SPaTS Task 1-231 –Paraffinic Diesel Emissions Testing

Tranche 1 Laboratory Test Report

Report for Department for Transport

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Executive summary

The objective of this research was to undertake robust, independent comparative testing comparing the emissions performance of vehicles using paraffinic diesel with the emissions performance of the same vehicles using conventional diesel.

High concentrations of nitrogen dioxide, particularly in urban areas, are a significant problem in the UK, with an estimated effect on mortality equivalent to 23,500 deaths annually. Diesel vehicles (both, light and heavy duty) are of primary concern in relation to emissions at or near the roadside. Emissions from these vehicles represent a large proportion of the total contribution of both oxides of nitrogen (NOx) and primary nitrogen dioxide (NO_2). This in turn leads to elevated NO_2 concentrations at receptors close to the road network.

Whilst vehicle emission standards are crucial in reducing NOx emissions from transport, currently they have failed to deliver the **projected reductions** in ambient nitrogen dioxide (NO_2) in the real world despite, all light duty vehicles and engines for use in heavy duty vehicles having to meet the European Type Approval limits. Air quality monitoring shows that there continues to be widespread exceedance of NO_2 thresholds particularly in urban areas and near major roads.

Paraffinic diesel is promoted as producing lower NOx emissions at the tail pipe than conventional diesel. They are also promoted as being compatible with existing diesel vehicles without the need for any modification to the engine, though this has not been widely tested. It is essential that emissions from vehicles travelling on the road network are better understood, including whether the use of paraffinic diesel can help reduce levels of tailpipe NO_2 emissions. This project quantifies any differences in levels of tailpipe pollutants, primarily NOx emissions, between the two types of fuel (paraffinic diesel and regular diesel), while validating that there are no adverse effects on other air quality pollutants or greenhouse gas (GHG) emissions. Its results will support Government's air quality plans and help inform local authority decisions about possible measures to improve air quality whilst maintaining progress on reducing greenhouse gas emissions.

The approach used in this project was based on dynamometer testing of five different vehicle categories, encompassing different emissions standards, tested over modern regulatory and/or realistic in-use driving cycles. The use of dynamometer testing ensured repeatable and comparable results were produced by reducing uncontrollable external factors such as, weather, traffic conditions and so on. The driving cycles were chosen specifically to ensure a good representation of real-world driving. All vehicles were tested using a single batch of analysed paraffinic diesel, and compared with a Table ES1.baseline diesel from a single batch of analysed fuel.

The combination of vehicles, their emission standards, and the driving cycles used is summarised in Table ES1.

Table ES1: Summary of vehicles tested in this testing programme

Vehicle categories	Emissions standards	Driving cycles	Number of vehicles
Medium passenger cars	Euro 4, Euro 5, Euro 6	WLTC & US06	3
TX4 Taxis	Euro 4, Euro 6	WLTC & PCO-Taxi	2
Light duty vans (N1 Class 3)	Euro 4, Euro 6	WLTC & US06	2
18 tonne rigid trucks	Euro IV, Euro VI	WHVC	2
Buses	Euro IV, Euro VI	New London Urban bus cycle	2

Further details regarding the choice of vehicle models, the exhaust abatement technologies fitted to them and the driving cycles are given in Chapter 3 of the report in the appropriate sub-section for each vehicle category. It was originally planned to test two TX4 taxis, a Euro 4 and Euro 6, however due to a vehicle breakdown testing of the Euro 6 taxi was not completed so, results for this vehicle were not obtained in the project.

This programme of testing was undertaken in the context of a larger investigation requested by DfT where there is the possibility of a second tranche of vehicle testing dependent on the outcomes of this study. In subsequent research, on-the-road driving, using PEMS would be used to check for NOx reductions in real world conditions if this Tranche 1 testing indicated it was appropriate.

Generally, driving cycles were repeated three times for each vehicle for both fuels, which were analysed to provide results for mean NOx emissions and an indication of the results reproducibility, via their standard deviation. The impact of cold starting was also assessed for the WLTC for the light duty vehicles.

Paraffinic diesel was found to modestly reduce NOx emissions, as is summarised in figures ES1 and ES2. The first shows absolute emissions of NOx for both fuels over all cycles driven. The second figure shows the **reduction** in NOx tailpipe emissions. In Figure ES1 the black error bars are the standard deviation of the NOx emissions over the three repeat runs.

Figure ES1: Absolute NOx emissions for all ten vehicles over different drive cycles when running on both fuels

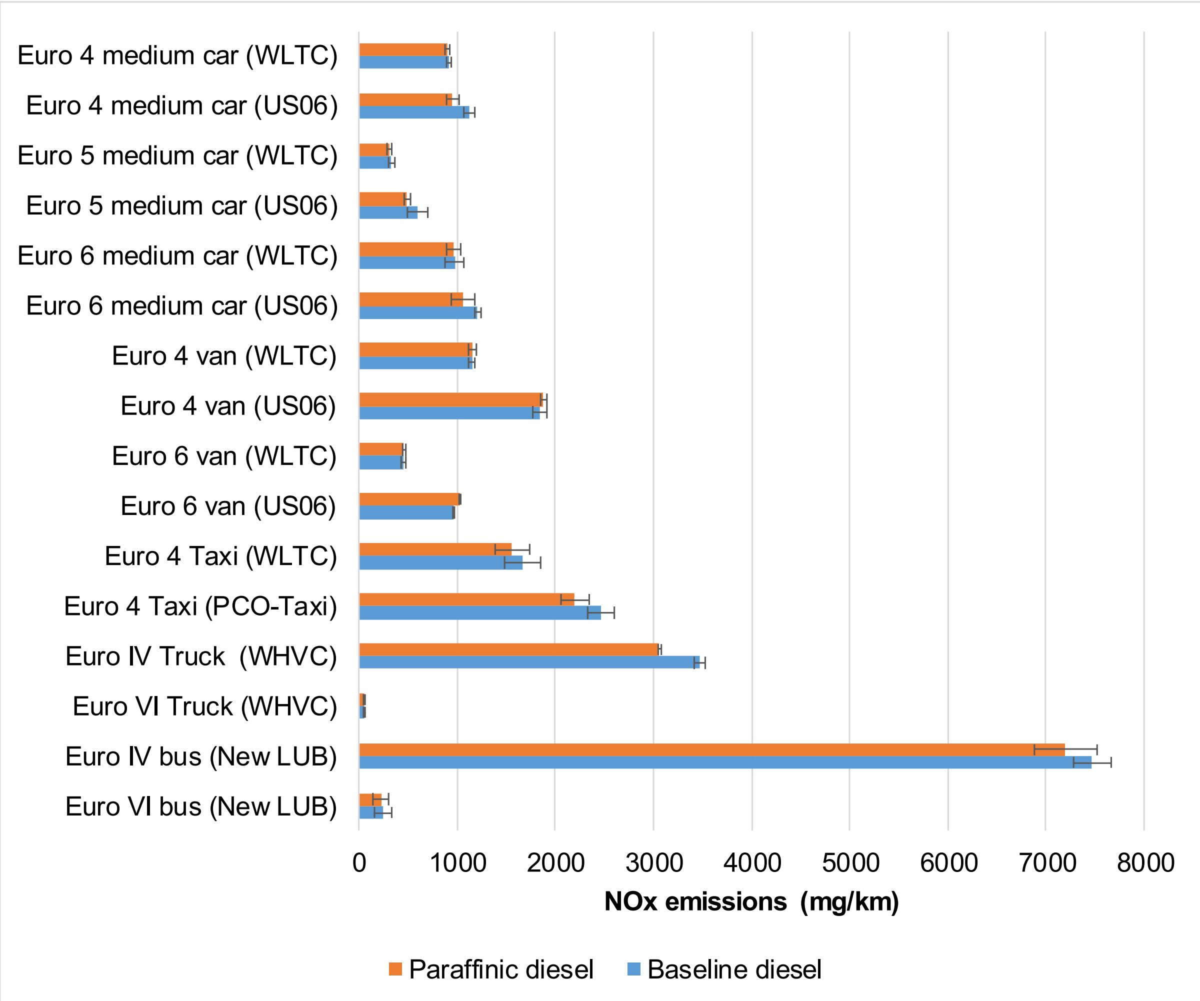
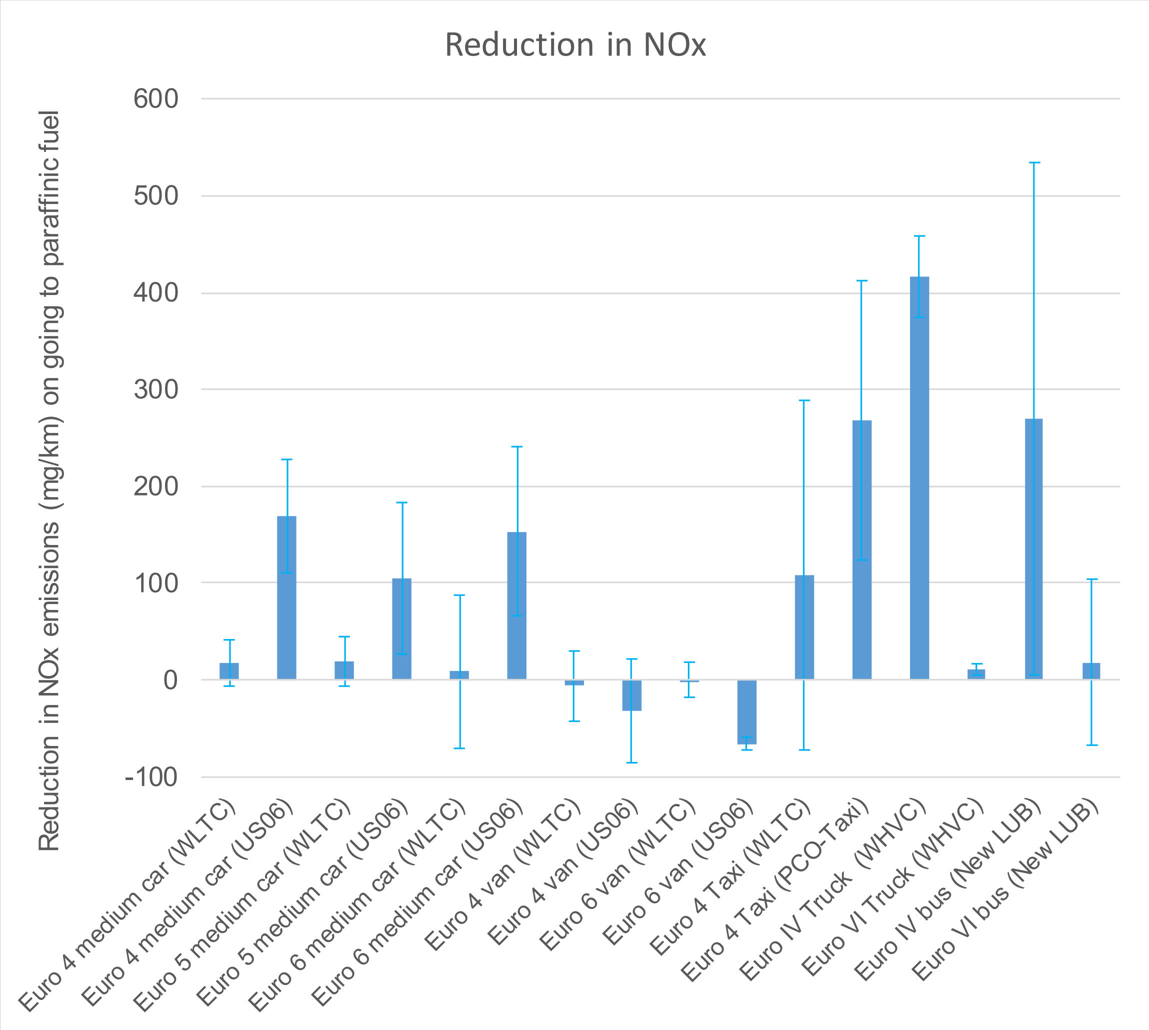


Figure ES2: Differences in absolute NOx emissions for all ten vehicles over different drive cycles when running on both fuels



In Figure ES2 the blue error bars are the root mean standard error of the NOx emissions, calculated from the standard deviations shown as error bars in Figure ES1, for the data from both fuels.

From the data in Figures ES1 and ES2 the following can be concluded:

Key Conclusion 1:

When driven with paraffinic diesel NOx emissions are generally lower than when driven with baseline diesel (in 8 of 10 vehicles). The differences are generally smaller than the cycle to cycle reproducibility (error bars) such that in isolation they are not significant. However, together they do strongly indicate that the use of paraffinic diesel is reducing NOx emissions by a modest amount for most vehicles.

A similar analysis for tailpipe CO_2 emissions leads to the following conclusions:

Key Conclusion 2:

When driven with paraffinic diesel tailpipe CO_2 emissions are generally lower than when driven with baseline diesel, by around 2.5%.

Key Conclusion 3:

The reduction in tailpipe CO_2 emissions when driven with paraffinic diesel is greater for HDV than for LDV.

It is emphasised that the two conclusions above consider only the Tank-to-Wheel greenhouse gas footprint for the two fuels, not the whole fuel carbon footprint, the full Well-to-Wheel footprint. It is generally found that the extraction of crude petroleum and refining it to make diesel fuel, requires less energy than the gas-to-liquid process of making paraffinic diesel. Therefore, overall the reduction in tailpipe CO_2 found in this study when using paraffinic fuel is not the whole fuel lifecycle impact of using this fuel.

In addition to NOx and CO_2 other regulatory emissions were measured, particulate matter (PM) using the regulatory filter analysis methodology, and carbon monoxide and hydrocarbons using the regulatory bag sampling methodology. From these results the following conclusions were reached:

Key Conclusion 4:

For diesel vehicles without a particle trap, or with high PM emissions, paraffinic diesel generally reduces PM emissions relative to baseline diesel by around 40%. (For the most modern vehicles which have very small PM emissions the impact of paraffinic diesel is more difficult to measure.)

Key Conclusion 5:

For the diesel vehicles tested emissions of carbon monoxide and hydrocarbons are generally small, inconsequential for air quality, and often with relatively large uncertainty. Therefore, when driven with paraffinic diesel it was found generally that changes in emissions of these pollutants were inconclusive. There was no evidence that they significantly increase but there was inconclusive evidence that for some vehicles they decrease.

Some potential side effects from using paraffinic diesel were examined. Specifically, whether emissions of ammonia or nitrous oxide (the latter being a potent greenhouse gas) are increased and if these emissions vary with the vehicles' emissions abatement technologies, e.g. with the fitting of selective catalytic reduction, or lean NOx traps. In addition to these two pollutants, the amount of primary nitrogen dioxide (the form of NOx important from an air quality perspective) emitted from vehicles was quantified. The metric used for this was $f(NO_2)$, the percentage of the total NOx emitted as nitrogen dioxide (NO_2). All three species were analysed using second-by-second Fourier Transform Infra-red spectroscopy.

From these results the following conclusions were reached:

Key Conclusion 6:

For the Euro VI truck and bus vehicles tested emissions of ammonia and nitrous oxide are high, and for the latter can add several percent to the vehicle's GHG emissions. Also, emissions of primary nitrogen dioxide can be a high proportion of the NOx emitted for both the paraffinic and baseline diesels. This is a consequence of vehicle exhaust treatment technology, and is largest for the more recent technologies.

Key Conclusion 7:

When driven with paraffinic diesel emissions of ammonia, nitrous oxide and primary nitrogen dioxide do not increase significantly for any vehicles. I.e. the use of paraffinic diesel was not observed to have detrimental side effects within the levels of certainty to which these additional pollutants were measured.

Based on the results obtained it is recommended that if DfT wish to proceed to Tranche 2 testing for **on-road testing** of vehicle emissions (to check if NOx reductions in real-world conditions mirror those seen from dynamometer testing), the following vehicles are considered:

Vehicle	Reasons
Euro 5 car	Relatively large overall reduction in NOx emissions when using paraffinic diesel and evidence that reduction is greater for urban driving
Euro 6 car	Large reduction in NOx emissions when using paraffinic diesel for urban driving, though when averaged over the whole WLTC the overall change in NOx emissions was small
Euro IV truck	Relatively large overall reduction in NOx emissions when using paraffinic diesel
Van from a different mass manufacturer	Recommend testing a different van make/model to investigate whether the results from the single manufacturer's vans tested were truly representative of the van fleet.

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Glossary of abbreviations

Abbreviation	Definition
CENEX PCO	Taxi testing cycle designed by CENEX and Millbrook.
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
ECD	Electron Capture Detector
EGR	Exhaust Gas Recirculation - type of emissions control system
EN 15940	CEN standard pertaining to automotive fuels – paraffinic diesels from synthesis or hydro-treatment
EN 590	Conventional diesel
FAME	Fatty acid methyl ester (a generic type of biodiesel
FTIR	Fourier Transform Infrared (FTIR) spectroscopy - Used for detecting levels of NOx speciation (N_2O, NO and NO2)
FTP	US Federal Test Procedure. The US 06 Test cycle was designed to augment this original procedure.
GC	Gas Chromatography
GHG	Greenhouse gas
GTL	Gas to liquid
GVW	Gross Vehicle Weight
HDV	Heavy Duty Vehicles
HE	Highways England
HGV	Heavy goods vehicle
HVO	Hydrogenated vegetable oil
LDV	Light Duty Vehicles
LNT	Lean NOx trap
LUB	London Urban Bus testing cycle
MLTB	Millbrook London Transport Bus testing cycle
NEDC	New European Driving Cycle
N1 van	Light duty van, up to 3.5 tonnes gross vehicle weight
OBD	On-Board Diagnostic. In-built vehicle diagnostic system, in this instance used in preconditioning to ensure there are no relevant faults
PCO	Public Carriage Office
PEMS	Portable Emissions Measurement Systems
PM	Particulate Matter
PN	Particle Number
RDE	Real Driving Emissions

Abbreviation	Definition
SCR	Selective Catalytic Reduction - type of emissions control system
US06	EPA testing Cycle, also known as Supplemental Federal Test Procedure (SFTP)
VERC	Vehicle Emissions Research Centre based at Ricardo Shoreham
VTEC	Variable Temperature Emissions Chamber, based at Millbrook Proving Ground
WHVC	World Harmonized Vehicle Testing Cycle
WHVP	World Harmonized Vehicle Testing Process
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

1 Introduction

1.1 Context for the research

High concentrations of nitrogen dioxide, particularly in urban areas, are a significant problem in the UK, with an estimated effect on mortality equivalent to 23,500 deaths annually.

UK Government is also committed to meeting the requirements of the National Emissions Ceiling Directive, which covers nitrogen dioxide, particulate matter, sulphur dioxide, ammonia and non-methane volatile organic compounds; with challenging targets to be met on NOx and particulate matter emissions by 2020.

Diesel vehicles (both light and heavy duty) are of primary concern in relation to emissions at or near the roadside. Emissions from these vehicles represent a large proportion of the total contribution of both oxides of nitrogen (NOx) and primary nitrogen dioxide (NO_2). This in turn leads to elevated NO_2 concentrations at receptors close to the road network.

Recent European vehicle emission standards have failed to deliver the **projected reductions** in ambient nitrogen dioxide (NO_2) in the real world. Whilst all light duty vehicles, and engines for use in heavy duty vehicles, do meet the European Type Approval limits applicable to them using the agreed test protocols, studies have demonstrated that real-world emissions are much greater, primarily due to diesel engine control strategies. As the predicted decline in emissions has not materialised under real world driving conditions and the proportion of diesel vehicles in the UK fleet has increased in recent years, this has meant the roadside concentrations of NO_2 have not declined as expected. There continues to be widespread exceedance of NO_2 air quality thresholds particularly in urban areas and near major roads.

Paraffinic diesel is promoted as producing lower NOx emissions at the tail pipe than conventional diesel. They are also promoted as being compatible with existing diesel vehicles without the need for any modification to the engine, though this has not been widely tested. It is essential that emissions from vehicles travelling on the road network are better understood, including whether the use of a paraffinic diesel can help reduce levels of NO_2.

Consequently, the Department for Transport has commissioned the Arup/AECOM consortium under the SPaTS framework contract.to deliver a programme of emissions testing to evaluate the real-world performance of paraffinic diesel (EN 15940 - Class A) as compared to conventional diesel (EN 590) for a limited number of Euro 4/IV, Euro 5 and Euro 6/VI vehicles. The project was led and delivered by Ricardo, a member of the Arup/AECOM consortium. The focus of the work is to evaluate differences in levels of tailpipe pollutants, primarily NOx emissions, between the two types of fuel, while validating that there are no adverse effects on other air quality pollutants or greenhouse gas (GHG) emissions. This work supports DfT's commitment to improve air quality and meet the requirements of the Air Quality Directive as soon as possible.

The results of this work will support Government's air quality plans and help support local authority decisions about measures to improve air quality whilst maintaining progress on reducing greenhouse gas emissions.

1.2 Objectives and outline of the scope of the research.

The principal objective of the research is to undertake robust, independent comparative testing comparing the emissions performance of vehicles using paraffinic diesel with the emissions performance of the same vehicles using conventional diesel.

The structure of the project comprises two tranches:

- Tranche 1 – Comparative **laboratory** emissions testing of vehicles using a) paraffinic and b) conventional diesel.
- Tranche 2: (Optional) **On-road testing** of vehicle emissions to check for NOx reductions in real-world conditions if the Tranche 1 results show a marked difference.

Tranche 1 research, consisting of comparative laboratory emissions testing has the following objectives:

- To provide indicative potential of paraffinic diesel for NO_2 reduction and
- To provide indicative potential side effects of using paraffinic diesel.

The emissions testing in Tranche 1 also included measurements of all regulated pollutants (and nitrous oxide for vehicles fitted with selective catalytic reduction (SCR) technology).

This document reports the results from research and testing undertaken as part of Tranche 1 of the test programme only.

The vehicle categories that were tested, and their respective emissions standards, are summarised in Table 1. The actual choice of the vehicles selected for testing, in terms of their emissions standards (which was a proxy for testing a range of emissions technologies), the make, model, engine size etc, was determined by the requirement to test a range of popular vehicles covering a range of different technologies, and the practicalities of sourcing vehicles. Further details on vehicles in each vehicle category are given in the relevant subsequent chapters.

Table 1: Categories of vehicle required for Tranche 1 testing programme

Vehicle categories	Vehicles required	Emissions standards
Medium cars	3 vehicles	Euro 4 Euro 5 Euro 6
Taxis	2 vehicles	Euro 4 Euro 6
Vans (N1 Class 3)	2 vehicles	Euro 4 Euro 6[1]
HGVs (Rigid / Artic) 14-26 tonnes	2 vehicles	Euro IV Euro VI
Buses	2 vehicles	Euro IV Euro VI
TOTAL	11 vehicles[1]	

Testing occurred using two fuels, a baseline diesel meeting EN 590 and a 100% paraffinic diesel meeting EN 15940 - Class A.

[1] The Euro 6 taxi was not fully tested, see section 3.3

2 Test procedures

This chapter explains the principal methodology followed for the vehicle testing, covering fuels, vehicle selection and testing, and the emissions analysis protocols.

2.1 Paraffinic diesel

Paraffinic diesel is a “synthetic” drop-in substitute for diesel. Currently, the vast majority of diesel originates from fossil crude oil. Crude oil is cracked/reformed and distilled to give a hydrocarbon liquid mixture which distils between 170°C and around 360°C with 5% - 95% distillation occurring between 200 – 356 °C. It contains a mixture of principally alkanes, and to meet the fuel standard EN590, it must not have more than 8% polycyclic aromatic hydrocarbons, a small quantity of alkenes and reduced sulphur. Pump diesel can be extended by adding biodiesel (FAME) up to 7% for EN590.

There are two types of paraffinic diesel, either made by a gas-to-liquid (GTL) process, or by hydrogenating biologically produced oils, e.g. hydrogenated vegetable oil (HVO). This project is using paraffinic diesel made by the GTL process. This two-step process firstly converts methane into synthesis gas (carbon monoxide and hydrogen), and then using the Fischer-Tropsch synthesis converts the synthesis gas into longer chain alkanes. Overall the process converts methane and oxygen into alkane fuels plus carbon monoxide and water. Consequently, this fuel contains less polycyclic aromatic hydrocarbons and sulphur relative to diesel from petroleum refining.

