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Heavy-Duty truck emissions performance with low carbon fuels under Euro 7 conditions

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Heavy-Duty truck emissions performance with low carbon fuels under Euro 7 conditions

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KEYWORDS

Low carbon diesel fuels, Euro 7, exhaust pollutants, RDE, HDV, HVO, EN590, EN14214, EN15940

INTERNET

This report is available as an Adobe pdf file on the Concawe website (www.concawe.eu).

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Abbreviations

ASC-	Ammonia slip catalyst
CAN-	Controller area network
CF -	Conformity factor
CO -	Carbon monoxide
CO_2 -	Carbon dioxide
CN -	Cetane number
CPC -	Condensation particle counter
CVS -	Constant volume sampling
DOC -	Diesel oxidation catalyst
DPF -	Diesel particulate filter
ECU -	Engine control unit
EATS -	Exhaust after treatment system
EFM -	Exhaust flow meter
EO -	Engine out
FAME -	Fatty acid methyl esters
FC -	Fuel consumption
FTIR -	Fourier-transform infrared (spectroscopy)
HDV -	Heavy-duty vehicle
HVO -	Hydrotreated vegetable oil
ICE -	Internal combustion engine
MAW -	Moving averaging window
NH3 -	Ammonia
NMHC -	Non-methane hydrocarbons
NMOG-	Non-methane organic gases
ISC-	In-service-conformity
NOx -	Nitrogen oxides
N2O -	Nitrous oxide
OBD -	On board diagnostics
OBM -	On board (emissions) monitoring
PM -	Particle mass
PN10 -	Particle number down to 10 nm
PN23 -	Particle number down to 23 nm
RDE -	Real driving emissions
SCR -	Selective catalytic reduction (catalyst)
TA -	Type approval
TfL UIP -	Transport for London, urban inter peak (cycle)
THC -	Total hydrocarbon content
TP -	Tailpipe
WHTC -	World harmonised transient cycle

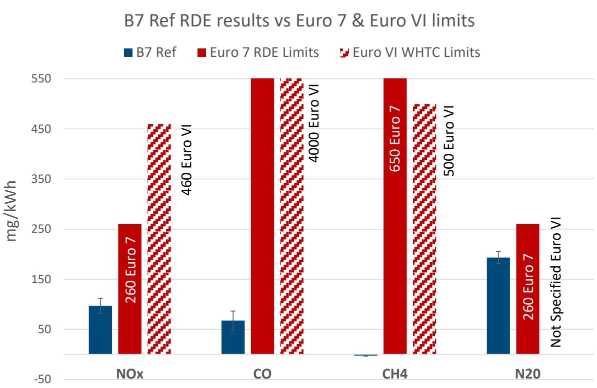
1. EXECUTIVE SUMMARY

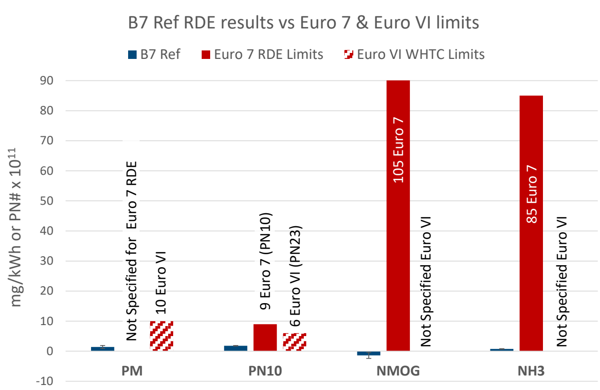
The scope of this experimental study was to examine low carbon fuel effects on a current commercially available state-of-the-art Euro VI step E HDV, tested under the proposed Euro 7 conditions and against Euro 7 emissions limits. In doing so, the aim of the work was to determine the gap between state of art HDV emissions performance and that required for Euro 7. As Euro 7 regulation requires the manufacturers to comply with the emission limits using all market fuels approved by the manufacturer, it was also intended to determine the effects of low carbon fuels on pollutant and CO_2 emissions performance. The testing activities were performed on a heavy-duty chassis dynamometer. The study included testing of five different diesel blends containing various amounts of the same three base fuels: EN590 petroleum diesel, EN14214 fatty-acid methyl ester (FAME) and EN15940 hydrotreated vegetable oil (HVO) as shown below:

1. Fuel A (reference): EN590 **B7 Ref**, 93.5 % petroleum diesel and 6.5 % FAME.
2. Fuel B: EN16709 **B30**, 70.5 % petroleum diesel and 29.5 % FAME.
3. Fuel C: EN590 **R33**, 67.5 % petroleum diesel, 6.6 % FAME and 26 % HVO.
4. Fuel D: **R80B20**, 80.6 % HVO and 19.4 % FAME.
5. Fuel E: EN15940 **HVO**, 100 % HVO.

The experimental campaign was divided into two phases. In the first phase, fuel effects of the five fuels were studied using a RDE-simulating (Real Driving Emissions) test cycle corresponding to Euro 7 conditions. In the second phase, tests were conducted over an urban driving cycle designed to be extremely demanding for the emissions control systems and beyond normal emissions compliance test regimes. In the second phase, only two fuels were tested: the most representative low carbon fuel (100 % HVO) compared to reference fuel, EN590 B7.

The key results of the experimental testing for the reference fuel are summarised as follows:





All results were well within the Euro 7 limits, with N_2O being the only pollutant close to the new limit. It follows that with overall emissions this low, the differences between other test fuels can be expected to be small. This was the case, and these results are presented and discussed in detail in the report.

The key findings of the experimental testing are summarised as follows:

- The results demonstrated that the tested state-of-the-art Euro VI Step E vehicle, with its current technology, i.e. engine and exhaust after-treatment system (EATS), could already comply with the emission limits defined in the Euro 7 regulation, over a representative simulated RDE cycle, with fuels including EN590 B7 and low carbon fuels comprising various ratios of petroleum diesel, FAME and HVO. However, the results also demonstrated that diesel-powered Euro VI HDVs can struggle with NO_x mitigation under extreme conditions, in particular where the vehicle is subjected to generally low loads (therefore low EATS temperature below efficient pollutant conversion thresholds) when combined with rapid and heavy transient driving. This phenomenon could potentially be managed by employing catalyst pre-heating measures.

- N_2O was the only exhaust component close to or above the declared Euro 7 limit with a final conformity factor between 0.65 to 1.01. However, N_2O is predominantly generated in the EATS and different catalyst materials can be employed to manage N_2O.

- Low carbon fuels containing paraffinic diesels were found to reduce TP (tailpipe) CO_2 emissions and increase powertrain efficiency simultaneously, demonstrating that such low carbon fuels based on various combinations of FAME and HVO can provide tailpipe as well as WTT carbon reduction benefits.

- Fuel effects on pollutant emissions at tailpipe were immeasurably small due to the highly efficient emissions control technology of modern IC engines, with closed loop control mitigating fuel effects.

Overall, the results of this study show that there are minimal gaps between the emissions control performance of the state-of-the-art Euro VI step E HDV tested and the performance required to fulfil Euro 7 requirements due to highly effective and mature exhaust after-treatment technology for IC engines. Furthermore, a range of low carbon fuels function well in this technology, with no demerits and some benefits in engine-out NOx emissions, cold start HC and CO emissions, TTW CO_2 reduction and improved efficiency.

2. INTRODUCTION

This report describes the work of a project commissioned by Concawe, *Heavy-Duty truck emissions performance with low carbon fuels under Euro 7 conditions*, executed by VTT.

The Euro 7 regulation requires the original equipment manufacturers (OEM) to comply with the given emission limits with all market fuels approved for use in their equipment. This is especially important for the heavy-duty vehicle (HDV) sector, as diesel powered internal combustion engines are foreseen, due to both technical and practical reasons, to preserve a strong market share for the next decades. One feasible option for reducing carbon emissions in diesel powered HDVs is by implementing low-carbon, alternative fuel blends. Typically, in type-approval, OEMs calibrate the equipment using standard reference fuels described in the predominant regulation. For example, in Euro VI, EN 590 B7 is used as the standard reference fuel. However, some OEM's may approve the usage of a large variety of alternative fuels, such as EN 14214 biodiesel (FAME) blends, beyond B7 or paraffinic diesels that meet EN 15940. One issue with alternative fuel types that do not comply with EN 590 is that they may potentially affect both vehicle powertrain and emissions performance. The main reason for this is that the engine control unit (ECU) is governing the engine based on a reference fuel calibration, (typically EN 590 B7 for European applications) and if the fuel properties deviate significantly from the reference, it may shift the operating point of both the ECU and the exhaust after treatment system (EATS). Now with Euro 7, which further lowers the emission limits compared to Euro VI, the direct effect of different diesel blend mixtures should be considered. This is especially important if any future market fuels may introduce negative effects on the emission performance, as these effects must be accounted for by the OEMs in type-approval. Another important aspect to consider is the fuel effects on powertrain performance, most importantly, powertrain efficiency in various conditions. Fuel properties may additionally influence cold start performance or the EATS especially in boundary conditions close to their lower operational limit.

Therefore, the main motivation for this project was twofold. Firstly, to assess the gap between incumbent, latest technology Euro VIE HDV emissions performance and the requirement for Euro 7, and secondly to deepen the understanding of how different diesel blends affect current state-of-the-art HDVs both in terms of powertrain and emission performance with respect to Euro 7 and beyond. The scope of the project was to study the response of five diesel fuel blends with one Heavy-duty vehicle, using test conditions and protocols which correspond to the Euro 7 procedures and assess emissions performance against the prospective Euro 7 limits. One of the five test fuels was used as reference, an EN 590 B7 diesel blend. The four other test fuels represented different mixtures of low carbon, drop-in type diesel fuel blends, containing multiple mixtures of EN590 and/or EN 14214 FAME and/or EN19540 Class A paraffinic diesel. Measurements were carried out on a heavy-duty chassis dynamometer using two test cycles. Firstly, in a representative RDE cycle derived from real world GPS data obtained from a Euro VI ISC cycle was used to determine the impact of all fuels on emission characteristics and engine performance. Secondly an urban driving cycle, the Transport for London Urban Inter-Peak (TfL UIP) was chosen to provide an extreme test of the emissions control capability of the vehicle. The TfL UIP combines periods of stationary operation with bursts of aggressive driving designed to simulate worst case conditions in London, where the exhaust aftertreatment system cools below efficient operating temperatures and is then required to process high throughputs of pollutants. TfL UIP testing was limited to only two fuels, the reference B7 fuel and the most representative low carbon fuel in the previous cycle.

These two test cycles represent completely different driving conditions, so that the operation of the vehicle and engine after treatment system could be analysed in various test conditions.

The results were processed according to the known features defined in the preliminary Euro 7 proposal[1] whenever applicable. Additionally, cumulative emissions over the complete test and by each test phase were analysed.

[1]Euro 7: Council adopts new rules on emission limits for cars, vans and trucks https://www.consilium.europa.eu/en/press/press-releases/2024/04/12/euro-7-council-adopts-new-rules-on-emission-limits-for-cars-vans-and-trucks/

3. PROJECT OBJECTIVES & SCOPE

Concawe invited VTT to participate in an experimental study involving testing of five diesel fuel blends for HDV applications. The five test fuel blends were a mix of commercial EN590 (without any bio-content), FAME and paraffinic diesel, in this case, hydrotreated vegetable oil (HVO), with EN590 B7 blend representing the reference fuel (B7 Ref). Experimental rationale and execution are detailed in Chapter 5.

3.1. PROJECT OBJECTIVES

The objective of the Concawe programme was to determine the gap in emissions performance between incumbent state of the art HDV Euro VIE technology and the Euro 7 requirements and also to determine the potential benefits of the aforementioned fuels on pollutant emissions, GHG emissions, fuel consumption and operability in heavy-duty vehicles. The analysis and evaluation of the experimental testing was requested to be performed according to proposed and drafted Euro 7 regulation.

3.2. PROJECT SCOPE

The content of the project phases consisted of the following work:

Phase 1. Selection of the test vehicle, tailoring and defining the test protocol:

a. VTT acquired the selected test vehicle and test fuels.
b. VTT recreated a suitable laboratory/dynamometer test cycle for the test vehicle based on real world GPS data extracted from an RDE/ISC route from the VTT database. Additionally, a second test cycle outside the normal Euro 7 test requirements, which would be extremely EATS-demanding (the TfL UIP) was recreated and implemented.

Phase 2. Experimental fuels testing under standard Euro 7 test conditions with five diesel fuel blends:

The experimental tests for five diesel fuel blends were conducted in VTT vehicle laboratory using the HD chassis dynamometer environment. Factors related to fuel change, conditioning, and applied emission sampling (according to proposed Euro 7 protocol) were accounted for as described later in chapter 5.3 “Experimental layout and measurement procedures”.

Phase 3. Additional testing under demanding conditions for two test fuels.

Conducting additional tests with a test cycle including highly transient, extra low and high engine loads. The objective of these tests was to test the vehicle in conditions which are heavily demanding of the exhaust aftertreatment system. The test fuels were: Reference EN590 B7 fuel and the most representative low carbon test fuel of the remaining four fuels assessed under standard conditions.

Phase 4. Data analysis and final reporting

Data analysis was conducted both in terms of time resolved data and using trip total data. Following data analysis was performed:

- Cold emissions (100th percentile of MAW), if applicable within RDE analysis
- Warm emissions (90th percentile of MAW), if applicable within RDE analysis
- For both RDE Average trip emissions over four phases and total cycle, both based on trip length and wheel work

4. AN OVERVIEW OF EURO 7 REGULATION

An initial proposal for the Euro 7 regulation, which is part of the European Commission's 2020 Sustainable and Smart Mobility Strategy and the 2021 Zero-Pollution Action Plan, was presented by the European Commission on 10 November 2022. The content of the proposal was based on multiple dedicated research programmes, which engaged both industry and research consortia. The initial approach would have brought several new methodologies to the type-approval (TA) procedure and would have emphasised even stronger cold start and low load emission performance by implementation of "emission budgets". In addition, several new regulated emission components were proposed. A year later, on 25th September 2023, the European Council adopted its position, or 'general approach'. This approach was, on the contrary, a streamlined upgrade from Euro 6/VI and was built upon the UN regulation No. 49 (applying the newest, 07 series of amendments). The approach would still be implementing some new emission components, similar to the EC's proposal. The Council and the Parliament finally reached a provisional political agreement on 18 December 2023, which was eventually adopted in April 2024 and published in May 2024. The outcome of the final trialogue was published and is available on the website of the European Council[2].

Compared to Euro VI, Euro 7 will introduce stricter emission limits to the already regulated emissions. To further improve air quality by reducing pollutants, the particulate number 23nm cut-off limit (PN23) has been reduced to 10nm (PN10), together with introduction of new regulated gaseous components, NH_3, N_2O and non-methane organic gases (NMOG). NMOG substitutes non-methane hydrocarbons (NMHC) and is defined as *'non-methane organic gases. Meaning the sum of non-oxygenated and oxygenated hydrocarbons, excluding methane, emitted from the tailpipe;"*, while NMHC is defined as *'non-methane hydrocarbons' or 'NMHC' meaning the total hydrocarbons, excluding methane, (and excluding oxygenated species), emitted from the tailpipe'*. Another major change for Euro 7 is the requirement for OBM (On-Board Monitoring). OBM is designed to enable constant monitoring of vehicle emissions performance, therefore giving oversight of the emissions performance of individual vehicles and whole vehicle types during normal operation in the field.

The type approval (TA) procedures for HDVs remain similar to Euro VI. This means that laboratory engine testing will act as the primary method for determination of exhaust pollutants. The exhaust emission measurements are conducted in standardized test conditions using two test cycles, WHSC and WHTC. Then manufacturers are additionally required to demonstrate the emission performance in real-world conditions using PEMS. This test method resembles the in-service-conformity (ISC) procedure, but minor differences apply. In ISC, vehicle payload is allowed between 10 to 100 percent. In PEMS demonstration, this is reduced to 50 – 60 percent. The regulatory emission limits have been revised such that separate limits for engine testing conducted in laboratory conditions, i.e. WHSC and WHTC, and Real Driving Emission (RDE) are applied. The summary of emission components and regulatory limits are displayed in Table 4-1. Trip composition is predefined depending on vehicle class, and a trip should consist of certain shares of urban, rural and motorway driving. The test conditions for both PEMS demonstrations and ISC tests are equal. The on-road results are quantified through a moving average window (MAW) principle. The MAW principle is described in more detail in chapter *5.8.2. Implementation of MAW calculations for determining exhaust emissions according to Euro 7*. The MAW emissions are separated as cold emissions conformity factors ($CF_{cold)}$ and warm conformity factors (CF_{warm}), which forms the final conformity factor, CF_{final}. CF_{final} is determined by the following equation: $CF_{final} = CF_{cold} * 0.14 + CF_{warm} * 0.86$. CF_{cold} represents the 100^{th} percentile MAW results accounting for all data starting

[2] https://www.consilium.europa.eu/en/press/press-releases/2024/04/12/euro-7-council-adopts-new-rules-on-emission-limits-for-cars-vans-and-trucks/

from cold start (coolant temperature above 30 °C), meanwhile CF_{warm} is determined as 90th percentile of warm MAWs starting from coolant temperature 70 °C and above. In Euro VI, permissible emissions have had separate, larger limits obtained by applying CF multipliers. For example, CF_{final} for NOx has been CF = 1.5 * legislative emission limit for Euro VI. These Euro VI CFs were permitted to allow for measurement inaccuracies at a time when experience with PEMS technology was developing.

Despite the TA test procedure being founded on UN regulation No. 49, some changes apply. These are mostly related to the RDE measurements, where the lower power threshold for valid windows has been reduced to 6 %, and the conformity factors (CF) have been reduced to 1. The reason for reduction of the CFs to 1 is that these factors have been accounted for in the separate emission limits for RDE defined in Table 4-1. A summary of the revisions is given in Table 4-2.

Most importantly, it is explicitly emphasised in Euro 7 that the exhaust emission compliance should be met with any market fuel and lubricant within the specifications issued by the manufacturer. This applies to the most common vehicle categories (M_1, M_2, M_3, N_1, N_2, N_3).

Table 4-1 Euro 7 exhaust emission limits[3] for vehicles of categories M2, M3, N2 and N3 with internal combustion engines.

Pollutant emissions	Euro VI WHSC	Euro VI WHTC	Euro 7 WHSC (CI) and WHTC (CI and PI)	Euro 7 Real Driving Emissions (RDE)
NO_x (mg/kWh)	400	460	200	260
PM (mg/kWh)	10	10	8	—
PN10 (#/kWh)	8.0×10^{11} (PN23)	6×10^{11} (PN23)	6×10^{11}	9×10^{11}
CO (mg/kWh)	1 500	4 000	1 500	1 950
NMOG* (mg/kWh)	(HC limit 130)	-	80	105
NH_3 (mg/kWh)	-**	-**	60	85
CH_4 (mg/kWh)	-***	500	500	650
N_2O (mg/kWh)	-	-	200	260

*NMOG, i.e. 'non-methane organic gases' or 'NMOG' means the sum of non-oxygenated and oxygenated hydrocarbons, excluding methane, emitted from the tailpipe;. Methodology for quantification to be announced.
**average 10 ppm concentration limit applies in WHSC and WHTC
***applicable only for PI and DF applications

Table 4-2 Conditions for testing compliance of vehicles of categories M_2, M_3, N_2 and N_3 with exhaust emission limits with any market fuel and lubricant within the specifications issued by the manufacturer

Laboratory exhaust emission measurement	RDE measurement
For all exhaust emission tests conducted using the WHTC/WHSC engine bench test cycles, Annex 4 to UN Regulation No 49	Annex 8 of UN Regulation No 49 shall apply with the following adaptations: (i) point A.1.4.2.2.2.1. of Appendix 1 to Annex 8 to UN Regulation No 49 shall read as follows: 'The valid windows are the windows whose average power exceeds the power threshold of 6 % of the maximum engine power' (ii) in relation to the conformity factor (CF) in Table 2 of point 6.3 of Annex 8 to UN Regulation No 49 the value = 1,0 shall be used for all pollutants; the applicable limits shall be the RDE limits in Table 2 of Annex I to this Regulation.

[3] REGULATION (EU)2024/... OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL https://data.consilium.europa.eu/doc/document/PE-109-2023-INIT/en/pdf

5. EXPERIMENTAL

The tests described in this report were executed at VTT engine and vehicle test facilities in Otaniemi, Finland. The test facility consists of a chassis dynamometer, vehicle and environment data loggers and emission analysing equipment, as well as fuel blending.

5.1. TEST FUELS

The fuel matrix consisted of five diesel fuel blends containing different quantities of petroleum EN590 diesel, biodiesel (FAME) and renewable paraffinic diesel, HVO. All test fuels were blended by VTT from single base fuel batches. The target was to choose representative fuels from the market, currently and likely in the future. The fuel blending was executed on a mass-based blending principle. The fuel properties of the base fuels are shown in Appendix 1. The base fuels did not contain any performance additives.

The initial targeted fuel matrix is shown in detail in Table 5-1, followed by the final, realised fuel matrix shown in Table 5-2. Fuel A was defined as reference fuel, which was an EN 590 B7 blend. The main motivation for this is that EN 590 B7 is used as the reference fuel both in the Euro VI regulation[4] and UN Regulation No 49[5], 07 series of amendments, which served as the basis for the proposed Euro 7 regulation. Prior to any testing activities, the fuel blends were sent for analysis, implementing accredited methods for determination of basic fuel properties and to ensure all fuels complied with their respective fuel standards/specifications. The main characteristics of the test fuels are shown in Table 5-3 and fuel CO_2 intensity is shown in Figure 5-1, followed by a description of each blend and the rationale behind including it in the test program.

A more detailed list of fuel properties is shown in Appendix 2.

CO_2 intensity was calculated using following formula:

$$CO_2\ intensity\ \left[\frac{gCO_2}{MJ}\right] = \left(\frac{\frac{Carbon\ Content(\%\ by\ mass)}{100} \times 44}{12 \times\ LHV\ \left[\frac{MJ}{kg}\right]}\right) \times 1000$$

Where:

- Carbon content (% by mass): The percentage of the fuel's mass that is carbon
- 44/12: The ratio of the molecular weight of CO_2 (44 g/mol) to the atomic weight of carbon (12 g/mol).
- LHV (MJ/kg): The lower heating value represents the energy released per kilogram of fuel burned, excluding the latent heat of water vaporization.

[4]Commission Regulation (EU) No 582/2011
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02011R0582-20221210
[5] UN Regulation No 49, 07 series of amendments

Table 5-1 Targeted test fuel matrix

Targeted test fuel matrix			
No.	**Fuel**	**Specification**	**Comment**
A	B7 Ref	EN 590	Petroleum diesel containing no HVO, FAME min. 6 vol%
B	B30	EN16709	Containing no HVO, FAME min. 29 vol%
C	R33	EN590	Containing 26 vol% HVO, FAME 7 vol%, (Nominal maximum renewable content whilst still complying with EN 590 min density limit, though in this case a higher proportion of HVO could have been used given the relatively high density of petroleum diesel used)
D	R80B20	N/A - for future reference	Containing 80 vol% HVO complying with EN15940 and FAME 20 vol% complying with EN14214
E	HVO	EN15940	Containing no FAME and no petroleum diesel

Table 5-2 Final calculated test fuel matrix

Final test fuel matrix								
Test fuel No.	**EN590 B0**	**FAME**	**HVO**	**Sum**	**EN590 B0**	**FAME**	**HVO**	**Sum**
	vol%	**vol%**	**vol%**	**vol%**	**mass%**	**mass%**	**mass%**	**mass%**
Fuel A B7 Ref	93.5 %	6.5 %	0.0 %	100 %	93.2 %	6.8 %	0.0 %	100 %
Fuel B B30	70.5 %	29.5 %	0.0 %	100 %	69.5 %	30.5 %	0.0 %	100 %
Fuel C R33	67.5 %	6.6 %	26 %	100 %	68.5 %	7.0 %	24.5 %	100 %
Fuel D R80B20	0.0 %	19.4 %	80.6 %	100 %	0.0 %	21.4 %	78.6 %	100 %
Fuel E HVO	0.0 %	0.0 %	100%	100 %	0.0 %	0.0 %	100.0 %	100 %

Table 5-3: Main characteristics of finished test fuels.

Property	**Units**	**EN590 Limits**	**B7 Ref**	**B30**	**R33**	**R80B20**	**HVO**
			Fuel A	**Fuel B**	**Fuel C**	**Fuel D**	**Fuel E**
Cetane Number	(CFR)	51 min	52,9	51,6	55,8	67,6	73,3
Density at 15°C	kg/m^3	815 min	843,7	852,7	828,3	800,3	780,6
Distillation IBP	°C	-	176,6	179,5	182,9	227,7	200,8
Dist. 50% v/v	°C	-	288,6	307,5	287,2	288,3	281.0
Dist. 95% v/v	°C	360 max	342,5	344,3	339,8	332,5	297,7
Distillation FBP	°C	-	351,6	348,7	349,4	341,4	310,0
Viscosity at 40°C	mm2/s	2 min 4.5 max	3,336	3,516	3,248	3,192	2,978
Aromatics, Total	%(m/m)	-	19	14,4	13,9	<0,8	0,40
Aromatics, Poly (2+3)	%(m/m)	8 max	2	1,6	1,4	<0.8	0,1
FAME	%(V/V)	7 max	6,6	29,5	6,7	19,8	-
Oxygen	%(m/m)		0,65	3	0,75	2,1	0,00
Hydrogen	%(m/m)		13,4	13,1	13,8	14,4	15,20
Carbon	%(m/m)		85,9	83,8	85,5	83,6	84,8
Net Heating Value	MJ/kg		42,75	41,44	42,99	42,74	43,92
Lubricity, HFRR (WSD)	µm	460 max	230	170	210	150	385
CO_2 intensity	g CO_2 / MJ		73,7	74,2	72,9	71,7	70,8
CO_2 intensity	g CO_2/kg		3149,7	3072,7	3135,0	3065,3	3109,3

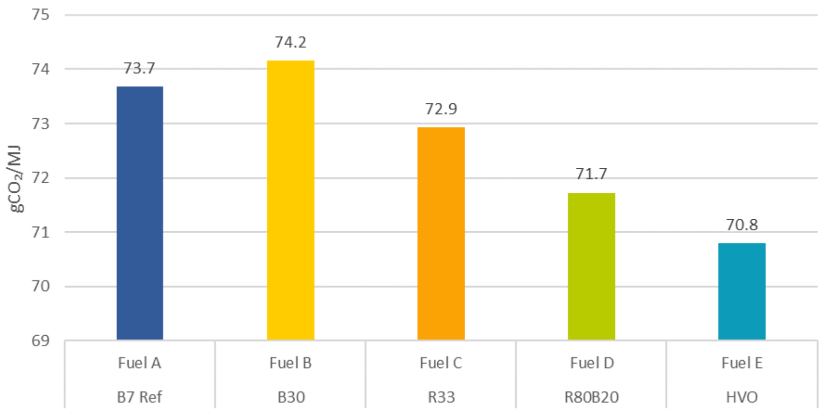


Figure 5-1 Calculated fuel CO_2 intensity

The rationale behind each fuel selection for this study is described below:

Fuel A - B7 Ref:

The B7 Ref fuel was selected to represent a current European diesel road fuel complying with EN590 and serves as the reference fuel. The base fuel is crude-derived petroleum diesel (93.5%v/v) and is blended with FAME type biodiesel which complied with EN14214. The density was close to the top of the density range permitted in the EN590 specification: 845g/L and the cetane number was close to the EN590 specification of 51.

