted that all three vehicles are equipped with EGR for NOx control as well as either SCR or LNT plus pSCR. The data collected in the study does not allow for the relative impact of EGR and the other NOx abatement technologies to be decoupled. It is assumed that both systems are used to control NOx in these tests. Both SCR-equipped vehicles (V1 & V2) produce emissions below 80mg/km (i.e. RDE CF < 1) as well as Euro 6d (CF=1.5) and Euro 6d temp (CF=2.1) limits over all cycles. Urban driving emissions from these vehicles are higher than NEDC, WLTC and total RDE. Emissions from the LNT-equipped Vehicle 3 are below the Euro 6 limit (CF<1) from NEDC but are higher for all other cycles and rank with test duration, being highest in the longest test - the RDE. This indicates that the vehicle is more effectively controlling NOx after cold start than after extended periods of driving.

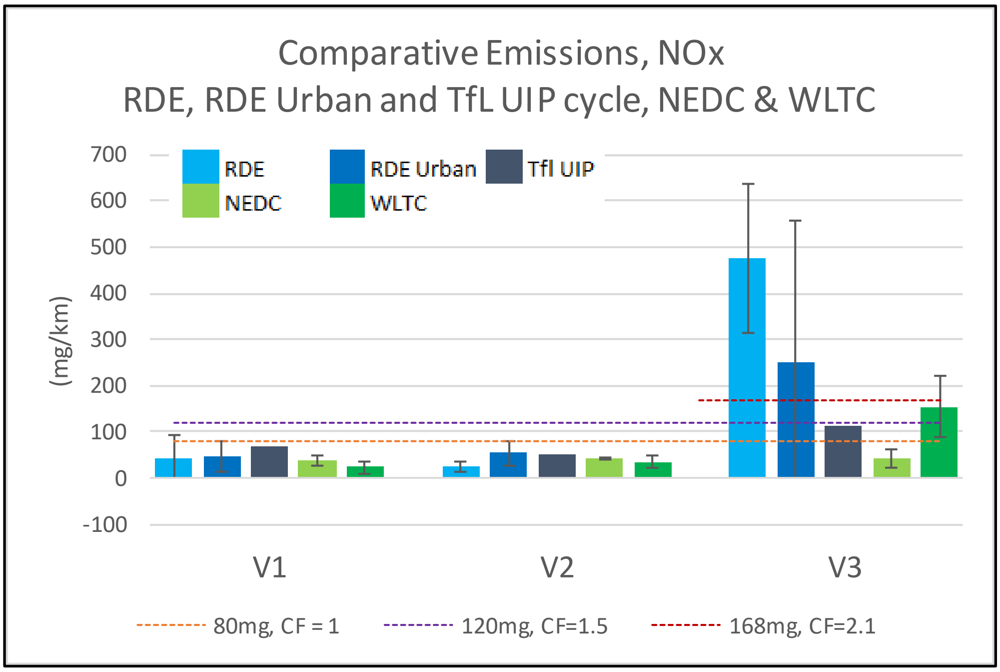


Figure 4. NOx emissions compared across test cycles. Error bars represent 95% confidence intervals on the mean

3.1.2. Particulate Number (PN)

PN is lower than the Euro 6 limit (CF<1) for all three vehicles in all test cycles and there is little difference across the cycles. Vehicles 1 and 2 are equipped with combined SCRF systems which consist of a combination of SCR and DPF. Vehicle 3, equipped with a DPF alone has higher PN emissions than the other cars (Figure 5) but the means are still below the limit.

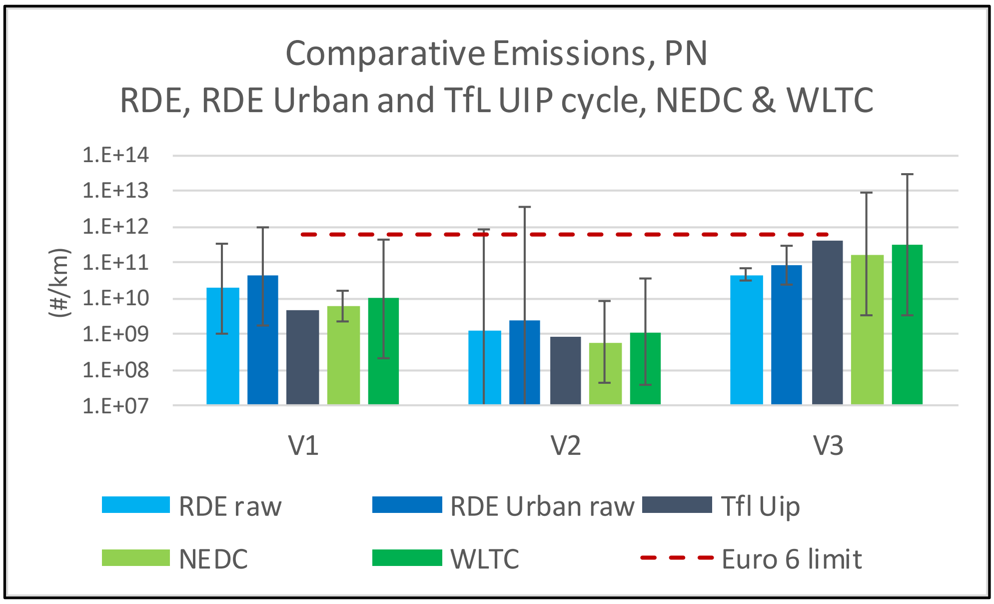


Figure 5 PN compared across test cycles (geometric means). Error bars represent 95% confidence intervals on the mean.

3.1.3. CO_2 and CO

CO_2 emissions were higher in the urban cycles and highest in the most congested TfL cycle for all three cars (Figure 6). Even in the NEDC, CO_2 is much higher than the certification values, given that the tests in this work were run with road loads based on actual vehicle as-found masses as well as accounting for the mass of the PEMS kit (165kg) to ensure comparability between the CD and road test results. NEDC certification CO_2 data for the vehicles are: V1 119g/km, V2 112g/km and V3 109g/km. Some additional factors may contribute to comparatively higher emissions in the on-road testing such as the influence of wind, cornering and road surface.

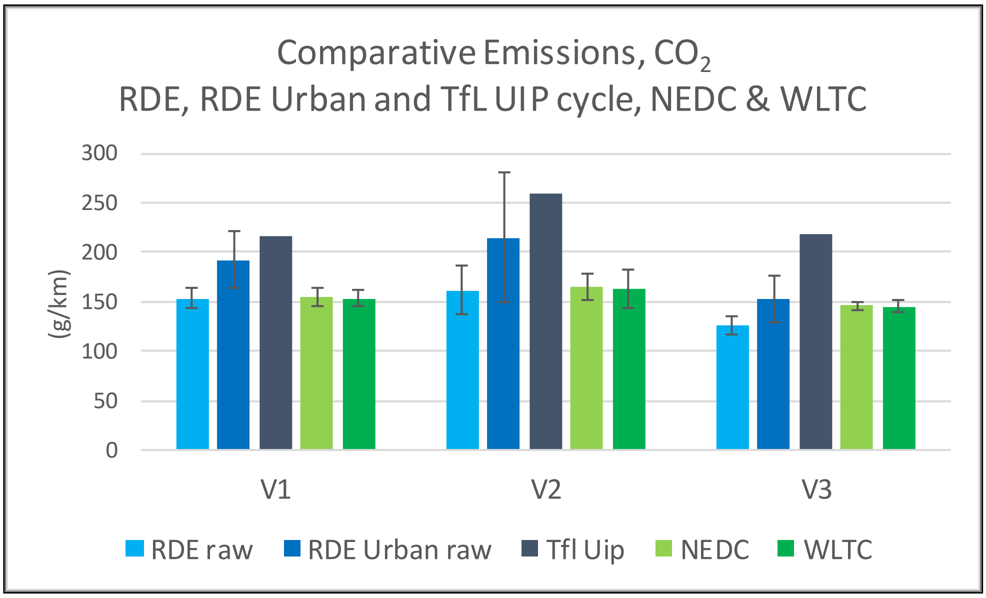


Figure 6 CO_2 emissions compared across test cycles. Error bars are shown that represent the 95% confidence intervals on the mean where repeat tests are available.