This project tested vehicles running on two fuels. A pure paraffinic diesel produced by Shell, using their gas to liquid (GTL) process, and a baseline diesel, which also was provided by Shell. The paraffinic diesel meets fuel standard EN15490 – Class A and the baseline diesel meets standard EN 590. Both fuels were analysed, and differed in a few key parameters as listed in Table 2.

Table 2: Characteristics of the two diesel fuels used in this investigation

Parameter	GTL Paraffinic diesel	Baseline diesel
Cetane number	71.9 rating	53.5 rating
Density	779.8 kg/m^3	839.8 kg/m^3
FAME content	<0.05% v/v	2.92% v/v
Sulphur content	< 1 ppm by weight	10.3 ppm by weight
Kinematic Viscosity at 40°C	2.571 mm^2/s	3.209 mm^2/s
Carbon content	85.3%	86.7%
Hydrogen content	14.6%	13.3%
Oxygen content	< 0.01%	< 0.01%

2.2 Vehicle testing

For Tranche 1 laboratory testing the project consortium comprised two testing houses: Millbrook Proving Ground and Ricardo’s Shoreham Technical Centre. These test houses provide both complementary and overlapping facilities. Millbrook alone has a dynamometer able to test the two heavy duty vehicles using their heavy duty Variable Temperature Emissions Chamber (VTEC). Both Millbrook and Ricardo have light duty testing facilities (with both locations having a twin-roller-dynamometers in their facilities, and Shoreham Technical Centre alone having a single axle dynamometer.

The primary and key objective of the project is to undertake robust, independent **comparative emissions testing of vehicles, comparing paraffinic diesel to conventional diesel**. It is emphasised that the testing is comparative and not focused on absolute emissions, as for light duty vehicle type approval testing, or heavy duty engine type approval testing. This key difference means that the back-to-back tests should:

- Use the same vehicle, the same driving cycles and the same dynamometer settings
- Are performed on vehicles working within their normal operating vehicle speed / engine load map, provided that the dynamometer settings are appropriate for the vehicle (for example using truck dynamometer settings for the testing of a passenger car would not be appropriate).

The project used dynamometer settings as follows:

- Inertia – was based on the actual weight of the semi-loaded vehicle, from weighing the vehicle to be tested in running order (or making adjustments for fuel load etc). This kerb weight was adjusted according to:
    - For medium passenger cars and taxis, according to WLTP methodology 15% of the difference between the technically permissible maximum laden weight and the measured weight in running order;
    - For vans, according to the World Light-duty Test Procedure (WLTP) methodology 28% of the difference between the technically permissible maximum laden weight and the measured weight in running order;
    - Trucks were tested at two thirds of their maximum laden weight, i.e. 66.7% of the difference between the vehicles gross vehicle weight (18 tonnes) and the and the measured weight in running order;
    - Buses were tested according to the Low Carbon Vehicle Partnership (LowCVP) document: "Low+Emission+Bus+Testing+guidance+notes_Final" which stipulates test weight should be: unladen kerb weight (confirmed by the test facility) + 50% of the seated passenger capacity @ nominal 68kg per passenger.
- Dynamometer retarding forces F^0, F^1, F^2 and F^3 were based on those appropriate for the vehicle type selected from the parameters used by the test houses from the previous testing of analogous vehicles.

Further details of the testing programme are given in the following chapter. These cover details of the driving cycles used, and the fuel testing sequence for each vehicle category.

2.3 Vehicle selection and test cycles summary

The project sought to test a range of vehicle categories and technologies. The term “emissions standard” is used in DfT’s “Request for Proposal” is a proxy for emissions technology.

The technologies used by different vehicle manufacturers to meet the emissions standards vary, both between manufacturers and for Euro 5/V and Euro 6/VI standards. The vehicles were selected to be complementary with regard to the emissions technologies they employed, specifically with some vehicles not having SCR fitted, and other having this NOx abatement technology fitted. At the same time vehicles were selected to be popular, high volume selling models. Further details of each vehicle are given in the first sub-section of each corresponding chapter below.

As individual vehicles were identified their characteristics were checked with DfT to ensure that individually, and within the vehicle category, an appropriate mix of vehicles had been selected within the constraints of the number of vehicles available.

The test driving cycles selected were regulated cycles that are representative of real-world driving. For light duty vehicles all were tested using the Worldwide-harmonized Light vehicle Test Cycle (WLTC). For the cars and vans this was augmented with a higher speed cycle demanding higher engine output power (the US06, or supplemental FTP driving cycle), whereas for taxis it was the PCO-CENEX taxi cycle. For the trucks the World Harmonized Vehicle Testing Cycle was used, a road cycle derived from the regulatory engine World Harmonized Testing Cycle (WHTC), and for the buses the new London Urban Bus (LowCVP UK Bus) cycle was used. (further details about the test cycles is given in the first sub-section describing the testing and results from each type of vehicle. It is also important to note that none of the vehicles were tested against the regulatory cycle they were approved against (because we wanted the cycles to be more like real-world driving) and therefore the emissions measured cannot be compared directly against the regulatory limits.

2.4 Emissions analysis

For a typical test cycle (see Chapters 3 to 7 for the test cycles for each specific vehicle category), regulated emissions over the whole cycle, and its component phases were measured using standard, regulatory bag analysis. The oxides of nitrogen (NOx) samples were analysed for their nitrogen dioxide (NO_2) and nitric oxide (NO) content.

Also, modal data was collected for the gaseous regulated emissions (NOx, hydrocarbons (HC), carbon monoxide (CO) and carbon dioxide (CO_2)) at 1 Hz. The modal data enables a more detailed analysis of exactly at which points of the driving cycle NOx is being emitted, and provides an assessment as to whether any impact of paraffinic diesel is general, across the cycle, or occurs at specific engine speed load points. The regulated emissions over the whole cycle, and the cycle's component phases, were calculated from these data and checked against/compared with the bag values. Speciation of NOx was also undertaken, with modal analysis of NO_2 and NO.

For vehicles fitted with selective catalytic reduction (SCR) technology, it is noted that the SCR unit may cause additional reactions involving the exhaust gases and aqueous urea. Potential emissions from such vehicles include N_2O, a potent greenhouse gas, and ammonia (NH_3, a regulated pollutant for HDV from Euro VI). Conversations with Ricardo's expert on vehicle exhaust after-treatment indicated that emissions of N_2O and NH_3 from non-SCR vehicles are both low and well characterised. Consequently, it was emissions of these species over cycles for vehicles fitted with SCR exhaust after-treatment that were more carefully quantified. The primary analysis principle was modal via Fourier Transform Infra-red (FTIR) spectroscopy, augmented by a post-cycle analysis using gas chromatography with an electron capture detector (GC + ECD), which is more specific for N_2O, suffering less from interference from other species.

Particulate matter (PM) emissions were also analysed. The mass of PM emitted was measured using standard filter methods, and particle number (PN) was measured using the equipment specified and used in accordance with Euro 6 LDV and Euro VI HDV type approval regulations.

3 Testing results

The test results for the five vehicle categories (passenger cars, vans, taxis, trucks and buses) are systematically recorded in the following sections.

3.1 Passenger cars

3.1.1 Vehicle selection, their characteristics and drive cycles used

The vehicles were selected not only to cover three different emission standards, but also to span three manufacturing groups, and a range of performance characteristics all within the "medium car" envelope. The emissions standards, engine capacity and peak power of the models tested were:

Euro 4	1.7 TDCi	74 kW peak power
Euro 5	2.0 GTD TDi	125 kW peak power
Euro 6	1.5 TDCi	77 kW peak power.

All three vehicles were tested using Ricardo Shoreham's Vehicle Emissions Research Centre (VERC). Some detailed characteristics of the three cars actually tested are given in Table 3.

Table 3: Characteristics of the medium cars tested in this investigation

Parameter	Euro 4 car	Euro 5 car	Euro 6 car
Date of registration	January 2008	March 2012	April 2016
Mileage at the start of testing	116,200 miles	59,766 miles	23,680 miles
Inertia used for testing	1,550 kg	1,502 kg	1,518 kg
Emissions control strategy	EGR and DOC (no DPF or SCR)	EGR, DOC and DPF (no SCR)	EGR, DOC, DPF and LNT (no SCR)
Engine size, peak power	1,686 ccs, 99 hp (74 kw)	1,968 ccs, 167 hp (125 kW)	1,500 ccs, 105 hp (77 kW)
Transmission type	Manual 5 speed	Manual 6 speed	Manual 6 speed

The fuel comparison testing sequence used for testing the three cars was:

Baseline diesel	Hot start WLTC	then hot start US06
Paraffinic diesel	Cold start WLTC	then hot start US06
Paraffinic diesel	Hot start WLTC	then hot start US06
Baseline diesel	Cold start WLTC	then hot start US06
Baseline diesel	Hot start WLTC	then hot start US06
Paraffinic diesel	Hot start WLTC	then hot start US06

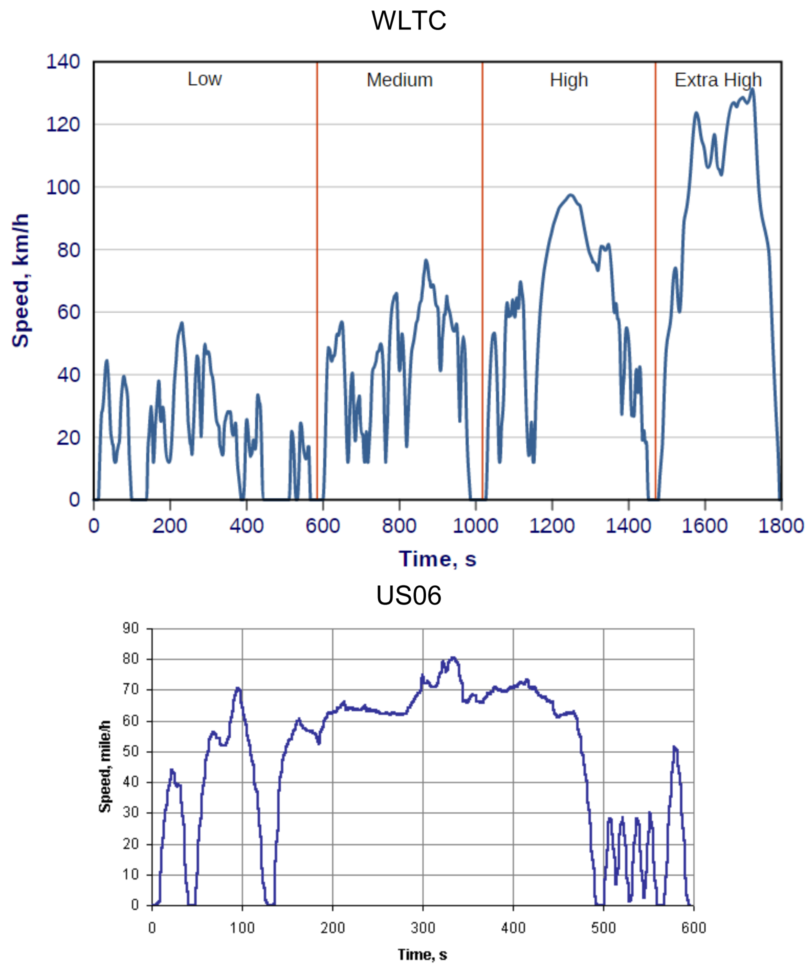
This is summarised as: **D – P – P – D – D – P** where **D** denotes both a WLTC and US06 cycle being driven using the conventional diesel, and **P** denotes the use of paraffinic diesel. Red lettering denotes cold start for WLTC and black lettering denotes hot start for WLTC.

Fuel changes involved draining the tank, swapping the fuel filter, flushing and preparation by preconditioning driving at least 50 km on standard roads.

All three cars were tested using the Worldwide Harmonised Light vehicle Test Cycle (WLTC) with much of the testing protocol following that of the Worldwide Harmonised Light vehicle Test Procedure

(WLTP). This is shown in Figure 1[2]. In addition, the cars were driven over the US06 cycle because this provides a greater power / engine speed envelope than the WLTC. Preconditioning for the WLTC cycle was the US06 cycle, and for the US06 cycle was the high and extra high phases of WLTC. It is noted that for this fuel inter-comparison, the important factor is consistency of testing protocol, rather than all the absolute details. This is distinctly different from generating type approval data, where adherence to all details within the WLTP is critical to obtain accurate absolute emissions.

Figure 1: Time-vehicle speed profile for the Worldwide Harmonised Light vehicle Test Cycle and US06 cycle



Cold starting is a further potentially important parameter for LDV. Therefore, of the three WLTC tests with each fuel two were hot start tests, whilst one was a cold start test.

3.1.2 NOx emissions results

The regulatory NOx emissions results for the individual phases of the WLTC and the whole US06 cycles, for both fuels are reported in Table 4, Table 5 and Table 6 for the Euro 4, 5 and 6 medium cars, respectively. Run 2 was the cold start WLTC and is denoted in the three tables by the deeper blue coloured cells. The mean and standard deviation values of the data are given from analysing the three runs.

In the lower part of the table the absolute difference (mean emissions when running on paraffinic diesel minus the mean emissions with baseline diesel) are given for the four separate phases of the WLTC, and the whole cycle. Negative values indicate that the mean NOx emissions for paraffinic diesel are less than the mean emissions for the baseline diesel. Beneath the absolute differences are

[2] Taken from original proposal

the differences expressed as a percentage change relative to the mean emissions for the baseline diesel. The third row in the lower part of the table gives the absolute and relative differences in mean emissions when using paraffinic diesel, relative to the baseline diesel, for the whole US06 cycle.

Table 4: Bag analysis results of NOx emissions from the Euro 4 medium car driven using baseline diesel and paraffinic diesel

EURO 4 MEDIUM CAR NOx RESULTS						
Drive cycle	**Fuel**	**Run 1** (mg/km)	**Run 2** (mg/km)	**Run 3** (mg/km)	**Mean** (mg/km)	**Standard deviation** (mg/km)
WLTC Phase 1	Baseline	850.6	544.3	743.4	712.76	155.45
WLTC Phase 2	Baseline	1145.5	1031.3	1078.5	1085.13	57.39
WLTC Phase 3	Baseline	967.4	933.0	950.2	950.18	17.21
WLTC Phase 4	Baseline	821.0	898.0	882.8	867.28	40.76
WLTC whole cycle	Baseline	936.3	889.3	925.0	916.87	24.54
US06 whole cycle	Baseline	1056.9	1146.8	1166.5	1123.40	58.42
WLTC Phase 1	Paraffinic	680.4	563.6	770.0	671.33	103.52
WLTC Phase 2	Paraffinic	1047.8	995.1	1073.4	1038.76	39.91
WLTC Phase 3	Paraffinic	915.0	910.2	918.1	914.42	3.97
WLTC Phase 4	Paraffinic	893.5	894.4	891.8	893.22	1.34
WLTC whole cycle	Paraffinic	903.3	875.8	920.7	899.93	22.65
US06 whole cycle	Paraffinic	914.4	926.4	1022.03	954.27	58.98

	Phase 1	Phase 2	Phase 3	Phase 4	Whole
Effect of paraffinic diesel (mg/km) for WLTC cycle phases	-41.4	-46.4	-35.8	25.95	-16.94
Effect of paraffinic diesel (%) for WLTC cycle phases	-5.8%	-4.3%	-3.8%	2.8%	-1.8%
Effect of paraffinic diesel (mg/km) for whole US06 cycle	-169.13 mg/km i.e. -15.1%				

Some observations on these data are:

For both baseline and paraffinic diesel fuelled cycles:

- Overall mean NOx emissions are moderately high, around 900 mg/km, which is around three and a half times the Type Approval value measured over the NEDC;
- NOx emissions vary little between the different phases. For the US06 cycle with baseline diesel emissions are around 20% higher than the emissions for the whole WLTC.
- The impact of cold starting is to decrease NOx emissions for Phase 1 by around 200 mg/km (around a 27% decrease, assessed from amalgamating the change for both fuels);
- Reproducibility is, on the whole, moderately good for Phases 3 and 4 of WLTC, never greater than 41 mg/km, or around 4.7%, for the hot and cold starts combined. For Phases 1 and 2 hot starts only, reproducibility shows more variability.

- The first US06 cycle run using baseline diesel has lower NOx emissions. This run was also noted as being an outlier with lower CO_2 emissions, also. This could be excluded from the analysis, but since Phase 1 contributes little to the WLTC whole cycle emissions, it is not.

For the difference in NOx emissions between the paraffinic diesel and baseline diesel fuelled cycles:

- There is negligible difference in the NOx emissions between the two fuels visible from their modal data.
- However, for the aggregated data, there is a small decrease in NOx emissions when fuelled with paraffinic diesel, around 2% for the whole WLTC. This is too small to show up as an easily discernible difference in the modal data.
- The difference is larger for the slower WLTC phases, but the differences are always smaller than the variability (standard deviation) of the data.
- However, for the US06 cycle the difference was found to be large (a 169 ±60 mg/km reduction, i.e. 15%) which was greater than the variability of the data, i.e. is significant.

Table 5: Bag analysis results of NOx emissions from the Euro 5 medium car driven using baseline diesel and paraffinic diesel fuels

EURO 5 MEDIUM CAR NOx RESULTS						
Drive cycle	**Fuel**	**Run 1** (mg/km)	**Run 2** (mg/km)	**Run 3** (mg/km)	**Mean** (mg/km)	**Standard deviation** (mg/km)
WLTC Phase 1	Baseline	398.6	352.4	385.1	378.73	23.74
WLTC Phase 2	Baseline	411.5	323.8	326.9	354.08	49.76
WLTC Phase 3	Baseline	333.7	299.6	258.3	297.19	37.76
WLTC Phase 4	Baseline	354.0	325.3	296.9	325.41	28.52
WLTC whole cycle	Baseline	365.4	320.7	302.9	**329.67**	32.23
US06 whole cycle	Baseline	718.8	559.1	514.0	597.32	107.61
WLTC Phase 1	Paraffinic	321.4	335.3	392.2	349.64	37.50
WLTC Phase 2	Paraffinic	331.6	282.3	375.1	329.68	46.42
WLTC Phase 3	Paraffinic	275.9	274.3	293.2	281.12	10.46
WLTC Phase 4	Paraffinic	320.3	307.9	310.2	312.78	6.57
WLTC whole cycle	Paraffinic	309.1	296.0	329.1	**311.38**	16.70
US06 whole cycle	Paraffinic	525.6	477.1	474.24	492.32	28.86

	Phase 1	Phase 2	Phase 3	Phase 4	Whole
Effect of paraffinic diesel (mg/km) for WLTC cycle phases	-29.1	-24.4	-16.1	-12.62	-18.29
Effect of paraffinic diesel (%) for WLTC cycle phases	-7.7%	-6.9%	-5.4%	-3.8%	-5.5%
Effect of paraffinic diesel (mg/km) for whole US06 cycle			-105.00	mg/km	-17.6%
Effect of paraffinic diesel (mg/km) for whole cycle after excluding Run 1 with baseline diesel			-44.25	mg/km	-8.2%

Some observations on these data are:

For both baseline and paraffinic diesel fuelled cycles:

- Overall mean NOx emissions are moderate, around 320 mg/km, reasonable given the emission standard for a Euro 5 car, over the NEDC, is 180 mg/km.
- NOx emissions are relatively constant over the four phases of WLTC and not very much larger for US06. This could be a consequence of this vehicle operating well within its maximum power range at all points on all drive cycles.
- The impact of cold starting is small, with NOx emissions over Phase 1 being reduced by around 30 mg/km (a reduction of around 8%) below the mean for the two hot starts. But, this is in the context of relative large variations in the hot start data.
- Reproducibility is, on the whole, good for Phases 3 and 4 of WLTC for the paraffinic diesel (± 15 mg/km) but is greater for the baseline diesel (± 35 mg/km).

For the difference in NOx emissions between the paraffinic diesel and baseline diesel fuelled cycles:

- In the context of the comments above, the reduction in the mean NOx emissions for paraffinic diesel (18 mg/km) is a reduction, but it is smaller than the variance between the NOx emissions for the trio of runs (± 32 and ± 17 mg/km for the baseline diesel and paraffinic diesel fuels respectively). Therefore, in isolation this difference is not statistically significant.
- For the US06 runs there is an outlier, Run 1 with the baseline diesel, which has NOx emissions around 200 mg/km higher than the average of the other five runs (two with the baseline diesel and three with the paraffinic diesel). Its inclusion in the analysis, leads to the initial conclusion that the paraffinic diesel is making a large impact. However, if this run is excluded from the analysis the impact of the paraffinic diesel is a 44 mg/km (8.2%) reduction as reported at the bottom line of Table 5.

Table 6: Bag analysis results of NOx emissions from the Euro 6 medium car driven using baseline diesel and paraffinic diesel fuels

EURO 6 MEDIUM CAR NOx RESULTS						
Drive cycle	**Fuel**	**Run 1** (mg/km)	**Run 2** (mg/km)	**Run 3** (mg/km)	**Mean** (mg/km)	**Standard deviation** (mg/km)
WLTC Phase 1	Baseline	343.0	363.2	202.2	302.77	87.72
WLTC Phase 2	Baseline	836.6	737.7	618.4	730.90	109.23
WLTC Phase 3	Baseline	800.5	1103.8	602.7	835.64	252.38
WLTC Phase 4	Baseline	1664.6	1266.4	1519.5	1483.48	201.51
WLTC whole cycle	Baseline	1053.7	988.4	878.6	973.54	88.48
US06 whole cycle	Baseline	1247.9	1173.1	1212.8	1211.28	37.38
WLTC Phase 1	Paraffinic	202.4	240.5	249.3	230.72	24.89
WLTC Phase 2	Paraffinic	641.5	655.8	739.4	678.91	52.85
WLTC Phase 3	Paraffinic	855.4	790.0	822.4	822.59	32.69
WLTC Phase 4	Paraffinic	1313.8	1617.4	1648.6	1526.61	184.93
WLTC whole cycle	Paraffinic	888.4	983.0	1022.6	964.66	68.95
US06 whole cycle	Paraffinic	1121.8	1130.1	922.8	1058.25	117.37

	Phase 1	Phase 2	Phase 3	Phase 4	Whole
Effect of paraffinic diesel (mg/km) for WLTC cycle phases	-72.1	-52.0	-13.1	43.13	-8.88
Effect of paraffinic diesel (%) for WLTC cycle phases	-23.8%	-7.1%	-1.6%	4.4%	-0.9%
Effect of paraffinic diesel mg/km for whole US06 cycle	-153.03	mg/km	i.e.	-12.6%	

Some observations on these data are:

For both baseline and paraffinic diesel fuelled cycles:

- Overall mean NOx emissions are quite high, around 960 mg/km when averaged over the whole WLTC. This is larger for the Euro 6 car than the NOx emissions observed for the Euro 5 car (particularly in the context that the emission standard for a Euro 5 car, over the NEDC, is 180 mg/km and for the Euro 6 car is 80 mg/km over the NEDC).
- NOx emissions are particularly high for Phase 4 of WLTC and US06, when they are greater than 1,000 mg/km. These are the two (sub-)cycles when the engine is required to produce the highest power.
- There are some outlying data points, e.g. Run 2, relative to Run 1 when using baseline diesel. It was observed that low NOx emissions occurred for phases where high CO_2 emissions were also seen. It is thought these might be caused by a relatively infrequent lean NOx trap regeneration events.
- However, other sizeable variability is seen for other phases. These variations lead to standard deviations that are larger than those seen for the other medium cars.
- The impact of cold starting is minimal in the context of the other variations seen.

For the difference in NOx emissions between the paraffinic diesel and baseline diesel fuelled cycles:

- In the context of the comments above, there is a small difference in the NOx emissions between the two fuels (the difference in means is less than 1% - although as noted above the much higher variability within phases suggests this may be a coincidental cancelling of errors, rather than an intrinsically high level of reproducibility).
- The differences between the means of each phase is of interest. For Phase 1 it is large, with the paraffinic diesel showing on average a reduction in NOx emissions of 72 mg/km (24%). Smaller reductions are seen for other cycles.