Fuel B - B30:

The B30 fuel was selected to enable the evaluation of the impact of high FAME content levels, much higher than currently permissible in EN590. Elevated NOx levels may be expected from a high FAME content, and the study will show to what extent this could be mitigated by the sophisticated NOx-reduction exhaust aftertreatment system used in the Euro VI step E vehicle tested here.

Fuel C - R33:

The fuel was blended with increased renewable content, using a combination of HVO and FAME to maintain compliance with EN590 specification. Fuel blends with 26% HVO plus 7% FAME have been subject of previous industry publications where maximum renewable content within EN590 was targeted[6]. However, further increases to the total renewable content are possible depending upon the relative density of blend components and that the minimum density limit of EN590 has been reduced to 815 kg/m^3 where it was previously 820kg/m^3. This fuel could represent scenarios in which availability of renewable/paraffinic fuels are limited or to help decarbonise applications not certified for EN15940 fuels and to determine in these cases whether emissions benefits scale with paraffinic fuel content, while remaining within the existing EN590 specification.

Fuel D - R80B20:

This fuel represents a fully renewable fuel which could be a feasible diesel-like fuel in future regulations. ASTM 7467 is an example of this kind of specification. The density was too low to comply with EN590 but higher than a pure paraffinic diesel as the density was around 800kg/m3.

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[6] https://www.neste.com/news/diesel-r33-enables-co-2-savings-of-at-least-20-percent-test-phase-completed-in-germany

Fuel E - HVO:

The paraffinic diesel was chosen to represent paraffinic fuels, which could be derived from natural gas (GTL), biological sources (such as HVO, BTL) and PTL fuels. The results will be indicative for other low-carbon paraffinic fuels within EN 15940. In this case the fuel is 100% renewable HVO falling in the lower end of the EN15940, class A specification in terms of density. This enables the study to evaluate the impact of low density, high H/C ratio, low aromatics and high cetane number on emissions and performance.

5.2. TEST VEHICLE

5.2.1. Test Vehicle Selection

For best market and future relevance, the test vehicle was specified such that it would represent a vehicle class which would most likely continue to use large volumes of low carbon and alternative diesel fuels in the long term. Long haul trucks (tractor trailers) are the most common types of heavy-duty vehicles (HDV) in the European market, which make up the majority of the HDV CO_2 emissions in the EU[7]. As long-haul trucks are typically operated with higher loads and in energy intensive tasks, they are typically equipped with larger and higher-powered engines compared to any other counterparts of the more common HDV segments. Despite the goal to move towards zero tailpipe emission vehicles in the EU, it is estimated that long haul trucks would be the most technologically challenging to electrify. Recent reports also suggest that it’s more cost effective[8] to initially focus the potential for electrification on lighter HDVs which typically operate on short distances, in densely populated areas, e.g. delivery and refuse trucks. The electrification of lighter HD applications is more easily justified by charging infra-structure, operational range, availability of battery material and general practical perspective. The remaining space left by the European Union regarding the CO_2 regulation will likely be for heavy-duty trucks dependent on the ICE. These will most probably be used in long-haul applications. It should also be noted that the studies and reports referred to in this report, which address the predictions of future (long-haul) HDV markets does not account for any hybrid application simply because the interest and gains obtained from these applications are low, and thus the HDV market is likely to disperse into two main categories: 1. all electric applications for lighter and short distance HDVs and 2. HDVs with large energy consumption combined with long daily mileage retaining ICEs or adopting fuel cells.

The truck model was selected based on market share and truck availability. HDV vehicle sales in EU by manufacturer is largely split into five brands[9], Mercedes-Benz, Scania, DAF, Volvo and MAN. Then, vehicles were screened based on availability, mileage, age, and technology. The most suitable option available was a Euro VI Step E Volvo FH460 tractor. The vehicle had a suitable engine, a 13 litre in-line six-cylinder common rail diesel engine, coupled with a turbo-compound forced induction system. The transmission was an i-shift automatic unit with robotized shifting. The test vehicle EATS consisted of a diesel oxidation catalyst (DOC), a diesel particulate filter (DPF), AdBlue® dosing system followed by a selective catalytic reduction catalyst (SCR), and lastly with an ammonia slip catalyst (ASC). The EATS had two NOx sensors, one located upstream, and one downstream of the SCR/ASC unit. The SCR catalyst was coated with Copper-Iron-Zeolite hybrid (CuFeZ). Furthermore, the D13 TC engine was fitted with a cooled, high-pressure exhaust gas recirculation system (EGR). These features can be considered to represent current state-of-the-art technology and fulfil the criterion of a suitable test vehicle. A table detailing the vehicle specifications is shown in Table 5-4.

[7] https://theicct.org/wp-content/uploads/2023/07/hdv-co2-emissions-eu-2020-reporting-2-jul23.pdf
[8] https://theicct.org/wp-content/uploads/2023/01/hdv-europe-decarb-costs-jan23.pdf
[9] https://theicct.org/wp content/uploads/2023/07/hdv co2 emissions eu 2020 reporting 2 jul23.pdf

Table 5-4 Specification of the tested HDV.

Vehicle category	N3
Make	Volvo
Model	FH460
Model year	2022
Emission class	Euro VI Step E
Chassis	6x2
Engine	D13K460, TURBO-TC, inline 6 cylinders, displacement 12.8 litres
Peak power (kW)	345 (1250 – 1600 r/min)
Peak torque (Nm)	2600 (900 – 1300 r/min)
Emission control	EGR, DOC, DPF, SCR, ASC
FIE	Common rail
Tractor unladen weight, tractor (kg)	8905
GVW (kg)	30 800
Vehicle total mileage (km)	114 000

Exhaust aftertreatment layout:

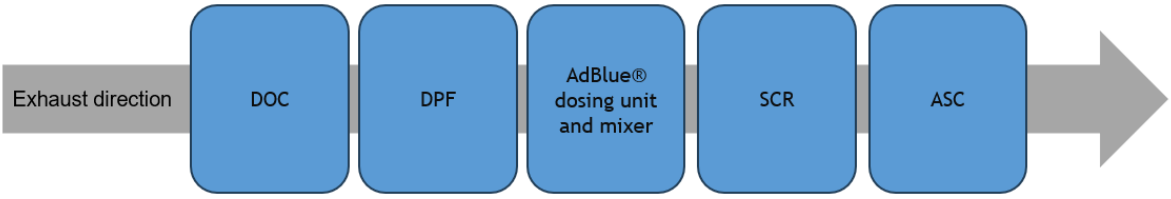


Figure 5-2 An illustration of the vehicle exhaust aftertreatment layout.

Figure 5-3: The test vehicle on the heavy-duty chassis dynamometer.

Figure 5-4: A rear-view of the test vehicle installed on the heavy-duty chassis dynamometer.

5.2.2. Vehicle Payload and simulated road-loads

To test a vehicle on a chassis dynamometer, a simulation model for the vehicle is required. As the test vehicle represented a long-haul truck, values simulating a combination-truck pulling a semi-trailer was used. The test vehicle would have been suitable for this application as it was tractor type truck. The load on the simulated trailer was an average load value used in continental Europe. According to Eurostat, the average load for an HDV is 14400 kg[10]. It was decided to use an enclosed box trailer type as this type is the most common trailer type for generic transport services. As the mass of such trailer type varies, the mass used was an average of two example trailers. One of them is presented in Figure 5-5. The load on the kingpin is not included in the mass of the empty trailers so an example value for this was used as this value was available for one example trailer. Using this value, the total simulated tractor-trailer mass was 30800 kg. The breakdown of the simulated masses is shown in Table 5-5.

[10] Eurostat https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Road_freight_transport_by_journey_characteristics#Road_freight_transport_in_tonnage_and_average_loads

Figure 5-5 One of the example trailers used for the road load model generation.

Table 5-5 A breakdown of the simulated masses

Trailer [kg]	Kingpin [kg]	Truck [kg]	Load [kg]	Total [kg]
6000	1500	8900	14400	30800

Besides the simulated inertia, friction parameters F0, F1 and F2 are also needed. VTT has a calculation template for the road load model generation. It contains data from previously done coast down tests using various loads. The template contains tyre data along with the vehicle data. The first iteration of the road load model was tested using the new test cycle on the chassis dynamometer. The parameters for the initial iteration are displayed in Table 5-6. However, the measured work from the wheels was less than was expected. The target for the work was four times the WHTC work as a minimum. As the vehicle/engine work criterion was not met, the F2 parameter was increased, and the test was repeated. The F2 parameter is the parameter simulating the aerodynamic drag so the increase would be realistic for a less aerodynamic vehicle combination. With the increased F2 parameter a suitable work target was met. The final road load parameters are shown in Table 5-7.

Table 5-6 Key parameters for the initial road load iteration

Inertia, simulated mass [kg]	F0 [N]	F1 [N/km/h]	F2 [N/(km/h)^2]
30800	1404	-7.064	0.3741

Table 5-7 Key parameters for the final road load model

Inertia, simulated mass [kg]	F0 [N]	F1 [N/km/h]	F2 [N/(km/h)^2]
30800	1404	-7.064	0.5000

5.3. EXPERIMENTAL SET UP AND MEASUREMENT PROCEDURES

The test facility consists of a chassis dynamometer, vehicle and environment data loggers and emission analysing equipment. The emission measurement system implements a full flow constant volume sampler dilution tunnel (CVS). Following exhaust components were measured: CO_2, CO, NO_x, NO, THC, CH_4, NMHC, N_2O, NH_3 PN10, PN23 and PM.

Note that because NMHC with the equipment used was more reliable, in this case, it is assumed that NMHC = NMOG. Currently regulated Euro VI emissions were measured with CVS/AMA i60 bag sampling, determining average gaseous exhaust results over the whole cycle and each phase. N_2O and NH_3 were measured using a fourier-transform infrared analyser (FTIR). PN10 and PN23 were measured with a Butanol Condensing Particle Counter (CPC) with a fixed dilution ratio diluter.

PM was collected with an AVL PSS system, applied with Pall TX40 type filters. The engine exhaust mass flow was determined from the exhaust dilution rate in CVS. Vehicle fuel consumption (FC) was primarily calculated from carbon balance based on CO_2 (and CO) results acquired from exhaust bag sampling in combination with fuel carbon content proportioned to total determined exhaust mass flow. These FC calculations were then double checked and compared with values from a fuel scale. The final FC result for measured fuel was determined from the change in fuel mass on a weight balance acquired over the whole test cycle. Because the vehicle urea reservoir was located such that any gravimetric scaling would require extending the OEM urea lines, vehicle AdBlue consumption was not measured. Based on previous experience, extending the urea lines between reservoir and pump increase the risk of defective urea-injection, hence it was seen as an excessive risk that could potentially interrupt the normal operation of the test vehicle. Available CAN-bus channels (J1939) were logged using a Windows laptop, a CAN-bus adapter, and specialised software during the tests.

A comprehensive list of measurement equipment used is shown in Table 5-8. Furthermore, detailed pictures of the test configuration are shown in Figure 5-6, Figure 5-7 and Figure 5-8.

Table 5-8: Test apparatus and measured variables.

Device make, model	Measurement description	Principle of operation
AVL CVS i60, CVS 2000	Diluted exhaust. flow	Full Flow CFV-CVS
AVL i60, IRD	CO concentration	NDIR
AVL i60, IRD	CO_2 concentration	NDIR
AVL i60, HFID	HC concentration	Heated FID
AVL i60, HCLD	NO/NO_x concentration	Heated CLD
AVL PSS i60	Particulate mass	mass sampler
Fuel scale	Fuel consumption	Gravimetric
Airmodus A20 and Dekati DEED-100	Particulate number down to 10 nm	CPC+ Diluter
Airmodus A23 and Dekati DEED-100	Particulate number down to 23 nm	CPC+ Diluter
FROUDE CONSINE AC Dynamometer	Torque & vehicle speed	load cell & inductive counter
Froude logger	Ambient test cell and exhaust gas temperatures (exhaust tail-pipe outlet)	K-type thermocouple
CAN-logger	CAN data logger (vehicle CAN data)*	J1939
Vehicle upstream/downstream engine SCR NO_x sensor	NO_x	OEM NO_x sensor
Rowaco FTIR, after engine after treatment	NH_3, N_2O	FT-IR

*Engine coolant temperature [°C], Engine speed [rpm], Engine torque [%], Engine load [%], accelerator pedal position [%], fuel rate [kg/h], NOx upstream [ppm], NOx downstream [ppm]

Figure 5-6 Fuel scale and test fuel rig.

Figure 5-7 FTIR connected to the exhaust line of the test vehicle.

Figure 5-8 Exhaust line connected to the exhaust flow meter (EFM).

5.4. TEST MATRIX

The matrix of simulated RDE testing conforming with Euro 7 requirements was built with the following criteria:

- Initially repeat tests with the reference fuel, Fuel A until the deviation in CO_2 between two consecutive tests was within +/- 2 %.
- Perform fuel testing with all five fuel blends in a randomised order.
- Produce at least three repetitions per fuel.
- Fuel order was divided into three test sequences, containing one repetition of each fuel in a predefined order.
- Conduct extra tests for fuels for which results were discarded due to equipment failure or were deemed invalid due to engineering reasons described in chapter 5.7 (in this case D + C).

The final test sequence for simulated RDE tests is shown in Table 5-9.

Table 5-9 Final fuel test order for simulated RDE tests

Sequence	Ref.		Test sequence 1					Test sequence 2					Test sequence 3					Extra	
Test #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Fuel	A	A	C	A	D	B	E	A	E	C	D	B	C	B	E	D	A	D	C

Table 5-10 Fuel test order for tests under TfL UIP cycle

Sequence	Test sequence					
Test #	1	2	3	4	5	6
Fuel	A	X	A	X	A	X

Where Fuel X is the most representative low carbon fuel in simulated RDE conditions, Fuel E (HVO) was chosen as the test fuel.

5.5. TEST CYCLES

5.5.1. Simulated RDE test cycle

In order to test the effect of the five fuel blends on current Euro VI technology under simulated RDE Euro 7 conditions the following parameters were used:

- Recreation of a Euro 7 compatible driving cycle (should fulfil at least 4x WHTC work).
- Transferring of a Euro VI ISC cycle, e.g. *"VTT ISC Espoo"* road profile to form a tailored dynamometer cycle.
- An on-road (PEMS) test route for heavy vehicles was used to generate a chassis dynamometer test cycle meeting the Euro 7 requirements. The data was extracted from GPS data from actual testing previously conducted in the Espoo area in Finland. The route was however due to practical reasons shortened and the average speed was slightly adjusted but otherwise, the route remained unchanged.
- Road loads: VTT has a database for heavy-duty vehicle parameters.
- Test condition: +23°C ±2 °C. ambient temperatures.
- Final work = ~4.2 x WHTC.

The speed profile of the RDE Euro 7 compliant cycle is illustrated in Figure 5-9 and key driving parameters in Table 5-11. Correspondingly, example histograms of accelerator pedal position and engine load are shown in Table 5-10.

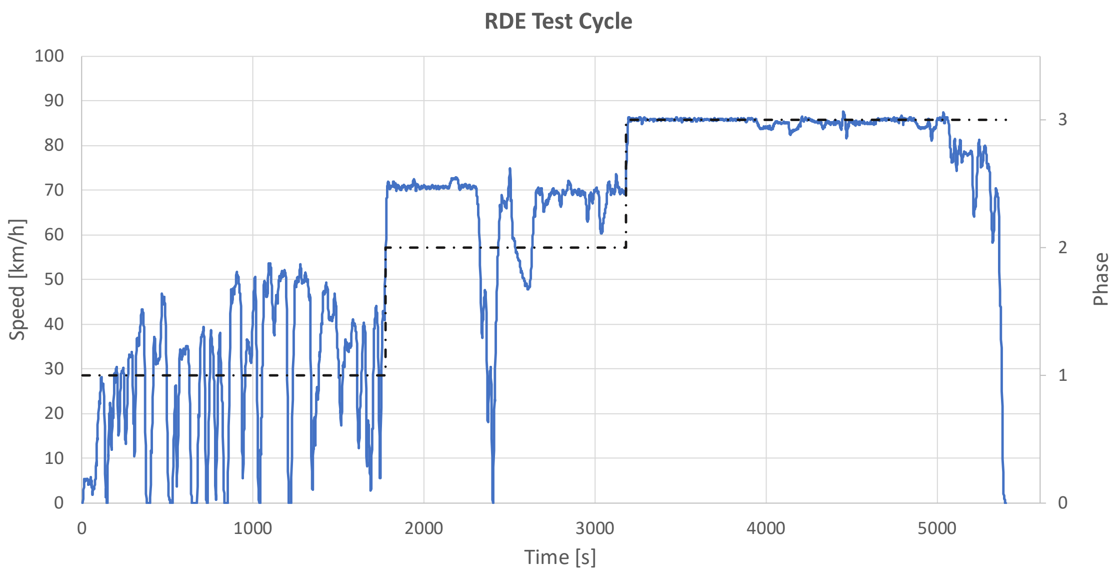


Figure 5-9 VTT Euro 7 RDE test cycle

Table 5-11 Key driving parameters of the VTT Euro 7 RDE cycle

Trip sections	Time	Distance	Trip requirements[11], share of trip	Actual Share of trip	Required average speed[10]	Actual average speed
	[s]	km	[%]	[%]	[km/h]	[km/h]
Urban	1773	13.7	30 % ±5 %	33 %	15 -30	28.0
Rural	1408	25.4	25 % ±5 %	26 %	45 - 70	65.2
Motorway	2219	51.0	45 % ±5 %	41 %	>70	82.7
Total	5400	90.1	100	100 %	-	60.2

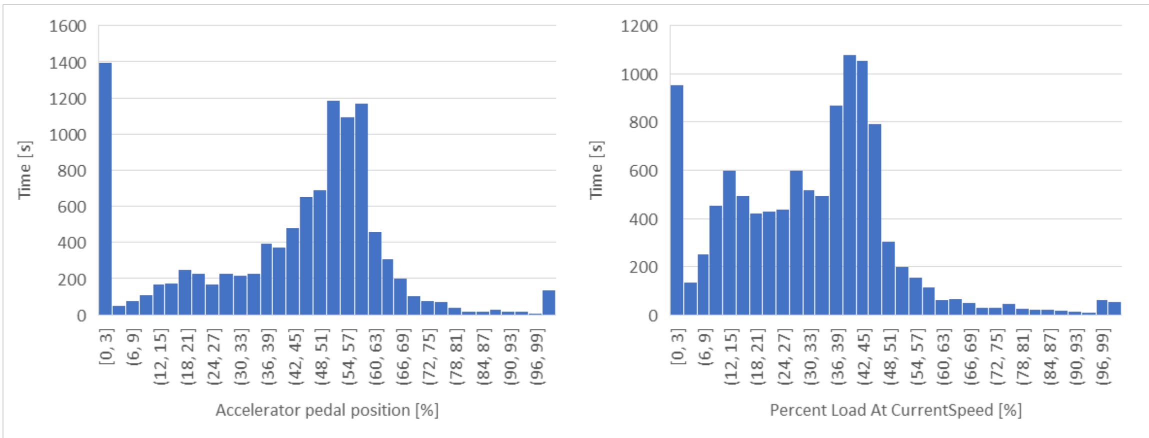


Figure 5-10 A histogram of recorded accelerator pedal position [%] and corresponding engine load [%] at given engine speed. Data collected from vehicle CAN-bus.

5.5.2. Test cycle in demanding urban conditions

For additional testing, the vehicle was tested with a suitable test cycle, where the goal was to simulate extremely demanding emissions and non-fuel-efficient driving conditions.

It was formerly concluded during a Concawe test campaign executed in 2020[12], that a simulated test cycle from London urban area, TfL UIP, created by Transport for London (TfL[13]), would be well suited for this purpose. TfL UIP cycle is based on real world data recorded by TfL in London from urban driving conditions in between peak traffic times. The cycle represents traffic conditions where the average speed is low and idle times are rather long, followed by rapid and repeated low speed accelerations. Based on earlier experience, TfL UIP tends to cause exceptional stress on vehicle EATS, as the cycle contains both long idle times and high loads, thus resulting in low EATS temperatures (therefore relatively low NOx conversion efficiencies) between the transient phases and high demand on the EATS, especially SCR in the transients. This cycle therefore provides a ‘worst case real world scenario’ for the NOx control capabilities of the vehicle.

[11] According to paragraph 4.5 in Annex 8 UN Regulation No 49 - Uniform provisions concerning the measures to be taken against the emission of gaseous and particulate pollutants from compression-ignition engines and positive ignition engines for use in vehicles [2023/64]
https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:42023X0064

[12] Williams, R., Pettinen, R., Ziman, P., Kar, K., & Dauphin, R. (2021). Fuel effects on regulated and unregulated emissions from two commercial Euro V and Euro VI road transport vehicles. Sustainability, 13(14), Article 7985. https://doi.org/10.3390/su13147985

[13] Acknowledgments: The authors thank Transport for London for providing with the test cycle that was used in this campaign
https://tfl.gov.uk/

Furthermore, as data was already obtained in a previous Concawe study in 2020, the justification for repeating similar tests for improved comparability was strengthened.

The TfL UIP cycle is a 38-minute-long test cycle with a total distance of 8.7 km. The TfL UIP cycle was for measuring purposes split in half; two phases for isolating cold start conditions if needed. However, because the profile is rather suitable for fulfilling the other criteria set for the conditions, it was nevertheless seen as the most appropriate test cycle for this purpose.

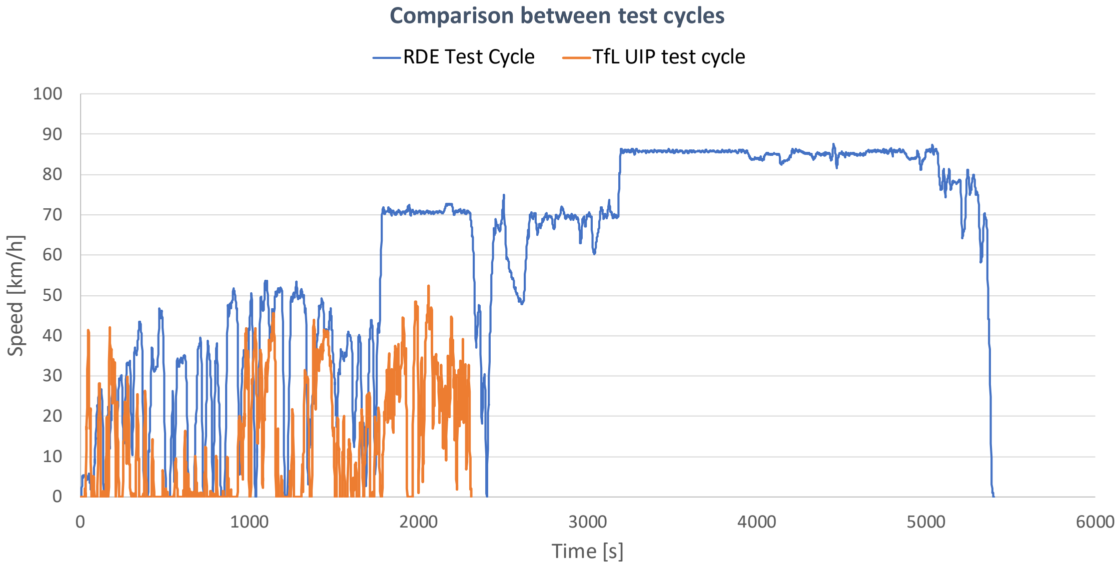


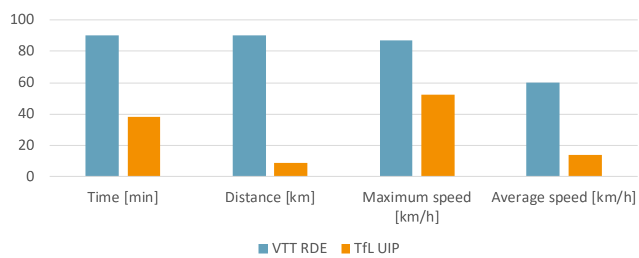
Figure 5-11 Comparison between speed profile of TfL UIP and RDE test cycles.

Table 5-12 The key parameters of TfL UIP test cycle

Trip sections	Time	Distance	Average speed
	[s]	km	[km/h]
Phase 1	1200	2.9	8.6
Phase 2	1110	5.8	19.0
Total	2310	8.7	13.6

Table 5-13 Comparison of the VTT RDE and TfL UIP test cycles

Cycle	Time	Distance	Maximum speed	Average speed
	[s]	km	[km/h]	[km/h]
VTT RDE	5400	90.1	87	60.2
TfL UIP	2310	8.9	52.3	13.9



5.6. TEST PREPARATIONS AND TEST PROCEDURE

The test procedure, practices and preparations were planned and executed as follows:

Day prior to first test:

1. Fuel change, flushing of fuel system (flush through with 20l of fuel from fuel return line).
2. Conditioning of vehicle and dynamometer driving at 80 km/h: a. Operate the vehicle 80km/h for 10 minutes.
3. Refill fuel system. Run one world harmonized vehicle cycle (WHVC) for transient conditioning, with the purpose to condition the ECU/transmission for the given fuel.
4. Vehicle cool down and soaking before testing the next day.