For Vehicle 3, urban driving CO emissions (RDE urban and TfL) were more than double those of the other test cycles comprising an extra-urban phase. In all cycles, CO emissions were generally at least an order of magnitude lower than the Euro 6 limit of 500 mg/kg (Figure 7).

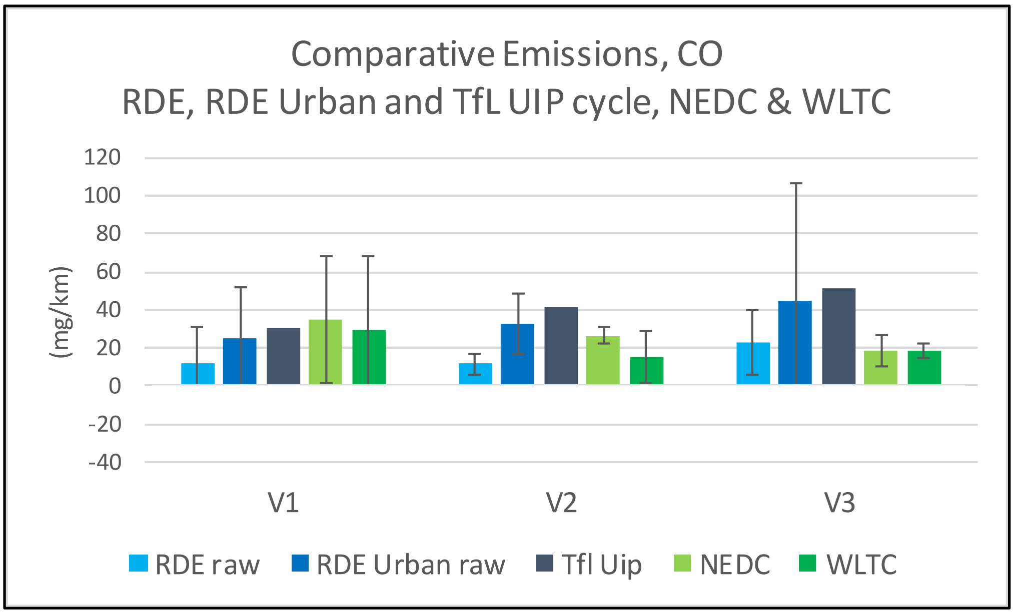


Figure 7 CO emissions compared across test cycles. Bars represent the 95% confidence interval on the mean.

3.2. COMPARISON OF RDE AND TFL AT 23°C FOR ALL FOUR VEHICLES

This section compares results from the RDE, the urban sub-section of the RDE and the TfL UIP test run at 23°C for all four vehicles tested. The results are in order of the sub-category/age of the vehicle.

3.2.1. NOx

NOx tends to be higher under the lower speed tests for vehicles fitted with SCR but the opposite applies for the car with LNT. It is postulated that the car with LNT has limited capacity for NOx reduction and can cope better under the congested TfL cycle where pollutant throughput is low on a time basis (g/s) but high on a distance (g/km) basis, (see Figure 8). In absolute terms the Euro 6d-TEMP vehicle does not perform as well as the earlier cars equipped with SCR, but nevertheless it both fully meets Euro 6d-TEMP requirements and emits a quantity of NOx that is lower than the full Euro 6 limit of 80mg/km over RDE and in the urban section of the RDE. Over the ~9 km TfL UIP the 6d-TEMP car produces around 3 times more NOx than in the ~30 km urban section of the RDE highlighting the difference in severity and catalyst light-off influence between RDE urban driving and the much shorter, more dynamic and very congested urban driving. This also highlights another point: the earlier SCR cars appear to be minimizing NOx as far as possible under each of the test scenarios, whereas the 6d-TEMP car appears to be managing NOx most stringently under regulatory RDE test conditions, possibly in order to balance requirements for low CO_2 against low NOx.

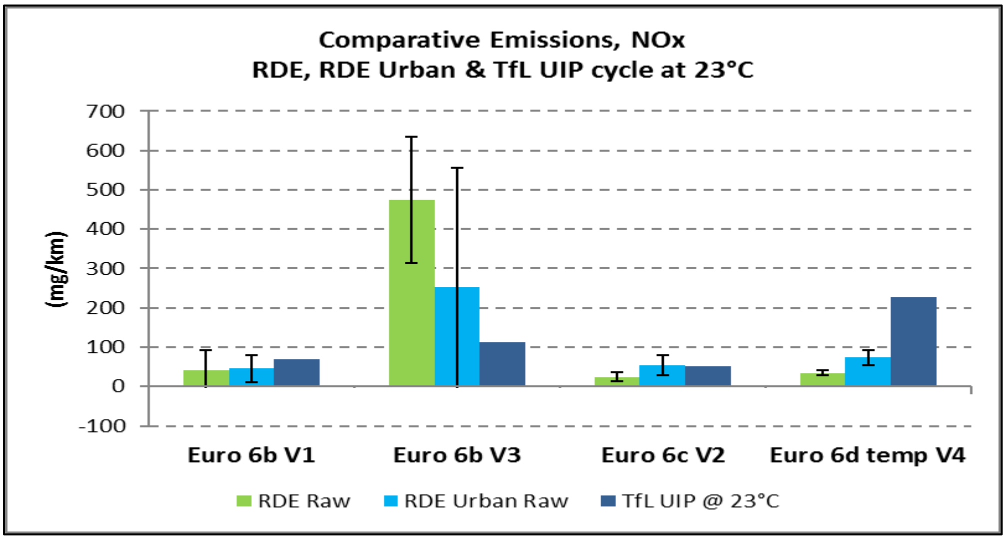


Figure 8 NOx over RDE, RDE urban and TfL UIP at 23°C

3.2.2. Particulate Number (PN)

PN is below the full Euro 6 limit of 6 x 10^{11} for all vehicle/test combinations illustrating the effectiveness of modern DPF technology, even over the congested TfL cycle (Figure 9).

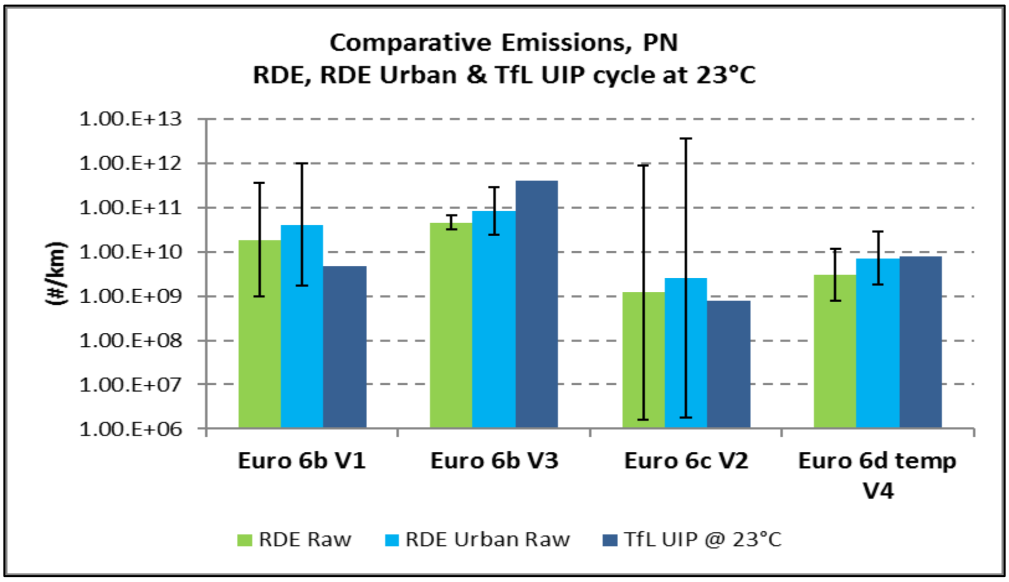


Figure 9 PN over RDE, RDE urban and TfL UIP at 23°C

3.2.3. CO_2 and CO

There is little surprising in the CO_2 results within each vehicle, with more urban driving and congested driving leading to higher CO_2. Across the vehicles, the Euro 6d-TEMP car produces least CO_2. In absolute terms CO_2 is higher than the certification values because of the mass of the PEMS and on road, because of the additional losses associated with on-road driving that are not accounted for in certification CD tests such as cornering, wind, road surface and elevation change, as well the higher duty of the RDE versus the NEDC.