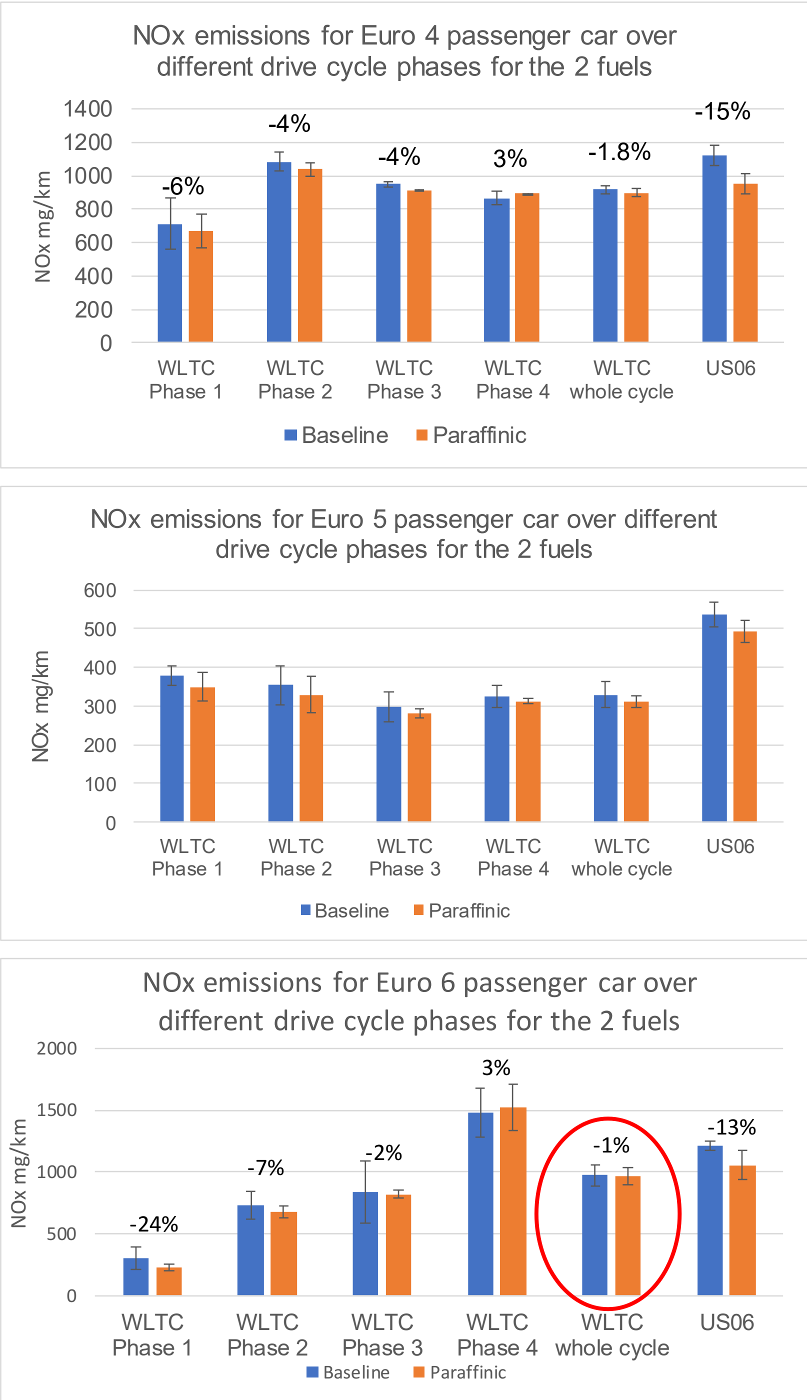
Modal plots of the data were generated and compared. They showed little difference between the two fuels for any of the three cars. However, they did show marked differences between the regions in the drive cycles under which NOx emissions do occur for the different cars.

Whilst the modal data gives the instantaneous NOx emissions during the driving cycle, its high temporal resolution makes it difficult to discern general patterns. The data in Tables 4, 5 and 6 give the phase by phase emissions for the two fuels, in addition to the whole cycle emissions. These data are plotted in Figure 2 as adjacent columns for the two fuels (blue for the baseline diesel, and orange for the paraffinic diesel. The standard deviations of the data, recorded in the last column of each table, are included for each column. These are quite large for Phase 1 of the WLTC because of the impact of the cold start cycle.

Figure 2 illustrates how the different vehicles show different phase-to-phase variations, with the Euro 4 and 5 cars showing only a small variation between cycle phases, but the Euro 6 car showing a much larger variation.

The different vertical scales of NOx emissions (mg/km) is noteworthy, as too is fact that these emissions are “off regulatory cycle”, i.e. are measured over driving cycles different to those used at type approval.

Figure 2: Phase by phase NOx emissions for the three medium cars running on both fuels



3.1.3 CO_2, regulated emissions and unregulated emissions results

Table 7 reports the average CO_2 emissions over the two hot-start WLTC and the three US06 cycles, and the cold start WLTC cycle for each vehicle when running on baseline diesel and paraffinic diesel fuels.

The impact of the paraffinic diesel on these values, in absolute terms (g/km) and as a percentage of the average emissions from the baseline diesel, are reported in the next two rows of the table.

Table 7: Bag analysis results of CO_2 emissions from the three medium cars driven using baseline diesel and paraffinic diesel fuels

	Baseline diesel			Paraffinic diesel		
	Hot starts		Cold starts	Hot starts		Cold starts
Euro 4 medium car	Average (g/km)	Standard deviation (g/km)	Value (g/km)	Average (g/km)	Standard deviation (g/km)	Value (g/km)
WLTC whole cycle	190.45	1.90	194.41	182.82	1.90	188.06
US06 whole cycle	200.96	5.25		192.83	1.30	
Effect of paraffinic diesel (g/km) for mean of whole WLTC	-7.63	1.90	-6.35			
Effect of paraffinic diesel (g/km) for mean of US06	-8.13	3.82				
Euro 5 medium car						
WLTC whole cycle	163.31	2.14	168.06	160.35	3.17	162.83
US06 whole cycle	182.24	4.67		173.22	0.66	
Effect of paraffinic diesel (g/km) for mean of whole WLTC	-2.96	2.70	-5.23			
Effect of paraffinic diesel (g/km) for mean of US06	-9.02	3.34				
Euro 6 medium car						
WLTC whole cycle	148.62	1.98	183.17	149.25	5.17	145.78
US06 whole cycle	184.75	4.37		180.93	0.69	
Effect of paraffinic diesel (g/km) for mean of whole WLTC	0.62	3.91	-37.39			
Effect of paraffinic diesel (g/km) for mean of US06	-3.82	3.13				

For the Euro 4 and 5 cars the paraffinic diesel reduces CO_2 emissions by an amount greater than the standard deviation of the data by an average of 5.3 g CO_2/km (or 2.9%). For the Euro 6 car a small increase was seen (0.62 ± 3.91 g/km) but this change was less than the standard deviation of this vehicle's data and therefore, is not considered significant or typical.

For all three cars, average CO_2 emissions over the three-replicate hot start US06 cycles reduced for paraffinic diesel. The average reduction was 7.0 ± 3.44 g/km (3.7 ± 1.8%).

Table 8 reports the average emission results for seven other pollutants over the two hot-start WLTC and the three US06 cycles, and the cold start WLTC cycle for each vehicle when running on baseline diesel and paraffinic diesel fuels. Changes in emissions due to use of paraffinic diesel are described in the last column, recorded as a ratio between the two sets of results.

For some regulated species, e.g. CO emissions from all three cars, the emissions are always small, less than 71 mg/km for the hot starts, the variability of these is at least 10%. These emissions are too small for the ratio between the emissions for paraffinic diesel and baseline diesel to be significant or meaningful, and therefore are not quoted. For a small number of measurements, e.g. hydrocarbons or particulate matter from the Euro 4 car, the smaller variability in measurements relative to the difference between the emissions for paraffinic diesel and baseline diesel, makes the ratio between the emissions for paraffinic diesel and baseline diesel significant and its percentage is recorded.

For the unregulated emissions the actual difference is given as an approximate percentage of the emissions from the baseline diesel, together with the uncertainty (error) of this difference. In most cases the difference is a small reduction, that is insignificant relative to the error.

Table 8: Emission results for CO, HC, PM, PN, f(NO_2), NH_3 and N_2O from the medium cars driven using baseline diesel and paraffinic diesel fuels

	Car's emission standard	Average of 4 hot starts (from both fuels) (mg/km)	Average of 2 cold starts (mg/km)	NEDC limit value (mg/km)[3]	Paraffinic to baseline diesel ratio
Carbon Monoxide	Euro 4	70.22	63.25	500	too small to be significant
	Euro 5	14.98	61.01	500	too small to be significant
	Euro 6	31.77	111.28	500	too small to be significant
Hydrocarbons	Euro 4	15.28	40.22	50	around 60%
	Euro 5	9.12	19.29	50	too small to be significant
	Euro 6	9.73	11.79	90	too small to be significant
Particulate Matter	Euro 4	42.52	53.76	15	around 70%
	Euro 5	0.42	0.37	5	too small to be significant
	Euro 6	0.72	1.22	4.5	too small to be significant
Particulate Number	Euro 4	8.34E+13	9.23E+13		
	Euro 5	2.80E+08	9.56E+08		
	Euro 6	7.79E+10	2.31E+11	6.00E+11	
				CO_2e g/km	
f(NO_2)	Euro 4	23.91%	19.03%		1% ±3.5%
	Euro 5	26.65%	20.28%		-9% ±9.6%
	Euro 6	20.40%	16.88%		0% ± 4.3%
Ammonia	Euro 4	1.74	3.62		15% ± 66%
	Euro 5	1.09	0.83		-45% ± 52%
	Euro 6	1.79	1.94		-26% ± 12%
Nitrous oxide	Euro 4	15.14	16.46	4.5	-20% ± 7%
	Euro 5	5.32	5.74	1.6	-37% ± 34%
	Euro 6	9.96	8.35	3.0	0% ± 26%

The emissions of carbon monoxide (CO) and hydrocarbons (HC) are low, quantified from the bag analysis, and are below the regulatory limits for the NEDC. These regulated pollutants are of little concern to air quality whether using diesel or paraffinic diesel. However, overall the paraffinic diesel tended to cause small reductions in these emissions.

[3] Note the NEDC limit values are only for comparison: the vehicles were type approved to NEDC but not tested using the NEDC in this study

For particulate mass (PM) and particulate number (PN), the impact of the diesel particulate filter (DPF) fitted to the Euro 5 and Euro 6 cars is clearly evident, and these emissions are too low to see any significant impact from the paraffinic diesel. However, for the Euro 4 vehicle, average PM emissions over the whole WLTC reduced from 55 mg/km to 37 mg/km, a 32% reduction.

The emissions of nitrogen dioxide (NO_2), the percentage of the oxides of nitrogen (NOx) emissions emitted as NO_2, ammonia and nitrous oxide, were all quantified using Fourier Transform Infra-red spectroscopy (FTIR).

Emissions of primary NO_2, as a percentage of the NOx emissions, known as f(NO_2), were in the region of 17% - 27% for all three cars. The lean NOx trap fitted to the Euro 6 car, did not lead to significant changes in this parameter relative to the Euro 4 or Euro 5 cars.

Emissions of ammonia and nitrous oxide, two unregulated pollutants with the latter being a potent greenhouse gas (GHG), were relatively low for all three cars. The global warming potential of nitrous oxide is around 298 times that of carbon dioxide. The nitrous oxide emissions from the hot-start WLTC tests are expressed in equivalent emissions of CO_2 in the penultimate column of Table 8. Relative to the direct CO_2 emissions reported in Table 7, these are modest at 2.4%, 1.0% and 2.0% additional GHG emissions for the baseline diesel.

The impact of paraffinic diesel on emissions of NO_2 and nitrous oxide are given in the final column of Table 8 together with the uncertainty in this measurement. In most cases the difference is a small reduction, that is insignificant relative to the error.

Consequently, these data give evidence that paraffinic diesel does not lead to increased emissions for the other pollutants (NO_2, nitrous oxide and ammonia).

For the Euro 6 car a sample of the bag emissions was checked using GC-ECD to analyse the N_2O emissions using an alternative technique to FTIR that is much less prone to interference. These results were broadly similar to the FTIR N_2O data shown at bottom of Table 8.

3.2 Light commercial vehicles

3.2.1 Vehicle selection, their characteristics and drive cycles used

Both the vans tested were the best-selling N1 Class 3 van for many years. Some characteristics of the two specific vans tested are summarised in Table 9. Both vans were tested using Ricardo Shoreham's Vehicle Emissions Research Centre (VERC).

Table 9: Characteristics of the vans tested in this investigation

Parameter	Euro 4 van	Euro 6 van
Date of registration	November 2008	May 2017
Mileage at the start of testing	142,000 miles	5,475 miles
Gross Vehicle Weight	3,500 kg	3,500 kg
Inertia used for testing	2,527 kg	2,668 kg
Emissions control strategy	EGR, DOC and DPF no SCR	EGR, DOC, DPF and SCR
Engine size, peak power	2.4 litres, 100 hp (75 kw)	2.0 litres, 105 hp (77 kw)
Transmission type	Manual 5 speed	Manual 6 speed

The drive cycles used were the same as for the passenger cars, i.e. WLTC and USO6. Much of the test protocol used was that of the WLTP. However, it is emphasised that for this fuel inter-comparison, the important aspect is consistency of testing protocol, rather than all the absolute details. This is distinctly different from generating type approval data, where adherence to the WLTP is critical.

In general three repetitions of each of the two test cycles was driven with each of the two fuels, i.e. a total of twelve cycles. This used the same test sequence as for the passenger cars, see Section 3.1.1, and is summarised as: **D – P – P – D – D – P** where **D** denotes a WLTC and US06 cycle being driven using the conventional diesel, and **P** denotes the use of 100% paraffinic diesel. WLTC and US06 (**D** or **P**) denote hot start WLTC and US06 driving cycles, and **P** or **D** denote a cold start WLTC followed by a hot start US06 cycle with each fuel.

3.2.2 NOx emissions results

The regulatory NOx emissions results for the individual phases of the WLTC and the whole US06 cycles, for both fuels are reported in Table 10 and Table 11 for the Euro 4, and 6, vans, respectively.

Table 10: Bag analysis results of NOx emissions from the Euro 4 van driven using baseline diesel and paraffinic diesel fuels

EURO 4 VAN NOx RESULTS						
Drive cycle	**Fuel**	**Run 1 (mg/km)**	**Run 2 (mg/km)**	**Run 3 (mg/km)**	**Mean (mg/km)**	**Standard deviation (mg/km)**
WLTC Phase 1	Baseline	816.9	1,190.6	793.0	933.5	201.6
WLTC Phase 2	Baseline	627.9	637.5	729.6	665.0	47.3
WLTC Phase 3	Baseline	505.3	579.0	567.0	550.4	14.3
WLTC Phase 4	Baseline	2,078.5	2,036.0	1,977.1	2,030.5	32.6
WLTC whole cycle	Baseline	1,129.2	1,189.6	1,130.3	1,149.7	30.2
US06 whole cycle	Baseline	1,765.4	1,880.0	1,885.1	1,843.5	67.7
WLTC Phase 1	Paraffinic	962.7	1,143.9	766.7	957.8	188.6
WLTC Phase 2	Paraffinic	735.9	586.7	678.9	667.2	50.2
WLTC Phase 3	Paraffinic	616.8	506.4	508.9	544.0	21.0
WLTC Phase 4	Paraffinic	2,070.1	1,998.6	2,050.8	2,039.8	27.5
WLTC whole cycle	Paraffinic	1,204.0	1,137.5	1,126.1	1,155.8	42.1
US06 whole cycle	Paraffinic	1,838.5	1,896.4	1,892.2	1,875.7	32.3

	Phase 1	Phase 2	Phase 3	Phase 4	Whole
Effect of paraffinic diesel (mg/km) for mean of WLTC phases	24.24	2.16	-6.39	9.27	6.16
Effect of paraffinic diesel (%) for mean of WLTC phases	2.60%	0.32%	-1.16%	0.46%	0.54%
Effect of paraffinic diesel (mg/km) for US06	32.21 mg/km i.e. 1.75%				

Some observations on the data for the Euro 4 van are:

For both baseline and paraffinic diesel fuelled cycles:

- Overall mean NOx emissions are high, around 1,150 mg/km. This is nearly three times the Euro 4 emission standard for N1 Class 3 vans 390 mg/km, but over for the NEDC, i.e. a more lightly loaded van and a gentler driving cycle.
- NOx emissions are particularly high for Phase 4 of WLTC and for US06 cycle, when they are close to 2,000 mg/km. Both the WLTC phase 4 and the US06 cycle have a high average speed and the van's engine is running at high power.
- The impact of cold starting is to **increase** NOx emissions over Phase 1 by around 330 mg/km from 835 mg/km to 1,167 mg/km (a 40% increase) amalgamating the change for both fuels;

- Reproducibility is, on the whole, good for Phases 3 and 4 of WLTC, never greater than 33 mg/km, or around 1.5%, for the hot and cold starts combined. For Phases 1 and 2 hot starts only, reproducibility shows more variability. For example, Phase 1 for Runs 1 and 3 with paraffinic diesel (both hot start WLTCs) differ by nearly 200 mg/km relative to a mean value of 860 mg/km.

For the difference in NOx emissions between the paraffinic diesel and baseline diesel fuelled cycles:

- In the context of the comments above, there is negligible difference in the NOx emissions between the two fuels (<1%).
- The differences between the means of each phase shows very small (insignificant) increases when using paraffinic diesel for three of the four phases, and also for the US06 cycle.

Table 11 Bag analysis results of NOx emissions from the Euro 6 van driven using baseline diesel and paraffinic diesel fuels

EURO 6 VAN NOx RESULTS						
Drive cycle	Fuel	Run 1 (mg/km)	Run 2 (mg/km)	Run 3 (mg/km)	Mean (mg/km)	Standard deviation (mg/km)
WLTC Phase 1	Baseline	520.1	368.3	514.1	467.50	85.96
WLTC Phase 2	Baseline	290.4	301.1	286.1	292.52	7.68
WLTC Phase 3	Baseline	151.7	154.5	131.8	146.02	12.37
WLTC Phase 4	Baseline	801.2	922.6	762.2	828.65	83.65
WLTC whole cycle	Baseline	459.5	485.6	438.4	461.14	23.67
US06 whole cycle	Baseline		971.1	959.7	965.40	8.02
WLTC Phase 1	Paraffinic	587.1	326.3	587.5	500.33	150.68
WLTC Phase 2	Paraffinic	248.4	279.9	313.9	280.73	32.78
WLTC Phase 3	Paraffinic	139.2	173.6	154.9	155.92	17.22
WLTC Phase 4	Paraffinic	825.8	832.7	793.2	817.25	21.10
WLTC whole cycle	Paraffinic	464.3	449.3	470.8	461.47	11.07
US06 whole cycle	Paraffinic	1023.1	1031.9	1656.2	1028.01	4.51

	Phase 1	Phase 2	Phase 3	Phase 4	Whole
Effect of paraffinic diesel (mg/km) for mean of WLTC phases	32.8	-11.8	9.9	-11.40	0.33
Effect of paraffinic diesel (%) for mean of WLTC phases	7.0%	-4.0%	6.8%	-2.5%	0.1%
Effect of paraffinic diesel for US06-			-62.61 mg/km		6.5%

There was a problem with the emissions measurements for Run 1 of the US06 cycle that meant the data collected were meaningless. However, this was not spotted until after the vehicle had been returned off hire, and so the cycle could not be rerun. This leads to the blank in the table above.

Some other observations on the data for the Euro 6 van are:

For both baseline and paraffinic diesel fuelled cycles:

- Overall mean NOx emissions are moderately high, around 460 mg/km relative to the Euro 5 emission standard for N1 Class 3 vans, 280 mg/km over the NEDC, i.e. for a more lightly loaded van and a gentler driving cycle.

- NOx emissions are particularly high for Phase 4 of WLTC and US06, when they are around 800 - 1,000 mg/km. Both the WLTC phase 4 and the US06 cycle are when the engine is required to produce the highest power.
- The impact of cold starting is significant: giving **reductions** in NOx emissions over Phase 1 for both fuels, by around 150 mg/km, or -30%, for the baseline diesel and by around 260 mg/km, or -45%, for the paraffinic diesel. This is in contrast to the Euro 4 van where cold starting caused an **increase** in NOx emissions over Phase 1.
- Reproducibility is moderate for Phases 3 and 4 of WLTC. For the whole WLTC it is around 5% for the baseline diesel and 2.5% for the paraffinic diesel. However, the much higher variability within phases suggests this may be a coincidental cancelling of errors, rather than an intrinsically high level of reproducibility.

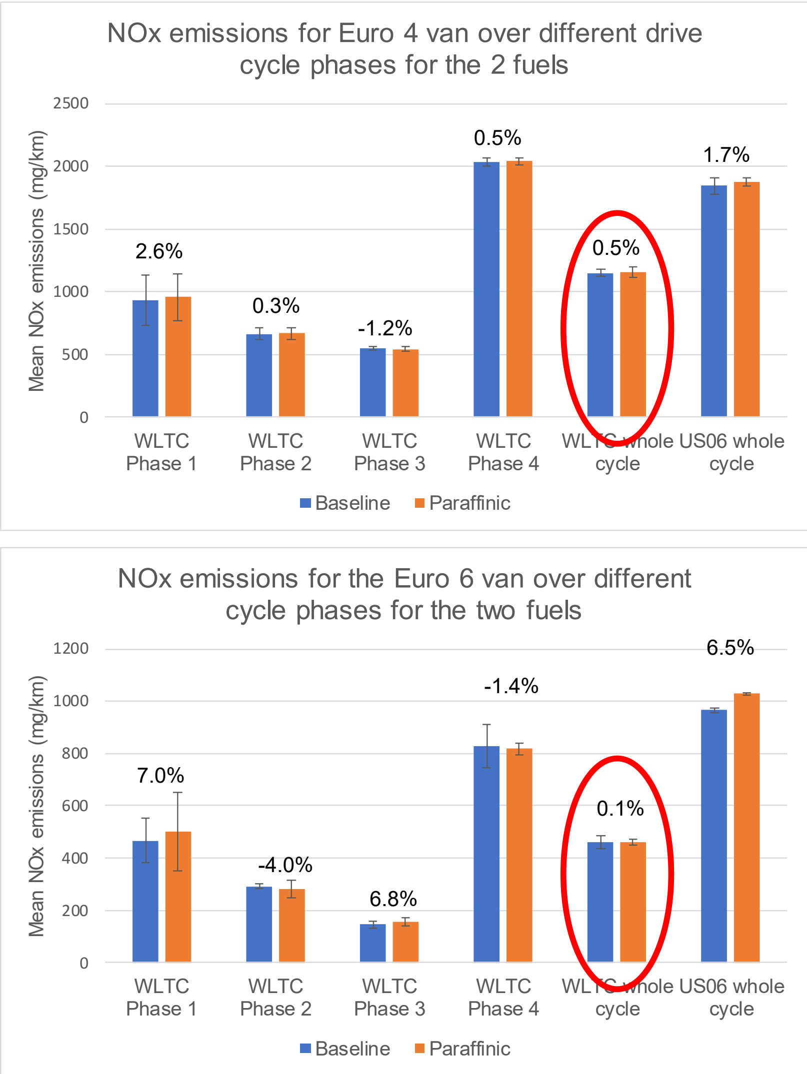
For the difference in NOx emissions between the paraffinic diesel and baseline diesel fuelled cycles:

- In the context of the comments above, there is negligible difference in the NOx emissions between the two fuels (the difference in means is less than 0.1% - although as noted above the much higher variability within phases suggests this may be a coincidental cancelling of errors, rather than an intrinsically high level of reproducibility).
- The differences between the means of each phase shows small increases when using paraffinic diesel for two of the four phases of WLTC, and small decreases for the other two phases.

To summarise, the data in the tables shows that the impact of using paraffinic diesel on NOx emissions for both the Euro 4 and Euro 6 N1 vans is negligible. Whilst very small increases in NOx emissions are seen for the paraffinic diesel, this is small relative to the run-to-run variability.

The data in Table 10 and Table 11 are plotted in Figure 3 as adjacent columns for the two fuels. The standard deviations of the data, recorded in the last column of the tables are included for each column. These are quite large for Phase 1 of the WLTC because of the impact of the cold start cycle. This graphical presentational format further shows how the impact of changing fuel on NOx emissions for both N1 vans is negligible.