Every test day:

1. Prepare test set-up, calibrate analysers and ensure proper functioning of all systems.
2. Vehicle testing using the RDE cycle.
3. Analysis and evacuation of the sample bags.
4. Fuel change, flushing of fuel system (20 l of fuel from fuel return line).
5. Conditioning of vehicle and dynamometer driving at 80 km/h for 10 minutes.
6. Refill fuel for the next test. Then run one WHVC cycle for transient conditioning.
7. Vehicle cool down and soaking before testing the next day.

5.7. MONITORING OF RESULT QUALITY

The monitoring of result quality and repeatability was based on three factors described below. Special attention was paid to any trends taking place for variables concerning reference fuel A.

1. Checking initial repeatability using reference fuel A. Perform initial tests, i.e. shakedown tests, for monitoring of test repeatability. The criterion was set such that at least two consecutive tests with reference fuel A should produce similar CO_2/fuel consumption (FC) and wheel work results, within +/- 2 %. When these criteria were fulfilled, the monitoring of the result quality was advanced based on the second factor described below.

2. FC and CO_2 results were cross checked by calculating FC from measured CO_2 results and CO_2 from measured FC. The correlation of the two different fuel consumption results were cross checked throughout the campaign. If any abnormal behaviour would occur, the testing would be immediately paused for further inspection of the root cause.

3. The consistency of wheel work data was followed throughout the campaign. It was assumed that from a performance perspective, despite fuels causing some deviation in ECU calibration, the wheel work would remain sufficiently constant. If any severe deviation would have occurred, the campaign would be paused for further inspection.

5.8. POST PROCESSING OF TEST RESULTS

5.8.1. General overview of post processing

The results obtained from this experimental campaign consisted of real-time readings coming from the measurement devices which were logged. Non-transient values, such as barometric pressure and humidity, and filter weights for particulate matter, were collected manually. The particulate mass filters were weighed before and after the test run. One filter was used for each phase of each test. Besides the gaseous real-time measurements, sample bags were also gathered during each phase. One phase produces one exhaust bag and one background bag. These are analysed and processed automatically after a test has been executed. The real-time measurement devices consisted of gaseous readings from several sources, two particle number counters, CAN-bus logger, exhaust flow meter and chassis dynamometer performance values. The chassis dynamometer's control system was also logging fuel mass from a scale, temperature readings and ambient conditions from the test chamber.

All gathered values from a single test were compiled together in a Microsoft Excel calculation template. The data sources were synchronized manually using key components that are known to behave similarly. The CO_2 readings came from three different sources and exhaust mass flow could be calculated from two of these. The separate exhaust flow meter could be synchronized with the calculated exhaust flow. The particle number readings could be synchronized together and then with the vehicle speed.

NOx correction for humidity were corrected using k_h-factors based on ambient air conditions. This is a standardized procedure for correcting NOx emissions in laboratory vehicle emission testing, e.g. described in UN Regulation No 49 07 series of amendments, Annex 4, paragraph 8.2, stated as follows:

$$k_{h,D} = \frac{15,698 * H_a}{1000} + 0.832$$

Where H_a is the intake air humidity, g water per kg dry air.

With this kind of a test cycle, the synchronization is always a compromise as the time interval to get perfect synchronization fluctuates. This happens due to the exhaust flow changes and the distance between the sample points. To achieve the best possible synchronization, high load periods are used for the synchronization. These are the moments when most of the emission components tend to be at their peaks. The synchronization is then at its worst while the exhaust emissions are at their lowest levels.

After the synchronization of the data, multiple Microsoft Visual Basic macros were used to process the data. Each test produced 3 or 4 (each phase and full test depending on cycle) rows of data with each consisting of ~200 values. All test results were compiled into a compilation file to produce the graphs and the tables. This data was initially analysed in a chronological order to identify any non-fuel related trends.

Finally, a simple linear correlation analysis between test results and single fuel properties was conducted. The objective for this analysis was to perform a rapid screening of possible connection between specific independent fuel properties (or meaningful/non-meaningful properties) and the test results. Because this work was outside of the scope of the project, the contents and results related to this analysis is only available in Appendix 3.

5.8.2. Implementation of MAW calculations for determining exhaust emissions according to Euro 7

As described in chapter 4. “*An overview of Euro 7 regulation*”, the quantification of exhaust emissions in RDE conditions for Euro 7 are an implementation of the UN regulation No. 49 (07 series of amendments). This procedure was implemented for quantification of vehicle emission characteristics in respect to Euro 7. The fundamental principle of the procedure is based on dividing the cumulative trip emissions recorded from the RDE-test into sub-sets determined by engine specific reference work, or cumulative CO_2 mass respectively. The reference work for a specific engine is defined based on a type approval engine test conducted in laboratory conditions (World Harmonized Transient Cycle, WHTC). The length of each sub-set is equivalent to reference work and corresponding cumulative emissions for each sub-set are divided by the reference work value, forming one averaging window as shown in Figure 5-12. One sub-set is calculated for each increment in time that is equal to the data sampling period, forming a moving average of the complete test, i.e. all collected averaging windows. This assessment of the complete sub-sets of windows are called the moving average window (MAW). The cumulative work for the test is collected from the instantaneous OBD/CAN work during the test trip and the emissions are calculated using appropriate emission analysers specified in the regulation.

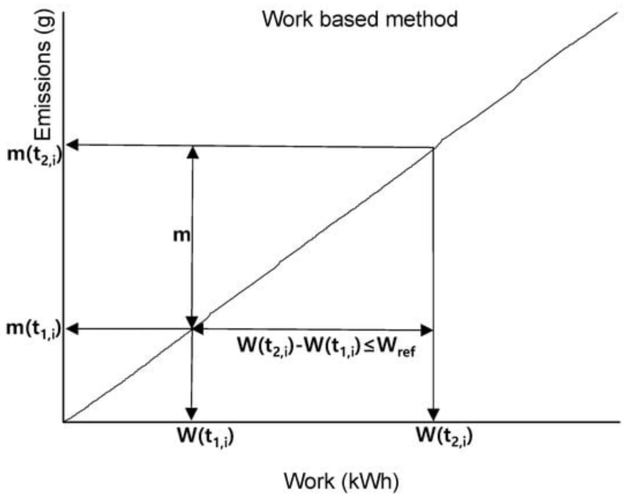


Figure 5-12 Work based method for defining MAW emissions[14].

According to UN regulation No. 49, 07 series of amendments, the procedure is as follows:

The duration ($t_{2,i}$ - $t_{1,i}$ of the ith averaging window is determined by:

(1) $$W(t_{2,i}))-W(t_{1,i})\geq W_{ref}$$

where:

- $W(t_{j,i})$ is the engine work [kWh] measured between the start and time $t_{j,i}$
- W_{ref} is the engine reference work from WHTC [kWh]
  - In this case, reference WHTC work was unknown and approximated using the known engine power curve.

[14] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:42023X0064

and the specific emissions e [g/kWh] or [#/kWh] are calculated for each window and each pollutant following:

$$e = m/(W(t_{2,i})) - W(t_{1,i})) \quad (2)$$

where:

- m is the change in emissions (per component) over the given window [mg/window] or [#/window]

Emission values from each work window express the equivalent of exhaust emissions during one equivalent of WHTC reference work.

It should be noted that because portable emission measurement systems (PEMS) devices are implemented only in real world RDE tests, laboratory grade, stationary equipment was used instead in this specific campaign. The primary reasons for this were that laboratory grade equipment has less uncertainty and the data sets provided in the laboratory-environment are more easily implementable for additional emission components, which does not currently exist for Euro VI grade PEMS devices.

6. FUEL EFFECTS IN SIMULATED RDE TESTS

6.1. AN OVERVIEW OF TEST VEHICLE PERFORMANCE USING REFERENCE FUEL A

As explained in chapter 5.7. *MONITORING OF RESULT QUALITY*, the performance of reference fuel A (EN590 B7 ref) was monitored closely throughout the simulated RDE experimental campaign to ensure good quality measurements. The reference fuel was therefore tested five times instead of the regular three repetitions for the other test fuels. The higher number of repetitions for the reference fuel determined the baseline performance of the vehicle, but also quantified the repeatability of the entire test set-up throughout the campaign. Therefore, in particular the repeatability and trends of engine and wheel work together with CO_2 and fuel consumption (FC) results for fuel A were monitored.

The recorded work from the ECU and dynamometer for fuel A alone is shown in chronological order in Figure 6-1, and other key performance metrics are shown in Table 6-1. The average engine work monitored from the ECU using the CAN-bus was 120.4 kWh, with a deviation of +1.6 – 1.4 kWh and 106.2 kWh + 0.8 – 0.5 kWh measured from the wheels respectively, resulting in a brake specific fuel consumption (BSFC) of 206.5 g/kWh (from engine/ECU), 234 g/kWh measured from the wheels. The total powertrain efficiency was on average ca. 36.4 % with a calculated drivetrain loss estimated between engine and wheels of 12 %. These numbers correspond to a fuel consumption of 27.6 kg or 32.7 litres of fuel per 100 km. The deviation in CO_2 results for all five tests with reference fuel A was less than +/- 0.75 % for the distance based, and less than +/-0.6 % for wheel work-based results.

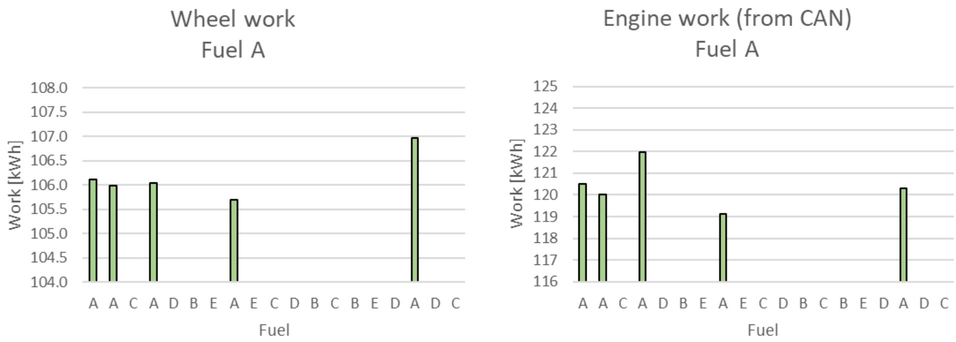


Figure 6-1 Wheel work recorded from fuel A in a chronological test order.

Table 6-1 A summary of key performance metrics recorded for fuel A in the RDE cycle.

	Cumulative fuel consumption	Work engine	BSFC Engine	Work wheels	BSFC Wheels	Powertrain efficiency	Fuel consumption	
	g	kWh	g/kWh	kWh	g/kWh	%	kg/100 km	l/100 km
Average	24541	120.4	206.5	106.2	234.1	36.4 %	27.6	32.7
Min	24373	119.1	204.8	105.7	233.2	36.3 %	27.4	32.4
max	24630	122.0	207.3	107.0	235.5	36.6 %	27.7	32.8

The baseline emission performance for reference fuel A is shown as distance-based results in Table 6-2 and as work-based (measured from engine work, CAN J1939) results in Table 6-3. Table 6-3 includes for comparison the Euro 7 emission limits both in laboratory and in RDE conditions. The general conclusion of the emission performance in given test conditions is rather evident – the emission performance of the given test vehicle is exceptionally good overall, meaning total emission trip results are significantly lower than any regulatory limits.

For example, trip NO_x emissions are between 69 and 98 mg/kWh, compared to Euro 7 limits, 200 mg/kWh for laboratory conditions and 260 mg/kWh for RDE tests. HC, CH_4 and NH_3 emissions were found to be nearly non-existent (close or below detection limit), meanwhile CO emissions are in the region of 60 mg/kWh compared to Euro 7 laboratory limit of 1500 mg/kWh. PN/PM emissions results were between 15 and 27 % of the regulatory requirements set in laboratory conditions. In given ambient conditions and circumstances, the Euro 6 step E test vehicle selected for the campaign would easily fulfil the Euro 7 criteria.

Table 6-2 An overview of distance-based emission results for fuel A

Emission type	CO_2	CO	HC	CH_4	NMHC*	NO_x	N_2O	NH_3	PN_{23}	PN_{10}	PM
per distance	g/km	mg/km							#*10^11/km		mg/km
Average	867.7	79.6	-4.3	-3.1	-1.6	113.7	219.0	0.9	0.8	2.1	1.7
Min	861.3	61.3	-5.6	-3.9	-2.2	91.8	206.5	0.8	0.8	2.0	1.2
Max	871.2	105.2	-1.3	-1.6	0.0	130.8	246.2	1.0	0.9	2.2	2.3

Table 6-3 An overview of ECU work-based emission results for fuel A

Emission type	CO_2	CO	HC	CH_4	NMHC*	NO_x	N_2O	NH_3	PN_{23}	PN_{10}	PM
Engine work based	g/kWh	mg/kWh							#*10^11/kWh		mg/kWh
Average	649.8	59.6	-3.2	-2.3	-1.2	85.1	164.0	0.7	0.6	1.6	1.2
Min	644.4	45.8	-4.1	-2.9	-1.7	68.8	152.8	0.6	0.6	1.5	0.9
Max	652.4	78.9	-1.0	-1.2	0.0	98.3	184.5	0.8	0.7	1.7	1.7
Euro 7 WHTC	-	1500	-	500	80*	200	200	60	-	6	8
Euro 7 RDE	-	1950	-	650	105*	260	260	85	-	9.0	-

*NMOG, i.e. 'non-methane organic gases' or 'NMOG' means the sum of non-oxygenated and oxygenated hydrocarbons, excluding methane, emitted from the tailpipe. Methodology for quantification to be announced. Because NMHC with used equipment was seen more reliable, in this case it is assumed that NMHC = NMOG

However, tests in the emission-demanding TfL UIP test cycle proved challenging for the test vehicle, as expected. The CO_2 emissions increased from 867 g/km to 1987 g/km, also CO and NOx emissions increased dramatically. Here, the CO emissions were ca. 20 times higher, 1591 mg/km. The NOx emissions increased from 114 mg/km to 3222 mg/km. Interestingly, a lesser effect on hydrocarbon emissions was seen. The PN10 and PN23 rose to 3.8×10^{11}/km and 2.0×10^{11}/km respectively. The average results recorded for reference fuel A from the VTT RDE cycle and TfL UIP are shown in Table 6-4.

Table 6-4 Vehicle emission performance compared between VTT RDE test cycle and TfL UIP

Emission type	CO_2	CO	HC	CH_4	NMHC	NO_x	N_2O	NH_3	PN_{23}	PN_{10}	PM
Distance based results	g/km	mg/km							#*10^11/km		mg/km
VTT RDE	868	79.6	-4.3	-3.1	-1.6	113.7	219.0	0.9	0.8	2.1	1.7
TfL UIP	1987	1591.2	7.9	-4.0	11.3	3222.5	262.4	2.2	2.0	3.8	2.4

6.1.1. Vehicle emission performance compared to previous measurements

To understand more comprehensively the baseline emission characteristics of the Euro VI step E test vehicle, the emission performance for reference fuel A was compared to results from two previous Euro VI HDV test campaigns conducted by VTT in 2020 and 2022 respectively. In 2020, VTT conducted in collaboration with Concawe fuel tests with a Euro VI step B HDV using

WHVC and TfL UIP test cycles[15]. In 2022, VTT conducted together with The ICCT on-road PEMS tests[16] for two Euro VI step D vehicles. During the PEMS tests, both an ISC compatible route, and an EATS demanding, “low-load-cycle” resembling route around the Helsinki metropolitan area was used. The given test vehicles are introduced in more detail in Table 6-5. The results from all vehicles are compared in Table 6-6.

The results shown in Table 6-6 suggest that the emission response of Euro VI vehicles may vary significantly depending on multiple variables, primarily on test conditions, vehicle model and emission class (Euro VI sub class). Nevertheless, notable improvements in emission performance throughout the Euro VI amendments can be noted. The results obtained with the test vehicle (Volvo FH460) and reference fuel A shows that in the VTT RDE cycle, the Euro VI step E vehicle outperformed all other Euro VI HDVs in terms of HC, NO_x and particulates. Especially NO_x (85 mg/kWh) and PN (0.63 * 10^{11}/kWh) emissions can be considered extremely low. CO_2 emissions ranged between 650 to 1100 g/kWh depending on vehicle type and test cycle. Comparing CO_2 characteristics could be challenging because the HDVs were tested with a large variety of laden masses, ambient conditions and test cycles, hence great variation in CO_2 may be expected. As a result, no direct efficiency related conclusions can be drawn.

However, results obtained in TfL UIP, suggest that the given Euro VI vehicles face challenges in NO_x suppression, regardless of Euro VI sub class, during low load testing, where slow average speeds are combined with highly transient driving. The NO_x emissions of the Euro VI step B and Euro VI step E vehicles were comparable, more than 1000 mg/kWh above the permissible Euro VI limit. The reason for this is insufficient thermal management of the EATS during low load driving. Similar phenomena were seen for the two Euro VI step D vehicles, which produced evidently higher NO_x emissions during the low load cycle compared to a regular ISC-test. This is a widely recognized problem, as Euro VI class vehicles are due to practical reasons forced to rely on SCR systems for maximizing NO_x mitigation, which in turn tend to suffer from inappropriate thermal management especially when driving in conditions that cause insufficient exhaust gas temperatures (i.e. low loads).

Table 6-5 Main specifications of the compared Euro VI HDVs.

	Vehicle	Emission class	EATS	MY
HDV Fuel A	Volvo FH 460	Euro VI E	EGR, DOC, DPF, SCR, ASC	2022
HDV 1	Volvo 8900	Euro VI B	EGR, DOC, DPF, SCR, ASC	2016
HDV 2	VDL Citea LLE	Euro VI D	EGR, DOC, DPF, SCR, ASC	2020
HDV 3	Scania Citywide	Euro VI D	EGR, DOC, DPF, SCR, ASC	2018

[15] https://www.concawe.eu/wp-content/uploads/Fuel-Effects-on-Regulated-and-Unregulated-Emissions-from.pdf
[16] https://theicct.org/wp-content/uploads/2023/02/An-in-depth-analysis-of-post-processing-methods-on-heavy-duty-Euro-VI-exhaust-emissions_2nd_revision_.pdf

Table 6-6 Performance comparison of the given test vehicle using reference fuel A with data from two former test campaigns. Work calculated from ECU work.

Test vehicle emission performance compared to other measurements													
	Cycle	Amb. T	CO2	CO	HC	CH4	NMHC	NOx	N2O	NH3	PN23	PN10	PM
Engine work		°C	g/kWh	mg/kWh							#*10^11/kWh		mg/kWh
Euro VI Limits	**WHTC**			**4000**	**130**	**500**	**-**	**460**	**-**	**-**	**6**	**-**	**10**
Euro 7 Limits	**RDE**			**1950**	**-**	**650**	**-**	**260**	**260**	**85**	**-**	**9**	**-**
HDV Fuel A	**VTT RDE**	**23**	**650**	**60**	**-3**	**-2**	**-1**	**85**	**164**	**1**	**0.63**	**1.59**	**1.24**
HDV Fuel A	**TfL UIP**	**23**	**1002**	**801**	**4**	**-2**	**6**	**1627**	**132**	**1**	**1.03**	**1.91**	**1.22**
HDV 1	WHVC	23	1009	29	9	1	8	734	307	10	1.24	-	1.53
HDV 1	TfL UIP	23	1113	46	6	1	5	1481	454	8	1.16	-	1.58
HDV 2	ISC	4	673	6	13	-	-	355	172	34	2.54	2.24	-
HDV 3	ISC	-3	816	36	153	-	-	1020	106	27	4.56	2.76	-
HDV 2	Low Load Cycle*	-10	738	30	27	-	-	3424	452	78	7.65	3.45	-
HDV 3	Low Load Cycle*	3.7	935	85	23	-	-	1454	122	>1	3.58	2.37	-

*Low Load Cycle is a tailored on-road cycle designed by VTT to provoke the EATS. Low Load Cycle consists mostly of slow speed urban driving around dense traffic conditions combined with occasional, highly transient operation.

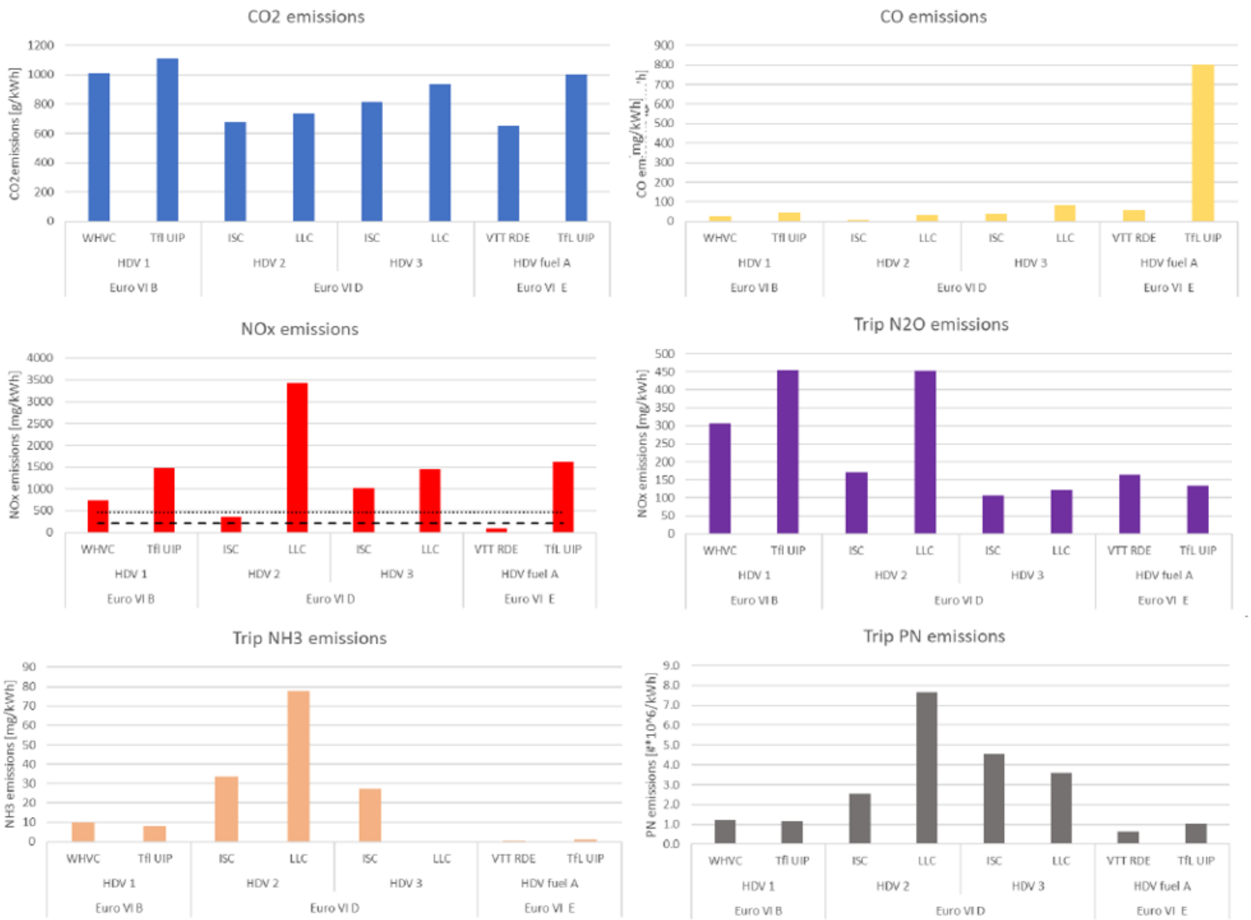


Figure 6-2 Tail-pipe emission performance recorded for Euro VI B, D and E HDVs. Note: the dotted lines marked on the NOx plot indicate the Euro VI and Euro 7 WHTC limits

To highlight the progress in technology over a short period of time among the Euro VI vehicles discussed, the charts below highlight the improved performance of the Euro VI Step E vehicle as tested in the current study. Although the results shown here are tested over different drive cycles, the trend towards extremely low emission levels is evident and representative. This progression towards lower pollutant emission capabilities of modern internal combustion engines is one of the flagship messages from this study.

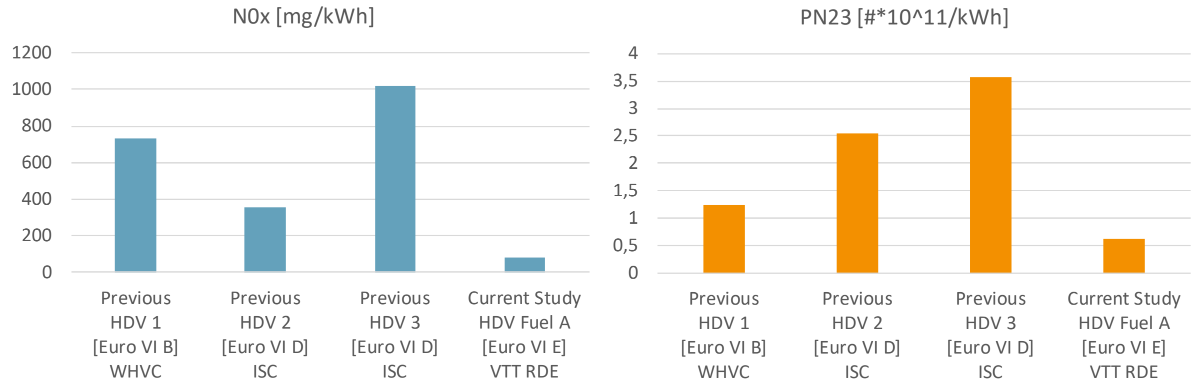


Figure 6-3 Summary Comparison of NOx and PN results across the various test campaigns

6.2. FUEL EFFECTS ON POWERTRAIN PERFORMANCE, FUEL CONSUMPTION AND CO_2 EMISSIONS IN THE RDE CYCLE

The results presented from the experimental work are indicated in charts as an average (sample mean) of the results from each repeated test for each fuel. Error bars are indicated for each fuel using a statistical analysis representing a 95% confidence level. This analysis is done in a conventional way by calculating the standard deviation from the repeats and then the standard error. The critical t-value based on the number of repeats is then found and used to calculate the margin of error. The margin of error in the positive and negative direction indicates the 95% confidence interval (error bars). This methodology has been applied across the experimental results.