CO is not usually a cause for concern in modern diesels as it is usually controlled to an order of magnitude below the Euro 6 limit. This is the case for the three earlier cars in these data, but the 6d-TEMP car produces notably higher CO in the TfL cycle. This is however still below the Euro 6 limit for CO of 500mg/km and may reflect a compromise between minimizing CO_2 while producing compliant local emissions.

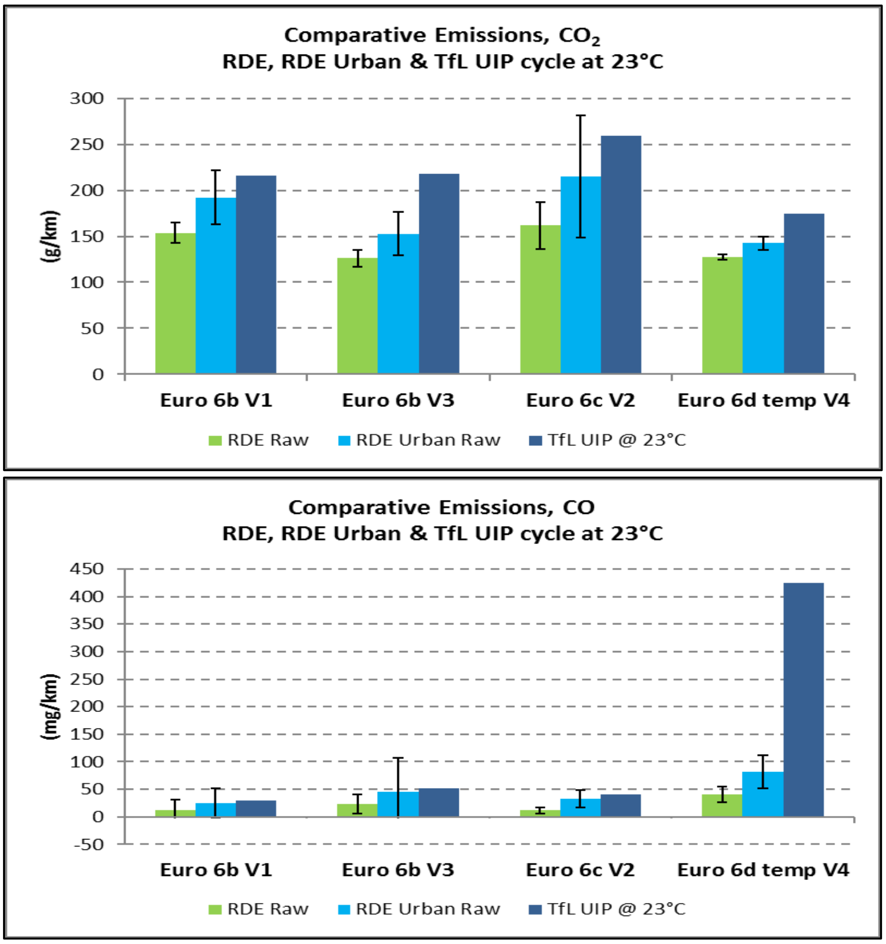


Figure 10 CO_2 and CO over RDE, RDE urban and TfL UIP at 23°C

3.3. TFL UIP TESTS OVER A RANGE OF TEMPERATURES

3.3.1. NOx and fraction of NO_2

All cars tended to produce higher NOx at lower temperatures. This would be expected due to lower conversion efficiencies of the aftertreatment and reduced EGR for engine protection at lower temperature. The increase in NOx towards lower temperature tended to be linear and similar in the earlier SCR-equipped cars but substantially higher in the 6d-TEMP car at -15°C, possibly due to the ramp-out of EGR between this and the -6°C test point, to limit the risk of EGR icing and avoiding a fuel penalty from applying thermal management outside the RDE regime. The LNT-equipped car produced much higher NOx towards lower temperatures. This could be because the LNT efficiency is lower at lower temperatures, leaving more NOx unabated and emitted.

Fraction of NO_2 (fNO_2) in the NOx emissions was lowest in the earlier SCR-equipped cars and highest in the 6d-TEMP car across the temperature range. It should be noted that the fNO_2 from the earlier SCR cars V1 and V2 is lower than would be typically expected from cars with this aftertreatment technology, rather than the fNO_2 from the 6d-TEMP car being conspicuously high. While it would have been more encouraging to see similarly low fNO_2 levels also from the later vehicle, at

<35%, the fraction of NO_2 is still relatively low compared to other Euro 6 vehicles [16,17].