Figure 3: Phase by phase NOx emissions for the two N1 Class 3 vans tested with both fuels



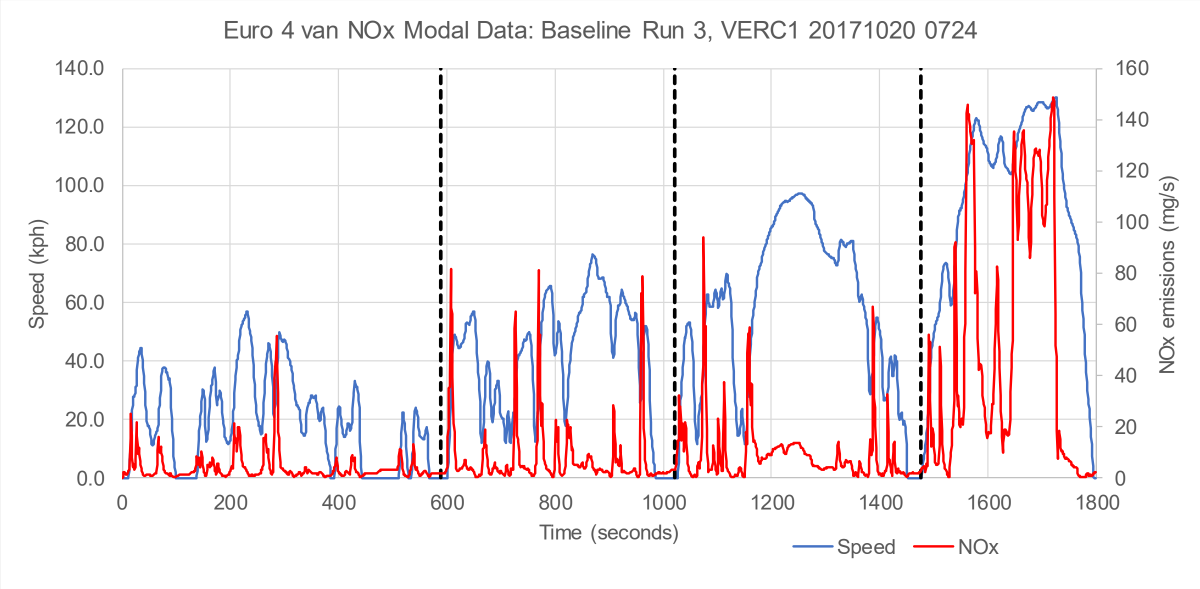
Modal plots of the data were generated and compared. They showed little difference between the two fuels. However, they did show marked differences between the conditions under which NOx emissions occur for the Euro 4 and Euro 6 vans in baseline tests. This is shown in Figure 4.

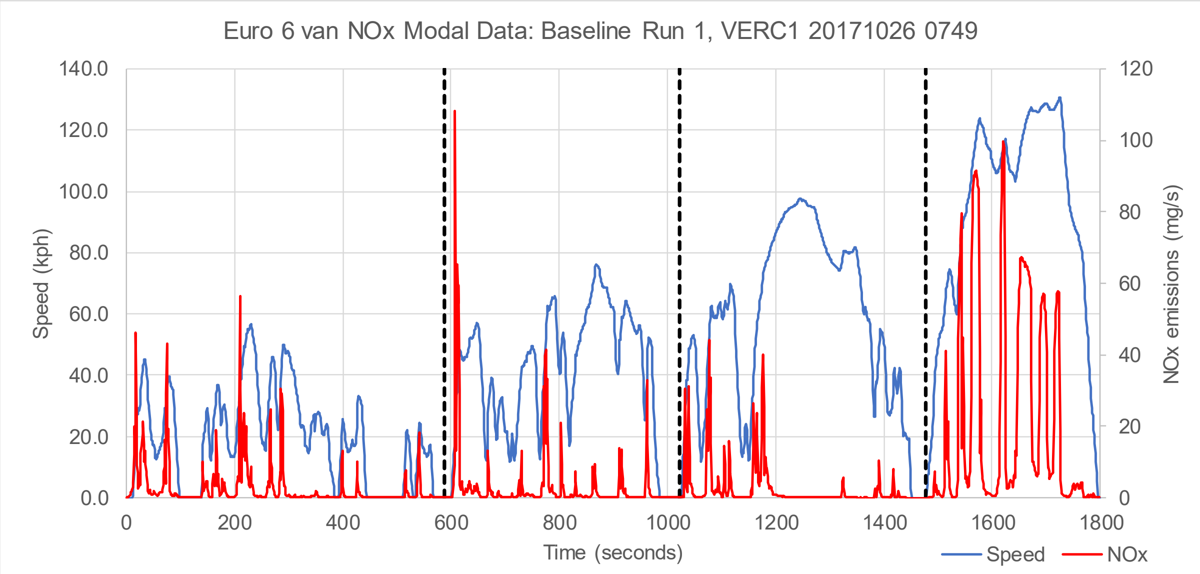
Some comments on the modal data shown in Figure 4 are:

- The two graphs are plotted using different vertical scales.
- A comparison of emissions at low load, including idle, e.g. 450 – 500 seconds show reduced emissions for the Euro 6 van, demonstrating the effect of the SCR system.
- Emissions at high load, e.g. 1,200 – 1,300 secs further demonstrate the efficacy of the SCR system.

The differences summarised in the tabulated NOx emissions over different phases, in Table 10 and Table 11, are consistent with the differences observed in the graphs of modal emissions.

Figure 4: Typical modal data for the Euro 4 and Euro 6 N1 Class 3 vans driving the WLTC using baseline diesel





3.2.3 CO_2, regulated emissions and unregulated emissions results

The analysis of the CO_2 data was used as an indication of the reproducibility between runs. The results are summarised in Table 12 for the two fuels. Averages for the two hot start WLTC runs and the three hot start US06 cycles, and the result from the single cold start WLTC are shown for the two fuels. Table 12 also reports the difference in the CO_2 emissions between the two fuels.

Table 12: Bag analysis results of CO_2 emissions from the vans driven using baseline diesel and paraffinic diesel fuels

	Baseline diesel			Paraffinic diesel		
	Hot starts		Cold starts	Hot starts		Cold starts
Euro 4 van	Average (g/km)	Standard deviation (g/km)	Value (g/km)	Average (g/km)	Standard deviation (g/km)	Value (g/km)
WLTC whole cycle	298.7	5.0	306.3	284.0	0.6	293.2
US06 whole cycle	378.0	4.9		375.3	7.1	
Effect of paraffinic diesel (g/km) for mean of whole WLTC	-14.8	3.6	-13.1			
Effect of paraffinic diesel (g/km) for mean of US06	-2.7	6.1				
Euro 6 van						
WLTC whole cycle	274.2	15.4	273.7	266.2	4.1	275.4
US06 whole cycle	317.5	1.2		325.4	4.4	
Effect of paraffinic diesel (g/km) for mean of whole WLTC	-8.0	11.3	1.7			
Effect of paraffinic diesel (g/km) for mean of US06	-7.9	3.2				

For both vans use of paraffinic diesel led to reduced CO_2 emissions. This is consistent with the different physical properties of the two fuels, summarised in Table 2, and is caused principally by the lower carbon content and higher cetane rating of the paraffinic diesel, relative to the baseline, diesel. The differences were not significant for the US06 cycle, indeed, for the Euro 6 van CO_2 emissions increased slightly for the paraffinic diesel.

The emissions of carbon monoxide (CO), hydrocarbons (HC), particulate mass (PM), particulate number (PN), the fraction of the NOx that is emitted as primary NO_2 ($f(NO_2)$), ammonia (NH_3) and nitrous oxide (N_2O) are all summarised in Table 13 for both vans. The data for CO and HC is from the regulatory bag analysis, for $f(NO_2)$, NH_3 and N_2O results come from the analysis of Fourier Transform Infra-red modal data, and for PM and PN results come from a regulatory filter paper system and a regulatory particle number counting system.

For most species results varied very little between the two fuels. Sometimes (e.g. for CO and HC) this was because the emissions were very small, particularly with respect to the standard, and any difference caused by the fuel was small relative to the measurement reproducibility. For these species the “paraffinic to baseline diesel ratio” column is reported as “Around 1”, and is not significant given the variance of the data.

The values of the non-regulated pollutants ($f(NO_2)$, NH_3 and N_2O) were found to be more a consequence of the vehicle’s combustion characteristics than whether it ran on baseline diesel or paraffinic diesel.

Table 13: Emission results for CO, HC, PM, PN, f(NO_2), NH_3 and N_2O from the vans driven using baseline diesel and paraffinic diesel fuels

	Baseline	Average of 4 hot starts (from both fuels) (mg/km)	Average of 2 cold starts (mg/km)	NEDC limit value (mg/km)*	Paraffinic to baseline diesel ratio
Carbon Monoxide	Euro 4	19.1	46.5	740	Too small to be significant
	Euro 6	46.5	227.3	740	Too small to be significant
Hydrocarbons	Euro 4	5.59	8.56	90	Too small to be significant
	Euro 6	1.54	8.47	70	Too small to be significant
PM	Euro 4	99.1	118.3	60	~40%
	Euro 6	2.31	4.34	4.5	Around 1
PN	Euro 4	To high	to be	measured	
	Euro 6	3.2E+10	4.8e+10	6E+11	Around 1
f(NO_2)	Euro 4	16.0%	13.3%		1.2% ±2.5%
	Euro 6	7.8%	6.5%		1.3% ±0.9%
Ammonia	Euro 4	1.81	1.63		-24% ±7%
	Euro 6	1.24	0.55		-30% ±30%
Nitrous oxide	Euro 4	6.5	5.8		-18% ±5%
	Euro 6	34.6	32.4		4% ±9%

* Note – the taxis were not type approved to the New LUB cycle

For CO, HC, PN and NH_3 emissions are small and vary little between the two fuels. Consequently, no further data are reported or comments made.

However, noteworthy emissions measurements were:

Particulate mass emissions:

For the Euro 4 van there is a small (around 20%) increase between the cold and hot start emissions of PM. More noteworthy is that there is around a 60% reduction in PM emissions when run on paraffinic diesel relative to when run on baseline diesel. This difference is around four times larger than the run to run variability in PM emissions, and is statistically significant.

For the Euro 6 van, PM emissions are small, and although there is around a 30% reduction when run on paraffinic diesel rather than when run on baseline diesel (1.1 mg/km) this is smaller than the run to run variability.

PM, apart from CO_2 emissions discussed above, is the only species where it was noted that the use of paraffinic diesel made a significant difference, generating a positive benefit in terms of emissions that affect air quality.

Nitrous oxide

Nitrous oxide emissions from the Euro 4 van are around 6.3 mg/km (averaged over the twelve hot and cold start WLTC run using both fuels). This is equivalent to CO_2e emissions of around 1.9 g CO_2/km, an additional approximately 0.6% increase in CO_2e emissions.

However, for the Euro 6 van the additional emissions are around 33.9 mg/km. This is equivalent to CO_2e emissions of around 10 g CO_2/km, an additional approximately 3.7% increase in CO_2e emissions. It is emphasised that this is not a consequence of the paraffinic diesel, rather a consequence of this vehicle's powertrain combustion characteristics, and is most probably a consequence of the SCR system and its calibration.

3.3 Taxis

3.3.1 Vehicle selection, their characteristics and drive cycles used

Both taxis tested were the TX4 model, the classic London black cab. One meeting Euro 4 emissions standards and the other meeting current Euro 6 standards. It should be noted that the manufacturer of these vehicles has changed with the original LTI Ltd having been under several different holding companies in the last decade. It is recognised that many taxis outside London are other large cars, e.g. Mercedes, but for this scoping project, the choice of TX4 was appropriate, not least because there are many black cabs in use, and they often operate in areas where air quality is poor.

Table 14: Characteristics of the taxis tested in this investigation

Parameter	Euro 4 taxi	Euro 6 taxi
Vehicle make and model	London Taxi Company (LTI) TX4	London Taxi Company (LTI) TX4
Date of registration and mileage at the start of testing	November 2006, 282,220 miles	December 2016, 21,440 miles
Gross Vehicle Weight	2,400 kg	2,400 kg
Inertia used for testing	2,121 kg	2,161 kg
Engine	VM Motori R 425 DIHC turbo diesel	VM Motori 2776cc B428 DOHC four cylinder diesel, 16 valve DI, turbo and intercooled.
Emissions control strategy	EGR and DPF no SCR	EGR, DOC, DPF and SCR
Engine size, peak power	2.5 litres, 101 hp (75 kw)	2,776 ccs, 238 hp (175 kw)
Transmission type	Chrysler 545RFE five-speed automatic	Five-speed automatic

The testing schedule used for both taxis was the Worldwide Harmonised Light vehicle Test Cycle (WLTC) with much of the testing protocol following that of the Worldwide Harmonised Light vehicle Test Procedure (WLTP) as for the medium cars and the light duty vans. In addition, the taxis were also tested using the PCO-CENEX taxi cycle. This is shown in Figure 5. Preconditioning for the WLTC and the PCO Taxi cycle were the high and extra high phases of the WLTC (Phase 3 and 4). It is noted that for this fuel inter-comparison, the important factor is consistency of testing protocol, rather than all the absolute details. This is distinctly different from generating type approval data, where adherence to the WLTP is critical.

One of the three WLTC tests with each fuel were cold starts, with the other two being hot start tests. All of the PCO Taxi cycles were hot start tests.

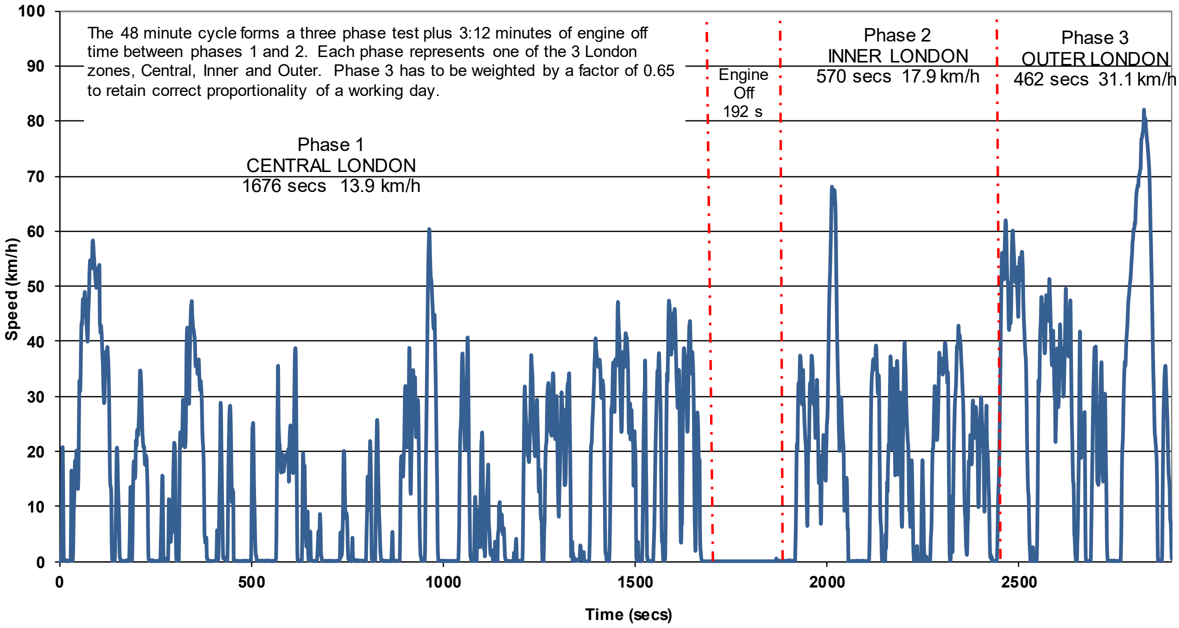
Unfortunately, both taxis proved mechanically unreliable. For the Euro 4 taxi faults were found to be:

- A cracked pipe connecting the EGR valve with the exhaust manifold, and
- A broken pressurised vent system case.

Faults led to detectors in the test cell seeing non-contained exhaust gases, and shutting the facility down. Both faults were repaired, and the whole test programme was ultimately successfully completed.

For the Euro 6 TX4, again faults led to detectors in the test cell seeing non-contained exhaust gases, and shutting the facility down. One run was successfully completed. The fault was ultimately traced to the ATF cooler core itself. This was too large a fault for the Ricardo engineers to repair on a relatively young hire vehicle. Therefore, following discussions with DfT and considering potential further delays that sourcing a replacement vehicle would likely present, it was agreed that testing of this vehicle should be abandoned following the competition of only one test. Therefore, results generated for Euro 6 TX4 are very limited..

Figure 5: Time-vehicle speed profile for the PCO Taxi cycle



For the Euro 4 taxi, three of each of the two test cycles were driven with each of the two fuels, i.e. a total of twelve tests. This used the same test sequence as for the passenger cars, see Section 3.1.1, except that the PCO-Taxi cycle replaces the US06 cycle, and is summarised as: **D – P – P – D – D – P** where **D** denotes both a WLTC and PCO-Taxi cycle being driven using the conventional diesel, and **P** denotes the use of 100% paraffinic diesel. WLTC and PCO-Taxi (**D** or **P**) denote hot start WLTC and PCO-taxi driving cycles, and **P** or **D** denote a cold start WLTC followed by a hot start PCO-Taxi cycle with each fuel.

In addition, due to a scheduling mistake, an additional cold start WLTC was run, this is one more than was originally planned, when the taxi was running on paraffinic diesel. This is recorded as “Run 4” in the following data tables.

3.3.2 NOx emissions results

The regulatory NOx emissions results for the individual phases of the WLTC and the whole US06 cycles, for both fuels are reported in Table 15 and Table 16 the Euro 4, and 6, taxis, respectively.

For the Euro 4 taxi some observations on these data are given below the table. However, these should be taken in the context of the general feedback that drivers reported that this taxi “did not drive well”. It will be seen in the next sub-section that run to run reproducibility for this taxi was the poorest for all the vehicles studies, and the comments below should be treated with caution.

Table 15: Bag analysis results of NOx emissions from the Euro 4 taxi driven using baseline diesel and paraffinic diesel fuels

EURO 4 TAXI NOx RESULTS							
Drive cycle	**Fuel**	**Run 1** (mg/km)	**Run 2** (mg/km)	**Run 3** (mg/km)	**Run 4** (mg/km)	**Mean** (mg/km)	**Standard deviation** (mg/km)
WLTC Phase 1	Baseline	1,580.3	1,866.5	1,844.8		1,763.8	159.32
WLTC Phase 2	Baseline	1,278.3	1,912.8	2,151.5		1,780.8	451.30
WLTC Phase 3	Baseline	1,213.9	1,738.7	1,503.0		1,485.2	262.85
WLTC Phase 4	Baseline	1,718.3	1,728.7	1,744.5		1,730.5	13.20
WLTC whole cycle	Baseline	1,454.6	1,787.6	1,766.1		1,669.4	186.35
PCO Taxi Phase 1	Baseline	2,518.0	2,946.0	2,859.7		2,774.6	226.32
PCO Taxi Phase 2	Baseline	2,565.7	2,111.6	2,464.6		2,380.6	238.43
PCO Taxi Phase 3	Baseline	2,225.1	1,511.3	2,337.8		2,024.7	448.21
PCO Taxi whole cycle		2,440.4	2,341.1	2,619.3		2,466.9	141.01
WLTC Phase 1	Paraffinic	1,702.0	1,743.8	1,596.9	1897.6	1735.07	124.75
WLTC Phase 2	Paraffinic	1,333.9	1,187.9	1,276.4	1352.7	1287.74	74.03
WLTC Phase 3	Paraffinic	1,328.9	1,083.8	1,338.7	1172.5	1230.99	124.20
WLTC Phase 4	Paraffinic	2,274.8	1,562.7	2309.8	1623.4	1942.69	404.69
WLTC whole cycle	Paraffinic	1,714.4	1,362.9	1,703.9	1465.8	1561.76	175.36
PCO Taxi Phase 1	Paraffinic	2,655.7	2,477.0	2,443.9		2525.52	113.91
PCO Taxi Phase 2	Paraffinic	2,341.9	2,028.3	2,024.7		2131.62	182.11
PCO Taxi Phase 3	Paraffinic	1,912.5	1,662.1	1,564.4		1712.96	179.54
PCO Taxi whole cycle	Paraffinic	2,367.5	2,137.5	2,092.8		2199.28	147.39

	Phase 1	Phase 2	Phase 3	Phase 4	Whole
Effect of paraffinic diesel (mg/km) for mean of WLTC phases	-28.8	-493.1	-254.2	212.2	-107.66
Effect of paraffinic diesel (%) for mean of WLTC phases	-1.6%	-27.7%	-17.1%	12.3%	-6.4%
Effect of paraffinic diesel (mg/km) for PCO Taxi cycle	-249.0	-249.0	-311.8		-267.6
Effect of paraffinic diesel (%) for PCO Taxi cycle	-9.0%	-10.5%	-15.4%		-10.8%

Some observations on these data are:

For both baseline and paraffinic diesel fuelled cycles:

- Overall mean NOx emissions are high, around 1,700 mg/km for the WLTC and 2,500 mg/km for the PCO Taxi cycle. The PCO-Taxi cycle is too different from the regulatory NEDC for any meaningful comparison to be made with the regulatory values.
- NOx emissions are variable. Replicate cycles that had higher NOx emissions were also found to have higher CO_2 emissions indicating poor run reproducibility for this vehicle.
- The impact of cold starting is to increase NOx emissions over Phase 1 by around 170 mg/km (10%) relative to the hot start WLTC. However, this is less clear than for other vehicles with smaller cycle to cycle variability. The difference is very similar for both fuels;

For the difference in NOx emissions between the paraffinic diesel and baseline diesel fuelled cycles:

- Care needs to be exercised not to over interpret the data because of the comments regarding the poor cycle to cycle reproducibility, as also evidenced from the variability in the CO_2 emissions.
- It was seen that whilst the phase by phase changes reveal poor reproducibility, when this is aggregated into the whole cycle differences are more meaningful. These indicate for the whole WLTC the impact of paraffinic diesel is to reduce NOx emissions by 108 ± 181 mg /km, and over the PCO Taxi cycle by 268 ± 144 mg/km.

Table 16: Bag analysis results of NOx emissions from the Euro 6 taxi driven using baseline diesel and paraffinic diesel fuels

EURO 6 TAXI NOx RESULTS						
Drive cycle	**Fuel**	**Run 1** (mg/km)	**Run 2** (mg/km)	**Run 3** (mg/km)	**Mean** (mg/km)	**Standard deviation** (mg/km)
WLTC Phase 1	Baseline	608.1	No			
WLTC Phase 2	Baseline	728.7		data		
WLTC Phase 3	Baseline	527.9			available	
WLTC Phase 4	Baseline	1,610.6				
WLTC whole cycle	Baseline	963.7	Because			
PCO Taxi Phase 1	Baseline	1,418.8		of		
PCO Taxi Phase 2	Baseline	935.0			vehicle	
PCO Taxi Phase 3	Baseline	632.4				breakdown
PCO Taxi whole cycle	Baseline	1,078.8				
WLTC whole cycle	Paraffinic		No	data	available	Breakdown
PCO Taxi whole cycle	Paraffinic		Because	of	vehicle	Breakdown

Only a single WLTC and PCO Taxi cycle were driven before a vehicle breakdown prevented further testing. Comparison with the Euro 4 TX4 data indicates this Euro 6 taxi had NOx emissions 57.7% and 43.7% of those of the Euro 4 vehicle for the WLTC and PCO-Taxi cycles, respectively.

No data was collected on the impact of paraffinic diesel on NOx emissions.

However, if the conclusions from the other three cars and the Euro 4 taxi successfully tested using the WLTC, summarised in Figure 16, are applicable to this vehicle, then the impact of the paraffinic diesel would be to reduce NOx emissions by around 3 – 4%. (Inclusion of the two light duty vans would reduce the average NOx reduction to 2.35%.) On the above WLTC data with the baseline diesel this would imply the paraffinic diesel would be expected to lead to a reduction of 30 – 40 mg NOx/km for this Euro 6 taxi. However, it is emphasised this is not a measurement, but conjecture based on other measurements.

3.3.3 CO_2, regulated emissions and unregulated emissions results

As for other vehicles, the analysis of the CO_2 data was used as an indication of the reproducibility between runs. The results are summarised in Table 17 for the two fuels. Averages for the two hot start WLTC runs and the three hot start PCO-taxi cycles, and the result from the single cold start WLTC are shown for the two fuels for the Euro 4 taxi. The single result for the Euro 6 taxi is also given.