6.2.1. Work

In order to quantify the repeatability of the tests, wheel work data was primarily examined. The wheel work was calculated from positive power coming from the driving wheels to the chassis dynamometer rollers. The fuel effects on overall vehicle wheel work were found to be relatively small. This was as expected, given that for most of the cycle, a set speed/load profile was being followed, with the only exceptions being during full load acceleration events, where differences in fuel characteristics would be most likely manifested. The deviation between lowest to highest wheel work recorded from all 17 tests was 1.38 kWh or +/- 1.31 %. Despite the differences being small, it was noted that Fuel B (B30) deviated most from the group, resulting in lower average wheel work compared to any other fuel, as shown in Figure 6-4. It should be noted that the difference in performance between B30 and the other fuels is nevertheless below 0.5 kWh, which may be considered relatively small. However, these findings agreed rather well with the feedback obtained from the test driver, i.e. based on engine response, minor fuel effects could be noted between certain test fuels. It was concluded that it is questionable if any notable difference in real world conditions would be discerned, apart perhaps from during full load operation, because a direct back-to-back comparison cannot directly be made. Because the response of some fuels resembled each other, the test driver was however not able to exactly identify any specific fuels.

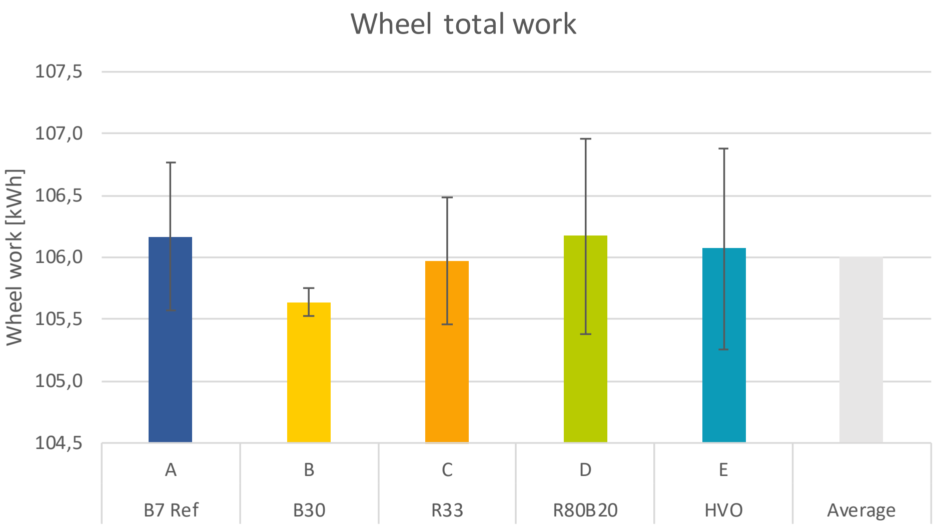


Figure 6-4 Average wheel work per test fuel

Examining the average engine work recorded from the ECU as shown in Figure 6-5, fuel trends disagreed somewhat with the recorded wheel work. Contrary to wheel work, all four test fuels (B, C, D and E) resulted in higher ECU calculated work compared to reference fuel A (B7 ref). The fuel response on ECU calculated work could be distinguished as two sub-groups: Fuels A (B7 ref), C (R33) and E (HVO), producing more comparable ECU work, resulting in typically lower values. The second group was Fuels B (B30) and D (R80B20), which resulted in higher engine work compared to the first sub-group. The generally common features with the fuels in each group was that Fuels A, C and E were all low FAME blends (0 to 7 % FAME); Fuels B and D contained higher FAME concentrations (20 to 30 % FAME). The deviation between maximum recorded ECU work (Fuel B and D) and average reference Fuel A was ca. 4 kWh or 3.3 %. This observation was suspected to be caused by the differences in fuel properties. For example, due to the high FAME content, fuels B and D had lowest mass-based energy density, and because the ECU is calibrated for EN590 fuel and fuel properties are not directly measured by the truck’s systems, the work calculated by the ECU may shift if fuel properties change.

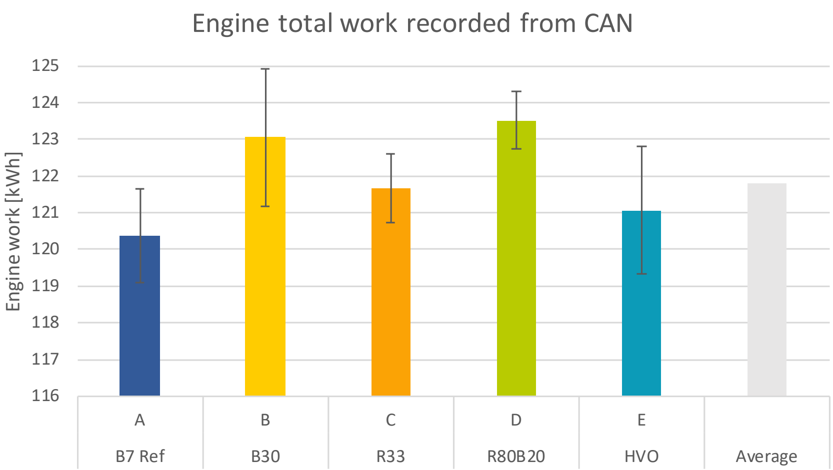


Figure 6-5 Average engine work per test fuel.

As it was suspected that the fuel properties, such as FAME content, cannot be detected by the ECU, other relevant CAN J1939 signals were compared to determine if this gap between ECU-assumed and actual fuel properties explained the differences observed. It was noted that “driver’s demand torque” signal agreed well with the trends obtained for engine work calculated from the CAN signal as seen in Figure 6-6. For example, drivers’ average torque was highest for Fuel B (B30), which in fact resulted in lowest average wheel work measured from the chassis dynamometer. This driver’s demand torque is based on accelerator pedal demand and in turn assumed injected fuel mass, based on a function of injection duration and rail pressure. If more fuel must be demanded (therefore injected) to meet a given work output than expected from a ‘standard’ fuel then this could be interpreted by the ECU as a higher work demand, when in fact it is due to a difference in fuel properties.

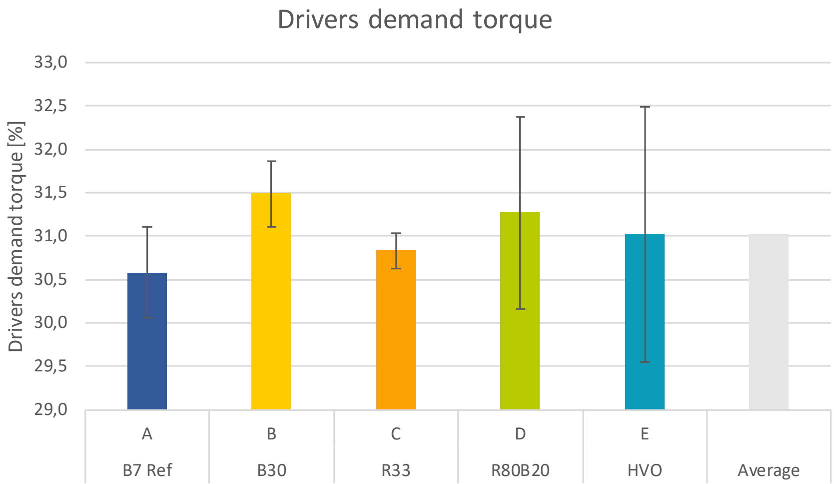


Figure 6-6 Average recorded drivers demand torque per test fuel.

These above-mentioned effects are important to understand especially considering that in RDE testing, engine work is determined using ECU based torque signal. The demonstrated differences in declared ECU work might influence the measuring margins and might contribute to increase in measurement uncertainty budget. For example, with the Euro 7 NO_x emission limit of 260 mg/kWh in RDE, the 3.3 % effect corresponds to ca. 9 mg/kWh. This issue has supposedly been identified and is therefore accounted for in the UN regulation No. 49, 07 series of amendments by requiring the manufacturers to correct the ECU power signal for each additional market fuel permitted by the manufacturer. This however only applies for engine manufacturers, meaning that no power correction factor could be applied e.g. in this campaign. Because of the fuels evidently influencing the ECU parameters, the work-specific results were instead calculated from the more consistent, wheel work values.

6.2.2. Fuel consumption and efficiency

Fuel consumption results are shown in Figure 6-7. Lowest mass-based FC was produced by Fuel E, which consisted of pure EN15940 paraffinic diesel, HVO. On the contrary, both fuel D (80 % HVO) and Fuel E (100 % HVO), produced highest vol.-based FC, with fuel D consuming ca. 5.3 % more fuel vol. compared to reference Fuel A. The fuel consumption results correlated overall very well (R^2 > 0.985) with the fuel energy content, as seen in Figure 6-8. The energy-efficiency was noted to be virtually constant, with minor advantages, ca. 0.2 % higher than average absolute numbers noted for Fuel E in all phases of the RDE cycle, as shown in Figure 6-9. It is postulated that a positive impact of HVO's high cetane number on thermodynamic efficiency could explain the efficiency benefit of fuel E.

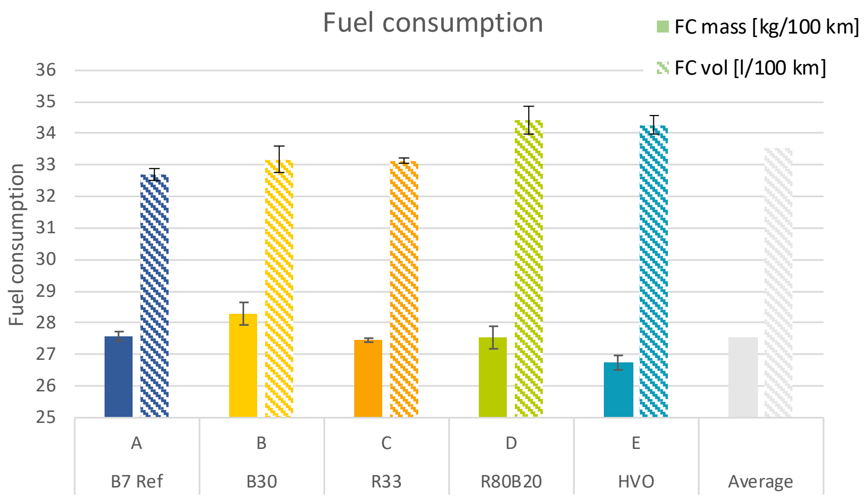


Figure 6-7 Mass and volumetric fuel consumption for given test fuels.

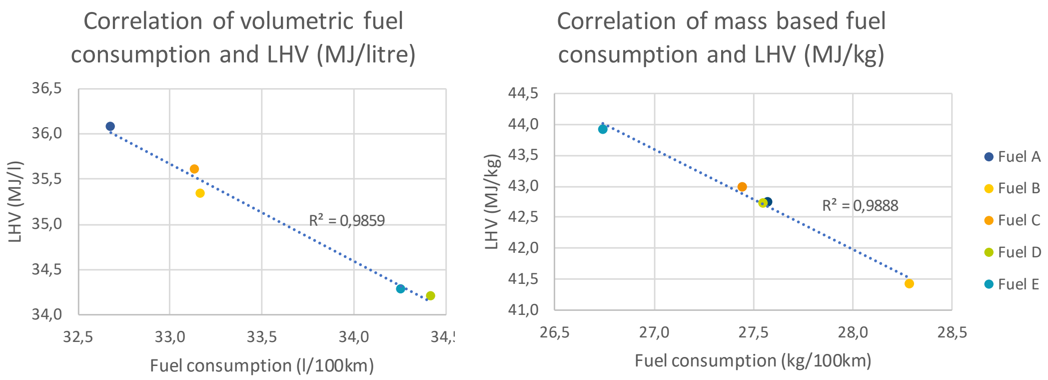


Figure 6-8 Correlation between FC and fuel LHV.

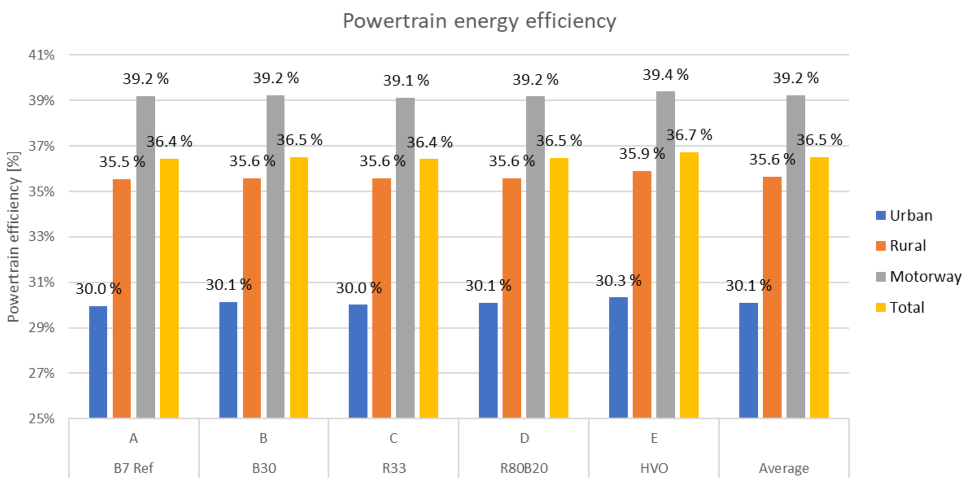


Figure 6-9 Calculated average powertrain energy efficiency per test fuel.

6.2.3. CO_2

Vehicle CO_2 emissions from both urban and total RDE cycle are presented in Figure 6-10. Despite the urban part producing more CO_2 due to the cold start conditions combined with low speed, transient driving, the trends between the urban and total results are similar overall and comparable. Based on the average total trip results and relative to EN590 B7 (Fuel A), Fuel B (B30) increased CO_2 emissions by ca. 0.5 %, while Fuel C (R33) reduced CO_2 by 0.8 %, Fuel D (R80B20) by 2.8 % and Fuel E (HVO) by 4.3 %. The fuel effects and CO_2 results are directly correlating with the calculated fuel CO_2 intensity as shown in Figure 6-11.

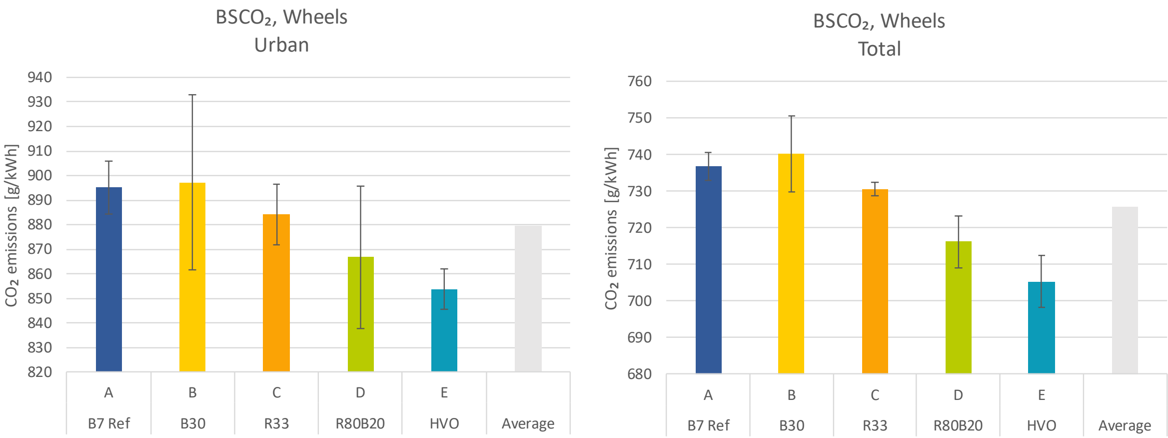


Figure 6-10 Wheel work-based CO_2 emissions for urban and total trip recorded on average per test fuel in the RDE test.

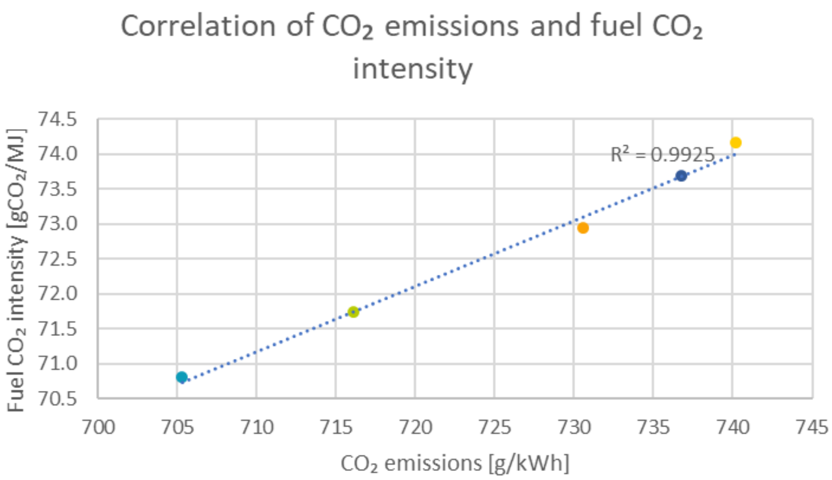


Figure 6-11 CO_2 emissions as a function of calculated fuel CO_2 intensity

6.3. FUEL EFFECTS ON POLLUTANT EMISSIONS IN RDE CYCLE

Overall CO and hydrocarbon emissions for the test vehicle were extremely low. The CO emissions for the total RDE test was below 70 mg/kWh (from wheels) as seen in Figure 6-12. The CO emissions of the cold start urban phase were typically ca. 3 to 4 times higher than for total cycle emissions, between 150 mg/kWh to 400 mg/kWh. Nevertheless, the CO emissions can be considered extremely low with respect to the predominant Euro 7 limit, 1500 mg/kWh in laboratory tests and 1950 mg/kWh in RDE.

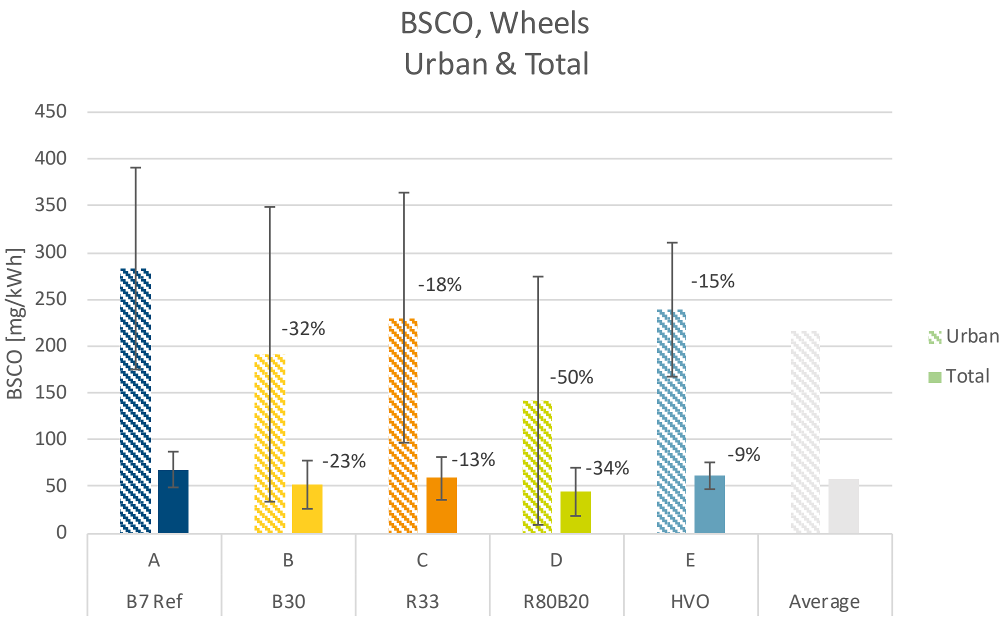


Figure 6-12 Wheel-work-based urban and total CO emissions recorded on average per test fuel in the RDE tests. Percentage reduction in CO for Fuels B-E vs Fuel A is also given

Similarly, hydrocarbon emissions were extremely low throughout the test campaign. The hydrocarbon emissions (HC, CH_4 and NMHC) were typically close or below the analyser detection limit, or as low as the laboratory background (some 0.5 to 2.2 ppm of average concentration). An example of HC emissions is shown in Figure 6-13. Due to these reasons, the priority on analysing the hydrocarbon emissions throughout the campaign was seen as insignificant and no attempt is made to assess fuel effects.

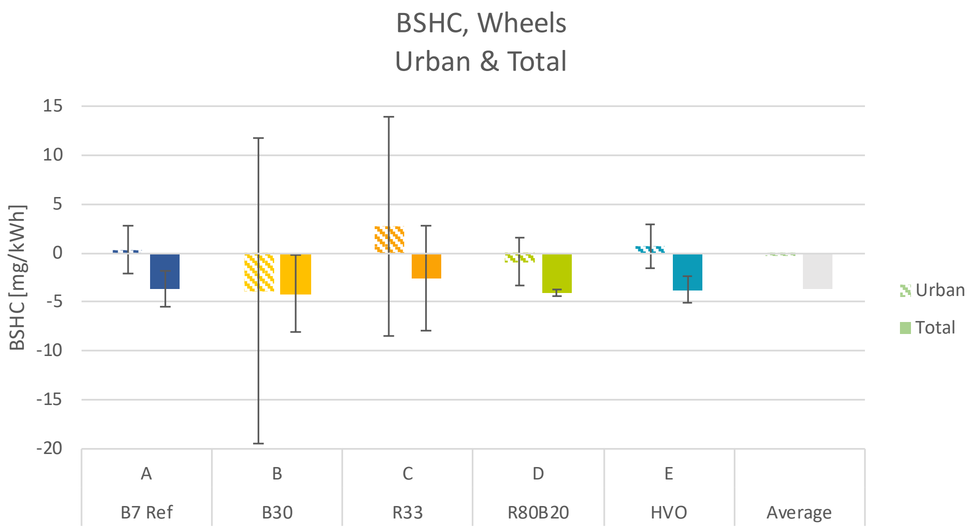


Figure 6-13 Wheel work based urban and total HC emissions recorded on average per test fuel in the RDE tests.

The vehicle tailpipe (TP) NO_x emissions were generally exceptionally low for the trip emissions in the RDE cycle, ca. 100 mg/kWh on average over the total cycle as seen in Figure 6-14. However, as known for modern EATS technologies, SCR systems need to reach a sufficient temperature before initiating the urea injection and attaining a useful NOx conversion efficiency. Therefore, most of the NO_x emissions were emitted during the cold start urban phase compared to other phases of the trip. For example, when NO_x emissions for the urban part were between 570 to 780 mg/kWh on average, the corresponding values for the rural part were below 5 mg/kWh and for motorway below 2 mg/kWh. This means that more than 97 % of the NO_x emissions were emitted during cold start urban phase. Due to the extremely low NO_x results obtained in the rural and motorway phases, the fuel effects in respective phases (rural/motorway) were not seen feasible nor significant to be properly evaluated. Furthermore, any fuel effects in this magnitude are debatable, because even great relative changes have a rather low impact on the outcome.

Essentially no fuel effects for TP NO_x emissions for the given test vehicle were apparent because strong non-fuel related vehicle/EATS behaviour was noted during the experiments. Around the mid-campaign, a clear and notable increasing trend in vehicle NO_x TP emissions was seen, as shown in Figure 6-15. The interesting detail about the trend was that the total TP NO_x emissions increased from ca. 100 mg/kWh to 250 mg/kWh at the highest, which can still be considered acceptable for a Euro VI vehicle. This issue was further analysed in more detail by checking NOx EO data, vehicle information monitor for possible error codes and by examining signs of possible DPF regeneration (from FC, CO_2, CO, HC and PN/PM data and from exhaust gas temperature, EGT). However, based on chronological NOx EO emission data (Figure 6-16), no indications of abnormal engine emission behaviour was found. Furthermore, as no direct indications of error could be identified, the experimental campaign was continued as planned. The NO_x TP emissions eventually decreased back to 100 mg/kWh after 2 to 3 test repetitions. As no error messages, nor any signs of regeneration were noted, the root cause for this behaviour could not be identified. It was initially suspected that the vehicle urea/SCR system might have some cyclic behaviour for various reasons, but because the non-standardized, OEM specified CAN protocol was not available, no information or data was extracted to support this theory. The increase in TP NO_x affected the NO_x TP results also throughout all phases in the RDE cycle, urban, rural and motorway, which would not be expected during regular regeneration. However, to minimize the effects of this unknown vehicle behaviour, complete data sets that contained trends of abnormally high NO_x TP (one test for both Fuel C, R33 and Fuel D, R80B20) were discarded. The test matrix was then later amended by additional repetitions for the respective fuels.

Despite this unstable TP NO_x behaviour being noted, possibilities for fuel related effects on TP NO_x and SCR behaviour could not completely be disregarded. For example, the chronological data indicates that Fuel B (B30) produced highest TP NO_x both well before and well after the abnormal vehicle behaviour took place. In order to further understand the NO_x behaviour in more detail, the engine out (EO) NO_x was then compared.

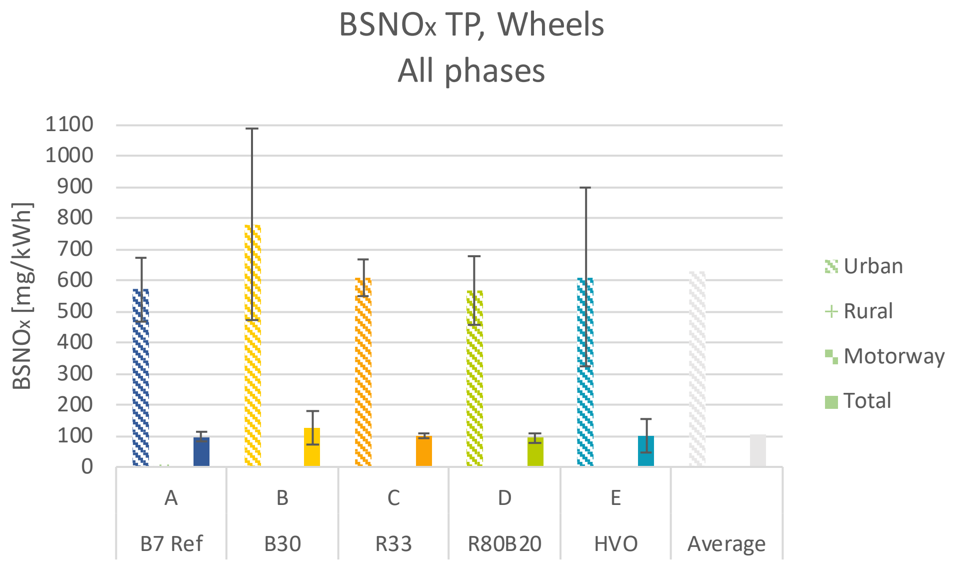


Figure 6-14 Wheel work-based NO_x TP emissions recorded on average for all phases per test fuel in the RDE tests. Note that the Rural and Motorway NOx emissions are barely visible or invisible due to the low levels.