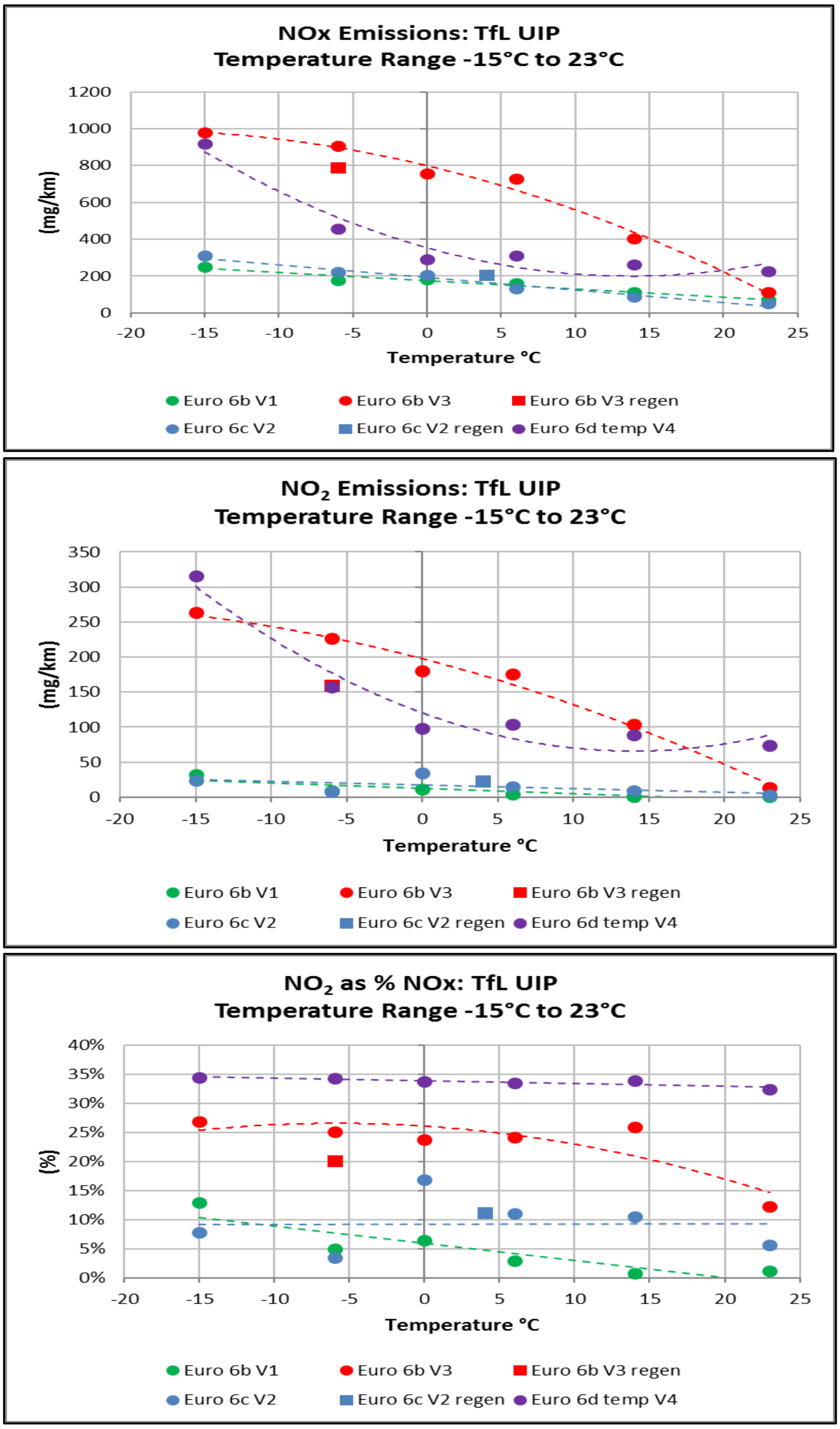


Figure 11 NOx, NO_2 and fraction of NO_2 over the TfL UIP cycle at -15 to 23°C

The fraction of NO_2 in NOx emissions is likely to become of increasing focus given that it is NO_2 that is critical to local air quality. Two studies which include fNO_2 measurements from 5 and 39 Euro 6 cars respectively, [17,18] conclude that fNO_2 is higher for cars with SCR than those relying on LNT or EGR as their principal means of NOx reduction. SCR is likely to become a dominant NOx after-treatment technology for diesel; therefore, design and calibration of after-treatment systems to minimize fNO_2 – as is exemplified the Concawe results of the two earlier Euro 6 SCR-equipped cars (Figure 11) will become more important in the future.

3.3.2. Particulate Number (PN)

PN emissions tend to increase towards lower temperatures possibly due to cat light-off effects and combustion air temperature effects. PN is substantially higher for the LNT vehicle that was initially thought to be due to a faulty DPF leading to increased particle breakthrough. Further investigation by testing a replacement DPF on the vehicle gave similar results to the original so the final hypothesis was that the low filtration efficiency was not a defect but an intentional trade-off to reduce the risk of filter plugging from ash build-up at the end of life by using a larger pore-size. PN from all of the SCR-equipped cars was within the Euro 6 limit even at the coldest temperatures apart from a test including a DPF regeneration that gave expectedly higher PN emissions.

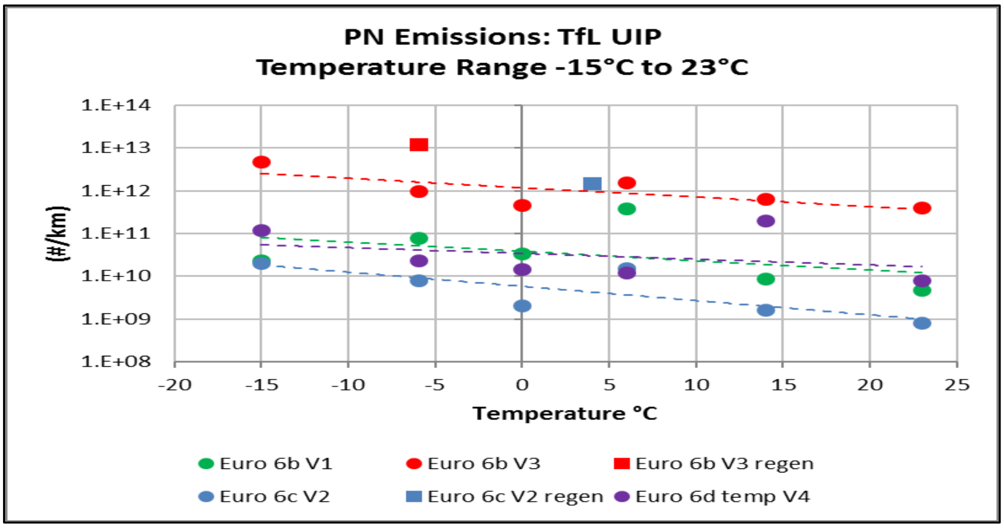


Figure 12 PN over the TfL UIP cycle at -15 to 23°C

3.3.3. CO_2 and CO

CO_2 increases towards cold temperatures that can be attributed to warm up effects on e.g. lubricant viscosity, exhaust thermal management up to catalyst light off temperature and also a declining use of stop-start. The Euro 6d-TEMP car produced substantially lower CO_2 than the others across the temperature range.

CO increased linearly towards cold temperatures for all cars indicating a higher proportion of the cycle being driven below the cat light-off temperature. However, this was conspicuously higher for the Euro 6d-TEMP car which produced more than three times the Euro 6 limit at -15°C, around 5 times more than the earlier cars (Figure 13).

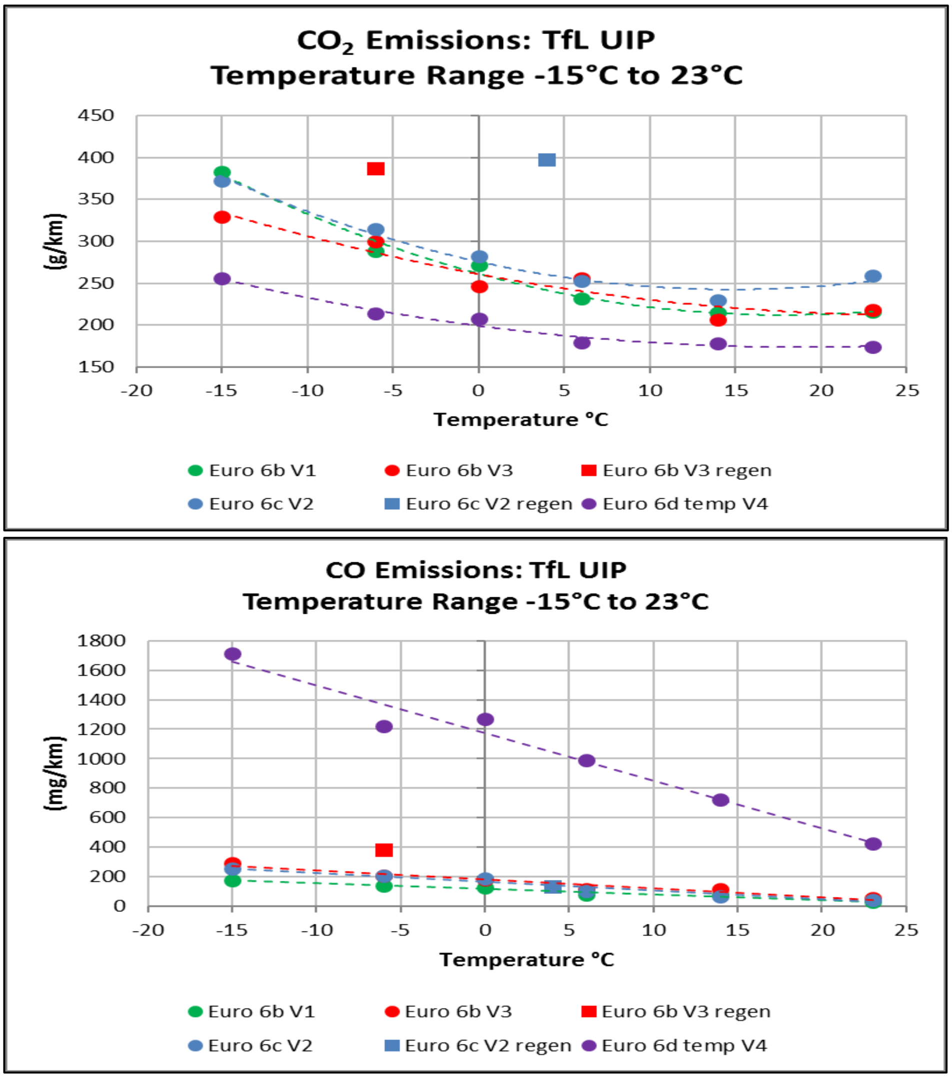
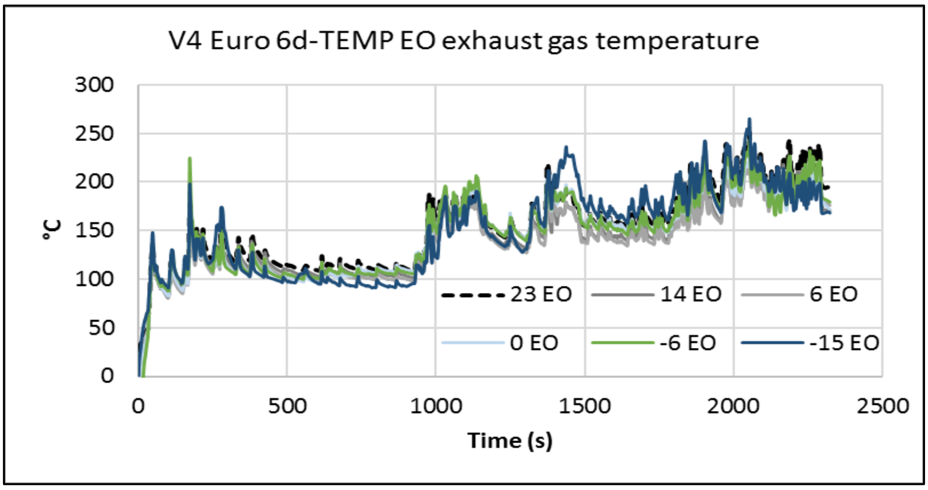