Drivers reported that the Euro 4 taxi "did not drive well". This comment is informative coming from professional test drivers, who expect a vehicle with an automatic gearbox to achieve the required speed on the Driver's Aid relatively simply. The observation that driving it was a challenge further supports the evidence that intrinsic vehicle variability made cycle to cycle reproducibility poor.

Table 17: Bag analysis results of CO_2 emissions from the taxis driven using baseline diesel and paraffinic diesel fuels

	Baseline diesel			Paraffinic diesel		
	Hot starts		Cold starts	Hot starts		Cold starts
Euro 4 taxi	Average (g/km)	Standard deviation (g/km)	Value (g/km)	Average (g/km)	Standard deviation (g/km)	Value (g/km)
WLTC whole cycle	275.3	26.72	316.7	272.2	4.76	257.8
PCO-taxi whole cycle	409.54	18.98		361.4	12.51	
Effect of paraffinic diesel (g/km) for mean of whole WLTC	-3.1	19.19	-58.8			
Effect of paraffinic diesel (g/km) for mean of PCO-taxi	-48.09	16.08				
Euro 6 taxi						
WLTC whole cycle	277.4	Only	Single	Run	completed	
PCO-taxi whole cycle	362.4	Only	Single	Run	completed	

The reproducibility results are the poorest of all the vehicles tested, even when allowance is made for the cold start cycles. For the three phases of the PCO Taxi cycle, all hot starts and therefore without the complication of cold starts, the standard deviation, which for other vehicles is less than 2%, is often around 5%. Further, there appears to be little pattern to this large variation.

This large variation does reduce the ability to analyse the impact of the paraffinic diesel. However, in order to present a consistent analysis methodology, the same procedures were used as for the data analysis of other vehicles. Various attempts were made to see if alternative methodologies generated useful insights. However, none were found, the fundamental issue appears to be the high level of variability when running this taxi over the same driving cycle.

Emissions of other regulated species, and potentially important non-regulated species are summarised in Table 18. **Note** for the Euro 6 results these are only based on a single run.

For HC, $f(NO_2)$ and NH_3 emissions are small and vary little between the two fuels for the Euro 4 taxi. Consequently, no further data are reported or comments made.

For CO and PM it was found that emissions over the WLTC (and the PCO taxi cycle) were reduced when using paraffinic diesel, as noted in the table. Emissions of nitrous oxide were relatively low, being 11.6 mg N_2O/km, an additional 1.2% CO_2e emissions.

Table 18: Emission results for CO, HC, PM, PN, $f(NO_2)$, NH_3 and N_2O from the taxis driven using baseline diesel and paraffinic diesel fuels

	Baseline	Average of 4 hot starts (from both fuels) (mg/km)	Average of 2 cold starts (mg/km)	NEDC limit value (mg/km)*	Paraffinic to baseline diesel ratio
Carbon Monoxide	Euro 4	191.3	236.0	740	~70%
	Euro 6	10.44		740	
Hydrocarbons	Euro 4	56.5	57.5	90	~100%
	Euro 6	18.89		70	
PM	Euro 4	8.4	8.9	60	~75%
	Euro 6	4.38		4.5	
$f(NO_2)$	Euro 4	5.00%	4.88%		0.3% ± 0.6%
	Euro 6	25.12%			
Ammonia	Euro 4	1.49	3.27		-31% ± 58%
	Euro 6	2.17			
Nitrous oxide	Euro 4	7.49	8.79		-13% ± 14%
	Euro 6	11.64			

* Note – the taxis were not type approved to the New LUB cycle

3.4 Trucks

3.4.1 Vehicle selection, their characteristics and drive cycles used

Both the trucks tested were 18 tonne GVW rigid, two axle trucks. Larger, 26 tonne GVW vehicles were of interest to the project, but were not available for hire. A summary of the characteristics of the two vehicles tested is given in Table 19.

Table 19: Characteristics of the trucks tested in this investigation

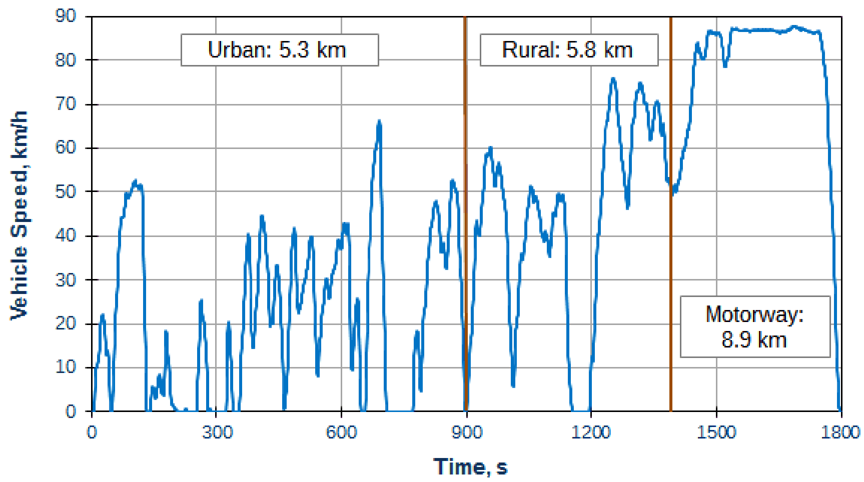
Parameter	Euro IV 18 t truck	Euro VI 18 t truck
Date of registration	May 2008	March 2017
Mileage at the start of testing	388,700 miles	2,000 miles
Gross Vehicle Weight	18,000 kg	18,000 kg
Inertia used for testing	15,649 kg	15,383 kg
Engine		MB OM 936 LA
Emissions control strategy	EGR, DOC and DPF no SCR	EGR, DOC, DPF and SCR
Engine size, peak power	9.3 litres, 230 hp (169 kw)	7.7 litres, 238 hp (175 kw)
Transmission type	8 speed synchromesh manual	Automated gearshift with 12 gears

The two vehicle's selected had quite different, complementary technologies. The non-SCR Euro IV truck being representative of the pre-SCR technology and the Euro VI truck representative of the latest heavy duty engine technology with its exhaust after-treatment systems. The rated power for both engines is similar, around 170 kW.

The drive cycle used for both trucks was the World Harmonised Vehicle Cycle (WHVC) tested according to the World Harmonized Vehicle Protocol (WHVP). This is a vehicle version of the engine type approval cycle, the World Harmonised Transient Cycle, WHTC, and is defined by the time – speed profile shown in Figure 1[4]. The trucks were preconditioned using the rural motorway phases of the WHVC, i.e. tests generally ran contiguously, and all tests involved hot starting, consistent with the procedure for engine homologation and because cold starts comprise only a small fraction of total operational use for HDVs.

The WHVC can be viewed as comprising three sections, representing urban, rural and motorway driving as shown in Figure 6.

Figure 6: Time-vehicle speed profile for the World Harmonised Vehicle Cycle



Three test cycles were driven with each of the two fuels, i.e. a total of six cycles. For HDVs, changing fuel is not a simple or quick process. Therefore, the "on paper" ideal back-to-back test, switching between paraffinic diesel and baseline diesel for consecutive runs is both, expensive and will introduce inaccuracies because of the time it takes, and changes that might occur with the vehicle when running through the new fuel. Consequently, the three emissions tests using the baseline diesel were driven consecutively and then the fuel system was flushed and prepared for testing the paraffinic diesel. Preconditioning driving at least 50 km was undertaken as part of the fuel changing procedure. Three emissions tests using the paraffinic diesel were then driven consecutively.

For the Euro VI truck the fuel comparison testing sequence was: **D – D – D – P – P – P** where **D** denotes a cycle driven using the conventional baseline diesel and **P** denotes the use of 100% paraffinic diesel. For the Euro IV truck, where it was anticipated most likely that differences in NOx emissions might be seen, additional testing was included to help identify whether any differences in emissions performance between the fuel types are due to the fuel itself or other factors (e.g. vehicle performance issues or changes in metrological conditions). Consequently, for the Euro IV truck the fuel comparison testing sequence was: **D – D – D – P – P – P - D – D – D**. I.e. the same as for the initial six cycles for the Euro VI truck but with an additional fuel change back to conventional diesel, and three further cycles being driven.

[4] Taken from https://www.dieselnet.com/standards/cycles/whvc.php

3.4.2 NOx emissions results

The regulatory NOx emissions results for the individual phases of the WHVC cycles, for both fuels are reported in Table 20 and Table 21 for the Euro IV and VI trucks respectively. In Table 20 the mean emissions for the baseline diesel are calculated from all six baseline cycles. The data from which differences between the two fuels are calculated are the means highlighted in green.

Table 20: Bag analysis results of NOx emissions from the Euro IV truck driven using baseline diesel and paraffinic diesel fuels

EURO IV TRUCK NOx RESULTS						
Drive cycle	**Fuel**	**Run 1 (mg/km)**	**Run 2 (mg/km)**	**Run 3 (mg/km)**	**Mean (mg/km)**	**Standard deviation (mg/km)**
WHVC Phase 1	Baseline	5871.8	5846.7	5856.1	Means and standard deviations for both Baseline (1) and Baseline (2) data given below aside Baseline (2)	
WHVC Phase 2	Baseline	3472.0	3565.2	3462.1		
WHVC Phase 3	Baseline	2229.5	2066.5	2177.7		
WHVC whole cycle	Baseline	3537.0	3485.7	3506.8		
WHVC Phase 1	Paraffinic	5195.3	5140.4	5072.1	5135.93	61.70
WHVC Phase 2	Paraffinic	2910.6	2959.1	2960.4	2943.35	28.41
WHVC Phase 3	Paraffinic	1954.4	1901.2	1957.3	1937.63	31.55
WHVC whole cycle	Paraffinic	3076.8	3050.9	3055.3	3061.01	13.81
WHVC Phase 1	Baseline(2)	5947.9	5839.8	5735.7	5849.67	68.23
WHVC Phase 2	Baseline(2)	3451.8	3355.5	3260.2	3427.82	105.75
WHVC Phase 3	Baseline(2)	2141.3	2092.0	2097.3	2134.06	61.24
WHVC whole cycle	Baseline(2)	3515.6	3436.8	3381.2	3477.19	58.02

Euro IV truck	Phase 1	Phase 2	Phase 3	Whole
Effect of paraffinic diesel (mg/km) for whole cycle	-713.7	-484.5	-196.4	-416.17
Effect of paraffinic diesel (%) for whole cycle	-12.2%	-14.1%	-9.2%	-12.0%

Table 21: Bag analysis results of NOx emissions from the Euro VI truck driven using baseline diesel and paraffinic diesel fuels

EURO VI TRUCK NOx RESULTS						
Drive cycle	**Fuel**	**Run 1 (mg/km)**	**Run 2 (mg/km)**	**Run 3 (mg/km)**	**Mean (mg/km)**	**Standard deviation (mg/km)**
WHVC Phase 1	Baseline	139.4	157.6	134.4	143.79	12.24
WHVC Phase 2	Baseline	57.3	56.8	54.8	56.29	1.32
WHVC Phase 3	Baseline	8.1	8.2	9.0	8.44	0.47
WHVC whole cycle	Baseline	57.6	62.1	55.9	58.54	3.24
WHVC Phase 1	Paraffinic	137.4	111.1	110.7	119.76	15.30
WHVC Phase 2	Paraffinic	59.1	35.9	45.7	46.91	11.65
WHVC Phase 3	Paraffinic	6.0	5.4	6.3	5.91	0.51
WHVC whole cycle	Paraffinic	56.3	42.4	45.7	48.15	7.26

Euro VI truck	Phase 1	Phase 2	Phase 3	Whole
Effect of paraffinic diesel (mg/km) for whole cycle	-24.0	-9.4	-2.5	-10.39
Effect of paraffinic diesel (%) for whole cycle	-16.7%	-16.6%	-30.0%	-17.7%

An immediate observation from the above data is that NOx emissions for the Euro IV truck are high, with the mean for the six WHVC whole cycles when the truck is fuelled with baseline diesel being around 3,500 mg/km (i.e. 3.5 g/km).

The most striking feature of the Euro VI truck NOx data is that all these NOx emission figures (in units of mg/km) are very small with the mean for the three WHVC whole cycles when the truck is fuelled with baseline diesel being around 60 mg/km (i.e. around a sixtieth of the value for the Euro IV truck, and less than the Euro 6 emission standard for a passenger car, 80 mg/km over the NEDC).

The data also clearly shows that for both trucks **the use of paraffinic diesel lowers overall NOx emissions.**

The data above also shows how the choice of metric gives different rankings. The Euro IV truck gives the larger absolute reduction in NOx emissions, around thirty times that from the Euro VI truck. However, it is the Euro VI truck that shows the larger percentage change.

The data in Table 20 and Table 21 give the phase by phase emissions for the two fuels in addition to the whole cycle emissions. These are plotted in Figure 7 for the Euro IV and Euro VI trucks, respectively.

The data displayed in Figure 7 follows the same format that was used in Figure 2, for the medium cars. The very low NOx emissions from the Euro VI truck (less than 8.5 mg/km) over the high speed, Phase 3 of WHVC is noteworthy. This is further illustrated in Figure 9.

In terms of the NOx emissions for consecutive WHVC runs these are shown in Figure 8 for the Euro IV truck. It clearly shows the highly reproducible nature of these NOx emissions, with clear step changes caused by the changes in fuel. Consequently, for this vehicle the use of paraffinic diesel is generating a clear, and statistically significant, reduction in NOx emissions. Over the cycle this is -416 ± 42 mg/km (or 12.0 ± 1.2%).

Figure 7: Phase by phase NOx emissions for the two trucks tested with both fuels

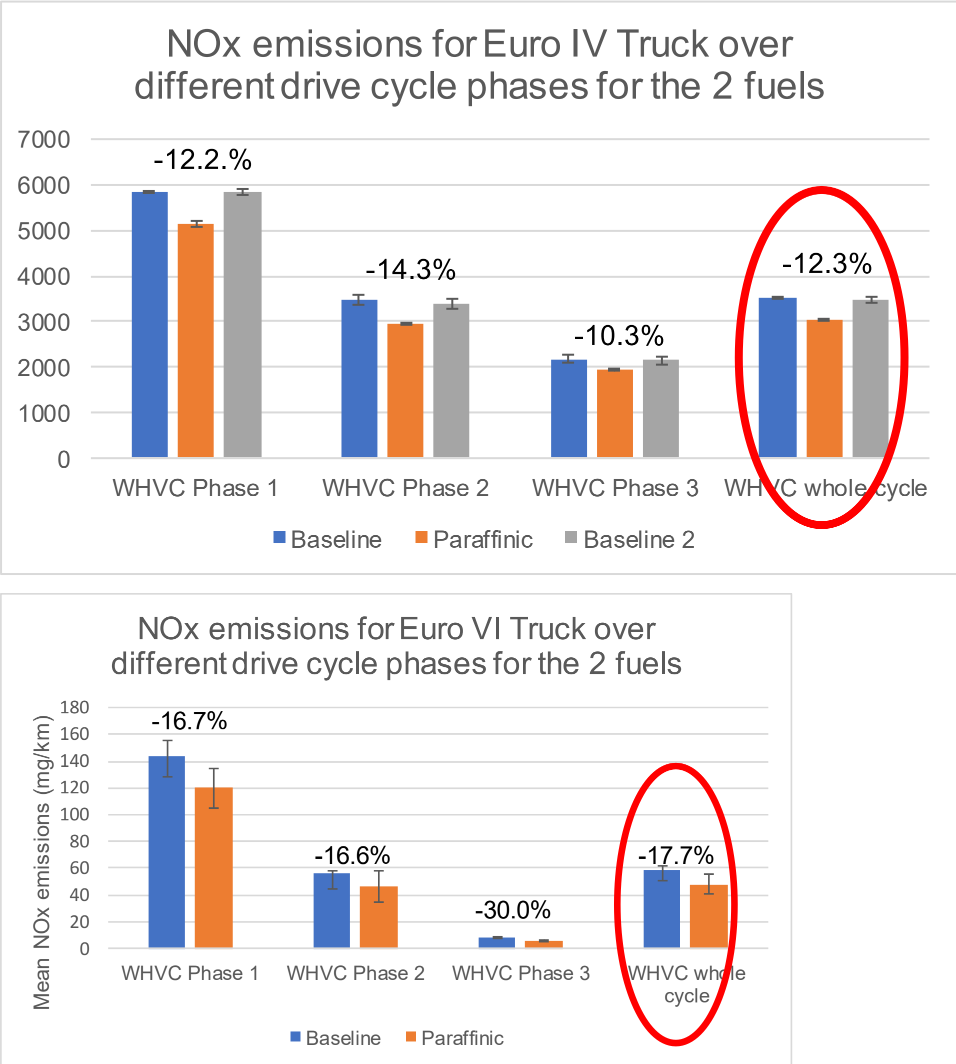
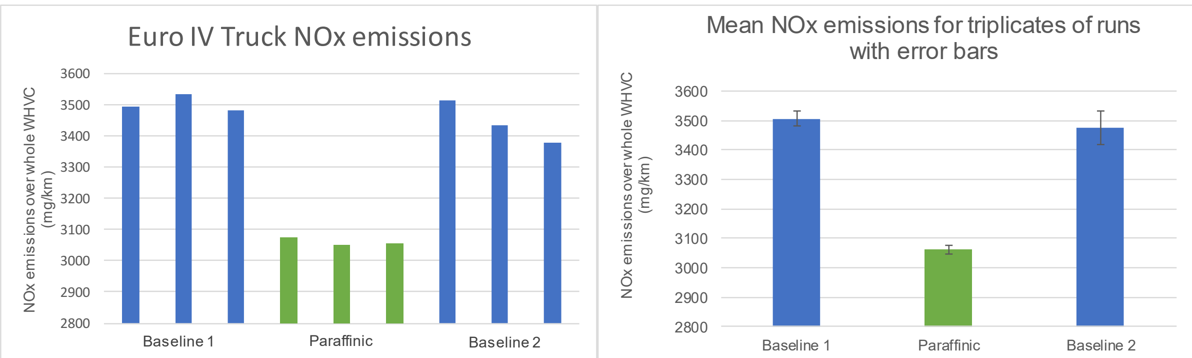


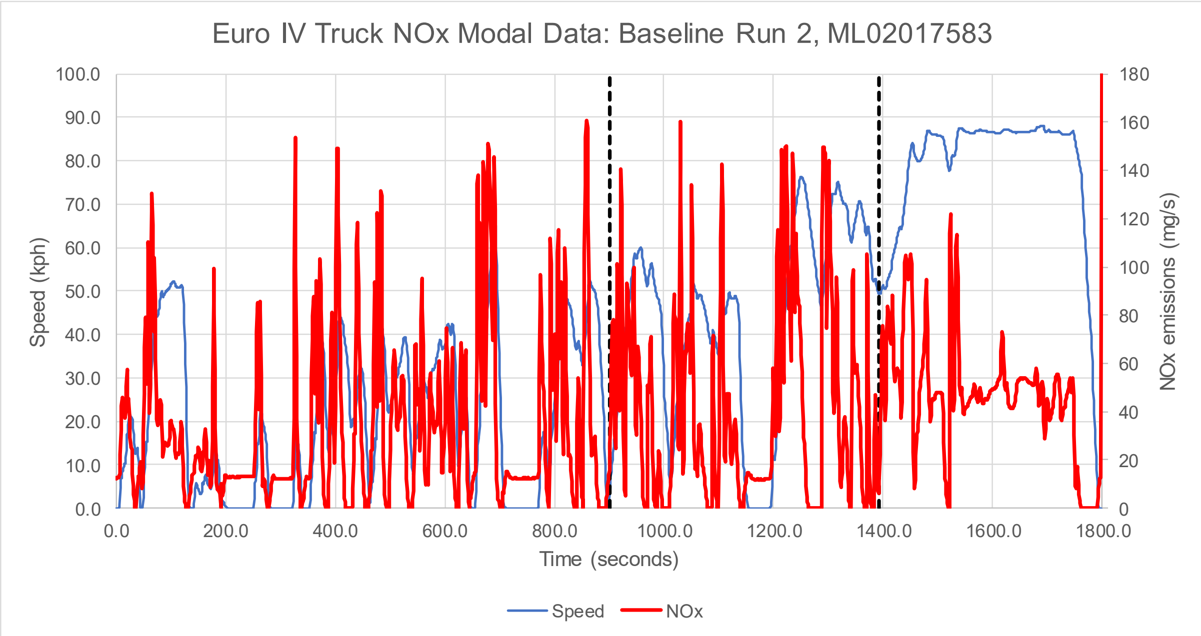
Figure 8: NOx emissions over the whole WLVC cycle for all nine runs with the Euro IV truck

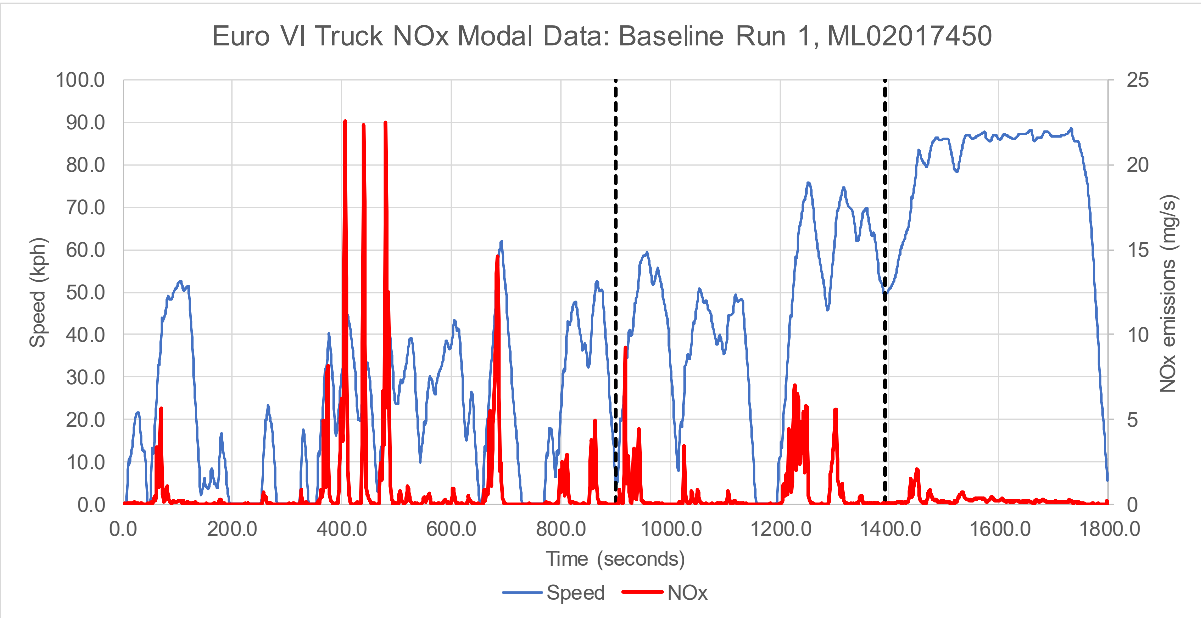


Modal data

Figure 9 shows typical modal data for both trucks running on the baseline diesel. In addition to the changes in the scale of the NOx emissions, with the Euro IV truck's scale being 7.2 times that for the Euro VI truck, the emissions during Phase 3 of WHVC (1,400 – 1,800 seconds) is very apparent. For this period of driving at a nearly constant 85 kph the Euro IV's NOx emissions are around 50 mg/s whereas for the Euro VI truck they are less than 1 mg/s. This is reflected in the mean emissions for this phase reported in Table 20 as 2,134 ± 61.2 mg/km for the Euro IV truck, and in Table 21 as 5.9 ± 0.5 mg/km for the Euro VI truck. This demonstrates the effect of a well calibrated SCR system at reducing NOx emissions when the heavy duty engine is running at a high, but relatively constant, load.

Figure 9: Typical modal data for the Euro IV and Euro VI trucks, both using baseline diesel





In contrast to the difference between the NOx emissions of the Euro IV truck and those from the Euro VI truck, it is difficult to see much difference between the emissions for the Euro IV truck running on the baseline diesel and paraffinic diesel fuels despite there being an overall 12% reduction in NOx emissions. The difference only becomes apparent when data is aggregated, e.g. by the different drive cycle phases, as in Table 20.