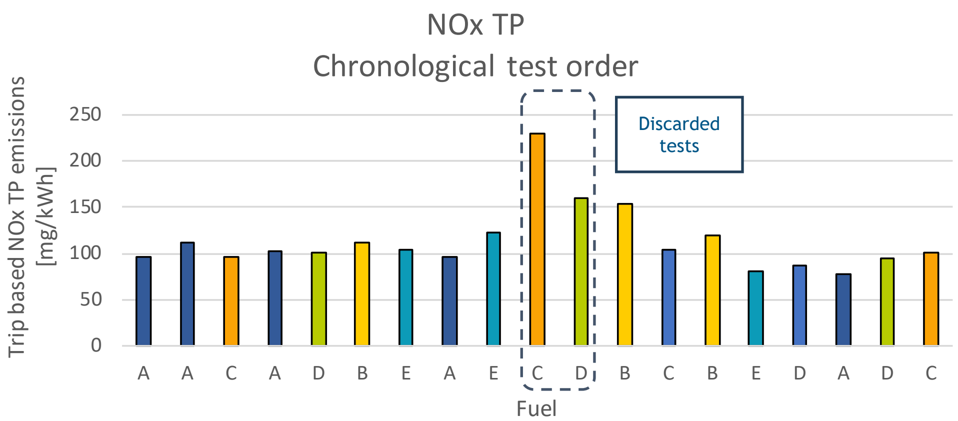


Figure 6-15 NO_x TP emission results displayed in a chronological order

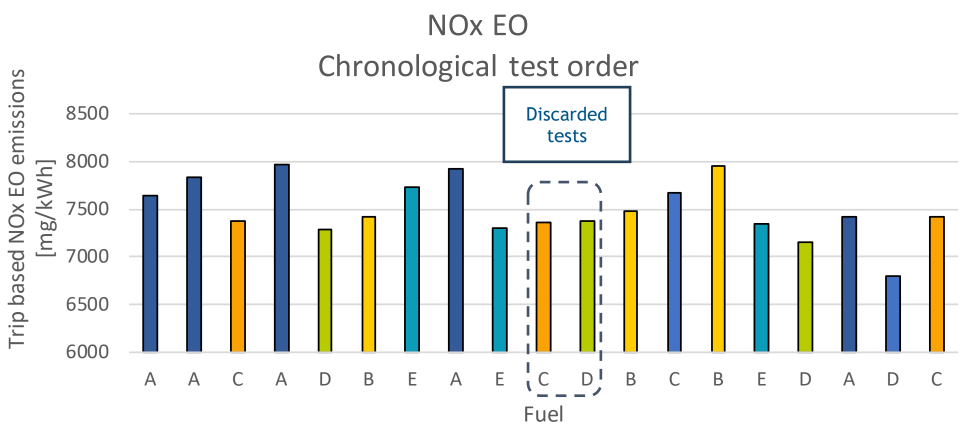


Figure 6-16 NO_x EO emission results displayed in a chronological order showing that the high tailpipe NOx results for the discarded tests was a function of the EATS, not the engine.

Possible fuel effects on NO_x emissions were further examined by comparing the NO_x engine out (EO) emissions. The recorded NO_x EO emissions were between 6800 to ca. 7900 mg/kWh over the total cycle. The corresponding urban NO_x EO emissions were on average some 1 - 6 % lower compared to total cycle EO NO_x, apart from Fuel B (B30), which increased the NO_x EO by ca. 1 %. Results show that all fuels (B, C, D and E) decreased EO NO_x compared to reference Fuel A (B7 Ref). Lowest total NO_x EO emissions were found for Fuel D (R80B20) reducing total NO_x EO by ca. 9 %, Fuels C (R33) and E (HVO) by ca. 4 % and Fuel B by ca. 2% compared to reference Fuel A (Figure 6-17). The major difference between NO_x EO and TP results was that Fuel B (B30) produced 32 % higher NO_x TP compared to reference Fuel A, meanwhile the NO_x EO emissions were 2 % lower. Because the total absolute TP NO_x emissions were generally around 100 mg/kWh, the relative increase should be considered insignificant compared to the change in NOx EO values. The conflict between the NO_x EO and TP trends for Fuel B (B30) demonstrates that the Euro VI SCR system variations affect NO_x TP emissions more than fuel properties do. However, fuel attributes may well influence NO_x EO, which may result in other improvements in e.g. urea consumption. However, because AdBlue consumption was not monitored, no data was available for supporting this hypothesis.

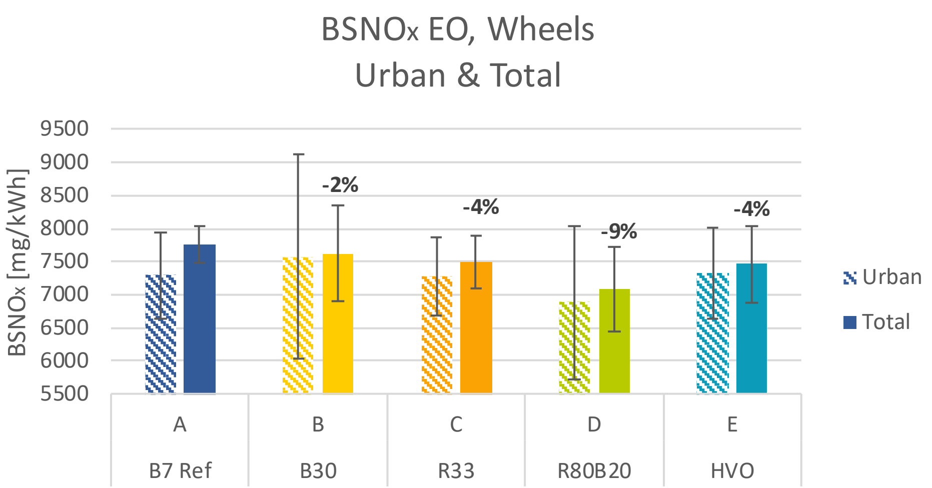


Figure 6-17 Wheel work based urban and total NO_x EO emissions recorded on average per test fuel in the RDE tests.

To analyse the dependency between NO_x EO and TP in more detail, the coefficient of determination (R^2) was determined for each phase (Figure 6-18). Highest R^2 was achieved for urban part, $R^2 = 0.6$. This is because during cold start (Urban), NO_x EO and TP are virtually equal as no urea injection or SCR activity occurs. SCR was operational well before the rural phase. This can be seen from the correlation between EO and TP, which is reduced to 0.15 in rural, and to 0.03 in motorway phases. These results agree well with the hypothesis that NO_x TP emissions are significantly less affected by fuel properties than the NO_x EO emissions.

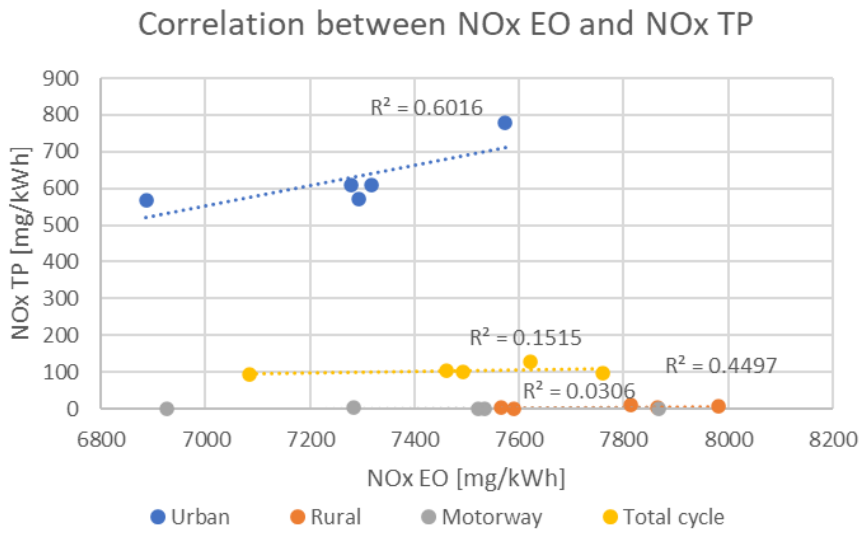


Figure 6-18 Correlation between NOx EO and NOx TP

The total NO_x reduction calculated between NO_x EO and TP is shown in Figure 6-19. Simultaneously, NO_x conversion efficiencies are shown per cycle phase. The total NO_x reduction for all fuels were more than 98 %. In rural and motorway phases, NO_x reduction was even higher, 99.9 %. The most meaningful difference in NO_x conversion was found in the urban phase. Fuels A (B7 ref), C (R33), D (R80B20) and E (HVO) resulted in relatively comparable values, between 91.6 to 92.2 %. Fuel B (B30) was the lowest with 89.6 %. Another important finding is that because the NO_x conversion efficiency overall is close to 99 %, the relative advantage in NO_x reduction is similar compared to the advantages described for NO_x EO. This means e.g. that when Fuel D (R80B20) decreased NO_x EO by 9%, urea consumption could hypothetically be reduced with a corresponding value. However, because urea consumption was not recorded during the campaign, no supporting data could be used for confirming this hypothesis. Regardless, it should be addressed that all fuels, (B, C, D and E) reduced NO_x compared to reference Fuel A. This means that if NO_x EO is decreased without compromising NO_x conversion efficiency, fuel properties may benefit SCR durability or urea consumption.

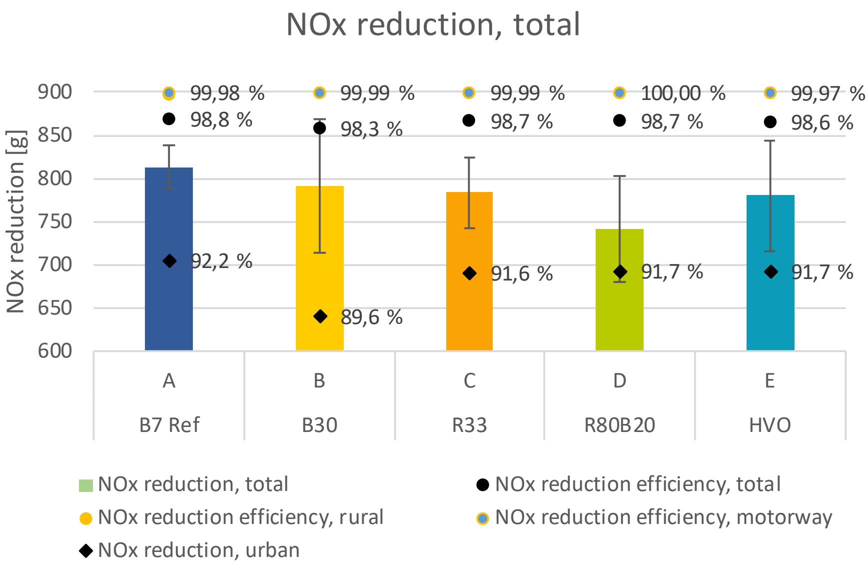


Figure 6-19 Total NO_x reduced by the SCR per fuel.

The N_2O emissions were found to have two opposite trends. The N_2O results were between 192 mg/kWh to 214 mg/kWh on average, with Fuel E (HVO) resulting in highest N_2O amongst the group, and reference Fuel A (B7 ref) yielded the lowest. On the other hand, N_2O trends for urban indicated the opposite, with Fuel E producing similar results as the reference Fuel A (ca. 134 to 139 mg/kWh), meanwhile Fuels B, C and D were on average comparable (ca. 150 mg/kWh). It can be considered that N_2O in the urban phase will be the least reliable because part of the time is pre-SCR light-off and therefore the exact light-off time will dominate N_2O emissions in this test phase, however, the correlation between N_2O and other gaseous emissions studied (especially NO_x), emissions were rather weak (R^2 below 0.5) and no direct fuel related significance could be quantified. Furthermore, most N_2O will be generated across the SCR catalyst, rather than being related to engine out values and therefore these apparent trends with respect to fuels may be coincidental. Given the range of experimental error, no significant differences can be concluded.

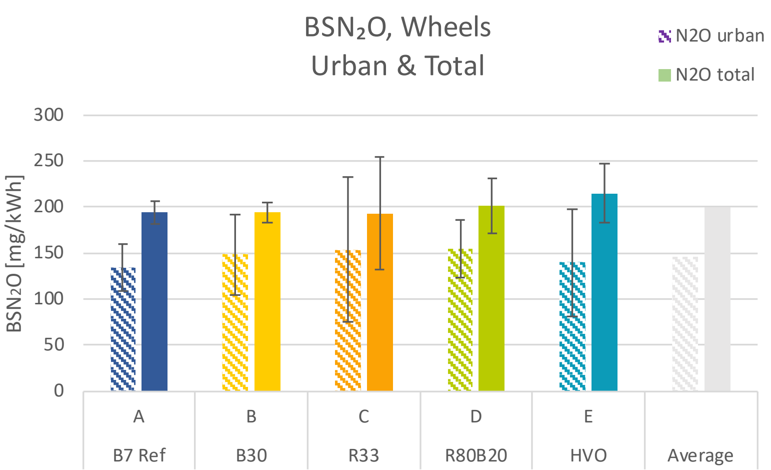


Figure 6-20 Wheel work based urban and total N_2O emissions recorded on average per test fuel in the RDE tests.

The ammonia (NH_3) emissions were found to be extremely low, below 1 mg/kWh for the total RDE cycle and below 1.5 mg/kWh for the urban part, as shown in Figure 6-21. These results demonstrate the effectiveness of current, sophisticated SCR system combined with ammonia slip catalyst (ASC) units. Because the NH_3 results were all below 1 mg/kWh, especially considering the Euro 7 limit of 60/85 mg/kWh, it was considered that no meaningful fuel effects could be found, furthermore, tailpipe ammonia would be expected to originate from the SCR system urea reductant, rather than be connected to the fuel.

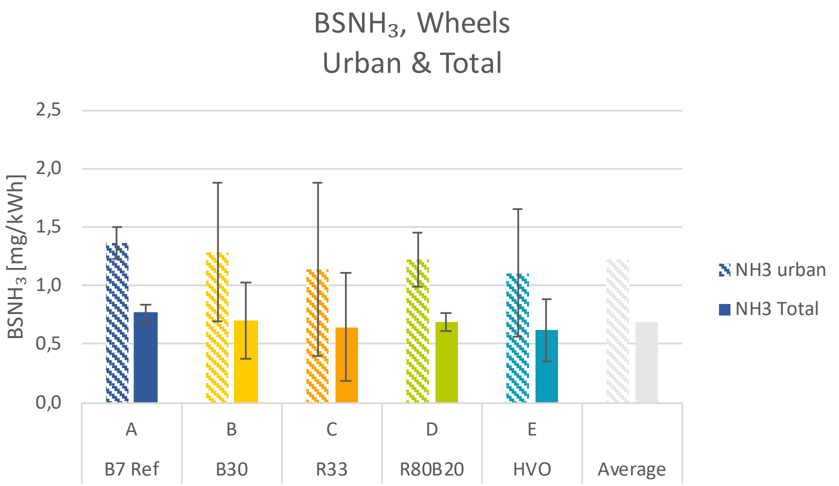


Figure 6-21 Wheel work based urban and total NH3 emissions recorded on average per test fuel in the RDE tests

Total recorded PN10 emissions were on average below 2.0×10^{11}/kWh and for PN23 below 1.0×10^{11}/kWh for all fuels as shown in Figure 6-22. In addition, PN results were reasonably consistent with a typical deviation within ca. 7 % to 14 %. These results suggests that the DPF filtration efficiency is overall very high for all fuels, and thus no evident fuel related trends could be noted. However, this was not the case for the urban conditions as seen in Figure 6-23. Despite the PN results being relatively low, PN10 typically below 2.5×10^{11}/kWh and PN23 below 2×10^{11} /kWh, distinction between the different test fuels could be identified. Especially Fuel D (R80B20) was found to emit higher average PN, but also created a larger deviation in both PN10 and PN23. Figure 6-24 displays the PN emissions from urban conditions chronologically. The increased PN emissions caused by Fuel D (R80B20) can clearly be seen amongst the other results. Due to insufficient data, no direct conclusions of the phenomena can be drawn. However, Figure 6-24 additionally shows that cyclic PN related trends can be seen, which indicates that any fuel effects may be dominated by vehicle/EATS characteristics, DPF soot loading and regeneration state.

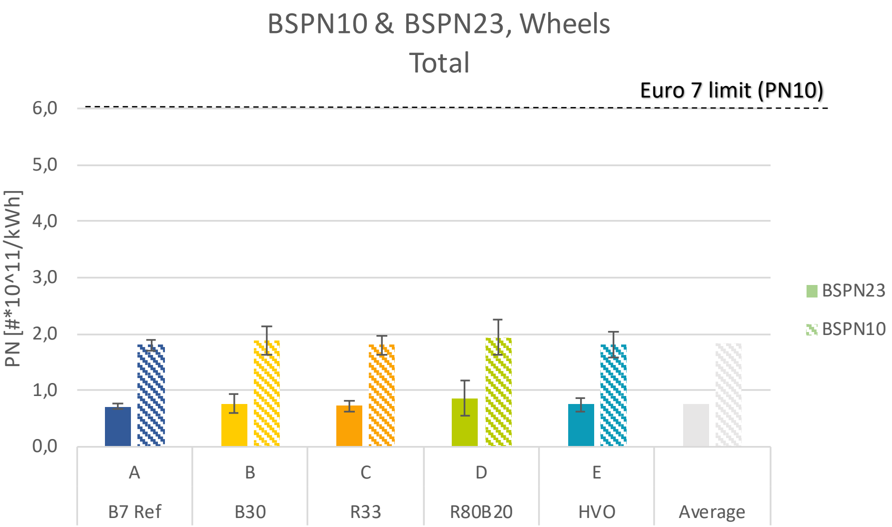


Figure 6-22 Wheel work based total PN10 & PN23 emissions recorded on average per test fuel in the RDE tests.

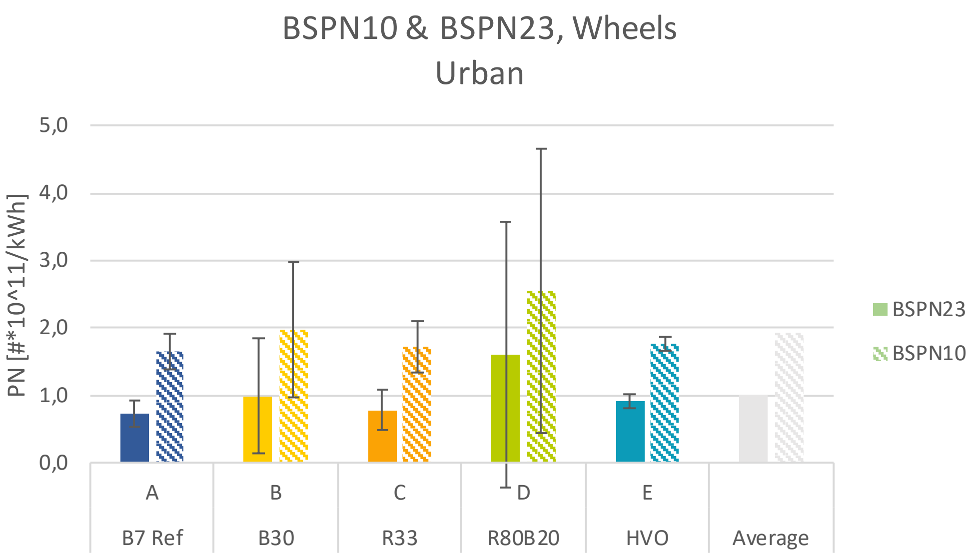


Figure 6-23 Wheel work based urban PN10 & PN23 emissions recorded on average per test fuel in the RDE tests.

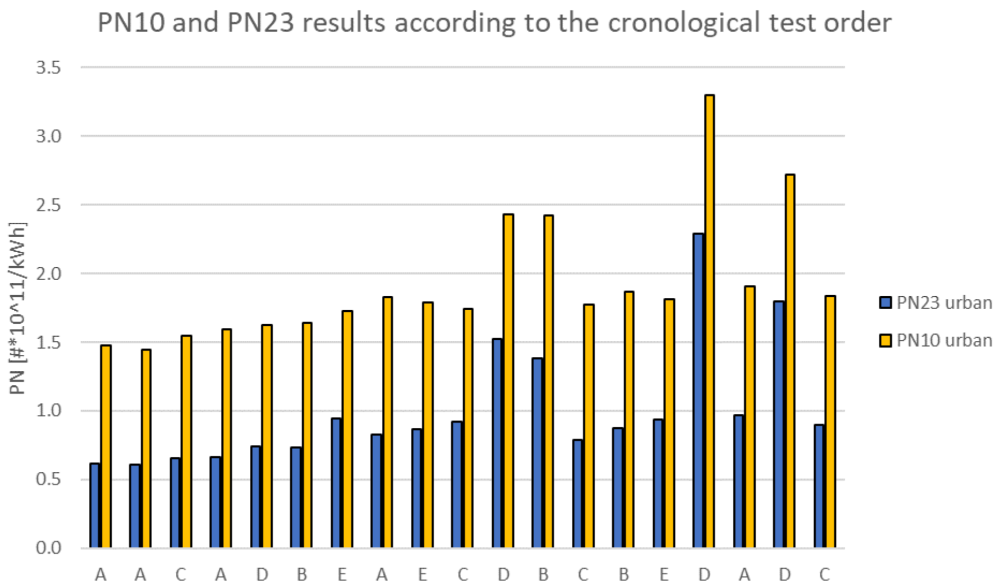


Figure 6-24 PN10 and PN23 results from RDE test in cold start urban conditions.

7. FUEL EFFECTS AND VEHICLE EMISSION PERFORMANCE IN RESPECT TO EURO 7 REGULATION

After the test campaign was completed, all recorded tests were post processed individually according to the Euro 7 RDE procedure. Both 100th percentile MAW (CF_{cold}) and 90th percentile MAW (CF_{warm}) were evaluated separately, whereafter the regulatory numbers were calculated as final conformity factors (CF_{final}) according to the method described in chapter *4. AN OVERVIEW OF EURO 7 REGULATION*. Although the CF_{final} is the meaningful indicator for determining the vehicle emission characteristics against the regulatory limits, both CF_{cold} and CF_{warm} values are displayed in this chapter for improved understanding of vehicle and fuel behaviour. Because it was noted earlier that fuel characteristics had some effects on ECU determined torque depending on fuel type, all MAW based results were initially calculated and compared using wheel work. The wheel work based MAW data was then corrected based on average powertrain loss determined by the ratio between engine work and wheel work data obtained from five successful tests conducted for reference fuel A. This ensured that less fuel related offset for the MAW results would be caused by the torque calculation estimated by the ECU, and thus improve the back-to-back comparability of given fuels. Finally, the correlation between CF_{cold} and urban wheel work based results, and CF_{final} and total wheel work based results were compared. This analysis would hypothetically indicate how well the reference work based results agree with the cold start urban part. Due to the extremely low emissions produced with all fuels for the following components: CO, hydrocarbons and NH_3, no significant fuel effects were seen, thus no further analysis in respect to Euro 7 limits were emphasized here.

Table 7-1 displays the 100th percentile, 90th percentile and final MAW based results expressed as absolute values. Corresponding average results of each fuel is shown in Table 7-2. The average values were separately assessed because this would ease the direct back-to-back comparison between each test fuel. Table 7-3 displays the CF factors for corresponding individually calculated MAW results, which were compared to permitted Euro 7 RDE limits. Cells in Table 7-3 which are highlighted in red colour exceed the permissible Euro 7 emission limits. It should also be noted that the Euro 7 limits were compared using all three CF numbers, CF_{cold}, CF_{warm} and CF_{final}. Analysing CF_{cold} and CF_{warm} separately is not part of the Euro 7 procedure but was instead seen as a demonstrative measure to compare the cold start and warm emission characteristics together. Finally, correlations between key exhaust components, CO_2, NO_x, N_2O and PN, for MAW based results in relation to wheel work-based results are shown in Figure 7-1.

The high-level findings from the MAW based results may be concluded as similar to the findings expressed in chapter *6.2. FUEL EFFECTS ON POWERTRAIN PERFORMANCE AND CO_2 EMISSIONS*. The MAW results analysed according to Euro 7 procedure may be concluded as follows:

- The correlation between MAW results and corresponding urban and total wheel work results were high overall (Figure 7-1), meaning that similar general findings and conclusions for the Euro 7 MAW results apply.

- CO, HC and NH_3 emissions are very low overall, hence no potential fuel effects could be observed. The final conformity factors were all below 0.05 in all cases, and even for CF_{cold} below 0.1.

- CF_{cold} results show that for the tested Euro VI Step E HDV, NO_x mitigation during cold start and engine warmup was the most challenging element regardless of fuel properties. The engine and EATS simply require sufficient time to reach operational temperature. NO_x MAW_{cold} results were in the range of 338 mg/kWh at lowest, and over 500 mg/kWh at highest. However, CF_{warm} results clearly demonstrate that in normal operational conditions, the tested Euro VI E vehicle was capable of producing ultra-low NO_x emissions as long as the EATS is up to its designed operational temperature. The results obtained from the tests also suggest that modern SCR systems can be sufficiently resilient to reduce the TP NO_x emissions within the variation produced by both fuel property and natural behaviour of the vehicle. For example, some deviation in the 90th percentile CF_{warm} results was seen, but all tests evidently produced on average below 10 mg/kWh. Because the weighting factor for CF_{cold} is only 0.14, the effect of cold start on CF_{final} is ultimately low. For example, the CF for 100th percentile MAW during cold start was between 1.1 to 2.1, corresponding CF_{final} values were around 0.2 to 0.3 (Table 7-3 and Table 7-2)

- Due to the very effective DPF, the CF_{final} factor for PN10 was ca. 0.2 for all tests regardless of fuel blend. This applied for all conformity factors ($CF_{cold,}$ CF_{warm} and CF_{final}) as seen in Table 7-3. This means that no evident nor meaningful fuel effect could be distinguished.