Figure 13 CO_2 and CO over the TfL UIP cycle at -15 to 23°C

3.3.4. Catalyst management

Higher CO and NOx especially at the lower ambient temperature TfL UIP tests in the Euro 6d-TEMP car suggested a difference in catalyst activity between this and the earlier SCR-equipped cars. Exhaust gas temperature and where available, pollutant conversion data, were scrutinized for evidence of the cause of these differences. It is evident from the exhaust gas temperature data plotted in Figure 11 that a significant catalyst heating strategy is being employed in the Euro 6b SCR car, V1, compared to the Euro 6d-TEMP car. The traces show that in V1, exhaust gas temperature is higher in the earlier parts of the tests (up to 1000s) at the lowest ambient temperatures, which will help offset the negative effects of low temperature on catalyst efficiency.



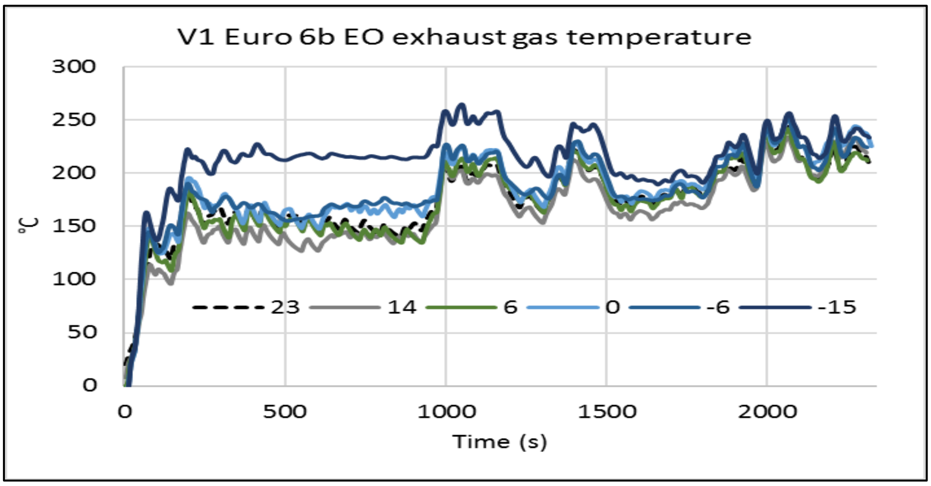


Figure 14 Exhaust gas temperature profiles across the TfL UIP cycle for V1 (Euro 6b, SCR) and V4 (Euro 6d-TEMP, SCR)

Cumulative tailpipe NOx data suggests that the earlier SCR-equipped cars are suppressing tailpipe NOx as far as practicable through active urea metering even at cold temperatures, whereas the Euro 6d-TEMP car is not (Figure 15). For the earlier SCR cars V1 and V2 the majority of NOx is emitted in the first 3 minutes after start up, after which tailpipe NOx is actively controlled via urea injection and so flattens off. In the Euro 6d-TEMP V4, tailpipe NOx is similar or lower to that of the earlier SCR cars in the initial minutes of testing, possibly due to the PNA capturing NOx under cold conditions. However, NOx continues to accumulate throughout the test rather than abating as is evident in the earlier SCR cars once the SCR catalysts are at efficient operating temperatures. NOx from V4 at the -15°C test temperature is substantially higher than at the other temperatures, indicating a difference in the NOx control strategy for this car at this temperature. Since Adblue freezes at -11ºC, it is highly likely that there is a strategy of stopping the injection of Adblue to protect the after-treatment system.

Tailpipe NOx from the LNT-equipped V3 is comparatively low in the initial minutes after start up, especially at higher ambient temperatures, but continues to accumulate to a level much higher than the early SCR cars, most notably at lower temperatures, possibly due to lack of LNT regeneration or EGR deactivation.