3.4.3 CO_2, regulated emissions and unregulated emissions results

The analysis of the CO_2 data was used as an indication of the reproducibility between runs. The results are summarised in Table 22 for the two fuels. For the Euro VI truck averages of the three (hot start) WHVC runs are shown for the two fuels. For the Euro IV truck an additional row of data gives the average of the three repeat WHVC runs also. Table 22 also reports the difference in the CO_2 emissions between the two fuels.

Table 22: Bag analysis results of CO_2 emissions from the trucks driven using baseline diesel and paraffinic diesel fuels

	Baseline diesel		Paraffinic diesel	
Euro IV truck	Average (g/km)	Standard deviation (g/km)	Average (g/km)	Standard deviation (g/km)
WHVC whole cycle	705.19	2.05	679.24	1.21
WHVC whole cycle repeat	709.07	15.31		
Effect of paraffinic diesel (g/km) for mean of whole WLTC	-27.9	8.9		
Euro VI truck	Average (g/km)	Standard deviation (g/km)	Average (g/km)	Standard deviation (g/km)
WLTC whole cycle	615.34	6.85	592.48	3.97
Effect of paraffinic diesel (g/km) for mean of whole WLTC	-22.86	5.60		

For both trucks the paraffinic diesel led to reduced CO_2 emissions that was more than 20 g/km. This is markedly larger than the standard deviations of the data, indicating it is statistically significant. Relative to the trucks' CO_2 emissions for the baseline diesel, the reduction was 3.9 ± 1.3% and 3.7 ± 0.9% for the Euro IV and Euro VI trucks, respectively.

The emissions of carbon monoxide (CO), hydrocarbons (HC), particulate mass (PM), particulate number (PN), the fraction of the NOx that is emitted as primary NO_2 ($f(NO_2)$), ammonia (NH_3) and nitrous oxide (N_2O) are all summarised in Table 23. The data for CO and HC is from the regulatory bag analysis, for $f(NO_2)$, NH_3 and N_2O comes from the analysis of Fourier Transform Infra-red modal data, and for PM and PN comes from a regulatory filter paper system and a regulatory particle number counting system.

Data are reported as the averages over the whole World Harmonised Vehicle Cycle (WHVC) and the standard deviation of the run values. For the Euro IV truck when fuelled with baseline diesel, this is the average and variance of six runs, whilst for the Euro IV truck when fuelled with paraffinic diesel, and for the Euro VI truck with both fuels, this is the average and variance of three runs.

For the regulated species, CO, HC, PM and PN and ammonia for Euro VI trucks, the emissions standards are given for engine type approval, in units of mass of pollutant /kWh mechanical work from the engine. From the power absorbed by the dynamometer a comparison can be made with the emissions measured in this study.

It was found the Euro IV vehicle emissions of CO and hydrocarbons are around 20% and 40%, respectively, of the engine standard when the vehicle ran on baseline diesel, i.e. are moderately small. Notwithstanding, the effect of switching to paraffinic diesel caused a reduction of around 18% in CO emissions, greater than the standard deviation of the data, but no significant change in hydrocarbon emissions.

For the Euro VI truck, emissions of CO and hydrocarbons are around 0.3% and 5%, respectively, of the engine standard, i.e. are very low. Whilst some changes were noted when running on paraffinic diesel these are too small, and are of comparable magnitude with the standard deviation of the data.

Therefore, they are insignificant for these pollutants, that are also unimportant in terms of their air quality impact.

Table 23 Emission results for CO, HC, PM, PN, f(NO_2), NH_3 and N_2O from the trucks driven using baseline diesel and paraffinic diesel fuels

		Baseline diesel		Paraffinic diesel	
		Average (mg/km)	Standard deviation (mg/km)	Average (mg/km)	Standard deviation (mg/km)
Carbon Monoxide	Euro IV	813.70	38.41	661.65	13.59
	Euro VI	13.06	1.46	10.41	1.46
Hydrocarbons	Euro IV	217.84	33.36	203.00	9.37
	Euro VI	7.78	2.48	28.58	11.05
PM	Euro IV	75.38	20.14	38.78	2.22
	Euro VI	Too small to measure			
PN	Euro IV	Too large to measure			
	Euro VI	8.94E+09	7.34E+08	6.88E+09	2.19E+09
f(NO_2)	Euro IV	1.6%	0.15%	1.7%	0.03%
	Euro VI	68.4%	0.7%	66.2%	0.3%
Ammonia	Euro IV	0.10	0.05	0.12	0.00
	Euro VI	16.97	3.76	5.04	0.00
Nitrous oxide	Euro IV	4.20	0.46	3.48	0.07
	Euro VI	73.46	1.32	58.12	4.46

Particulate mass and number emissions:

For PM, however, switching to paraffinic diesel caused a reduction of around 50% in PM emissions from the Euro IV truck. This is both, greater than the standard deviation of the data and **is significant** for this important pollutant in terms of air quality impact. For the Euro VI truck PM emissions were too small for any meaningful measurements to be recorded from the filter method.

This is supported by the Euro VI truck's PN emissions being around 1.5% (a sixtieth) of the regulatory standard.

Primary nitrogen dioxide

The two vehicles show quite different behaviour regarding their emissions of primary NO_2 (the f(NO_2) parameter). For the Euro IV truck primary NO_2 emissions were around 60 mg/km, around 1.7% of the total 3,500 mg/km NOx emissions. For the Euro VI truck primary NO_2 emissions were around 34 mg/km, around 68% of the total 60 mg/km NOx emissions. Consequently, the air quality road side impact of the low NOx emitting Euro VI truck is only around a half that of the much higher emitting Euro IV truck despite the WHVC average NOx emissions being around a sixtieth of that for the Euro IV truck.

Ammonia and nitrous oxide

Similarly, the two vehicles show quite different behaviour regarding their emissions of ammonia and nitrous oxide. The Euro IV truck has emissions that are towards the low end of the "typical truck emissions” range[5], emitting less than 1 mg/km of ammonia, and around 4 mg/km of nitrous oxide. This level of nitrous oxide emissions (a potent greenhouse gas) is equivalent to an additional 1.2 g/km CO_2 emissions, i.e. would constitute an additional GHG footprint of around 0.2%.

In contrast, the Euro VI truck has emissions that are towards the high end of the “typical truck emissions” range, emitting around 17 mg/km of ammonia (in the context of the emissions standard being 10 mg/kWh), and around 75 mg/km of nitrous oxide. This level of nitrous oxide emissions is equivalent to an additional 22 g/km CO_2 emissions, i.e. would constitute an additional GHG footprint of around 3.6%.

The above observations are principally a consequence of the Euro VI vehicle’s combustion chemistry and the exhaust emissions after-treatment technologies fitted to the vehicle. **Importantly for this project, the impact of changing to paraffinic diesel does not increase the emissions of either of these nitrogen containing pollutants.** Indeed, the data presented in Table 23 indicates that changing from baseline diesel to paraffinic diesel causes the emissions of ammonia to reduce by 70%, and of nitrous oxide to reduce by 20%.

3.5 Buses

3.5.1 Vehicle selection, their characteristics and drive cycles used

The project’s aim was to test buses having distinctly different emissions technologies. The original plan was to test a modern Euro VI bus, which would have SCR, and an older technology Euro IV bus that did not. However, it became apparent that all the Euro IV buses potentially available for hire also had SCR emission abatement technology. We are aware that some operators have used retro-fit SCR systems to reduce NOx emissions, helping their local authorities meet air quality challenges. It was decided that the Euro IV bus could be fitted with an OEM configured, not retro-fit, SCR system. A summary of the characteristics of the two buses tested is given in Table 24.

The two vehicle’s selected had quite different, complementary technologies. The Euro IV bus had been re-engined, complete with the engine’s exhaust after-treatment system. This vehicle, whilst not a non-SCR bus, was fitted with an early OEM SCR system. The Euro VI bus was a much later typical configuration with an OEM SCR system designed to meet the Euro VI engine regulations.

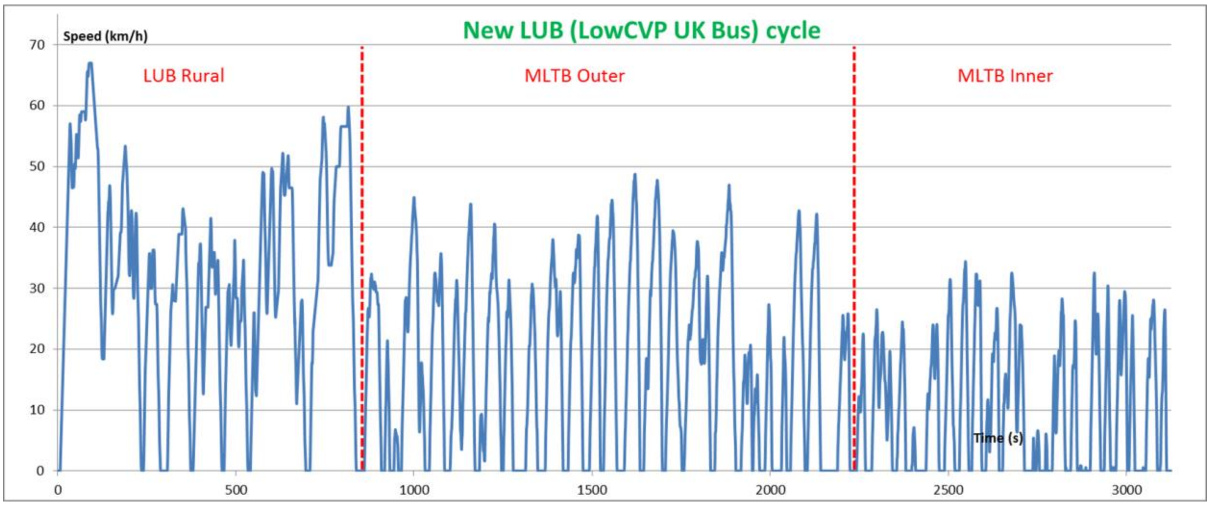
Table 24: Characteristics of the buses tested in this investigation

Parameter	Euro IV bus	Euro VI bus
Date of registration	October 2009	August 2017
Mileage at the start of testing	127,980 miles	1,090 miles
Vehicle Kerb Weight	7,096 kg	12,308 kg
Inertia used for testing	8,157 kg	14,697 kg
Emissions control strategy	EGR, DOC and DPF & SCR	EGR, DOC, DPF and SCR
Engine size, peak power	4.5 litres, 138 hp (102 kw)	9.0 litres, 250 hp (184 kw)
Transmission type	Automatic gearbox	Automatic gearbox

The drive cycle used for both buses was the new London Urban Bus (LowCVP UK Bus) cycle. This comprises the two phases of the Millbrook London Transport Bus (MLTB) cycle which follow a higher speed “rural” phase, (i.e. the London Urban Bus Rural phase). The time / vehicle speed profile for the full cycle is shown in Figure 10.

[5] Typical truck ammonia emissions are cited as being 2 – 11 mg/km from Section 1.A.3.b.(i)-(iv) “Road Transport” of the EEA/EMEP inventory Guidebook, available from https://www.eea.europa.eu/publications/emep-eea-guidebook-2016/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i/view

Figure 10: Time / vehicle speed profile for the new LUB Cycle



Note: this cycle is distinctly different from the light duty vehicle and heavy duty truck regulatory cycles because the average speed of each phase decreases, with the **highest speed phase coming first**, whereas for all the regulatory cycles the highest speed phase comes last, after urban and sub-urban phases. This important difference must be remembered when considering the impacts of paraffinic diesel on a phase by phase basis.

Three test cycles were driven with each of the two fuels, i.e. a total of six cycles. As noted in the previous section for the truck testing, changing fuel is not a simple or quick process. Therefore, the "on paper" ideal back-to-back test, switching between paraffinic diesel and baseline diesel for consecutive runs, is both expensive, and will introduce inaccuracies because of both the time it takes, and changes that might occur with the vehicle when running through the new fuel. Consequently, the three emissions tests using the baseline diesel were driven consecutively and then the fuel system was flushed and prepared for testing the paraffinic diesel. Preconditioning driving at least 50 km was undertaken as part of the fuel changing procedure. Three emissions tests using the paraffinic diesel were then driven consecutively.

For the Euro VI bus the fuel comparison testing sequence was: **D – D – D – P – P – P** where **D** denotes a cycle driven using the conventional diesel and **P** denotes the use of 100% paraffinic diesel. For the Euro IV bus, where it was anticipated most likely that differences in NOx emissions might be seen, additional testing was included to help identify whether any differences in emissions performance between the fuel types are due to the fuel itself or other factors (e.g. vehicle performance issues or changes in metrological conditions). Consequently, for the Euro IV bus the fuel comparison testing sequence was: **D – D – D – P – P – P - D – D – D**. I.e. the same as for the Euro VI bus but with an additional fuel change back to conventional diesel, and three further cycles being driven.

3.5.2 NOx emissions results

The regulatory NOx emissions results for the individual phases of the new LUB cycles, for both fuels are reported in Table 25 for the Euro IV bus and Table 26 for the Euro VI bus.

Table 25: Bag analysis results of NOx emissions from the Euro IV bus driven using baseline diesel and paraffinic diesel fuels

EURO IV BUS NOx RESULTS						
Drive cycle	**Fuel**	**Run 1 (mg/km)**	**Run 2 (mg/km)**	**Run 3 (mg/km)**	**Mean (mg/km)**	**Standard deviation (mg/km)**
LUB Phase 1	Baseline	4,405.7	4,641.1	4,459.7	Means and standard deviations for both Baseline (1) and Baseline (2) data given below aside Baseline (2)	
LUB Phase 2	Baseline	8,037.4	8,380.4	8,158.0		
LUB Phase 3	Baseline	14,379.6	14,221.1	13,879.0		
LUB whole cycle	Baseline	7,366.8	7,591.1	7,367.1		
LUB Phase 1	Paraffinic	3,840.4	4,468.9	4,344.4	4,217.9	332.8
LUB Phase 2	Paraffinic	7,548.3	8,225.4	8,102.4	7,958.7	360.7
LUB Phase 3	Paraffinic	13,729.9	14,003.2	14,170.8	13,968.0	222.6
LUB whole cycle	Paraffinic	6,826.9	7,420.9	7,336.7	7,194.8	321.4
LUB Phase 1	Baseline(2)	4,315.3	4,557.1	4,729.6	4,518.1	154.0
LUB Phase 2	Baseline(2)	7,934.6	8,449.1	8,645.2	8,267.5	269.9
LUB Phase 3	Baseline(2)	13,715.7	14,151.5	14,064.6	14,068.6	239.7
LUB whole cycle	Baseline(2)	7,187.4	7,567.0	7,711.0	7,465.0	191.4

Euro IV bus	Phase 1	Phase 2	Phase 3	Whole
Effect of paraffinic diesel (mg/km) for whole cycle	-300.2	-308.8	-100.6	-270.2
Effect of paraffinic diesel (%) for whole cycle	-7.12%	-3.88%	-0.72%	-3.62%

The data from which differences between the two diesels are calculated are the means highlighted in green.

The NOx emissions for the Euro IV bus are high, with the mean for the six WHVC whole cycles when the bus is fuelled with baseline diesel being around 7,200 mg/km (i.e. 7.2 g/km). This is the highest NOx emissions seen from any of the vehicles tested, despite the vehicle having an (early) SCR system fitted. It was confirmed that:

- On delivery the vehicle was checked by Millbrook's workshop facility and they reported no faults.
- During the first warmup on every test day the vehicle dashboard was also scrutinised for any warning/alarms. Any warnings or faults that occur during testing would also have been reported. None were seen on any occasion.

These emissions are around twice that anticipated if one makes some assumptions that around 1 kWh engine mechanical power is required to drive each kilometre of the new LUB cycle.[6]

However, it is emphasised this Tranche 1 research aims to be a scoping study, assessing different vehicles of different sizes and distinctly different technologies. It is not a direct checking of NOx

[6] For trucks not all the energy generated by the engine is used to overcome road load resistances, but most is. However, for buses, auxiliaries consume a much greater proportion of the engines output, around 26% relative to 5% for a truck (see Slide 24 of 32 of EC presentation on VECTO available from https://ec.europa.eu/clima/sites/clima/files/docs/0096/vecto_en.pdf). For the Euro IV bus the chassis dynamometer settings give around 0.65 kWh are absorbed by the dynamometer for each km driven of the LUB cycle. Because of the energy absorbed by on-vehicle powertrain components, and the auxiliaries, this is the foundation of the assumption that around 1 kWh engine power is required to drive each km of the new LUB cycle.

emissions, but rather an inter-comparison of what the emissions actually are for the two fuels assessed and how they change.

Notwithstanding, the impact of using paraffinic diesel over the whole new LUB cycle was a reduction in NOx emissions of 270 ± 169 mg NOx/km, a whole cycle reduction of 3.62% ± 2.27%. This is significant reduction in the context of the data's standard deviation. Moreover, it will be seen in the following section from the analysis of both buses' CO2 emissions that the variability in the NOx emissions does not arise from irreproducibility in work done by the engine for different runs, but is therefore a consequence of variability in the engines' NOx emissions.

Table 26: Bag analysis results of NOx emissions from the Euro VI bus driven using baseline diesel and paraffinic diesel fuels

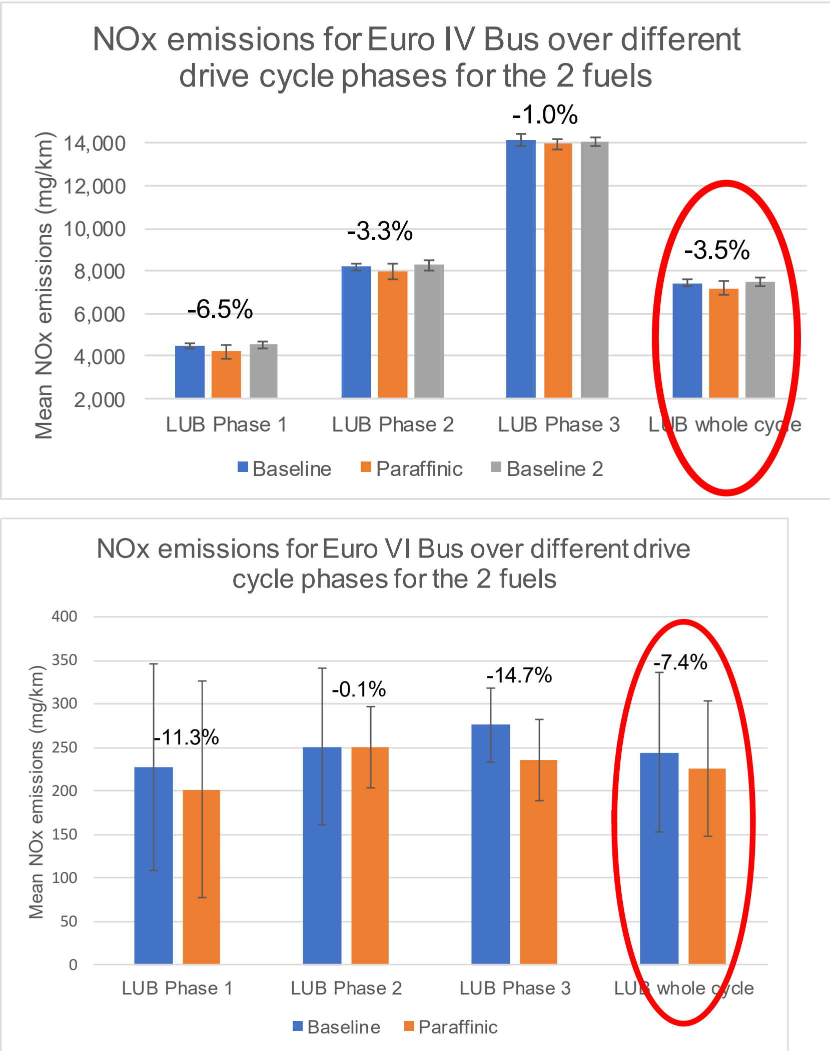
EURO VI BUS NOx RESULTS						
Drive cycle	**Fuel**	**Run 1 (mg/km)**	**Run 2 (mg/km)**	**Run 3 (mg/km)**	**Mean (mg/km)**	**Standard deviation (mg/km)**
LUB Phase 1 (g/km)	Baseline	327.8	96.1	258.0	227.31	118.85
LUB Phase 2 (g/km)	Baseline	348.9	172.7	230.5	250.71	89.83
LUB Phase 3 (g/km)	Baseline	324.0	262.0	242.7	276.24	42.47
LUB whole cycle (g/km)	Baseline	336.0	151.8	244.5	244.10	92.09
LUB Phase 1 (g/km)	Paraffinic	329.6	194.6	80.4	201.51	124.73
LUB Phase 2 (g/km)	Paraffinic	302.5	238.0	211.0	250.52	47.04
LUB Phase 3 (g/km)	Paraffinic	239.0	280.0	187.6	235.52	46.31
LUB whole cycle (g/km)	Paraffinic	304.8	224.6	148.6	225.99	78.11

Euro VI bus	Phase 1	Phase 2	Phase 3	Whole
Effect of paraffinic diesel (mg/km) for whole cycle	-25.8	-0.19	-40.72	-18.11
Effect of paraffinic diesel (%) for whole cycle	-11.35%	-0.08%	-14.74%	-7.42%

For this Euro VI bus NOx data are around 35% of the mg/kWh standard when allowance is made for mechanical engine power being required to drive, on average, 1 km of the new LUB cycle.

For this bus, like the Euro IV bus, the mean LUB cycle NOx emissions when the vehicles used paraffinic diesel is less than that when the vehicles used baseline diesel 18 ± 85 mg NOx/km, a whole cycle reduction of 7.4% ± 35%. (Though this difference is small relative to the measurement uncertainty.) This is further seen in the NOx emissions over the different drive cycle phases, shown in Figure 11. (Note the large difference in vertical scale between the two figures.) As for similar figures the percentage values at the top of the bars are the reduction in NOx due to use of paraffinic diesel compared with combined baseline.

Figure 11: Phase by phase NOx emissions for the Euro VI bus running on both fuels



The NOx emissions for consecutive cycles for the Euro IV bus are shown in Figure 12. This shows how the run to run reproducibility, and the reduction in NOx emissions caused by the paraffinic diesel, are not as pronounced as for the Euro IV truck (Figure 8).