- N_2O was overall closest to the permissible Euro 7 limit (Figure 7-3). Typically CF factors were between 0.7 to 0.9 (Table 7-3). Fuel E slightly exceeded the permissible limit in one test (CF_{final} = 1.01), possibly more due to measurement variation than a specific fuel effect. It is however expected that technical changes for N_2O mitigation will take place for EU 7 calibrated vehicles.

Table 7-1 100th percentile MAW, 90th percentile MAW and total weighted MAW emission results

CF corrected to engine power (with 12 % powertrain loss)								
		100th percentile cold						
		CO2	CO	NOx	NH3	N2O	CH4	PN10 mg/
Test #	Fuel	g/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	kWh	#*10^11/kWh
1 STD	A	769	124	327	1	151	-2	1.6
2 STD	A	765	134	409	1	164	0	1.5
4 STD	A	761	201	364	1	155	-1	1.7
8 STD	A	760	201	353	1	183	-1	1.8
17 STD	A	761	260	288	1	201	-1	1.7
6 STD	B	756	111	415	1	168	-1	1.7
12 STD	B	772	166	537			0	1.9
14 STD	B	766	95	452	1	199	-2	1.8
3 STD	C	759	125	357	1	145	2	1.6
13 STD	C	762	141	359	1	218	-1	1.8
19 STD	C	760	194	363	1	186	-1	1.7
5 STD	D	738	56	354			-1	1.7
16 STD	D	745	122	308	1	199	0	2.4
18 STD	D	737	113	353	1	186	-1	2.1
7 STD	E	725	161	378	1	248	0	1.8
9 STD	E	733	141	425	1	159	-3	1.6
15 STD	E	732	181	308	1	217	-1	1.6
		90th percentile hot						
		CO2	CO	NOx	NH3	N2O	CH4	PN10
Test #	Fuel	g/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	#*10^11/kWh
1 STD	A	697	25	34	1	202	-2	2.0
2 STD	A	696	22	5	1	185	-1	2.0
4 STD	A	700	25	0	1	193	-1	2.1
8 STD	A	692	33	2	1	199	-1	2.1
17 STD	A	688	76	0	1	211	-2	2.1
6 STD	B	692	24	1	1	195	-2	2.1
12 STD	B	703	32	16			-1	2.1
14 STD	B	695	25	2	1	218	-2	2.0
3 STD	C	688	21	2	1	173	1	1.9
13 STD	C	690	48	3	1	236	-2	2.1
19 STD	C	690	53	1	1	198	-2	2.0
5 STD	D	671	21	1			-2	2.0
16 STD	D	680	26	0	1	211	-1	2.2
18 STD	D	671	47	0	1	195	-2	2.2
7 STD	E	653	33	1	1	265	-1	2.0
9 STD	E	665	24	13	1	213	-2	2.0
15 STD	E	663	45	0	1	234	-2	1.9
		Total, weighted results						
		CO2	CO	NOx	NH3	N2O	CH4	PN10
Test #	Fuel	g/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	#*10^11/kWh
1 STD	A	707	38	75	1	194	-2	2.0
2 STD	A	706	38	62	1	182	-1	1.9
4 STD	A	708	50	51	1	188	-1	2.0
8 STD	A	702	56	51	1	196	-1	2.0
17 STD	A	698	102	40	1	210	-2	2.0
6 STD	B	701	36	59	1	191	-1	2.0
12 STD	B	712	50	89			-1	2.1
14 STD	B	705	34	65	1	216	-2	2.0
3 STD	C	698	35	52	1	169	1	1.9
13 STD	C	700	61	53	1	234	-2	2.0
19 STD	C	700	73	52	1	197	-2	2.0
5 STD	D	680	26	50			-2	2.0
16 STD	D	689	39	43	1	209	-1	2.3
18 STD	D	680	56	50	1	194	-2	2.2
7 STD	E	663	51	54	1	262	-1	1.9
9 STD	E	675	41	71	1	205	-2	1.9
15 STD	E	672	64	43	1	231	-1	1.9

Table 7-2 Averaged MAW based results per fuel.

Data type	Fuel no.	CO2	CO	NOx	NH3	N2O	CH4	PN10
		100th percentile cold						
		g/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	#*10^11/kWh
Average	A	763.2	184.0	348.4	1.0	170.6	-0.8	1.7
Average	B	764.6	123.8	467.9	1.0	183.5	-0.8	1.8
Average	C	760.4	153.3	359.5	0.9	182.8	0.0	1.7
Average	D	740.0	97.3	338.2	0.9	192.7	-0.3	2.1
Average	E	729.9	161.0	370.3	0.8	208.1	-1.5	1.7
Data type	Fuel no.	90th percentile hot						
		CO2	CO	NOx	NH3	N2O	CH4	PN10
		g/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	#*10^11/kWh
Average	A	694.5	36.1	8.3	0.8	198.0	-1.6	2.1
Average	B	696.8	26.8	6.0	0.7	206.5	-1.6	2.1
Average	C	689.7	40.6	2.1	0.7	202.4	-1.0	2.0
Average	D	674.0	31.3	0.3	0.7	203.2	-1.4	2.2
Average	E	660.5	34.0	4.8	0.6	237.1	-1.5	2.0
Data type	Fuel no.	Final results						
		CO2	CO	NOx	NH3	N2O	CH4	PN10
		g/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	#*10^11/kWh
Average	A	704.1	56.8	55.9	0.8	194.1	-1.5	2.0
Average	B	706.3	40.4	70.7	0.8	203.3	-1.5	2.0
Average	C	699.6	56.4	52.1	0.7	199.7	-0.9	2.0
Average	D	683.2	40.5	47.6	0.7	201.7	-1.2	2.1
Average	E	670.2	51.8	56.0	0.7	233.1	-1.5	1.9

Table 7-3 100th percentile CF, 90th percentile CF and final CF calculated from all RDE tests, where CF final is relevant to Euro 7 emissions compliance.

CF corrected to engine power (with 12 % powertrain loss)																			
		CF cold						CF hot						CF final					
Test #	Fuel	CO	NOx	NH3	N2O	CH4	PN10	CO	NOx	NH3	N2O	CH4	PN10	CO	NOx	NH3	N2O	CH4	PN10
1 STD	A	0.06	1.26	0.01	0.58	0.00	0.17	0.01	0.13	0.01	0.78	0.00	0.23	0.02	0.29	0.01	0.75	0.00	0.22
2 STD	A	0.07	1.57	0.01	0.63	0.00	0.17	0.01	0.02	0.01	0.71	0.00	0.22	0.02	0.24	0.01	0.70	0.00	0.22
4 STD	A	0.10	1.40	0.01	0.60	0.00	0.19	0.01	0.00	0.01	0.74	0.00	0.23	0.03	0.20	0.01	0.72	0.00	0.22
8 STD	A	0.10	1.36	0.01	0.70	0.00	0.20	0.02	0.01	0.01	0.76	0.00	0.23	0.03	0.20	0.01	0.76	0.00	0.23
17 STD	A	0.13	1.11	0.01	0.77	0.00	0.19	0.04	0.00	0.01	0.81	0.00	0.23	0.05	0.16	0.01	0.81	0.00	0.23
6 STD	B	0.06	1.60	0.01	0.65	0.00	0.18	0.01	0.00	0.01	0.75	0.00	0.23	0.02	0.23	0.01	0.73	0.00	0.22
12 STD	B	0.08	2.06			0.00	0.21	0.02	0.06			0.00	0.23	0.03	0.34			0.00	0.23
14 STD	B	0.05	1.74	0.01	0.76	0.00	0.20	0.01	0.01	0.01	0.84	0.00	0.22	0.02	0.25	0.01	0.83	0.00	0.22
3 STD	C	0.06	1.37	0.01	0.56	0.00	0.18	0.01	0.01	0.01	0.66	0.00	0.22	0.02	0.20	0.01	0.65	0.00	0.21
13 STD	C	0.07	1.38	0.01	0.84	0.00	0.20	0.02	0.01	0.01	0.91	0.00	0.23	0.03	0.20	0.01	0.90	0.00	0.22
19 STD	C	0.10	1.39	0.01	0.72	0.00	0.19	0.03	0.00	0.01	0.76	0.00	0.22	0.04	0.20	0.01	0.76	0.00	0.22
5 STD	D	0.03	1.36			0.00	0.19	0.01	0.00			0.00	0.22	0.01	0.19			0.00	0.22
16 STD	D	0.06	1.18	0.01	0.77	0.00	0.27	0.01	0.00	0.01	0.81	0.00	0.25	0.02	0.17	0.01	0.81	0.00	0.25
18 STD	D	0.06	1.36	0.01	0.72	0.00	0.23	0.02	0.00	0.01	0.75	0.00	0.25	0.03	0.19	0.01	0.75	0.00	0.24
7 STD	E	0.08	1.45	0.01	0.95	0.00	0.20	0.02	0.00	0.01	1.02	0.00	0.22	0.03	0.21	0.01	1.01	0.00	0.22
9 STD	E	0.07	1.64	0.01	0.61	0.00	0.18	0.01	0.05	0.01	0.82	0.00	0.22	0.02	0.27	0.01	0.79	0.00	0.22
15 STD	E	0.09	1.18	0.01	0.84	0.00	0.18	0.02	0.00	0.01	0.90	0.00	0.22	0.03	0.17	0.01	0.89	0.00	0.21

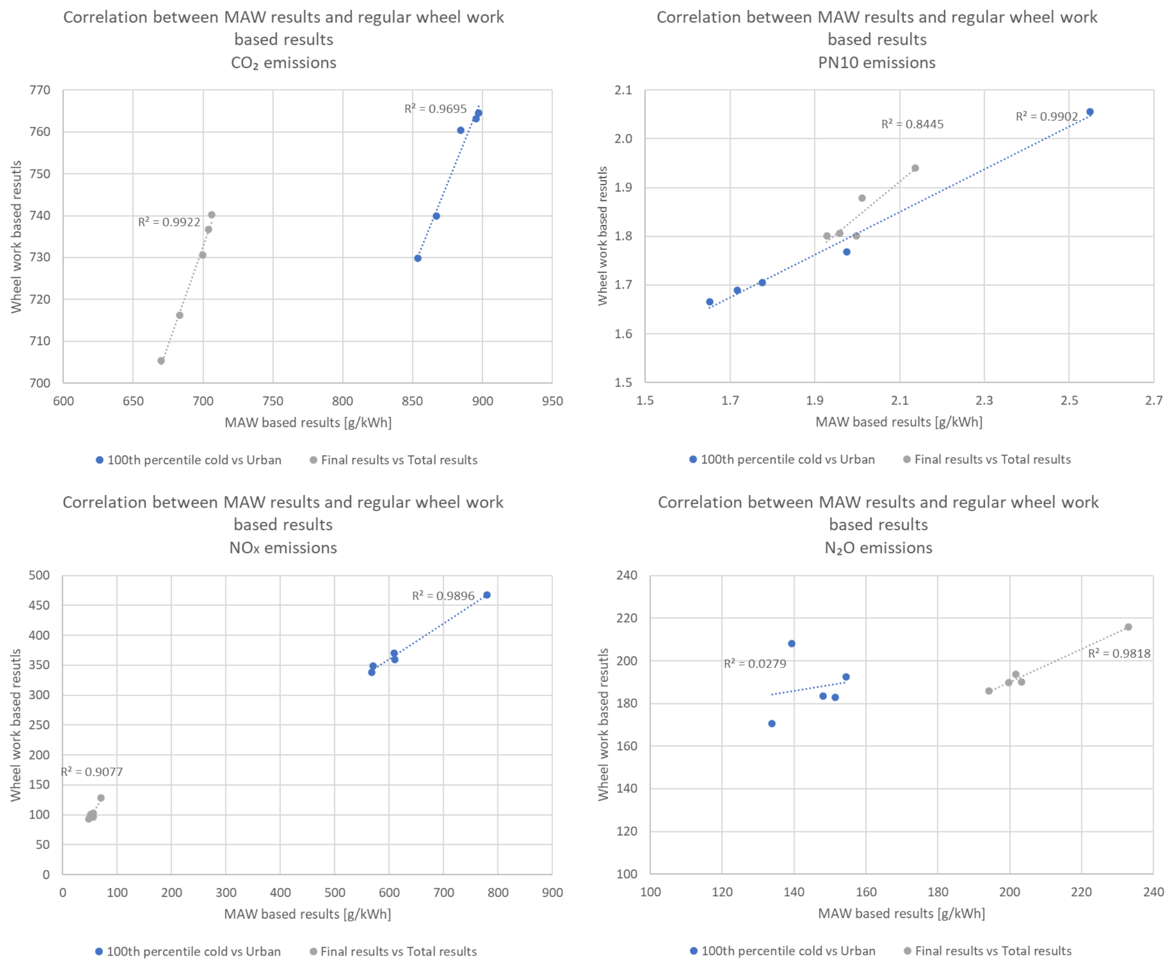


Figure 7-1 Correlation between MAW results and wheel work-based results in the RDE cycle

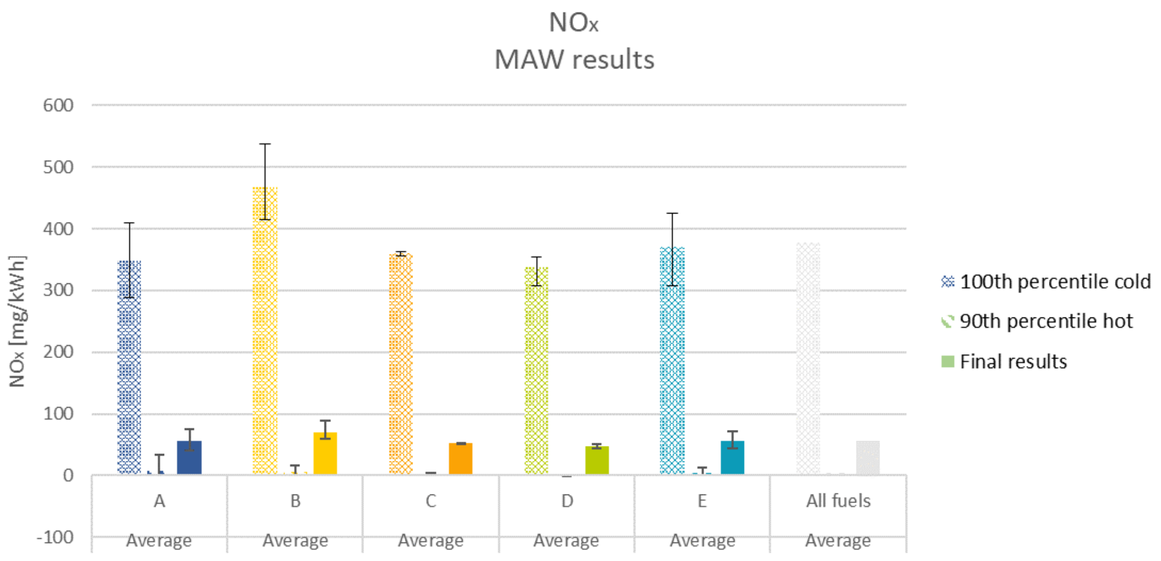


Figure 7-2 NO_x MAW results, 100th percentile, 90th percentile and combined MAW (Final results)

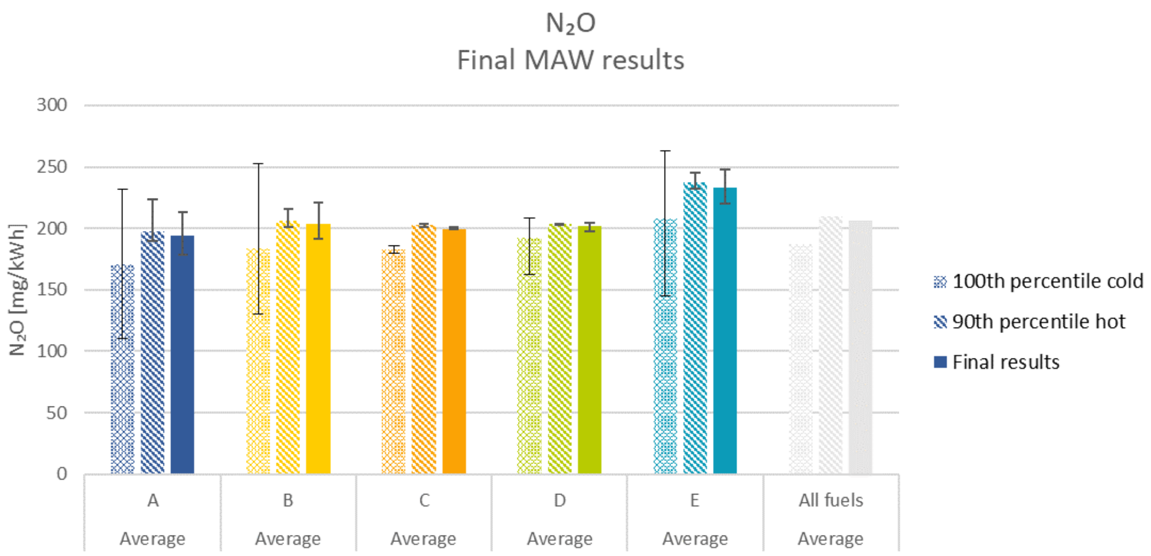


Figure 7-3 N_2O MAW results, 100th percentile, 90th percentile and combined MAW (Final results)

8. RESULTS FROM TEST IN EATS DEMANDING CYCLE

To compliment the previous test results and gain some insight into an extreme case of an urban EATS demanding test cycle, one test fuel was tested over the demanding TfL UIP urban cycle in addition to EN590 B7 (Fuel A). The most representative fuel from the RDE work would be chosen as the second fuel for TfL UIP testing with the intent of identifying a low carbon fuel with best emissions performance under extreme urban conditions. Therefore the results in key metrics from the RDE tests for fuels B-E were collected as average numbers and compared against the results for Fuel A. Since the TfL UIP cycle was known for being challenging for the EATS because of low loads, slow speeds and frequent accelerations from stand still, special attention was paid to the metrics quantified from the urban phase of the RDE cycle. HVO (Fuel E) was chosen as the second fuel and details of the selection for TfL UIP testing can be found in Appendix 4.

The general emission performance of the Euro VI test vehicle is described in more detail in chapter 6.1. *AN OVERVIEW OF THE PERFORMANCE OF TEST VEHICLE USING REFERENCE FUEL A*. Despite the low speed, this test cycle resulted in remarkably increased fuel consumption, and therefore correspondingly vehicle CO_2 emissions, combined with remarkable increase in exhaust pollutant emissions. Initially it was suspected that the initial conditioning of the vehicle was insufficient. If such issues would have occurred, this would most likely only affect the early repetitions. However, this was not the case for the majority of exhaust components. Monotonic and bidirectional trends across the test set were observed for most emissions. This was a phenomenon not seen in similar tests conducted at VTT for earlier Euro VI HDVs. Nevertheless, key conclusions from the testing are shown in the following:

The CO_2 emissions are displayed both in a chronological order and as average values per fuel in Figure 8-1. CO_2 emissions were ca. 4 -5 % lower with Fuel E in both phases and total trip. These numbers were in line with the results obtained in the RDE cycle.

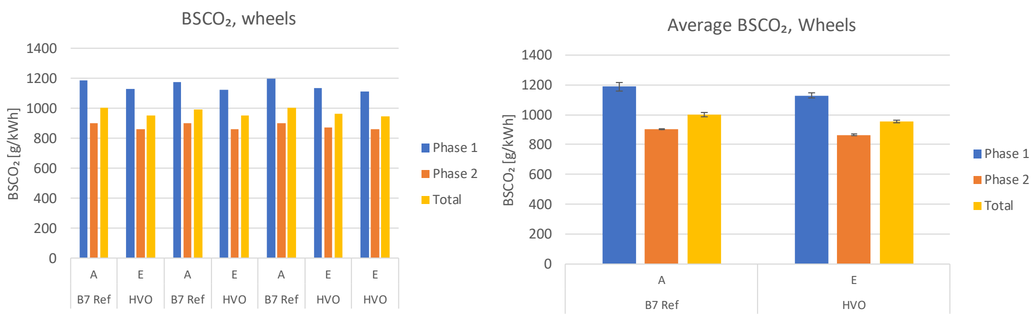


Figure 8-1 Brake wheel specific CO_2 emissions recorded in TfL UIP both in a chronological order and as averages calculated from all repetitions.

As discovered in the RDE cycle, most of the CO emissions were emitted early in the test, during cold start. This applied to the TfL UIP as well, in this case phase 1, which produced the majority of CO emission over the total trip. During phase 1, average CO emissions for Fuel A were ca. 2300 mg/kWh and ca. 1600 mg/kWh for Fuel E. CO emissions in phase 2 were below 50 mg/kWh for both fuels. The CO emissions were however somewhat variable/inconsistent for Fuel A as seen in Figure 8-2, resulting in a variation of ca. 1500 mg/kWh between the lowest and highest value. This phenomenon was not present for Fuel E, which also resulted in 28 % lower CO in phase 1 and 48 % lower CO in phase 2.

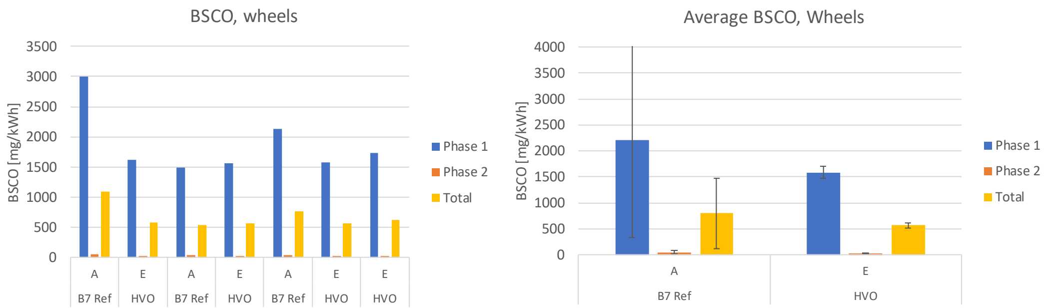


Figure 8-2 Brake wheel specific CO emissions recorded in TfL UIP both in a chronological order and as averages calculated from all repetitions.

Similarly to CO, NO_x TP results were affected by an obvious baseline drift throughout the TfL UIP testing. First, a gradual increase in NO_x TP was seen, followed by a decreasing pattern as shown in Figure 8-3. The emission trend was very similar for both test fuels, hence no conclusive fuel relationship could be determined. Simultaneously, N_2O emissions increased for the first three consecutive tests, whereafter they seemingly settled as seen in Figure 8-4. No direct fuel related trends were noted, and very little difference in average values could be seen. The N_2O emissions remained below 150 mg/kWh.

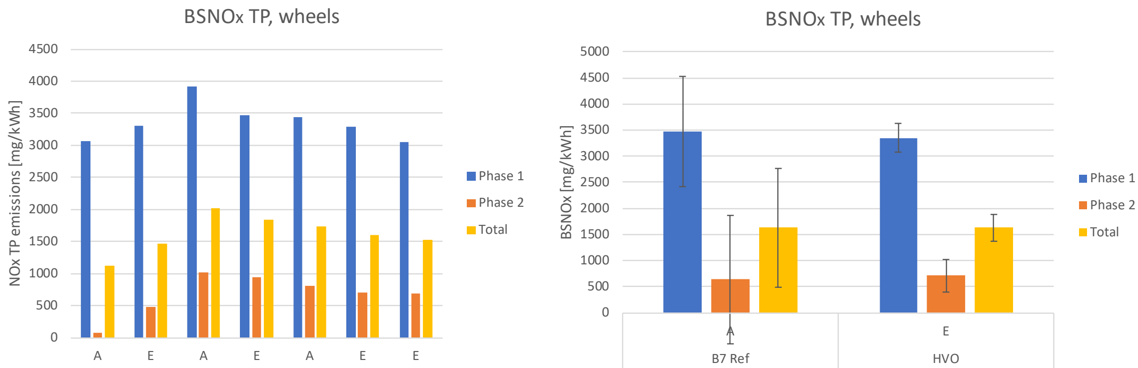


Figure 8-3 Brake wheel specific NO_x emissions recorded in TfL UIP both in a chronological order and as averages calculated from all repetitions.

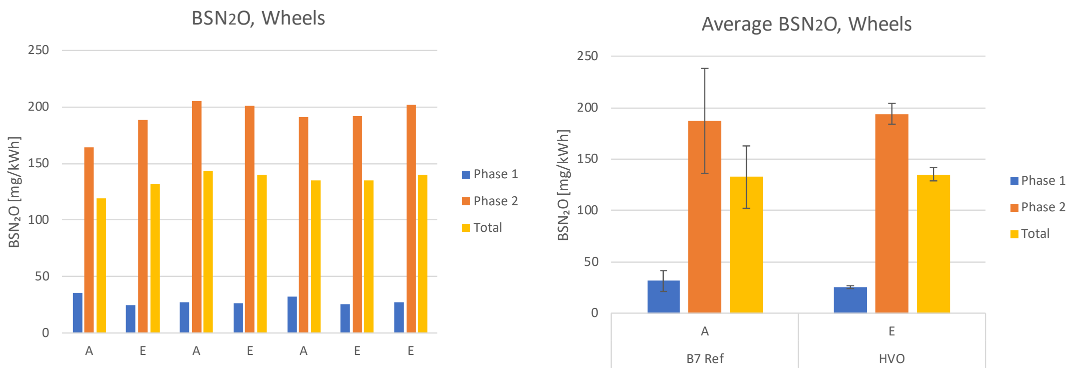


Figure 8-4 Wheel work based N_2O emissions from the different phases of TfL UIP both in a chronological order and as averages calculated from all repetitions.

Most of the HC emissions were produced during phase 1. HC emissions remained relatively constant throughout the tests. Fuel E produced somewhat lower results, but considering the absolute emission level, the impact is rather small.

Note that it is not unusual to see negative HC emissions when the after-treatment system is operating at design temperature, such as in phase 2, as the oxidation catalyst is also oxidising any hydro-carbons present in the intake air (background emissions) which is the zero reference for the instrument.