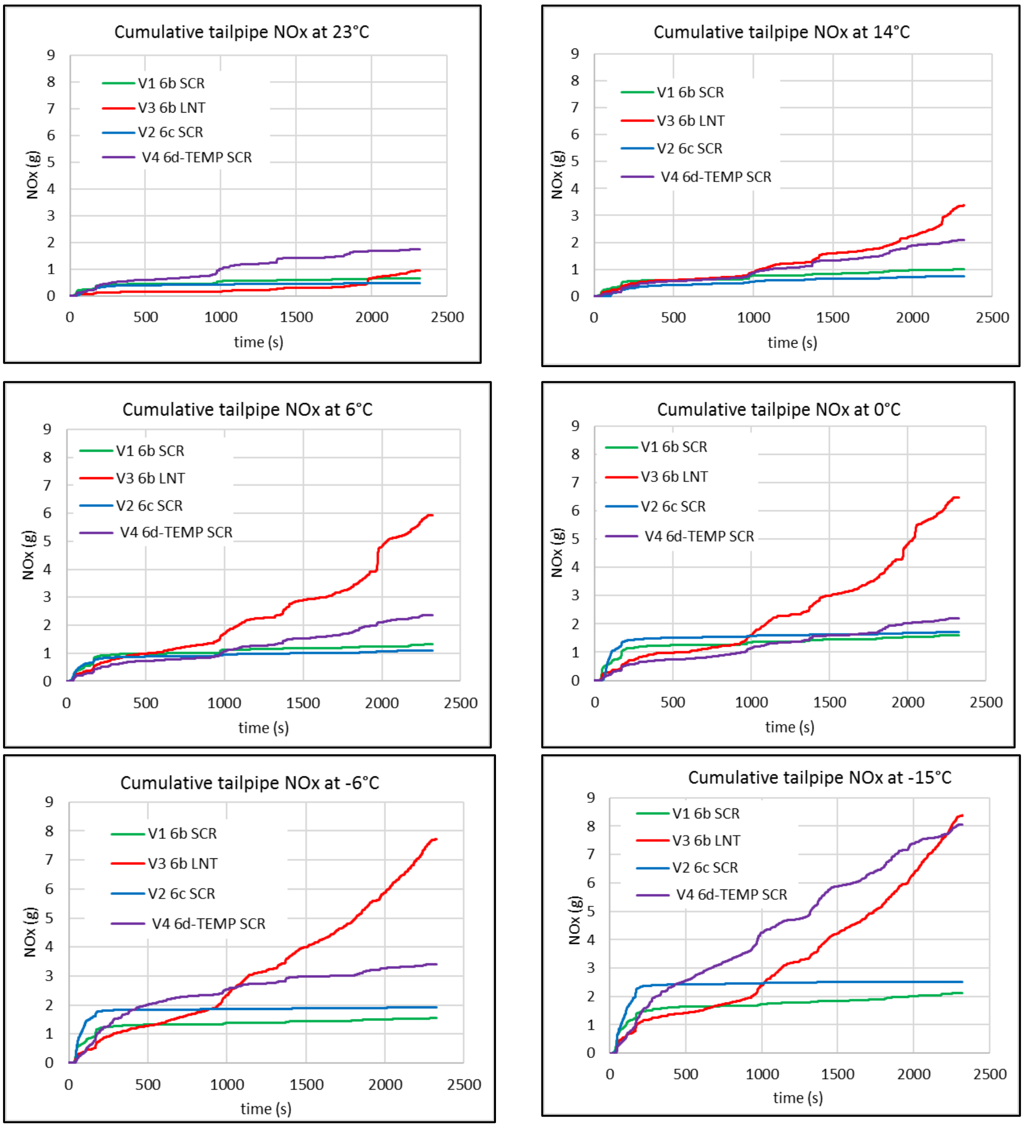


Figure 15 Cumulative tailpipe NOx over the TfL UIP cycle at -15 to 23°C

3.4. EURO 6D-TEMP TESTING AT HIGH SPEED

A single test was run on the Euro 6d-TEMP car at 160km/h on the CD to check NOx control over the higher speed 'autobahn' conditions. High NOx here could be due to calibration or insufficient SCR catalyst capacity. The results showed that the Euro 6d-TEMP V4 exhibited good NOx control, limiting NOx to 12mg/km under this condition. It was notable that 16% EGR was in use at this condition, already helping to abate NOx. Engine out and inter-catalyst NOx measurements enabled NOx conversion efficiency to be calculated post SCR as 81% and at tailpipe (post SCRF+SCR) 98.3%. It is evident from the data in Figure 16 that engine out NOx is, as expected, highest during the initial transient period.

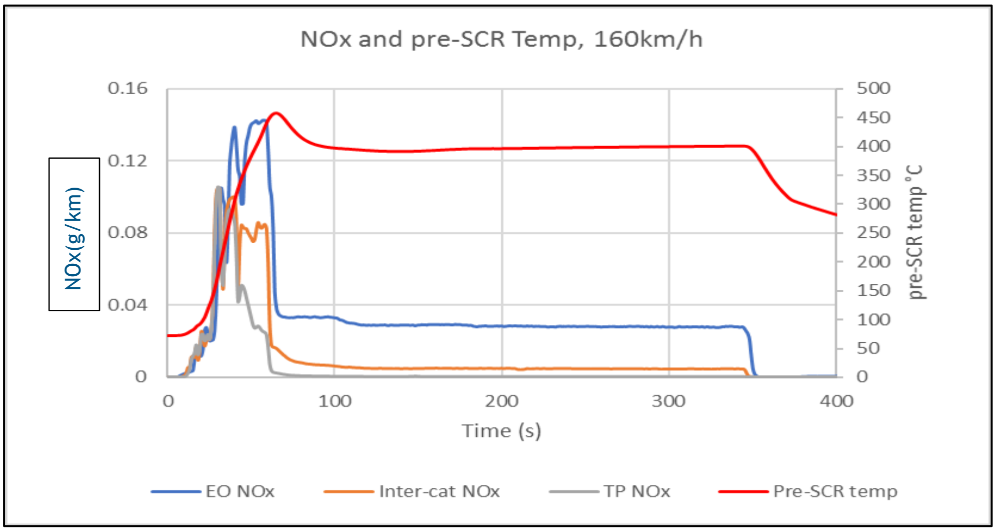


Figure 16 Engine out, inter-cat and tailpipe NOx and exhaust gas temperature during the high-speed test on the Euro 6d-TEMP V4 car (warm engine, speed ramped to 160km/hr

Another comparable study of Euro 6d-TEMP diesel car emissions by Emissions Analytics [19] appeared to show examples of vehicles tuned for RDE performance and a majority which are tuned to minimize NOx irrespective of drive cycle. The Emissions Analytics data measured NOx at 110km/h and 160km/h from 8 cars certified to Euro 6d-TEMP. All 8 cars produced less than 1.5 times the Euro 6 NOx limit at 110km/h and six of these remained below this level at 160km/h, whereas two cars produce around 8 times the Euro 6 limit at 160km/h, indicating a calibration (or catalyst sizing) suited to meeting moderate RDE demands for NOx control, but not to meet the demands of all reasonably foreseeable high speed driving conditions.

3.5. COMPARISONS BETWEEN THE TWO FUELS

A detailed discussion on the fuel comparisons is given in reference [12]. The main results from the RDE testing which were the only tests where both fuels were tested are summarized here with the plots given in Appendix 2. The error bars in the plots correspond to ±half the Least Significant Difference at the 90% confidence level. Given that there are no cases where the error bars for mean values on fuels 1 and 2 do not overlap, there are no statistically significant fuel differences even at this lower confidence level. Measures to increase the likelihood of measuring significant fuel differences could be to increase the number of repeat tests and testing fuels that differ in quality beyond the extremes of the EN590 specification.

4. CONCLUSIONS

Concawe have conducted a study of diesel passenger car emissions performance over a range of test scenarios and with a range of vehicles certified to Euro 6 which has now been extended from cars meeting Euro 6b and 6c to a Euro 6d-TEMP vehicle. The tests in this series of experiments have enabled a comparison of emissions performance to be made across Euro 6 vehicle technologies, certification sub-levels and test scenarios. Taken along with evidence from other relevant studies, it is concluded that:

Appropriately calibrated diesel cars fitted with EGR and SCR are capable of controlling NOx to sub-Euro 6d levels over a range of test cycles including RDE, congested urban cycles and at high speed 'autobahn' conditions. Along with low CO_2 they constitute a prudent choice for personal mobility into the next decades.

In challenging congested cold urban conditions, the diesel car tested which was equipped with LNT as its principal NOx control limited NOx adequately after cold start, whereas those equipped with urea-SCR performed well after an initial 2-3 minutes of warm up. A benefit in NOx control after cold start from the PNA employed in the Euro 6d-TEMP car was also evident. Typical future diesel aftertreatment systems are likely to benefit from combining SCR with LNT and/or PNA technologies.

- With SCR technology it is possible to achieve both low NOx and within this a low fraction of NO_2. However, this is not necessarily typical for current Euro 6 cars.

- Progression through the successive sub-levels of Euro 6 certification from Euro 6b through Euro 6d-TEMP does not necessarily result in achievement of the lowest possible emissions through full application of best available emissions control technology. OEMs appears to be complying specifically with Euro 6d-TEMP requirements instead of minimizing emissions, potentially to optimize CO_2 emissions or urea consumption or as interim cost-effective solutions while preparing for the more stringent Euro 6d legislation.