Figure 12: NOx emissions over the whole New LUB cycle for all nine runs with the Euro IV bus

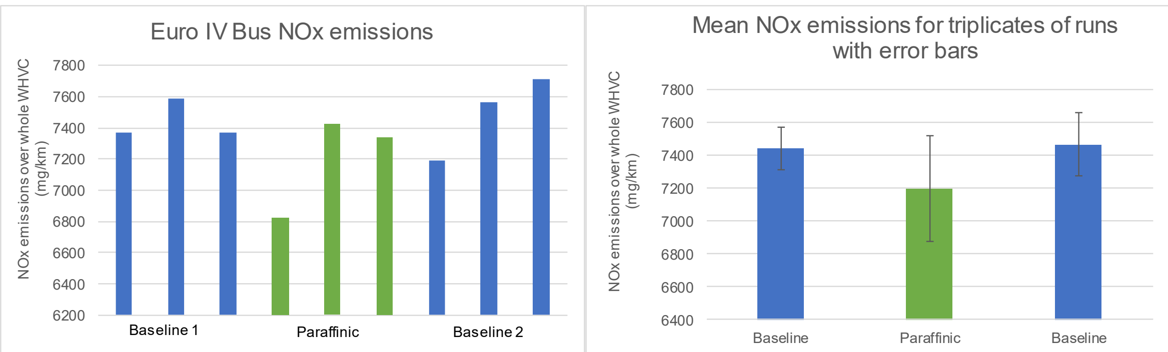
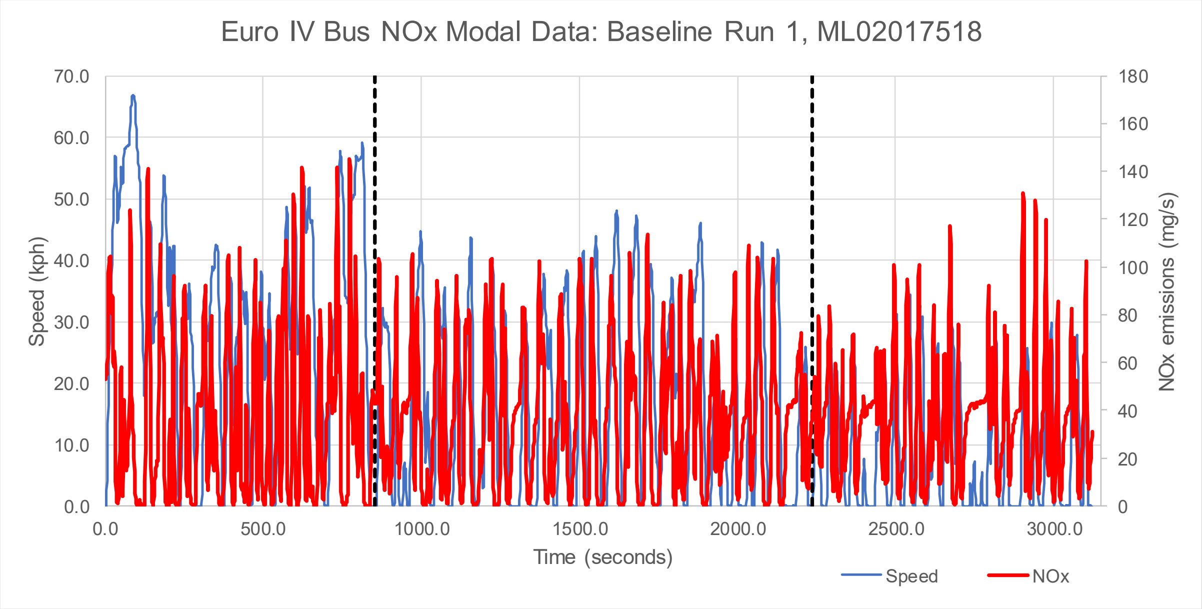
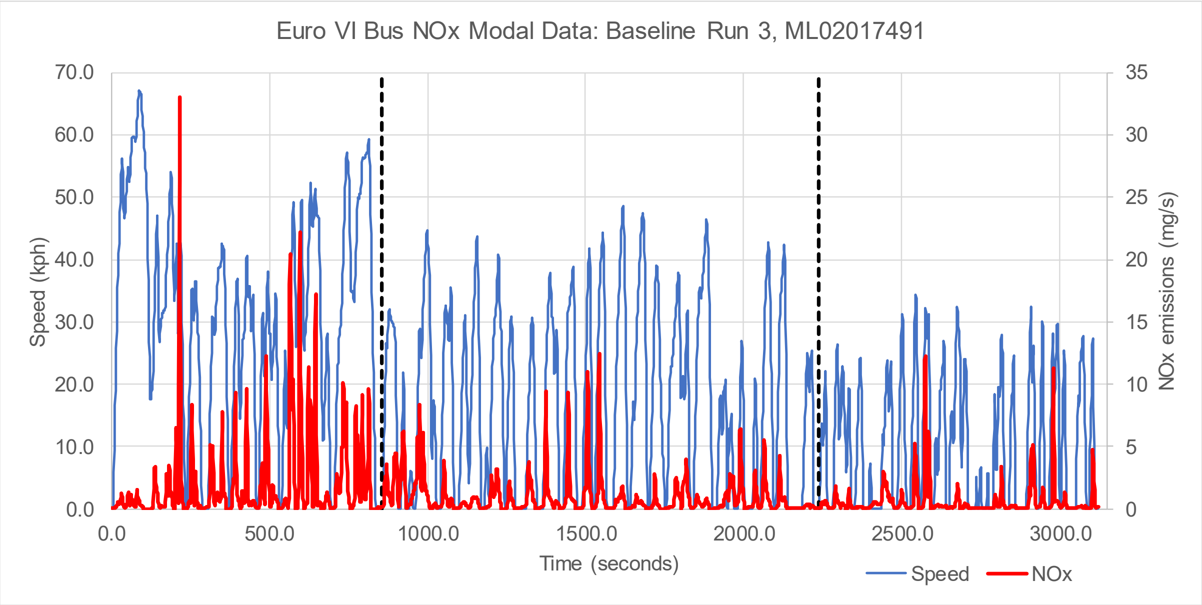


Figure 13 shows typical modal data for the two buses when using baseline diesel. The very transient time-speed nature of the drive cycle (Figure 10) makes it difficult to discern much visually. However, the different vertical NOx emission scales, with the Euro IV bus being five times that of the Euro VI bus, and the general much lower NOx emissions for the Euro VI bus, support the average NOx emissions reported in Table 25 and Table 26.

Figure 13: Typical modal data for the Euro IV and Euro VI buses, both using baseline diesel





3.5.3 CO_2, regulated emissions and unregulated emissions results

As for other vehicles, an analysis of the CO_2 data was used as an indication of the reproducibility between runs. The results are summarised in Table 27 for the two fuels. For the Euro VI bus averages of the three (hot start) new LUB runs are shown for the two fuels. For the Euro IV bus an additional row of data gives the average of the three repeat new LUB runs also.

For both vehicles the run to run reproducibility is high, with the standard deviation of the CO_2 emissions always being within 1%, and the root mean square error for the 5 sets of triplicate runs is ± 0.71%.

Table 27: Bag analysis results of CO_2 emissions from the buss driven using baseline diesel and paraffinic diesel fuels

	Baseline diesel		Paraffinic diesel	
Euro IV bus	Average (g/km)	Standard deviation (g/km)	Average (g/km)	Standard deviation (g/km)
New LUB whole cycle	735.11	4.41	703.17	6.98
New LUB whole cycle repeat	732.39	5.55		
Effect of paraffinic diesel (g/km) for mean of whole new LUB cycle	-31.94	5.74		
Euro VI bus	Average (g/km)	Standard deviation (g/km)	Average (g/km)	Standard deviation (g/km)
New LUB whole cycle	1137.67	1.91	1065.67	8.02
Effect of paraffinic diesel (g/km) for mean of whole new LUB cycle	-72.00	3.14		

Table 27 also reports the difference in the CO_2 emissions between the two fuels. For both buses the paraffinic diesel led to reduced CO_2 emissions. Because of the high reproducibility in CO_2 emissions, the differences seen with paraffinic diesel were markedly larger than the standard deviations of the data, indicating they are statistically significant. Relative to the buses' CO_2 emissions for the baseline diesel, the reduction is 4.2% ± 0.8% for the Euro IV bus, and 6.3% ± 0.3% for the Euro VI bus. As for other vehicles this is consistent with the different physical properties of the two fuels.

The emissions of carbon monoxide (CO), hydrocarbons (HC), particulate mass (PM), particulate number (PN), the fraction of the NOx that is emitted as primary NO_2 ($f(NO_2)$), ammonia (NH_3) and nitrous oxide (N_2O) are all summarised in Table 28. The measurement methodologies for these data are as described for previous vehicles, e.g. pertaining to Table 23.

Data are reported as the averages over the whole new London Urban Bus (new LUB) cycle and the standard deviation of the run values. For the Euro IV bus when fuelled with baseline diesel, this is the average and variance of six runs, whilst for the Euro IV bus when fuelled with paraffinic diesel, and for the Euro VI bus with both fuels, this is the average and variance of three runs.

After estimating the mechanical power required to be produced by the engine to deliver each kWh to the wheels, these data can be compared to the Euro IV and Euro VI engine emissions standards. (These parasitic loses are larger relative to other heavy duty vehicle types, because in addition to the powertrain loses through a buses automatic gearbox, buses use considerable larger amounts of pneumatic and electrical energy.)

Table 28: Emission results for CO, HC, PM, PN, f(NO_2), NH_3 and N_2O from the buses driven using baseline diesel and paraffinic diesel fuels

		Baseline diesel		Paraffinic diesel	
		Average (mg/km)	Standard deviation (mg/km)	Average (mg/km)	Standard deviation (mg/km)
Carbon Monoxide	Euro IV	1213.18	84.88	1037.75	27.31
	Euro VI	7.58	1.95	11.30	4.35
Hydrocarbons	Euro IV	34.70	5.28	44.42	8.99
	Euro VI	24.18	0.97	31.42	3.00
PM	Euro IV	85.62	11.29	63.20	2.02
	Euro VI	Too small to measure			
PN	Euro VI	7.91E+10	6.87E+10	1.39E+11	7.38E+10
f(NO_2)	Euro IV	0.76%	0.05%	0.67%	0.03%
	Euro VI	55.4%	2.3%	69.4%	7.7%
Ammonia	Euro IV	0.84	0.09	0.90	0.09
	Euro VI	0.65	0.33	0.32	0.00
Nitrous oxide	Euro IV	4.10	0.58	3.09	0.02
	Euro VI	21.58	3.78	21.75	6.76

After making assumptions regarding the engine power, to tractive force ratio, for the Euro IV bus emissions of CO and hydrocarbons are around 30% and 8%, respectively, of the engine standard when the vehicle ran on baseline diesel, i.e. are moderately small. Notwithstanding, as was observed for the buses, the effect of switching to paraffinic diesel caused a reduction of around 14% in CO emissions, greater than the standard deviation of the data, but no significant change in hydrocarbon emissions. Note that for trucks there was an 18% reduction in CO emissions.

For the Euro VI bus, emissions of CO and hydrocarbons are around 0.2% (very low) and 18% (well within), respectively, of the engine standard. Whilst some changes were noted when running on paraffinic diesel these too are small, when compared with the standard deviation of the data, and are insignificant for these pollutants that are unimportant in terms of their air quality impact.

Particulate mass and number emissions:

For PM, however, switching to paraffinic diesel caused a reduction of around 25% in PM emissions from the Euro IV bus. This is greater than the standard deviation of the data, and **is significant** for this important pollutant in terms of air quality impact. For the Euro VI bus PM emissions were too small for any meaningful measurements to be recorded from the filter method.

This is supported by the Euro VI bus's PN emissions being around 13%, and 23%, of the regulatory standard for the baseline diesel, and paraffinic diesel, respectively.

Primary nitrogen dioxide

As was seen for the trucks, the two buses show quite different behaviour regarding their emissions of primary NO_2 (the f(NO_2) parameter). For the Euro IV bus primary NO_2 emissions were around 60 mg/km, around 0.8% of the total 7,300 mg/km NOx emissions. In contrast, for the Euro VI bus primary NO_2 emissions were around 120 mg/km (140 mg/km), around 55% (70%) of the total 240 mg/km NOx emissions for the buses when running on baseline diesel (paraffinic diesel). Consequently, the road side air quality impact of the low NOx emitting Euro VI bus is **around twice as high,** as that of the much higher emitting Euro IV bus.

Ammonia and nitrous oxide

Both buses have low emissions of ammonia (less than 1 mg/km for either bus with either fuel).

The two vehicles show distinctly different behaviour regarding their emissions of nitrous oxide. The Euro IV bus has emissions that are towards the low end of the “typical emissions” range, emitting around 4 mg/km of nitrous oxide. This level of nitrous oxide emissions (a potent greenhouse gas) is equivalent to an additional 1.2 g/km CO2 emissions, i.e. would constitute an additional GHG footprint of around 0.2%.

In contrast, the Euro VI bus has emissions that are significantly larger, emitting around 22 mg/km of nitrous oxide. This level of nitrous oxide emissions is equivalent to an additional 6.6 g/km CO_2 emissions, i.e. would constitute an additional GHG footprint of around 0.9%. This is considerably less than the additional footprint seen for the Euro VI truck, where nitrous oxides emissions constituted an additional GHG footprint of 3.6%.

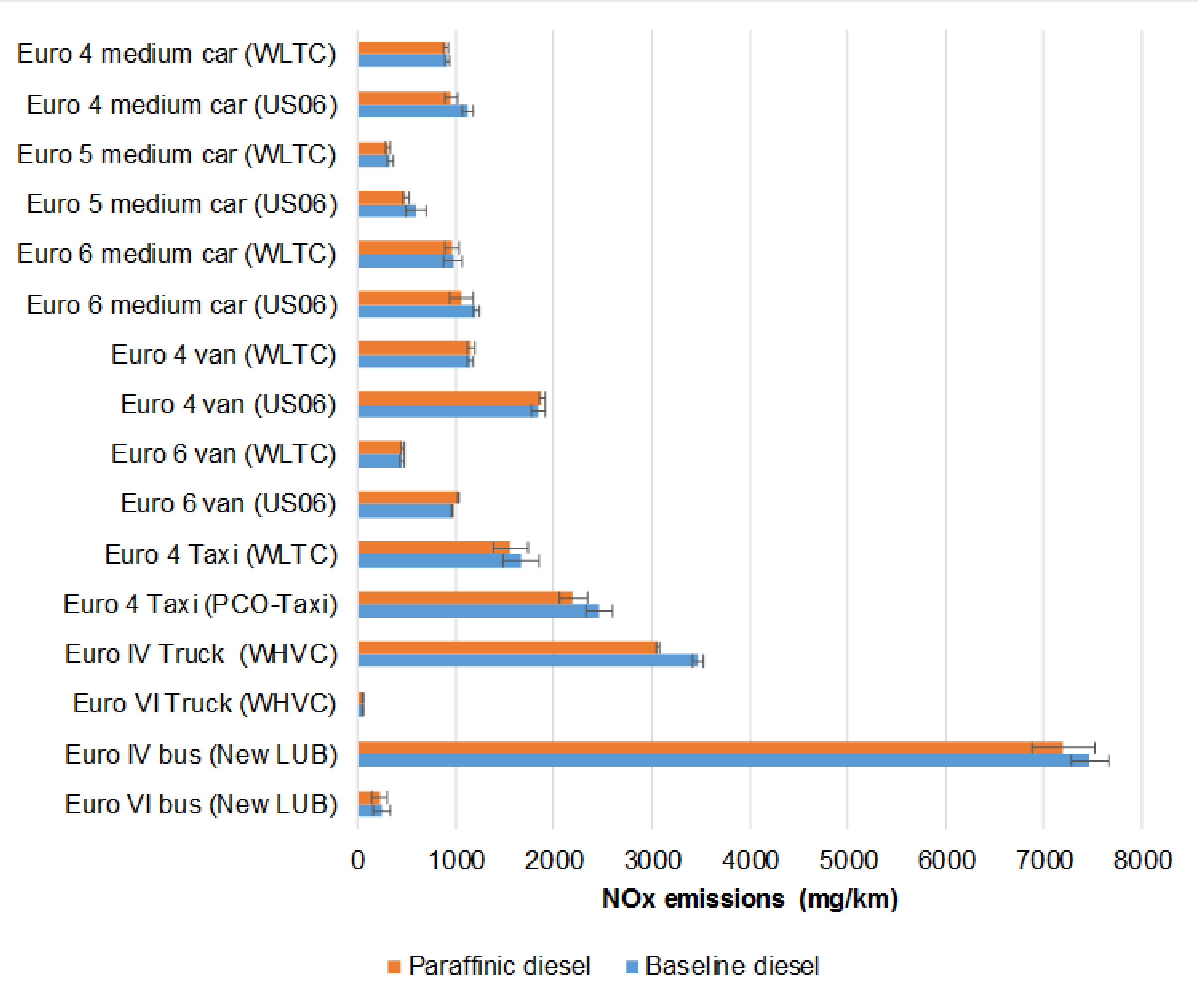
The above observations are principally a consequence of the Euro VI vehicle’s combustion chemistry and the exhaust emissions after-treatment technologies fitted to the vehicle. **Importantly for this project, the impact of changing to paraffinic diesel does not increase the emissions of either of these nitrogen containing pollutants.**

4 Discussion and conclusions

4.1 Impact of paraffinic diesel on NOx emissions

The results of the impact of paraffinic diesel on each of the five different vehicle categories investigated were presented and discussed in the previous chapter. For each vehicle a figure showing the driving cycle phase by phase NOx emissions when running on both fuels was given. The results for the whole driving cycle, together with error bars, are brought together in Figure 14, where the average absolute NOx emissions from each vehicle when running on baseline diesel are plotted alongside the equivalent averages when running on paraffinic diesel. In Figure 14 the black error bars are the standard deviation of the NOx emissions over the three repeat runs.

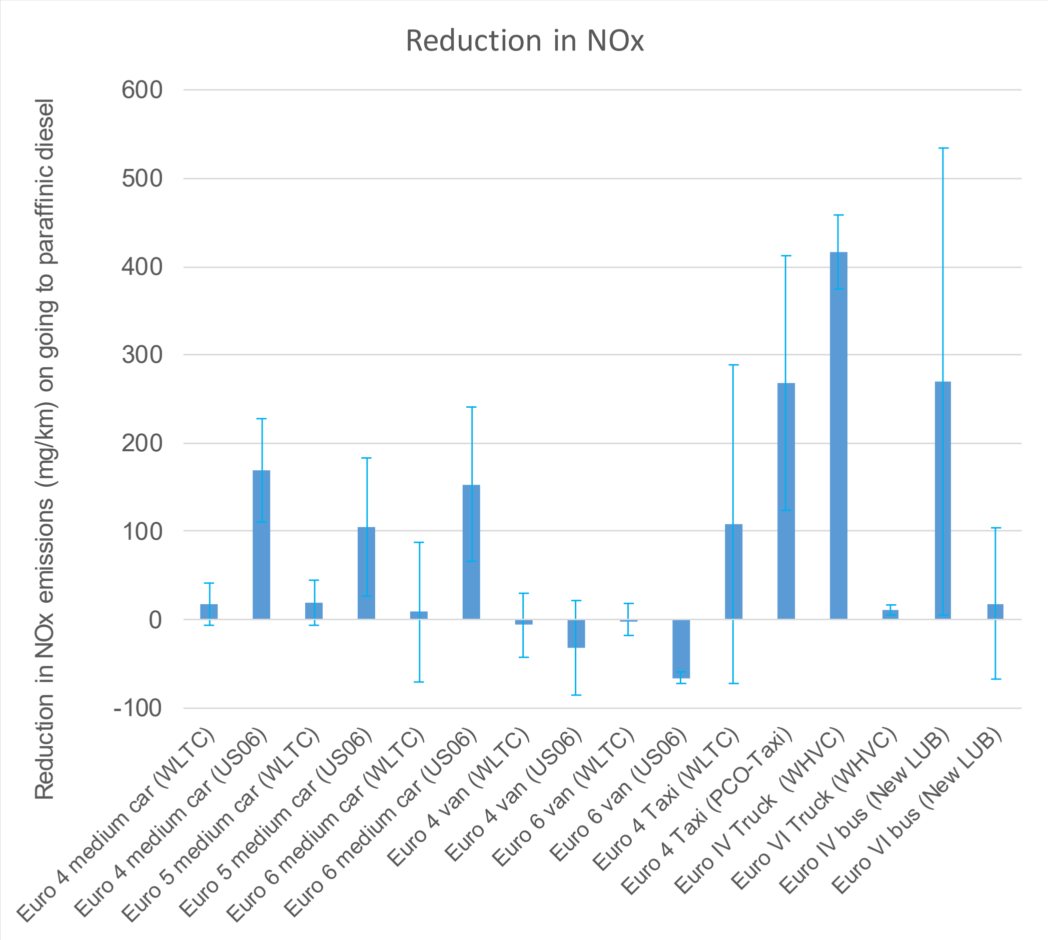
Figure 14: Absolute NOx emissions for all ten vehicles over different drive cycles when running on both fuels



For many vehicles the differences are small. They are more clearly seen in Figure 15 which contains plots of the reductions in the average absolute NOx emissions over whole cycles when the vehicle ran on paraffinic diesel relative to the baseline diesel. Note, positive values indicate lower NOx emissions occur with the paraffinic diesel.

In Figure 15 the blue error bars are the root mean standard error of the NOx emissions, calculated from the standard deviations shown as error bars in Figure 14, for the data from both fuels.

Figure 15: Differences in absolute NOx emissions for all ten vehicles over different drive cycles when running on both fuels



However, the differences are generally smaller than the cycle to cycle reproducibility (error bars) such that in isolation they are not significant for the amount of testing undertaken. It is emphasised that this is not to say the paraffinic diesel had a trivial or no impact on NOx emissions but, that from the data available the impact cannot be clearly measured. For the two vans NOx emissions **increased** when driven with paraffinic diesel relative to when driven with baseline diesel. But again this change was not statistically significant.

From Figure 15 the vehicles for which there was the largest **absolute** reduction in NOx emissions follow the order:

1. Euro IV truck;
2. Euro IV taxi over the PCO taxi cycle;
3. All three Euro 4, 5 and 6 cars over the US06 cycle;
4. Euro IV bus.

This order is not too surprising since, from Figure 14, they are also the vehicle/cycle combinations that have higher NOx emissions for both fuels.

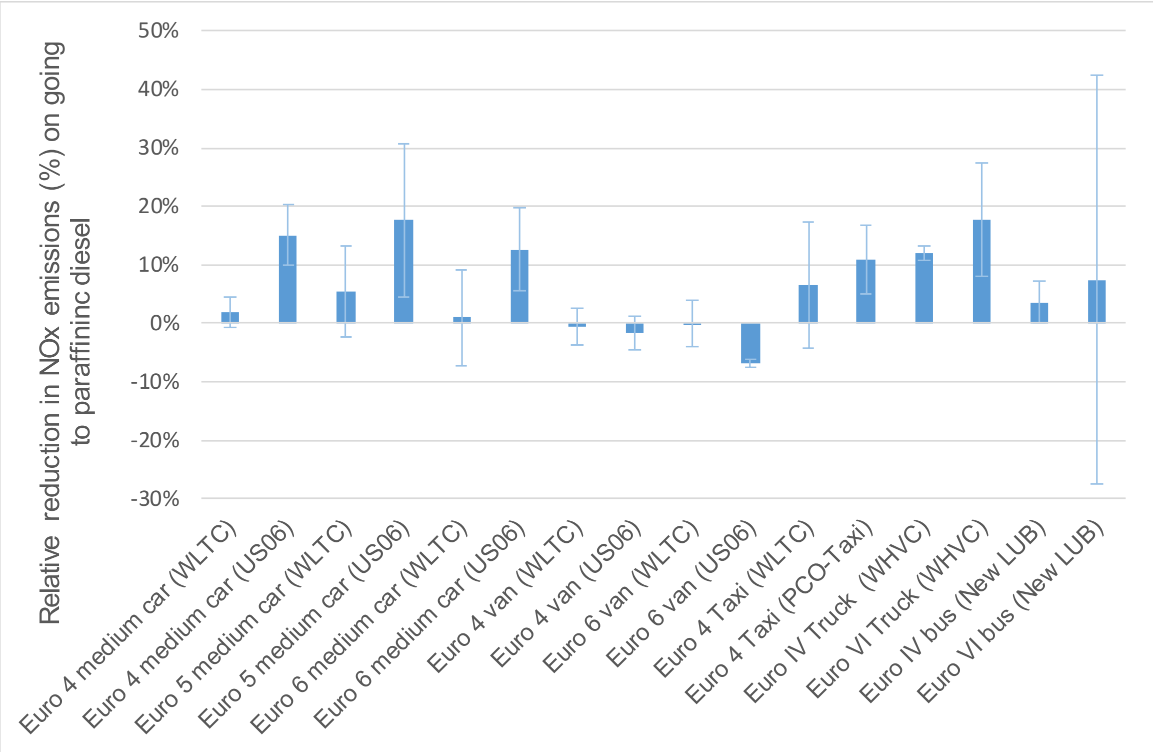
Key Conclusion 1:

When driven with paraffinic diesel NOx emissions are generally lower than when driven with baseline diesel (in 8 of 10 vehicles). The differences are generally smaller than the cycle to cycle reproducibility (error bars) such that in isolation they are not significant. However, together they do strongly indicate that the use of paraffinic diesel is reducing NOx emissions by a modest amount for most vehicles.

Additional statistical analysis, e.g. using a multivariate analysis package, would, it is anticipated confirm this overall conclusion. However, this would require a more sophisticated statistical analysis and is outside the scope of this Tranche 1 study.

A complementary way of viewing the data, and the presentation used in the publicity of ASFE, an organisation that promotes paraffinic diesel, is to plot the percentage reduction, relative to when the vehicle ran on baseline diesel. This is plotted in Figure 16.