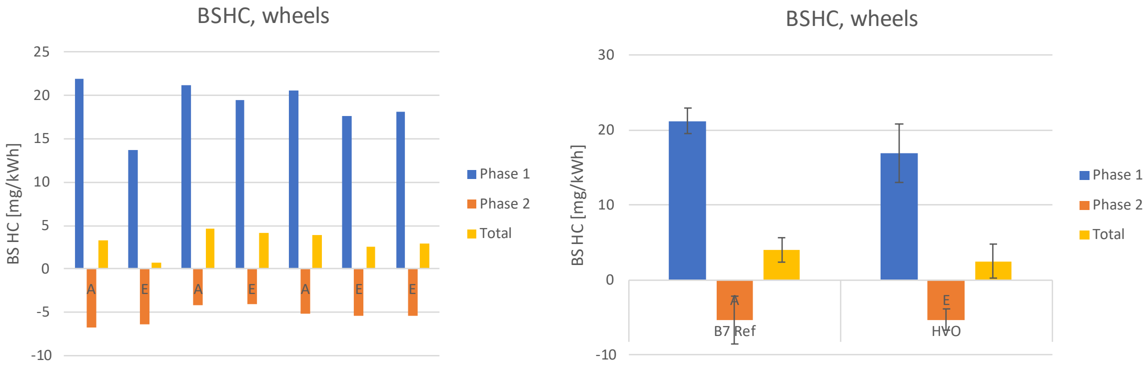


Figure 8-5 Wheel work-based HC emissions from the different phases of TfL UIP both in a chronological order and as averages calculated from all repetitions.

Ammonia results showed a constantly decreasing trend throughout the experimental campaign. Considering the patterns of NO_x, N_2O and NH_3 emissions, the SCR/ASC unit could possibly be affected by ammonia storage. The ammonia slip was however in general very low, below 2 mg/kWh.

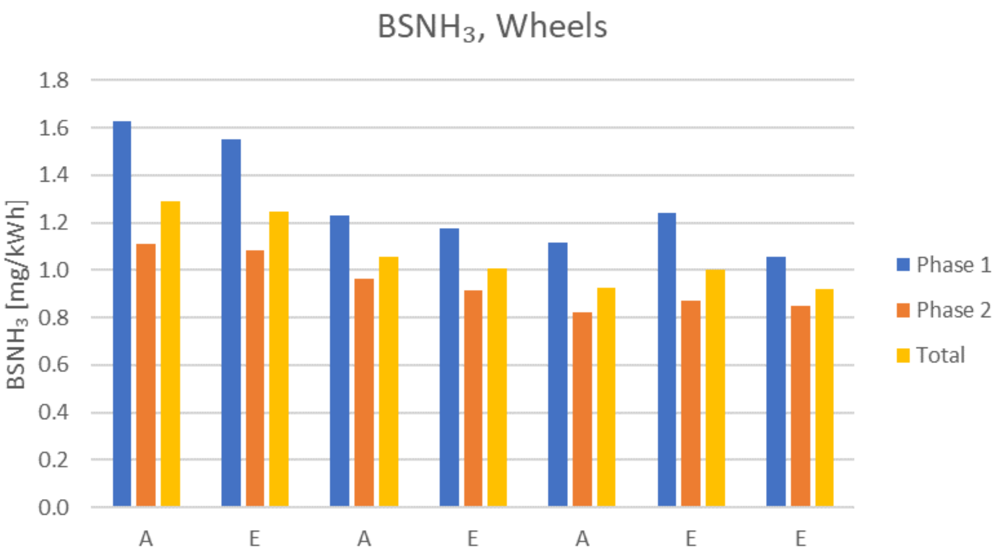


Figure 8-6 Recorded NH_3 emissions in a chronological order

Strong trends for both PN10 and PN23 emissions were seen, most likely due to changes in DPF soot loading as displayed in Figure 8-7. Due to sampling issues, no PN10 data for the first test with Fuel E could be obtained, hence this particular result was left blank (indicated with red in Figure 8-7. From PN23 data some indicative trends could still be seen. Both PN10 and PN23 gradually increased throughout the tests without any signs of fuel effects. Due to the limited quantity of test repetitions, it is unclear how the PN emissions would eventually settle. The OBD data obtained from the vehicle suggested that soot load decreased between the first and last test, possibly due to incomplete active DPF regenerations triggered during the higher load phases. In such drive cycles, when the DPF is reaching capacity, active regenerations may be triggered during higher load (therefore exhaust temperature) phases but are aborted when the vehicle returns to idle, due to the lower temperature and therefore much higher requirement for additional heat energy from fuel post injection to affect a regeneration. This finding was in line with the assumption that the filtration efficiency was strongly dependent on filter load. Because of the increasing trend, no average results were analysed.

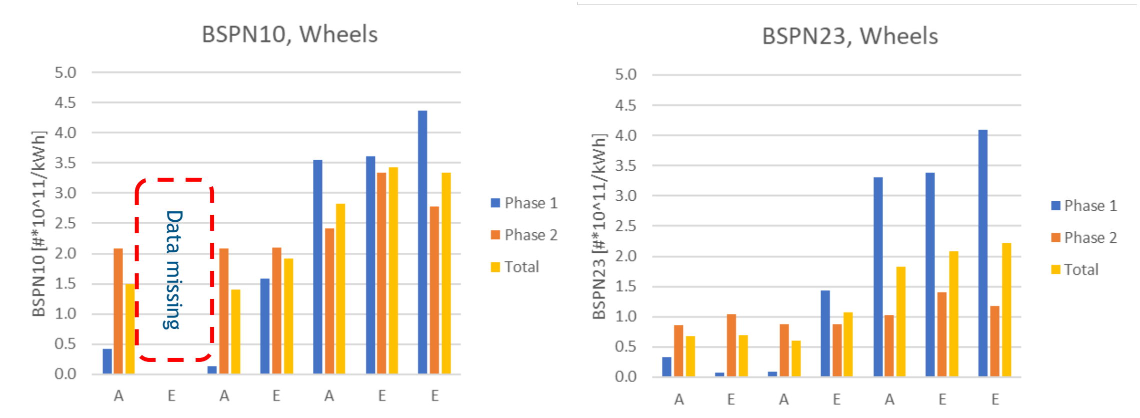


Figure 8-7 PN10 and PN23 results in a chronological order.

Therefore, due to strong trends in much of the pollutant emissions data, fuel effects were only observed for CO and HC, where levels were systematically lower for HVO (Fuel E) than EN590 B7 (Fuel A). These trends were primarily observed in Phase 1 of the test cycle, where the engine and aftertreatment system are coldest. This trend can be attributed to the lower aromatic content and higher cetane number of HVO.

9. RESULTS OVERVIEW AND DISCUSSION

9.1. RESULTS OVERVIEW

One of the headline outcomes of this study was how effectively the exhaust aftertreatment system of this Euro VI step E vehicle performed under Euro 7 conditions. This is demonstrated in the summary below showing the EN590 B7 reference fuel results alongside both the Euro 7 RDE and Euro VI WHTC limits. All results are well within the Euro 7 limits, with N_2O being the only pollutant close to the new limit.

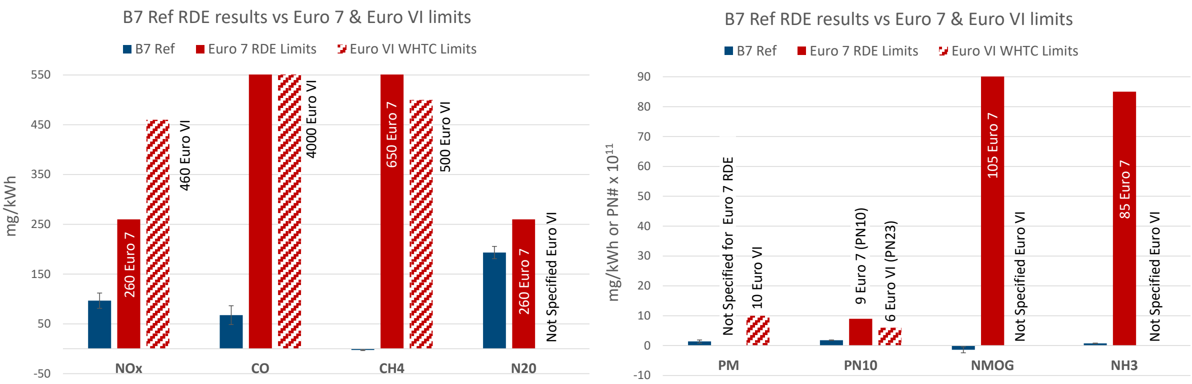


Figure 9-1 Summary chart of B7 Ref RDE results vs Euro 7 & Euro VI limits

It follows that with overall emissions this low, the differences between test fuels can be expected to be small. There were however some interesting differences over the range of fuels tested when closely analysing the results, and these differences are summarised as % difference relative to the EN590 B7 reference fuel in the charts below for the key vehicle performance and emissions factors. The error bars indicate the 95% confidence interval based on a statistical analysis over the number of tests completed for each fuel. Error bars which do not cross the x-axis are therefore significant at the 95% level.

It can be seen that the expected effects on CO_2 and fuel consumption from fuels containing HVO are evident in the data.

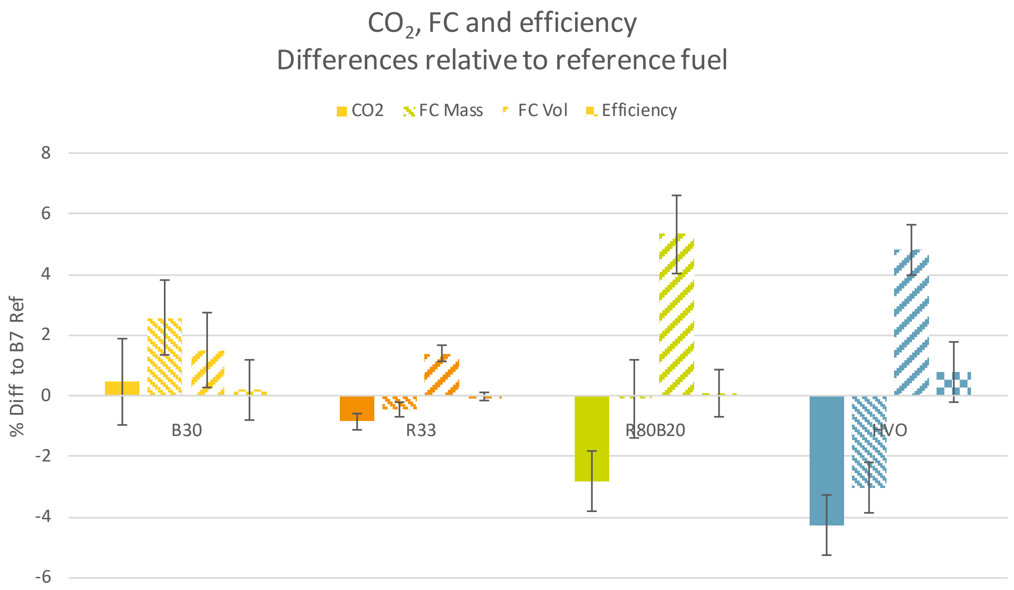


Figure 9-2 Fuel effects on CO_2 emissions and vehicle performance factors as % difference relative to reference fuel

The fuels effects on the key pollutants indicate very small differences between fuels, not exceeding the 95% confidence interval, and these are shown below:

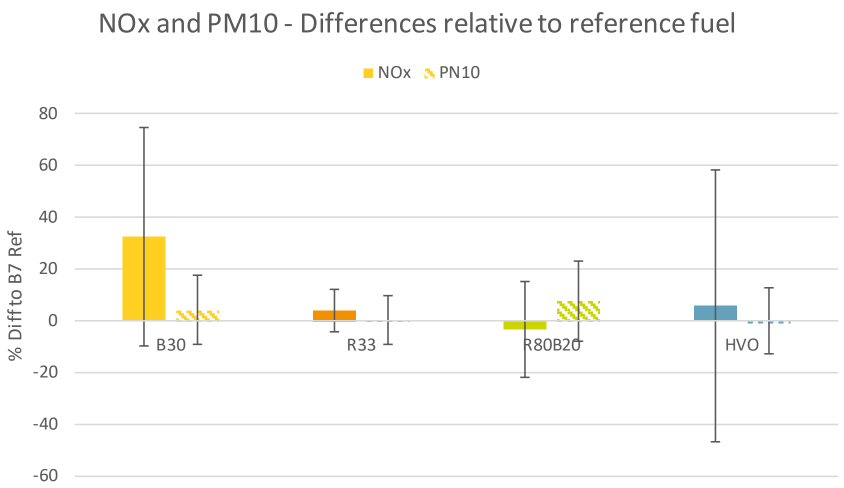


Figure 9-3 Fuel effects on NOx and PM10 as % difference relative to reference fuel

Finally, the additional testing conducted on the test cycle designed to be extremely demanding on the after-treatment system gave some insight as to the limitations of the after-treatment technology, and what use cases would best suit this type of vehicle. When looking at the EN590 B7 reference fuel compared to Euro 7 limits, it is interesting to compare the NOx and particulate results between the RDE and TfL UIP test cycles. The results show that while the particulate filter copes well with the highly transient cycle with long idle times, the SCR catalyst is not able to maintain the required temperatures to keep NOx levels as low as it does in the RDE cycle. This comparison is summarised below:

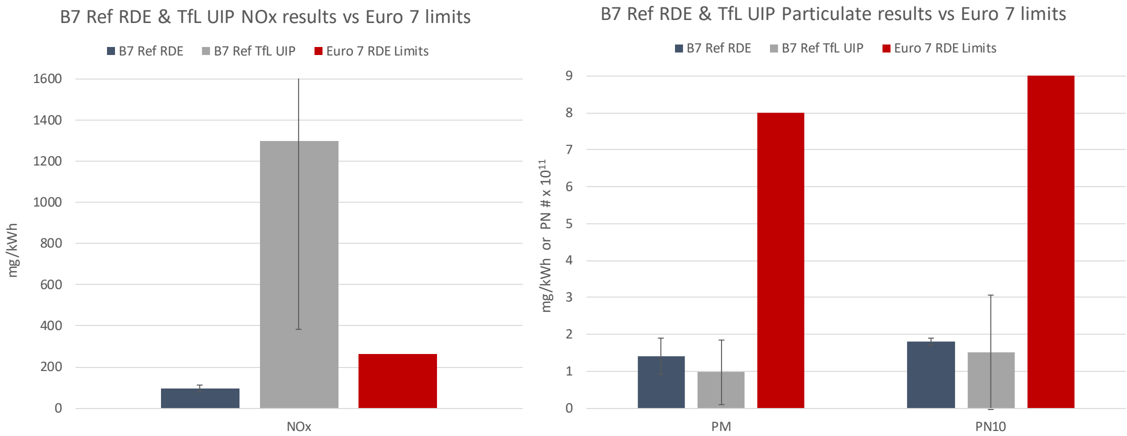


Figure 9-4 Comparison of the NOx and particulate emissions between the RDE and TfL UIP cycles

For the TfL UIP cycle, only the HVO fuel was tested to compare to the reference fuel and significant results were found in the CO and HC emissions. The results for phase 1 of the cycle relative to the EN590 B7 reference fuel are shown below:

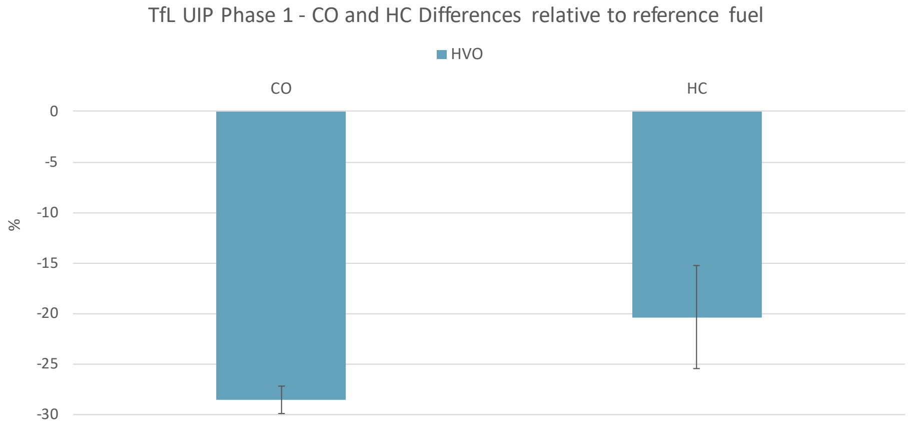


Figure 9-5 Fuel effects on CO and HC emissions in the TfL UIP cycle

9.2. VEHICLE PERFORMANCE

The results obtained from the experimental campaign conducted for this study have demonstrated that the exhaust emission performance of this Euro VI step E vehicle generally complies with both Euro VI and Euro 7 emission limits in normal, 23°C ambient temperature conditions and by a considerable margin in most pollutant emissions. Especially when the vehicle engine and EATS has reached its full operational thermal conditions, the measurements show that all gaseous emissions are being suppressed efficiently, often into the sub 10 mg/kWh region. Current DPF systems seem to comply well for PN23 but most importantly, for PN10 as well. Tailpipe PN emissions in the experiments were low, both in the regular RDE compliant test cycle, but also in the EATS demanding, transient TfL UIP.

The measurements also indicated that current Euro VI E HDVs may face some challenges, especially with NOx suppression, during cold start events and under low load conditions. The reason for this is that both conditions contribute to insufficient EATS thermal load required for the SCR unit to operate as intended. Since the initial deployment of Euro VI, this issue has been tackled by speeding up the engine/EATS warm-up by implementation of various thermal control related strategies. These measures have been a consequence of effective updates in Euro VI emissions regulation (step C, D and latest E) deployed by the EC, which has gradually phased in factors that account for cold start conditions and lower power thresholds. Euro 7 is no exception to the evolution of European emission legislation. Primarily, the further reduced emission limits place an even higher emphasis to both reduce the overall exhaust pollutants in combination with a reduction of the cold start emissions. This could be tackled by adoption of additional, close-coupled SCR units as already used in some cases and/or adoption of exhaust heating strategies. For example, Euro VI NOx limit for PEMS testing is currently 600 mg/kWh, meanwhile the corresponding limit for Euro 7 has been reduced to 260 mg/kWh. The results obtained in this project have proved that NOx TP emissions well below 260 mg/kWh can be achieved with ease. However, the efficient NOx mitigation seems to come with a trade-off. Reflecting on the vehicle performance against Euro 7 limits, the currently unregulated N_2O emissions were closest to the permissible Euro 7 emission limits. N_2O formation is generally not formed from the engine, but the EATS. N_2O is typically dependent on catalyst materials and EATS strategy/architecture. N_2O emissions may be generated from both the DOC or the SCR catalyst or even from the ASC[17]. Because no upstream catalyst emissions were measured, the primary source for N_2O measured in this campaign remains unconfirmed, but other works such as the aforementioned Concawe program executed at VTT indicate most N_2O is derived from the EATS and is not fuel dependent. It is nevertheless evident that some fine tuning in mitigation of N_2O is another challenge for the OEMs regarding Euro 7 type-approval as well as management of NOx under cold conditions.

As the measurements in this study were limited to one payload (50 %), the influence of lower payloads regarding emission performance remains unknown. The measurements conducted with TfL UIP cycle however demonstrated that when subjecting the vehicle to a mix of very low loads and/or low speed driving, combined with transient, rapid and high load accelerations, heavy stress on the vehicle EATS will be introduced. The reason for this is that subjecting the engine to ultra-low loads reduces the thermal state of the EATS below efficient operational conditions. The vehicle is then subjected to hard accelerations (high loads), causing rapid peaks in EO emissions, simultaneously as the temperature of the catalysts for proper emission reduction is insufficient. The DPF seems to be less influenced by this phenomenon because the filtration efficiency is not temperature dependent. These phenomena were clearly demonstrated through the tests conducted in the TfL UIP cycle, which increased the gaseous exhaust emissions, especially CO and NOx emissions dramatically. The vehicle thermal management regarding EATS was simply insufficient to be able to keep up with the required conditions for effective emissions reduction. The TfL UIP is however an extreme example of worst-case conditions. These conditions do not comply with any current and future standard regulatory tests. It is therefore natural that the manufacturers do not explicitly optimise designs for emission reduction in such conditions.

9.3. FUEL EFFECTS

As Euro 7 regulation requires the manufacturers to comply with the emission limits using all market fuels approved by the manufacturer, possible fuel effects must be considered. This applies especially for fuel blends and fuel types that may negatively influence the TP emission performance. This is particularly important if the vehicle emissions are close to the permissible legislative emission limits. Some effects for assumed vehicle ECU torque were noted. This could be important to perceived truck emissions performance because ECU torque is used during on-road emissions determination to calculate work-specific emissions, so, a lower calculated ECU torque would result in higher specific emissions results. The deviation for fuel with highest impact was around 3.3 %, which is

[17] https://www.energy.gov/eere/vehicles/articles/n2o-emissions-2010-scr-systems

still within the margins of acceptable error from the regulatory perspective. The fuels tending to affect ECU calculated torque most were those containing high concentrations of FAME. In the subject RDE tests, this phenomenon is not a cause for concern because emissions were far below Euro 7 limits, but could be more impactful in vehicles just meeting Euro 7 limits.

Due to the highly efficient emissions management of the vehicle technology, fuel effects on pollutant emissions at the tailpipe under RDE conditions were minimal. In older technology vehicles with less sophisticated emissions control, effects such as lower PM/PN and NOx might be expected for paraffinic fuels, as shown in a previous 2020 Concawe study referenced and described in section 6.1.1, but this was not the case in this modern vehicle. Some fuel effects were apparent, for example, engine-out NOx was lower for all low carbon fuels (B-E) than for the B7 reference and this could result in lower AdBlue consumption. HC and CO emissions were lower for HVO at tailpipe during the cold phase of TfL UIP cycle than for B7. Fuel D (80% HVO / 20% FAME) produced higher average PN results than the reference B7, but this could have been a result of experimental variation, given that the range in individual test results for this fuel was high. The data suggested an apparent negative effect of HVO on N_2O emissions, however as N_2O is almost completely a product of the EATS and not engine-out, this is likely to be coincidental rather than being systematically connected to the combustion characteristics of HVO. Overall fuel effects on pollutant emissions at tailpipe were immaterial due to the application of highly efficient emissions control, with closed loop control mitigating fuel effects.

Blends containing paraffinic diesels were found to reduce TP CO_2 emissions and increase powertrain efficiency simultaneously. This generally applies for fuels with higher CN and low CO_2 intensity, confirming that such low carbon fuels based on various combinations of FAME and HVO can provide tailpipe as well as WTT carbon reduction benefits.

Lastly, the dependencies between fuel properties and test data were screened by calculating the correlation coefficient between fuel properties and emission results. A general outline for fuel effects could be noted, but because the impact of fuel properties on vehicle performance was concluded interdependent and often suspected to be non-linear, a more detailed modelling of the emission results could produce more accurate estimates of combined fuel effects. This is however outside the scope for this study, and would not change the overriding conclusion that these effects are small in the context of the tailpipe Euro 7 limits.

10. CONCLUSIONS

The following conclusions from the experimental campaign may be drawn:

- The results demonstrated that the tested state-of-the-art Euro VI Step E vehicle, with its current technology, i.e. engine and exhaust after-treatment system (EATS), could already comply with the emission limits defined in the Euro 7 regulation with fuels including EN590 B7 and low carbon fuels comprising various ratios of petroleum diesel, FAME and HVO. However, the results also demonstrate that diesel-powered Euro VI HDVs can struggle with NO_x mitigation under extreme conditions, in particular where the vehicle is subjected to generally low loads (therefore low EATS temperature below efficient pollutant conversion thresholds) interspersed with rapid and heavy transient driving. This phenomenon could be managed by employing catalyst pre-heating measures.

- N_2O was the only exhaust component close to or above the declared Euro 7 limit with a final conformity factor between 0.65 and 1.01. However, N_2O is predominantly generated in the EATS and different catalyst materials can be employed to manage N_2O.

- Low carbon fuels containing paraffinic diesels were found to reduce TP CO_2 emissions and increase powertrain efficiency simultaneously, demonstrating that such low carbon fuels based on various combinations of FAME and HVO can provide tailpipe as well as WTT carbon reduction benefits.

- Fuel effects on pollutant emissions at tailpipe were immeasurably small due to the highly efficient emissions control technology, with closed loop control mitigating fuel effects.

- Overall, these results show that state-of-the-art Euro VI Step E HDV technology is capable of Euro 7 emissions performance and can perform equally well or better with a range of low carbon fuels containing FAME and HVO.

11. ACKNOWLEDGEMENTS

The authors of this report would like to acknowledge and give special thanks to the following parties:

- Transport for London is acknowledged for the TfL UIP test cycle.
- All STF-25 and FEMG members for the guidance, active involvement discussing and evaluating of the results along the experimental campaign.
- VTT laboratory staff for the hard work during the experimental campaign.
- Dieter Walter and Adrian Velaers for all the valuable support during the process of this project.