- Diesel fuel effects on emissions are difficult to detect in RDE testing where the fuel quality lies within the range of EN590

5. GLOSSARY

ASC	Ammonia Slip Catalyst
CD	Chassis Dynamometer
CF	Conformity Factor
CLD	Chemi-Luminescence Detector
CoC	Certificate of Conformity
CO	Carbon monoxide
CO_2	Carbon dioxide
CPC	Condensation Particle Counter
CVS	Constant Volume Sampling
DCT	Dual Clutch Transmission
DEF	Diesel Exhaust Fluid: aqueous urea solution used as a reductant to reduce NOx emissions via Selective Catalytic Reduction
DI	Direct Injection
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
(HP & LP) EGR	High & Low Pressure Exhaust Gas Circulation
EMS	Engine Management System
FAME	Fatty Acid Methyl Ester
FBP	Final Boiling Point
FID	Flame Ionization Detector
HC	Hydrocarbons
IDI	Indirect Injection
LD	Light-Duty
LNT	Lean NOx Trap
MAW	Moving Average Window
NCV	Net Calorific Value
NDIR	Non-Dispersive Infra Red
NEDC	New European Drive Cycle
NOx	Oxides of nitrogen
NO_2	Nitrogen dioxide
NTE	Not To Exceed pollutant limit applicable for RDE testing
OBD	On-Board Diagnostics
PEMS	Portable Emissions Measurement System
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
PMP	Particulate Measurement Programme
PN	Particle Number
PNA	Passive NOx Absorber
pSCR	passive Selective Catalytic Reduction
RDE	Real Driving Emissions on road emissions test procedure
SCR(F)	Selective Catalytic Reduction (on Filter)
TfL UIP	Transport for London Urban Inter -Peak
WLTC	World Harmonized Light-duty Test Cycle
WLTP	World Harmonized Light-duty Test Protocol

6. ACKNOWLEDGEMENTS

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APPENDIX 1 – PROPERTIES OF FUELS

Fuel 1

CORYTON advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G17/170	**Contact:**	Heather Hamje
Fuel Type:	EN590 B4 HD	**Order No:**	201700017
Customer:	Concawe	**Date:**	17/03/2017

Test	Method	Unit	Limit		Result
			Min	Max	
Appearance	Visual		Report		C&B
Cetane Number	EN ISO 5165		51.0	-	52.2
Cetane Index	EN ISO 4264		46.0	-	50.6
Density @ 15°C	EN ISO 12185	kg/L	0.8400	0.8450	0.8435
Cloud Point	ASTM D5773	°C	Report		-9
CFPP	EN 116	ºC	Report		-26
Flash Point	EN ISO 2719	ºC	55.0	-	64.5
Lubricity, wear scar diameter @ 60ºC	EN ISO 12156-1	µm	-	400	204
Sulfur	EN ISO 20846	mg/kg	-	10.0	7.1
Viscosity at 40ºC	ASTM D445	mm²/s	2.000	4.500	2.097
Water Content	EN ISO 12937	% m/m	-	0.020	0.015
FAME Content	EN 14078	% v/v	3.500	4.500	4.0
Polycyclic Aromatics Content	IP 391 mod	% m/m	-	8.0	7.5
Total Aromatics	IP 391 mod	% m/m	Report		27.0
Oxidation Stability	EN 15751	h	20.0	-	>20.0
Oxidation Stability (16h)	EN ISO 12205	g/m³	-	25	0
Ash Content	EN ISO 6245	% m/m	-	0.100	<0.001
Carbon Residue (10% Dis. Res)	EN ISO 10370	% m/m	-	0.20	<0.01
Copper Corrosion (3h at 50ºC)	ASTM D130	Rating	Class 1	-	1A
Total Contamination	EN 12662	mg/kg	-	24	<6
Carbon	ASTM D3343 mod	% m/m	Report		86.32
Hydrogen	ASTM D3343 mod	% m/m	Report		13.25
Oxygen	EN 14078	% m/m	Report		0.43
Gross Calorific Value	ASTM D3338 mod	MJ/kg	Report		45.63
Net Calorific Value	ASTM D3338 mod	MJ/kg	Report		42.82

Test	Method	Unit	Limit		Result
			Min	Max	
Distillation (Evaporated)					
E250	ASTM D86	% v/v		65	31.7
E350	ASTM D86	% v/v	85	.	91.7
IBP	ASTM D86	ºC	Report		175.9
10% Volume Evaporated	ASTM D86	ºC	Report		213.5
20% Volume Evaporated	ASTM D86	ºC	Report		232.4
30% Volume Evaporated	ASTM D86	ºC	Report		247.8
40% Volume Evaporated	ASTM D86	ºC	Report		261.4
50% Volume Evaporated	ASTM D86	ºC	Report		274.0
60% Volume Evaporated	ASTM D86	ºC	Report		288.8
70% Volume Evaporated	ASTM D86	ºC	Report		304.0
80% Volume Evaporated	ASTM D86	ºC	Report		320.8
90% Volume Evaporated	ASTM D86	ºC	Report		344.0
95% Volume Evaporated	ASTM D86	ºC	.	360	369.6
FBP	ASTM D86	ºC	Report		382.4
Residue	ASTM D86	% v/v	Report		1.8

Fuel 2

CORYTON advanced fuels

Certificate of Analysis

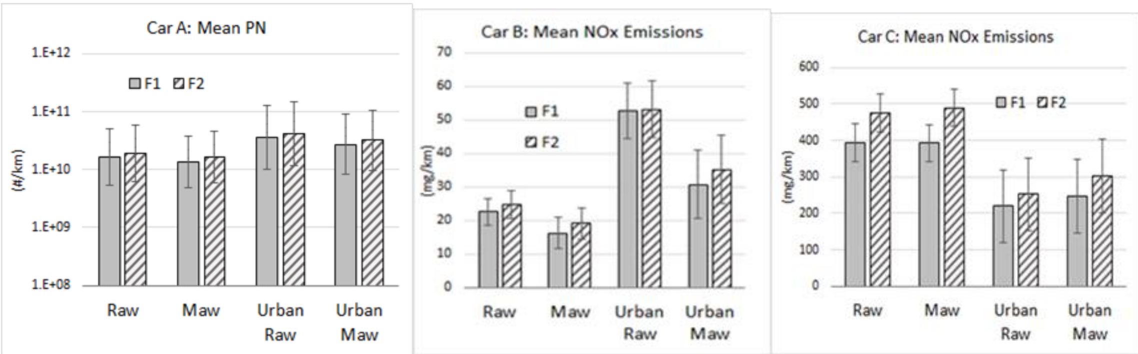
Fuel Blend No:	CAF-G17/171	**Contact:**	Heather Hamje
Fuel Type:	EN590 B4 LD	**Order No:**	201700017
Customer:	Concawe	**Date:**	17/03/2017

Test	Method	Unit	Limit		Result
			Min	Max	
Appearance	Visual		Report		C&B
Cetane Number	EN ISO 5165		51.0	-	53.0
Cetane Index	EN ISO 4264		46.0	-	53.8
Density @ 15°C	EN ISO 12185	kg/L	0.8200	0.8250	0.8218
Cloud Point	ASTM D5773	°C	Report		-11
CFPP	EN 116	°C	Report		-25
Flash Point	EN ISO 2719	°C	55.0	-	55.5
Lubricity, wear scar diameter @ 60°C	EN ISO 12156-1	µm	-	400	200
Sulfur	EN ISO 20846	mg/kg	-	10.0	7.9
Viscosity at 40°C	ASTM D445	mm²/s	2.000	4.500	2.278
Water Content	EN ISO 12937	% m/m	-	0.020	0.008
FAME Content	EN 14078	% v/v	3.500	4.500	4.100
Polycyclic Aromatics Content	IP 391 mod	% m/m	-	8.0	1.2
Total Aromatics	IP 391 mod	% m/m	Report		11.5
Oxidation Stability	EN 15751	h	20.0	-	>20.0
Oxidation Stability (16h)	EN ISO 12205	g/m³	-	25	1
Ash Content	EN ISO 6245	% m/m	-	0.100	<0.001
Carbon Residue (10% Dis. Res)	EN ISO 10370	% m/m	-	0.20	<0.01
Copper Corrosion (3h at 50°C)	ASTM D130	Rating	Class 1	-	1A
Total Contamination	EN 12662	mg/kg	-	24	<6
Carbon	ASTM D3343 mod	% m/m	Report		85.72
Hydrogen	ASTM D3343 mod	% m/m	Report		13.84
Oxygen	EN 14078	% m/m	Report		0.44
Gross Calorific Value	ASTM D3338 mod	MJ/kg	Report		46.06
Net Calorific Value	ASTM D3338 mod	MJ/kg	Report		43.12