APPENDIX 1 FUEL PROPERTIES OF THE BASE FUELS

Basic properties of the base fuel components

Property	Units	Method	EN590	HVO	FAME
Origin	-	-	Petroleum	Renewable	Renewable
Cetane Number	(CFR)	EN ISO 5165	54.2	73.3	52.1
Cetane Index	-	EN ISO 4264	54.1	-	-
Density at 15°C	kg/m3	EN ISO 12185	841.3	780.6	882.3
Distillation IBP	°C	EN ISO 3405	179.9	200.8	-
Dist. 10% v/v	°C	EN ISO 3405	225.5	261.6	-
Dist. 50% v/v	°C	EN ISO 3405	284.9	281.0	-
Dist. 90% v/v	°C	EN ISO 3405	332.5	292.8	-
Dist. 95% v/v	°C	EN ISO 3405	345.2	297.7	-
Dist. 250°C %	(V/V)	EN ISO 3405	22.8	4.6	-
Dist. 350°C %	(V/V)	EN ISO 3405	96.2	-	-
Distillation FBP	°C	EN ISO 3405	352	310.0	-
Flash Point	°C	EN ISO 2719 (Procedure A)	67.5	71.0	117.5
Cloud Point	°C	DIN EN ISO 22995	-8.5	-34.3	-8
Viscosity at 40°C	mm2/s	EN ISO 3104	3.301	2.978	4.402
Aromatics, Total	%(m/m)	EN 12916	19.6	0.4	-
Aromatics, Mono	%(m/m)	EN 12916	-	0.3	-
Aromatics, Di	%(m/m)	EN 12916	-	0.1	-
Aromatics, Tri+	%(m/m)	EN 12916	-	0.04	-
Aromatics, Poly (2+3)	%(m/m)	EN 12916	2	0.1	-
Sulfur	mg/kg	EN ISO 20846	4.5	<1	2.0
Corrosion - Copper, 3h at 50°C		EN ISO 2160	1a	1a	1a
Carbon Residue - 10% Dist. Residue	%(m/m)	EN ISO 10370	<0.1	<0.1	<0.01
Ash Content	%(m/m)	EN ISO 6245	<0.001	<0.001	<0.02
Water	%(m/m)	EN ISO 12937	0.0031	0.0024	0.0021
Total Contamination	mg/kg	EN 12662 (2014)	5	1.5	3
Oxidation Stability	h	EN 15751	-	-	14.7
CFPP	°C	EN 116	-14	-35	-22

APPENDIX 2 FUEL PROPERTIES OF FINAL TEST FUELS

Fuel properties for the final test fuels

			Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
Property	**Units**	**Method**	**B7 Ref**	**B30**	**R33**	**R80B20**	**HVO**
Cetane Number	(CFR)	EN ISO 5165	52,9	51,6	55,8	67,6	73,3
Cetane Index	-	EN ISO 4264	53,8	53,7	>56.5	>56.5	-
Density at 15°C	kg/m3	EN ISO 12185	843,7	852,7	828,3	800,3	780,6
Distillation IBP	°C	EN ISO 3405	176,6	179,5	182,9	227,7	200,8
Dist. 10% v/v	°C	EN ISO 3405	226,9	239,4	238,3	268,5	261,6
Dist. 50% v/v	°C	EN ISO 3405	288,6	307,5	287,2	288,3	281.0
Dist. 90% v/v	°C	EN ISO 3405	333	337,8	327,7	319,3	292,8
Dist. 95% v/v	°C	EN ISO 3405	342,5	344,3	339,8	332,5	297,7
Dist. 250°C %	(V/V)	EN ISO 3405	21,5	13,7	15,5	2,7	4,60
Dist. 350°C %	(V/V)	EN ISO 3405	97,2	-	-	-	-
Distillation FBP	°C	EN ISO 3405	351,6	348,7	349,4	341,4	310.0
Flash Point	°C	EN ISO 2719 (Procedure A)	68	70	74	100	71.0
Viscosity at 40°C	mm2/s	EN ISO 3104	3,336	3,516	3,248	3,192	2.978
Aromatics, Total	%(m/m)	EN 12916	19	14,4	13,9	<0.8	0.4
Aromatics, Mono	%(m/m)	EN 12916	17	12,8	12,5	<0.8	0.3
Aromatics, Di	%(m/m)	EN 12916	1,8	1,4	1,3	<0.8	0.1
Aromatics, Tri+	%(m/m)	EN 12916	0,2	0,2	0,1	<0.8	0.04
Aromatics, Poly (2+3)	%(m/m)	EN 12916	2	1,6	1,4	<0.8	0.1
Sulfur	mg/kg	EN ISO 20846	3,7	3,1	<3	<3	<1
Corrosion - Copper, 3h at 50°C		EN ISO 2160	1a	1a	1a	1a	1a
Carbon Residue - 10% Dist. Residue	%(m/m)	EN ISO 10370	<0.1	<0.1	<0.1	<0.1	<0.1
Ash Content	%(m/m)	EN ISO 6245	<0.001	<0.001	<0.001	<0.001	<0.001
Water	%(m/m)	EN ISO 12937	0,004	0,008	0,005	0,007	0,00
Total Contamination	mg/kg	EN 12662 (2014)	<12	<12	<12	<12	1.5
Oxidation Stability	h	EN 15751	24,9	20,1	30	31,7	-
FAME	%(V/V)	EN 14078	6,6	29,5	6,7	19,8	-
Oxygen	%(m/m)	ASTM D5291 (Method C)	0,65	3	0,75	2,1	0,00
Hydrogen	%(m/m)	ASTM D5291 (Method C)	13,4	13,1	13,8	14,4	15,20
Carbon	%(m/m)	ASTM D5291 (Method C)	85,9	83,8	85,5	83,6	84,8
Net Heating Value	MJ/kg	DIN 51900 Part 3	42,75	41,44	42,99	42,74	43,92
Lubricity, HFRR (WSD)	µm	EN ISO 12156-1 (Method A)	230	170	210	150	385
Manganese	mg/l	EN 16578	<0.5	<0.5	<0.5	<0.5	<0.5
Oxidation Stability	g/m3	EN ISO 12205	2	1	1	2	<1
CO_2 intensity	g CO_2 / MJ	Calculated	73,7	74,2	72,9	71,7	70,8
CO_2 intensity	g CO_2/kg	Calculated	3149,7	3072,7	3135,0	3065,3	3109,3

APPENDIX 3 LINEAR CORRELATION OF FUEL PROPERTIES AND HDV PERFORMANCE

The individual fuel properties and their possible impact on the key performance metrics were screened for identifying potential meaningful fuel characteristics. Firstly, the linear correlation between the known fuel properties was determined as shown in Table 0-1. Then, possible fuel effects in respect to emission and powertrain data were mapped by quantifying the correlation coefficient *r* between each component in the data set in relation to the known fuel properties. The data set used in the correlation analysis was extracted from the tests conducted in the RDE cycle. No data from the EATS-demanding cycle was used, because only two fuels were tested. The RDE results and fuel properties were compiled as a matrix map to improve the visualization of any significant fuel related dependencies. To distinguish differences between cold start and normal driving, this procedure was conducted both for the urban phase and for total trip RDE results. Because the hydrocarbon and ammonia emissions were previously concluded to be close to or below the analyser detection limit (close or below 1 mg/kWh), these results were discarded from this analysis.

As the mechanisms behind emission formation are complex, with the phenomenon often dependent on multiple fuel related variables, the effects of some fuel properties may be interdependent as seen in Table 0-1. This also means that multiple fuel characteristics may simultaneously or jointly impact the outcome, or the impacts of fuel properties may be non-linear. Solving such equations would require a detailed, mathematical multi-variable model, which was not in the scope of this project. The correlation analysis presented in this chapter was therefore conducted solely to identify an outline of possible key fuel properties that have a linear dependency on emission performance, rather than enabling discussion of the mechanisms behind any phenomenon. The correlation coefficients presented in the tables shown in this chapter can be determined as follows: values below 0 indicate a negative correlation meaning that the variable tends to increase as the other decreases. (This implies that the slope for correlation is negative). A value above 0 is a positive correlation meaning that the variables tend to increase together and result in a positive slope. Values closer to -1 or 1 have the strongest correlation. The stronger positive correlations are indicated in green, meanwhile the stronger negative correlations are indicated with red colour.

Table 0-1 Correlation between key fuel properties.

Fuel property	Cetane Number	Density at 15°C	Distillation IBP	Dist. 10% v/v	Dist. 50% v/v	Dist. 90% v/v	Dist. 95% v/v	Dist. 250°C %	Distillation FBP	Flash Point	Viscosity at 40°C	Aromatics, Total	Aromatics, Mono	Aromatics, Di	Aromatics, Tri+	Aromatics, Poly (2+3)	Sulfur	Water	FAME	Oxygen	Hydrogen	Carbon	Net Heating Value	Lubricity, HFRR (WSD)	CO2 intensity
Cetane Number	1.0																								
Density at 15°C	-1.0	1.0																							
Distillation IBP	0.8	-0.7	1.0																						
Dist. 10% v/v	0.9	-0.9	0.9	1.0																					
Dist. 50% v/v	-0.7	0.7	-0.4	-0.4	1.0																				
Dist. 90% v/v	-0.9	0.9	-0.5	-0.7	0.7	1.0																			
Dist. 95% v/v	-0.9	0.9	-0.4	-0.6	0.6	1.0	1.0																		
Dist. 250°C %	-0.9	0.8	-0.9	-1.0	0.3	0.7	0.7	1.0																	
Distillation FBP	-0.9	0.9	-0.4	-0.7	0.5	1.0	1.0	0.7	1.0																
Flash Point	0.5	-0.4	0.9	0.7	-0.2	-0.1	0.0	-0.7	0.0	1.0															
Viscosity at 40°C	-0.9	0.9	-0.5	-0.7	0.9	0.9	0.9	0.6	0.8	-0.2	1.0														
Aromatics, Total	-1.0	0.9	-0.9	-1.0	0.5	0.8	0.8	1.0	0.8	-0.6	0.8	1.0													
Aromatics, Mono	-1.0	0.9	-0.9	-1.0	0.5	0.8	0.8	1.0	0.8	-0.6	0.8	1.0	1.0												
Aromatics, Di	-0.9	0.9	-0.6	-0.9	0.5	0.9	0.9	0.9	0.9	-0.3	0.8	0.9	0.9	1.0											
Aromatics, Tri+	0.2	-0.2	0.8	0.5	0.0	0.1	0.2	-0.5	0.2	0.9	0.0	-0.4	-0.4	0.0	1.0										
Aromatics, Poly (2+3)	-1.0	0.9	-0.7	-0.9	0.5	0.9	0.9	0.9	0.9	-0.3	0.8	0.9	0.9	1.0	-0.1	1.0									
Sulfur	-0.8	0.8	-0.3	-0.6	0.5	0.9	1.0	0.7	1.0	0.1	0.8	0.7	0.7	0.9	0.3	0.9	1.0								
Water	-0.4	0.5	0.1	0.0	0.8	0.7	0.7	0.0	0.6	0.4	0.7	0.1	0.1	0.4	0.6	0.4	0.6	1.0							
FAME	-0.4	0.5	0.1	0.0	0.9	0.6	0.6	-0.1	0.5	0.3	0.7	0.1	0.1	0.3	0.5	0.3	0.5	1.0	1.0						
Oxygen	-0.4	0.5	0.1	0.0	0.9	0.6	0.6	-0.1	0.5	0.3	0.7	0.1	0.1	0.3	0.5	0.3	0.5	1.0	1.0	1.0					
Hydrogen	1.0	-1.0	0.7	0.8	-0.8	-1.0	-0.9	-0.8	-0.9	0.3	-1.0	-0.9	-0.9	-0.9	0.1	-0.9	-0.9	-0.6	-0.6	-0.6	1.0				
Carbon	-0.3	0.2	-0.6	-0.7	-0.5	0.0	0.0	0.7	0.1	-0.6	-0.1	0.6	0.6	0.4	-0.6	0.4	0.1	-0.7	-0.8	-0.8	-0.1	1.0			
Net Heating Value	0.7	-0.8	0.3	0.4	-1.0	-0.8	-0.8	-0.4	-0.7	0.0	-1.0	-0.5	-0.5	-0.7	-0.2	-0.7	-0.7	-0.9	-0.9	-0.9	0.9	0.4	1.0		
Lubricity, HFRR (WSD)	-0.6	0.5	-0.7	-0.9	-0.4	0.4	0.5	0.9	0.9	-0.7	0.0	0.8	0.8	0.8	-0.7	0.8	0.7	-0.9	-0.8	-0.8	-0.4	1.0	0.4	1.0	
CO2 intensity	-1.0	1.0	-0.7	-0.8	0.8	0.9	0.9	0.8	0.9	-0.4	1.0	0.9	0.9	0.9	-0.2	0.9	0.8	0.5	0.5	0.5	-1.0	0.2	-0.8	0.5	1.0

The correlation between fuel properties and key results for the urban phase are mapped in Table 0-2. Correspondingly, Table 0-3 displays the correlations of key fuel properties in relation to all key results for the total RDE. The outcomes extracted from the two datasets suggest following findings:

Fuel effects on cold start properties (RDE urban phase, Table 0-2)

- BSFC had a direct negative correlation with fuel LHV, which in turn had a high positive correlation with FAME content and 50 – 95 % distillation properties.
- CO_2 emissions were most dependent on cetane number (CN), density and CO_2 intensity. These three components have a direct 1:1 correlation to each other as seen from Table 0-1. The main factor for CO_2 emissions is fuel CO_2 intensity.
- No strong correlation between CO and fuel properties was found, but a negative relation between early distillation properties (IBP and T10) and FAME content was seen.
- A negative correlation between NO_x EO, early distillation properties and flash point was noted. Based on the linear correlation analysis, flash point can be seen to be dependent on IBP and Tri + aromatics.
- Apart from 50% distillation properties, a low correlation between NOx TP and fuel properties was found. 50 % distillation is dependent on multiple variables, e.g. FAME content.
- No meaningful fuel effect on urban N_2O emissions could be identified.
- PN23 and PN10 had similar fuel dependencies. Both have positive correlation with IBP, flash point and Tri + aromatics.
- The only meaningful correlation between PM and fuel properties was found for fuel flash point.

Table 0-2 Correlation between key performance related results in urban phase of the RDE cycle and fuel properties expressed as correlation coefficient r. Stronger linear correlations are indicated in stronger colours.

Correlation coefficient r, RDE results vs fuel properties, urban																					
Property	Cetane Number	Density at 15°C	Distillation							Flash Point	Viscosity at 40°C	Aromatics					Water	FAME	Net Heating Value	Lubricity, HFRR (WSD)	CO2 intensity
			IBP	10% v/v	50% v/v	90% v/v	95% v/v	250°C %	FBP			Total	Mono	Di	Tri+	Poly (2+3)					
BSFC	-0.81	0.87	-0.39	-0.49	0.94	0.90	0.84	0.46	0.78	-0.08	0.98	0.61	0.61	0.73	0.16	0.75	0.84	0.86	-0.99	-0.28	0.88
Efficiency	0.73	-0.68	0.35	0.66	-0.16	-0.80	-0.86	-0.72	-0.91	-0.02	-0.56	-0.74	-0.74	-0.89	-0.18	-0.86	-0.27	-0.12	0.38	-0.90	-0.67
CO2	-0.99	1.00	-0.74	-0.87	0.71	0.95	0.89	0.86	0.87	-0.42	0.93	0.94	0.94	0.95	-0.17	0.97	0.47	0.46	-0.78	0.57	1.00
CO	-0.28	0.22	-0.73	-0.68	-0.31	-0.02	-0.08	0.70	-0.03	-0.82	-0.07	0.55	0.55	0.29	-0.77	0.32	-0.73	-0.69	0.34	0.98	0.20
NOx EO	-0.53	0.55	-0.83	-0.61	0.56	0.27	0.12	0.52	0.06	-0.88	0.47	0.55	0.55	0.27	-0.79	0.33	0.00	0.13	-0.38	0.33	0.53
NOx TP	-0.45	0.51	-0.42	-0.23	0.88	0.38	0.26	0.13	0.16	-0.38	0.64	0.27	0.27	0.17	-0.29	0.22	0.56	0.68	-0.73	-0.30	0.53
N2O	0.03	-0.05	0.44	0.39	0.21	0.19	0.28	-0.40	0.27	0.65	0.12	-0.27	-0.26	-0.08	0.51	-0.12	0.65	0.48	-0.28	-0.68	-0.05
PN23	0.46	-0.40	0.90	0.78	0.04	-0.13	-0.05	-0.75	-0.07	0.94	-0.13	-0.67	-0.66	-0.35	0.93	-0.39	0.53	0.49	-0.12	-0.89	-0.38
PN10	0.37	-0.30	0.85	0.72	0.14	-0.03	0.06	-0.69	0.03	0.93	-0.02	-0.59	-0.59	-0.27	0.93	-0.30	0.62	0.58	-0.23	-0.92	-0.28
PM	0.19	-0.23	0.64	0.42	-0.24	0.08	0.24	-0.36	0.28	0.85	-0.14	-0.32	-0.31	-0.04	0.73	-0.10	0.35	0.14	0.06	-0.44	-0.24

Fuel effects on key metrics in total RDE trip (Table 0-3)

- Correlation between fuel properties, BSFC, CO_2, CO and NO_x TP were comparable to conclusions made from urban phase.
- NO_x EO was mostly dependent on fuel distillation properties, but also fuel flash point and aromatics.
- Correlation between N_2O and multiple fuel properties were noted, most importantly cetane number, late yield (90 %vol to FBP) and aromatics (mono-, di- and polyaromatics). Because the correlation between NO_x and N_2O was low, no direct or definitive conclusions could be made.
- PN10/23 seem to be somewhat dependent on Tri+ Aromatics. Furthermore, a connection between PN23 and flash point can be seen.
- No meaningful correlation between PM and fuel properties could be noted.

Table 0-3 Correlation between key performance related results from total RDE cycle and fuel properties expressed through coefficient of determination (R^2). Stronger linear correlations are indicated in stronger colours.

Correlation coefficient r, RDE results vs fuel properties, total																					
			Distillation									Aromatics									
Property	Cetane Number	Density at 15°C	IBP	10% v/v	50% v/v	90% v/v	95% v/v	250°C %	FBP	Flash Point	Viscosity at 40°C	Total	Mono	Di	Tri+	Poly (2+3)	Water	FAME	Net Heating Value	Lubricity, HFRR (WSD)	CO2 intensity
BSFC	-0.78	0.84	-0.35	-0.45	0.95	0.88	0.83	0.41	0.77	-0.04	0.97	0.57	0.57	0.70	0.19	0.71	0.87	0.89	-1.00	-0.36	0.86
Efficiency	0.70	-0.66	0.20	0.51	-0.28	-0.84	-0.91	-0.56	-0.95	-0.22	-0.62	-0.62	-0.63	-0.83	-0.36	-0.80	-0.50	-0.33	0.51	-0.67	-0.65
CO2	-1.00	1.00	-0.73	-0.86	0.72	0.96	0.90	0.84	0.88	-0.40	0.94	0.93	0.93	0.95	-0.17	0.96	0.50	0.48	-0.80	0.54	1.00
CO	-0.22	0.16	-0.69	-0.63	-0.35	-0.08	-0.15	0.65	-0.10	-0.81	-0.13	0.50	0.49	0.23	-0.77	0.26	-0.77	-0.72	0.39	0.98	0.14
NOx EO	-0.66	0.65	-0.95	-0.89	0.29	0.39	0.27	0.85	0.26	-0.94	0.45	0.81	0.81	0.57	-0.77	0.61	-0.27	-0.16	-0.22	0.77	0.64
NOx TP	-0.44	0.51	-0.46	-0.26	0.86	0.36	0.23	0.15	0.13	-0.44	0.63	0.29	0.28	0.17	-0.34	0.22	0.51	0.64	-0.70	-0.25	0.53
N2O	0.92	-0.89	0.52	0.74	-0.54	-0.96	-0.98	-0.75	-0.99	0.11	-0.83	-0.84	-0.84	-0.95	-0.07	-0.93	-0.54	-0.43	0.69	-0.82	-0.88
PN23	0.43	-0.36	0.88	0.76	0.10	-0.10	-0.02	-0.74	-0.05	0.93	-0.08	-0.64	-0.64	-0.33	0.92	-0.36	0.57	0.54	-0.18	-0.91	-0.34
PN10	0.13	-0.05	0.68	0.54	0.40	0.20	0.25	-0.54	0.21	0.83	0.24	-0.40	-0.39	-0.07	0.89	-0.10	0.80	0.77	-0.48	-0.97	-0.03
PM	-0.22	0.21	0.03	-0.30	-0.24	0.32	0.38	0.40	0.44	0.19	0.11	0.32	0.33	0.52	0.39	0.49	-0.11	-0.16	0.03	0.43	0.21

APPENDIX 4 DETERMINATION OF TEST FUEL FOR FURTHER TESTING IN EATS DEMANDING URBAN TEST CYCLE

Total RDE trip emissions were also considered in the fuel ranking for eliminating fuels that would hypothetically not perform well overall. The evaluation started by comparing absolute average results, then comparing the relative change in respect to fuel A. When considering meaningful fuel related impacts, both absolute and relative changes were considered. E.g. if a relative change would be large but in terms of absolute values the changes would be insignificant, the impact on fuel ranking was considered less impactful. Lastly, a numerical ranking per performance metric was formed, which would enable the comparison of Fuels B, C, D and E. The scale was determined between 1 – 4, with 1 being best performing fuel and value 4 the worst performing. All performance metrics were then summarized, giving a final score for each fuel for both urban phase and total trip. If two fuels would produce an equal rank value, the best performing fuel in both urban and total trip would be selected. In order to improve visualisation of the scoring in the tables, best performing properties were indicated in green, worst properties in red and with yellow those that scored in between.

The key performance metrics and average phase/trip results obtained for all test fuels are shown in Table 0-1. The relative impact of key performance metrics for Fuels B to E compared to Fuel A are shown in Table 0-2. Final fuel ranking for Fuels B, C, D and E is shown in Table 0-3. The key outcomes were concluded as follows:

- Powertrain efficiency remain relatively constant for Fuels A, B, C and E. Some improvement was seen for Fuel E both in urban and total RDE cycle.
- Volumetric FC increased with all fuels compared to reference Fuel A
- CO_2, CO decreased both in urban and total RDE cycle with all fuels compared to reference Fuel A. Impact on CO_2 was directly correlating with fuel carbon intensity
- NOx EO increased in urban phase Fuel B (B30); meanwhile other fuels produced less than reference Fuel A. All fuels reduced NO_x EO over total trip.
- TP NOx emissions were overall low, and little fuel effect was noted.
- In urban phase, N_2O increased with all Fuels, B, C, D and E. However, from given fuels, Fuel E (HVO) increased N_2O the least in urban, while emitting most over the total trip.
- Trip total PN10 emissions remain relatively comparable to reference Fuel A, apart from the urban phase with Fuel D (R80B20), which increased by 50 % or 1×10^{11} #/km.
- The fuel ranking scores were rather evident for the urban part, as Fuel E scored 19, Fuel C scored 25, Fuel D scored 25 and for Fuel B scored 27.
- Fuel ranking for total RDE results were twofold. Fuels B (B30) and D (R80B20) produced the highest scores, and Fuel C (R33) producing lowest, followed by Fuel E (HVO). Because the gap in urban results were significantly larger for Fuel E (HVO) compared to any other fuels, and especially considering that emphasis on urban was made, Fuel E was eventually chosen for further testing in TfL UIP.

Table 0-1 Key performance metrics for test fuels in urban phase and total RDE cycle

Average trip results from urban phase						
Per km (Urban)	Fuel A B7 ref	Fuel B B30	Fuel C R33	Fuel D R80B20	Fuel E HVO	Unit
FC mass	36.2	36.7	35.8	36.0	34.9	[kg/100 km]
FC vol	42.8	43.0	43.2	44.9	44.7	[l/100 km]
Powertrain Efficiency	30.0	30.1	30.0	30.1	30.3	%
CO_2	1137	1125	1120	1101	1084	g/km
CO	359	239	292	180	304	mg/km
NO_x EO	9443	9497	9215	8749	9293	mg/km
NO_x TP	724	977	773	721	772	mg/km
NO_x reduction	8719	8520	8442	8028	8521	mg/km
N_2O	171	186	194	197	177	mg/km
PN10	2.1	2.5	2.2	3.2	2.3	#*10^11/ km
PN23	0.9	1.2	1.0	2.0	1.2	

Average trip results from total trip						
Per km (total)	Fuel A B7 ref	Fuel B B30	Fuel C R33	Fuel D R80B20	Fuel E HVO	Unit
FC mass	27.6	28.3	27.4	27.5	26.7	[kg/100 km]
FC vol	32.7	33.2	33.1	34.4	34.3	[l/100 km]
Powertrain Efficiency	36.4	36.5	36.4	36.5	36.7	%
CO_2	868	868	860	844	831	g/km
CO	80	61	69	52	72	mg/km
NO_x EO	9219	8941	8818	8344	8790	mg/km
NO_x TP	114	150	118	110	121	mg/km
NO_x reduction	9105	8791	8699	8233	8669	mg/km
N_2O	228	228	227	237	253	mg/km
PN10	2.1	2.2	2.1	2.3	2.1	#*10^11/ km
PN23	0.8	0.9	0.8	1.0	0.9	

Table 0-2 Relative change of performance metrics compared to Fuel A

Per km (Urban)				
	Fuel B B30	Fuel C R33	Fuel D R80B20	Fuel E HVO
FC mass	1 %	-1 %	-1 %	-3 %
FC vol	0 %	1 %	5 %	4 %
Drivetrain efficiency	1 %	0 %	0 %	1 %
CO2	-1 %	-2 %	-3 %	-5 %
CO	-33 %	-19 %	-50 %	-15 %
NO_x EO	1 %	-2.4 %	-7 %	-1.6 %
NO_x TP	35 %	7 %	0 %	7 %
N_2O	8 %	13 %	15 %	4 %
PN10	18 %	4 %	54 %	7 %
PN23	33 %	6 %	118 %	24 %

Per km (total)				
	Fuel B B30	Fuel C R33	Fuel D R80B20	Fuel E HVO
FC mass	3 %	0 %	0 %	-3 %
FC vol	1 %	1 %	5 %	5 %
Drivetrain efficiency	0 %	0 %	0 %	1 %
CO2	0 %	-1 %	-3 %	-4 %
CO	-23 %	-13 %	-34 %	-9 %
NO_x EO	-3 %	-4 %	-9 %	-5 %
NO_x TP	32 %	4 %	-3 %	6 %
N_2O	0 %	0 %	4 %	11 %
PN10	4 %	0 %	8 %	0 %
PN23	7 %	1 %	20 %	4 %

Table 0-3 Fuel ranking of test fuels B to E for each performance metrics.

Per km (Urban)	Fuel B B30	Fuel C R33	Fuel D R80B20	Fuel E HVO
FC mass	4	2	3	1
FC vol	1	2	4	3
Efficiency	2	3	2	1
CO_2	4	3	2	1
CO	2	3	1	4
NO_x PreSCR	4	2	1	3
NO_x	4	3	1	2
N_2O	2	3	4	1
PN10	2	3	4	1
PN23	2	1	3	2
SUM	27	25	25	19

Per km (total)	Fuel B B30	Fuel C R33	Fuel D R80B20	Fuel E HVO
FC mass	4	2	3	1
FC vol	2	1	4	3
Efficiency	2	3	2	1
CO_2	4	3	2	1
CO	2	3	1	4
NO_x PreSCR	4	3	1	2
NO_x	4	2	1	3
N_2O	2	1	3	4
PN10	3	2	4	1
PN23	3	1	4	2
SUM	30	21	25	22

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