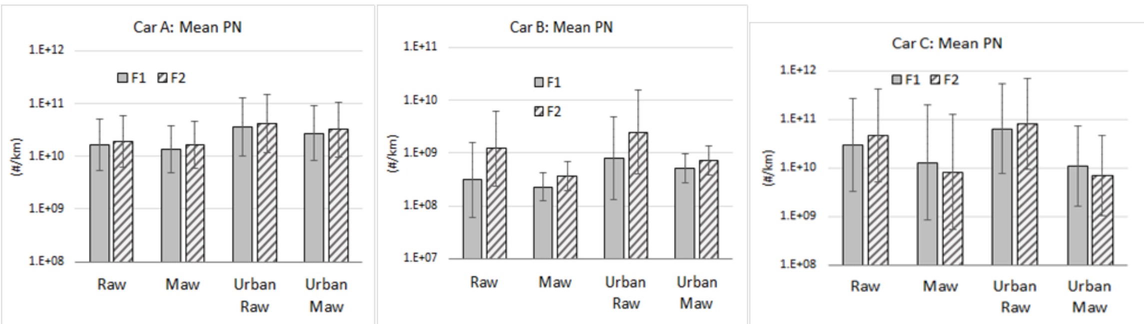
Test	Method	Unit	Limit		Result
			Min	Max	
Distillation (Evaporated)					
E250	ASTM D86	% v/v		65	47.1
E350	ASTM D86	% v/v	85		96.1
IBP	ASTM D86	°C	Report		159.6
10% Volume Evaporated	ASTM D86	°C	Report		189.3
20% Volume Evaporated	ASTM D86	°C	Report		203.8
30% Volume Evaporated	ASTM D86	°C	Report		219.4
40% Volume Evaporated	ASTM D86	°C	Report		236.9
50% Volume Evaporated	ASTM D86	°C	Report		255.0
60% Volume Evaporated	ASTM D86	°C	Report		272.3
70% Volume Evaporated	ASTM D86	°C	Report		290.2
80% Volume Evaporated	ASTM D86	°C	Report		309.0
90% Volume Evaporated	ASTM D86	°C	Report		329.7
95% Volume Evaporated	ASTM D86	°C		360	344.3
FBP	ASTM D86	°C	Report		355.2
Residue	ASTM D86	% v/v	Report		1.2

APPENDIX 2 – SELECTED EMISSIONS FOR THE TWO FUELS

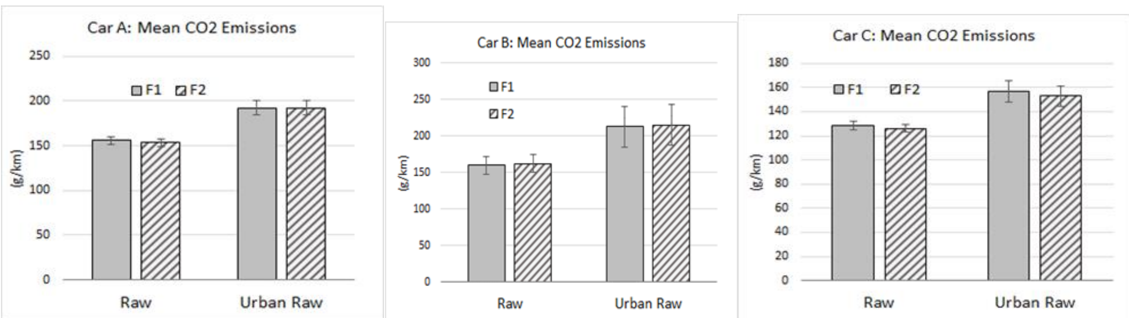
NOx



PN



CO2



APPENDIX 3 – TEST ORDER AND RESULTS FOR FUEL FOCUSSED TESTS

Car A							
Date	Fuel	Cycle	CO	CO2	NOX	PN	Comment
			[mg/km]	[g/km]	[mg/km]	[#/km]	
11-Apr-17	F1	RDE	8.038	161.5	58.95	3.594E+09	
13-Apr-17	F2	RDE	5.714	158.5	59.98	7.310E+10	
19-Apr-17	F2	NEDC	49.871	154.9	39.30	9.558E+09	
25-Apr-17	F1	RDE	8.232	154.4	78.40	5.500E+10	
28-Apr-17	F2	NEDC	26.427	158.8	41.01	4.337E+09	
03-May-17	F2	WLTC	29.796	156.2	28.10	5.386E+10	
04-May-17	F2	RDE	10.326	152.1	47.69	8.449E+09	
09-May-17	F1	RDE	11.160	167.7	170.02	4.769E+11	Regen during test
10-May-17	F1	RDE	18.796	151.4	63.84	2.360E+10	
16-May-17	F2	WLTC	44.563	154.5	21.55	6.682E+09	
17-May-17	F2	RDE	20.569	150.1	20.30	1.089E+10	
19-May-17	F2	NEDC	26.762	151.8	33.17	5.495E+09	
23-May-17	F2	WLTC	12.658	149.8	18.50	2.666E+09	
Car B							
Date	Fuel	Cycle	CO	CO2	NOX	PN	Comment
			[mg/km]	[g/km]	[mg/km]	[#/km]	
01-Jun-17	F1	RDE	13.448	177.1	65.19	2.725E+11	Regen during test
05-Jun-17	F2	RDE	14.021	151.1	19.61	1.226E+08	
06-Jun-17	F2	NEDC	22.290	174.6	40.83	1.220E+08	Stop/Start failed
08-Jun-17	F2	WLTC	11.903	155.8	31.56	3.238E+08	
15-Jun-17	F1	RDE	14.339	153.0	17.50	2.826E+08	
20-Jun-17	F2	NEDC	27.064	154.1	42.76	4.507E+09	
22-Jun-17	F2	WLTC	11.903	160.6	32.46	8.711E+08	
23-Jun-17	F2	RDE	16.072	185.4	65.81	5.758E+11	Regen during test
27-Jun-17	F1	RDE	14.000	148.0	25.68	3.471E+08	
05-Jul-17	F2	NEDC	28.574	165.2	44.59	1.978E+08	Stop/Start failed
06-Jul-17	F2	RDE	9.497	162.5	25.96	2.247E+10	
07-Jul-17	F2	NEDC	27.461	167.6	38.88	1.189E+09	Stop/Start failed
10-Jul-17	F2	WLTC	21.369	171.4	41.14	4.915E+09	Stop/Start failed
12-Jul-17	F2	RDE	11.280	171.4	28.88	6.423E+08	No fuel change
14-Jul-17	F1	RDE	9.873	178.9	24.69	3.093E+08	
Car C							
Date	Fuel	Cycle	CO	CO2	NOX	PN	Comment
			[mg/km]	[g/km]	[mg/km]	[#/km]	
28-Jul-17	F1	RDE	28.059	140.1	507.99	1.182E+12	F1 Regen in urban
31-Jul-17	F2	RDE	28.576	129.9	540.59	5.098E+10	replaces 01-Aug test
02-Aug-17	F2	NEDC	14.791	144.6	38.75	7.583E+11	
04-Aug-17	F2	WLTC	17.541	146.5	183.24	1.004E+12	
08-Aug-17	F1	RDE	105.483	135.9	475.96	1.340E+12	F1 Regen in Mway
11-Aug-17	F2	NEDC	21.245	147.4	49.13	3.170E+10	
15-Aug-17	F2	WLTC	18.292	146.3	143.38	3.653E+10	
15-Aug-17	F2	RDE	15.288	122.6	411.19	3.884E+10	replaces 16-Aug test
17-Aug-17	F1	RDE	44.788	129.7	404.31	3.571E+11	replaces 18-Aug test
23-Aug-17	F2	NEDC	19.315	145.5	33.26	1.824E+11	
24-Aug-17	F2	RDE	25.273	125.8	473.72	5.053E+10	F2
31-Aug-17	F1	RDE	28.267	127.3	381.75	2.465E+09	replaces 1-Sep test
07-Sep-17	F2	WLTC	20.448	141.9	132.57	7.325E+11	

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