Figure 16: Differences in NOx emissions (paraffinic relative to baseline diesel) for all ten vehicles over whole drive cycles expressed as a percentage reduction



From Figure 16 the vehicles for which there was the largest relative reduction in NOx emissions follows the order:

1. Euro VI truck;
2. All three Euro 4, 5 and 6 cars over the US06 cycle;
3. Euro IV truck;
4. Euro IV taxi.

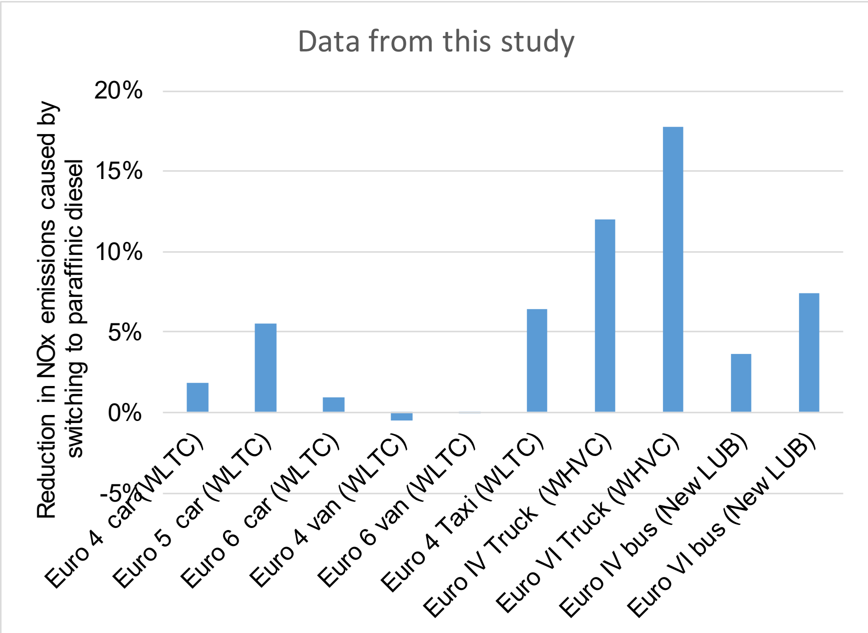
This order is of some interest but can be misleading. The highest ranked vehicle on this basis is the Euro VI truck with a reduction of 17.7% ± 9.6% is only a reduction of 10 ± 5.6 mg NOx/km, whereas the smaller reduction, 12% ± 1.2% for the Euro IV truck is a reduction of 416 ± 42 mg NOx/km.

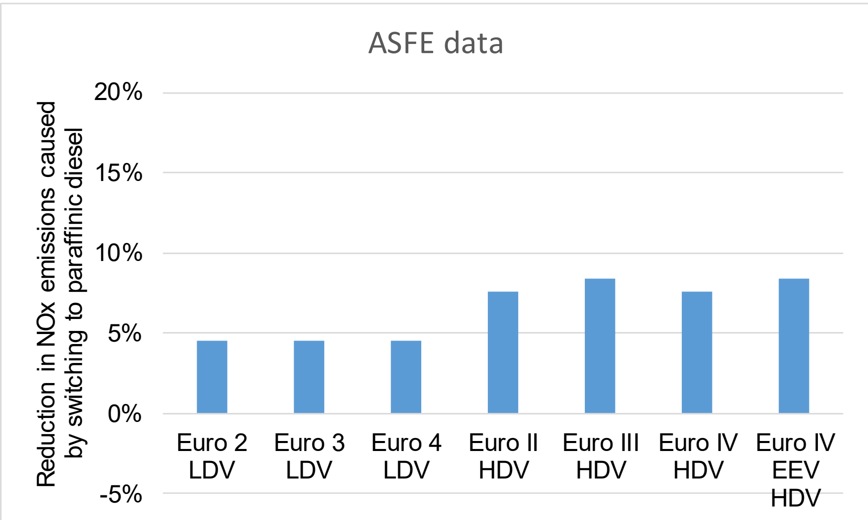
The changes in NOx emissions from the two vans do not conform to this overall pattern.

Also, because air quality challenges are most severe for urban environments, where driving is characterised by low average speeds, the larger reductions in NOx emissions over US06 cycle offer less benefit for addressing urban air quality challenges.

The relative NOx emissions data for the WLTC for the six light duty vehicles, the WHVC for the two trucks, and new LUB cycle for the two buses are shown in the upper half of Figure 17. The lower half of Figure 17 is ASFE data taken from a 2016 ASFE press statement published following the approval of a European Committee for Standardisation (CEN) specification for paraffinic diesel fuels in May 2016[7]. These data are plotted on the same vertical scale as the data from this study.

Figure 17: Relative NOx emissions for paraffinic diesel for 10 vehicles from this study and as reported in ASFE study.





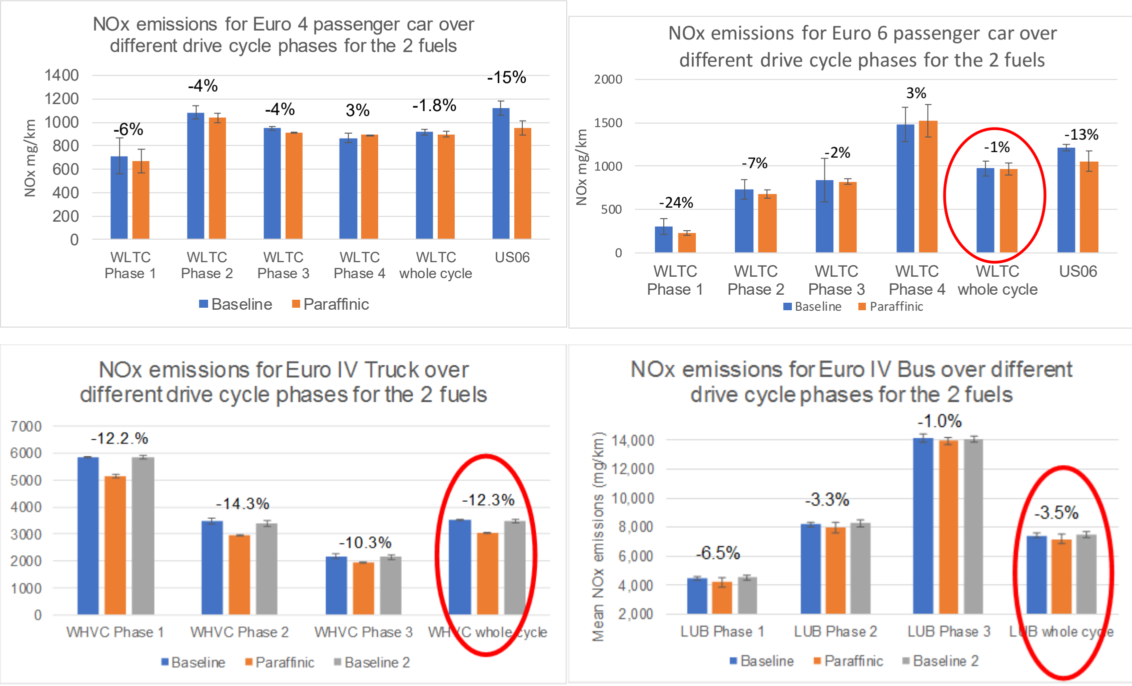
It is noted that for the ASFE data provides neither absolute changes in NOx emissions, nor any estimates of the uncertainty of measurements. Notwithstanding, features of the ASFE data (which is averaged over a range of vehicles) are:

- Reductions in NOx emissions for LDVs are relatively independent of Euro standard and are around 3% – 4%.
- Reductions in NOx emissions for HDVs are larger and too are relatively independent of emissions standard, being around 7.5% - 8.5%.

[7] Press statement available from http://www.synthetic-fuels.eu/images/ASFE_Statement_-_final_EN_specification_for_paraffinic_fuels_approved.pdf

The data from this study is consistent with the ASFE findings. However, these figures do not convey all the subtleties of the changes in NOx emissions for each vehicle which, can be substantial. Figure 18 shows the phase by phase NOx emissions for four vehicles.

Figure 18: Phase by phase NOx emissions for four vehicles running on both fuels



For the Euro 4 car and the Euro IV truck the absolute and relative changes in NOx emissions are relatively constant across the different phases of the drive cycles. Whereas for the Euro 6 car absolute emissions increase with average phase speed, and relative impact of paraffinic diesel reduces. For the Euro IV bus the opposite is true (since for this driving cycle alone average speed decreases for sequential phases).

The overall message from these four examples is that impact of paraffinic diesel on the slower portions of the driving cycles (typical of urban environments) varies from vehicle to vehicle.

4.2 Impact of paraffinic diesel on CO_2 emissions

Figures 19 to 21 show data analogous to those of Figure 14 to Figure 16 for the vehicles' CO_2, rather than NOx, emissions.

Figure 19: Absolute CO_2 emissions for all ten vehicles over different drive cycles when running on both fuels

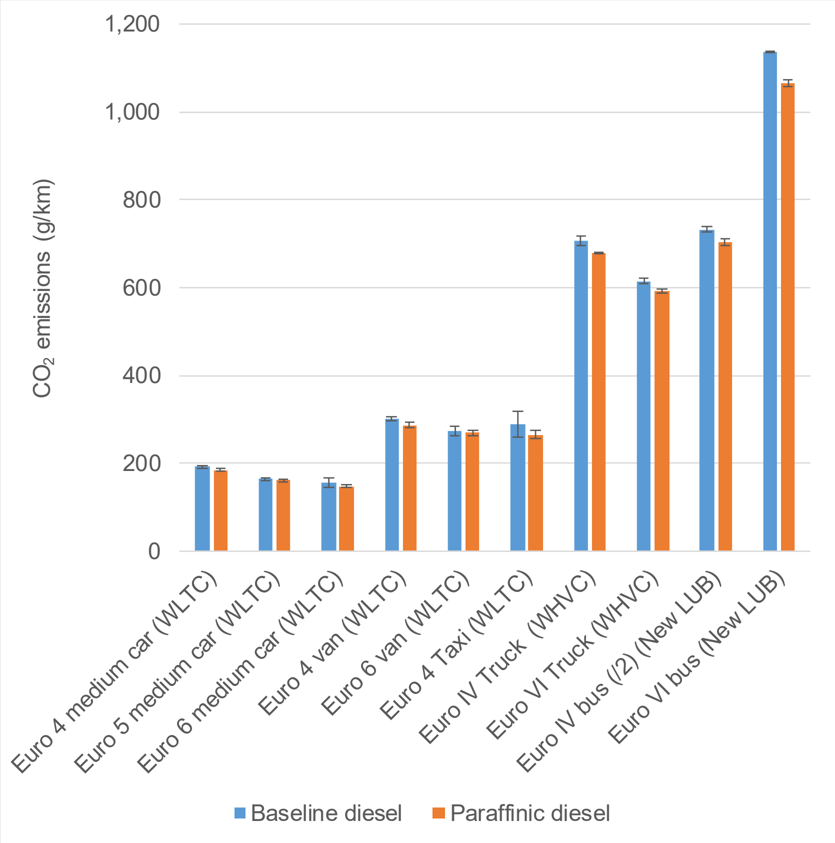


Figure 20: Differences in absolute CO_2 emissions for all ten vehicles over different drive cycles when running on both fuels

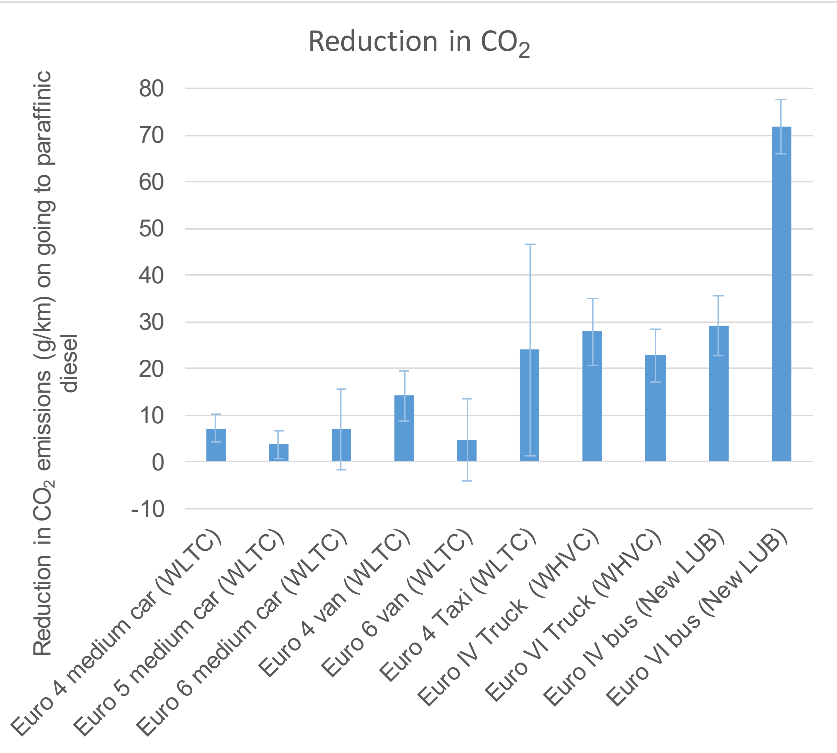
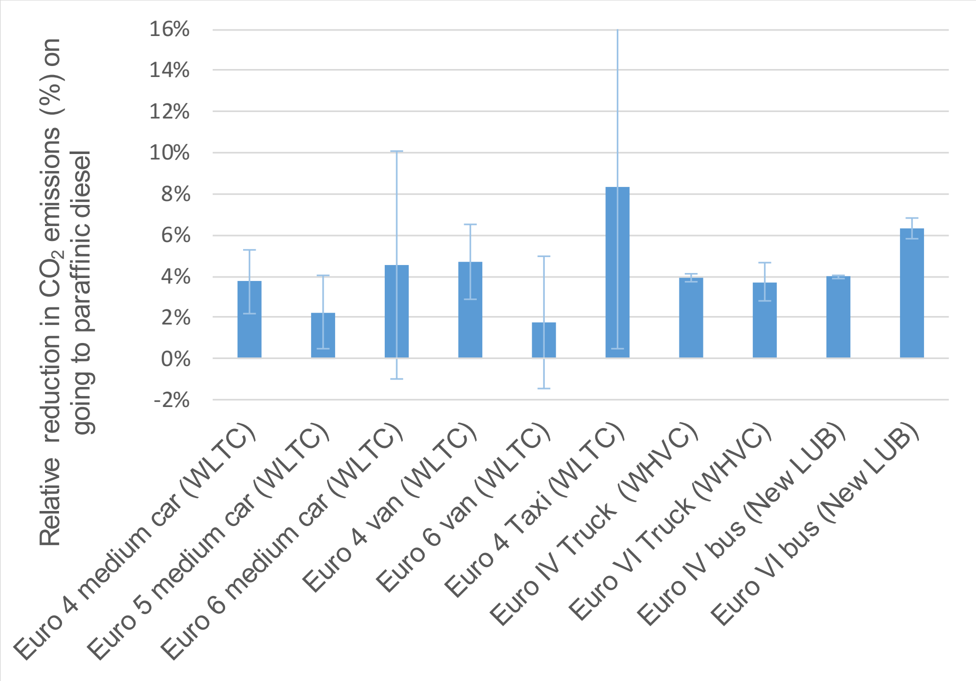


Figure 21: Differences in CO_2 emissions (paraffinic relative to baseline diesel) for all ten vehicles over whole drive cycles expressed as a percentage reduction



From these graphs it is concluded that paraffinic diesel does reduce tailpipe CO_2 emissions relative to the baseline diesel for the same driving cycle. For the four heavy-duty vehicles, where there are no complications caused by a cold start cycle, the reductions, around 4%, are always much greater than the uncertainty in the measurement. For the light duty vehicles this is generally the case. It is also noted that whereas the vans gave “different” NOx reductions with paraffinic diesel relative to other four light duty vehicles, they gave more consistent CO_2 reductions with paraffinic diesel.

This reduction in CO_2 emissions is consistent with the different physical properties of the two fuels, summarised in Table 2, and is caused principally by the lower carbon content and higher cetane rating of the paraffinic diesel, relative to the baseline diesel.

However, it is emphasised that the above data are on a tank-to-wheel basis, and might not constitute an overall reduction in carbon footprint dependent on the well-to-tank footprint of the two fuels.

Key Conclusion 2:

From this suite of three graphs it is concluded: **When driven with paraffinic diesel tailpipe CO_2 emissions are generally lower than when driven with baseline diesel, by around 2.5%**.

Key Conclusion 3:

The reduction in tailpipe CO_2 emissions when driven with paraffinic diesel is greater for HDV than for LDV.

4.3 Impact of paraffinic diesel on other regulated emissions

For the other regulated pollutants, particulate matter, (particle number for Euro 6 and Euro VI vehicles), hydrocarbons and carbon monoxide, it is particle emissions that are of most concern for air quality.

Figure 22 shows the PM emissions for the vehicles tested. It is noted that for the two Euro VI HDV PM emissions were too small to be measured using the regulatory filter paper technique, i.e. their emissions are < 0.5 mg/km. For all five Euro 4 or Euro IV vehicles, the figure shows there is a significant reduction in PM emissions with paraffinic diesel. This is shown in Figure 23. For these five vehicles the average reduction is around 30 mg/km, a 40% reduction. This is consistent with the data reported by ASFE, shown in the lower portion of Figure 23.

Figure 22: Differences in PM emissions (paraffinic relative to baseline diesel) for all ten vehicles over whole drive cycles expressed as a percentage reduction

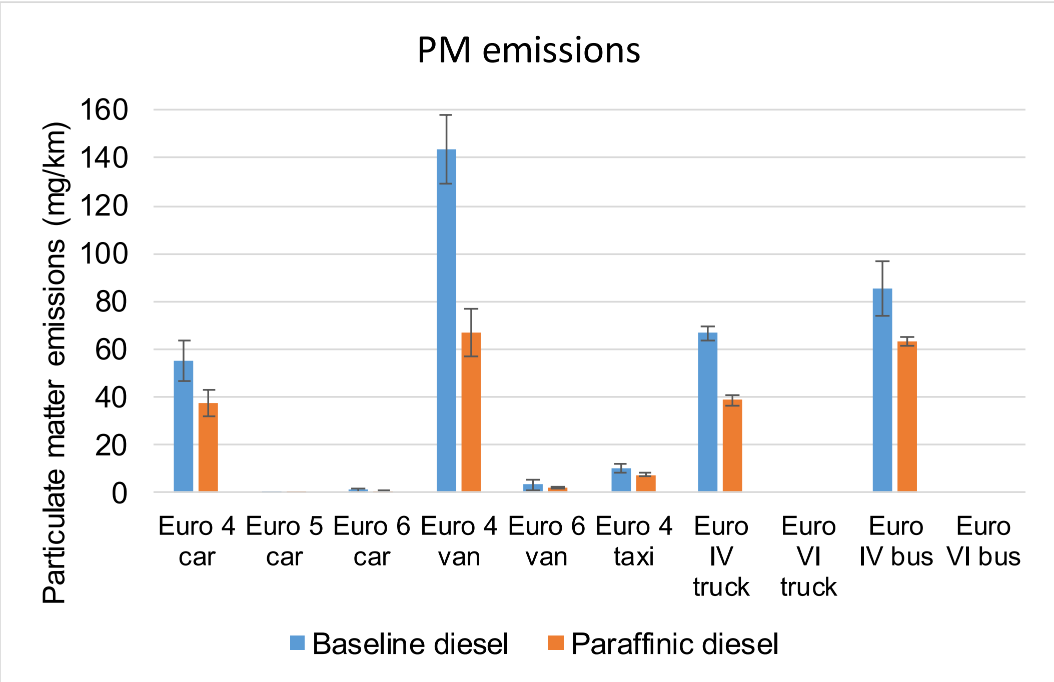
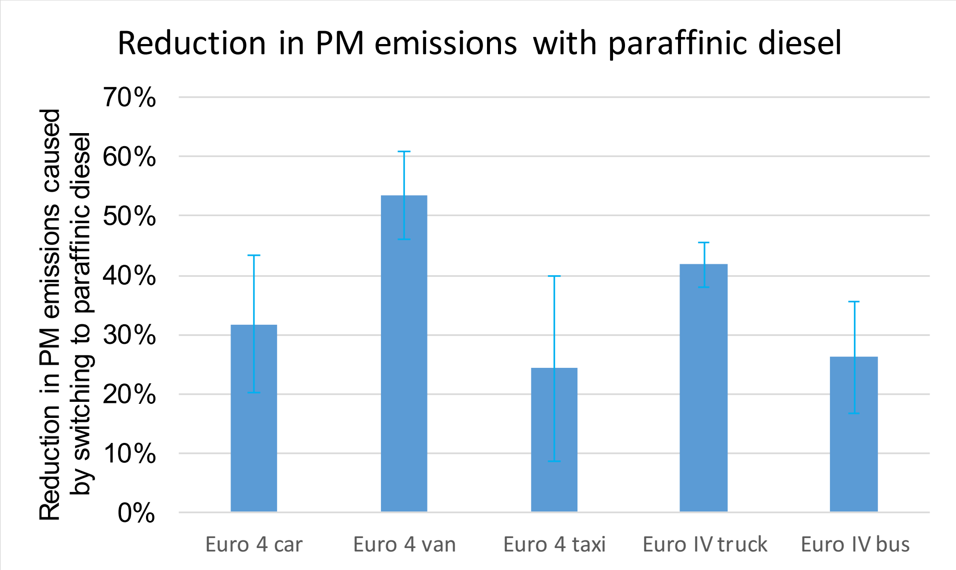
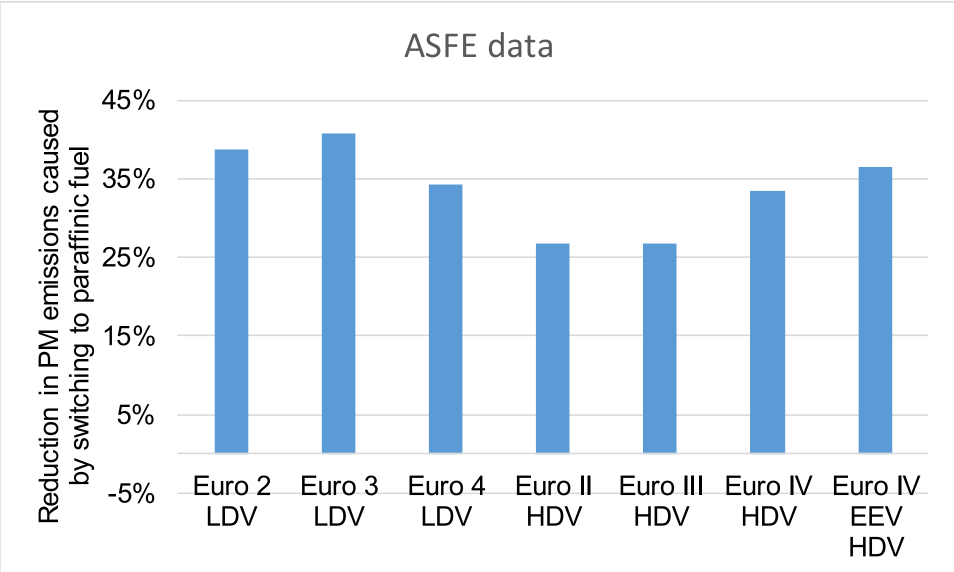


Figure 23: Differences in PM emissions (paraffinic relative to baseline diesel) for the five Euro 4/IV vehicles, expressed as a percentage reduction, together with ASFE findings





Key Conclusion 4:

For diesel vehicles without a particle trap, or with high PM emissions, paraffinic diesel generally reduces PM emissions relative to baseline diesel by around 40%. (For the most modern vehicles which have very small PM emissions the impact of paraffinic diesel is more difficult to measure.)

It was noted for the different vehicle categories that for the diesel vehicles tested emissions of carbon monoxide and hydrocarbons were generally low, and well within the vehicles' appropriate emissions standard, although the low emissions often led to high relative uncertainties. It is also noted that in terms of air quality, these are not of significant concern. For the majority of vehicles, the impact of using paraffinic diesel was negligible. For vehicles where a significant change was seen it was found that the use of paraffinic diesel decreased pollutant emissions.

Key Conclusion 5:

For the diesel vehicles tested emissions of carbon monoxide and hydrocarbons are generally small, inconsequential for air quality, and often with relatively large uncertainty. Therefore, when driven with paraffinic diesel it was found generally that changes in emissions of these pollutants were inconclusive. There was no evidence that they significantly increase but there was inconclusive evidence that for some vehicles they decrease.

4.4 Indicative view on potential side effects from paraffinic diesel

4.4.1 Potential side effects

The project's scope included assessing whether the use of paraffinic diesel might have unintended detrimental side effects. Specifically, whether emissions of ammonia or nitrous oxide (the latter being a potent greenhouse gas) are increased, and also how these emissions vary with the vehicles' emissions abatement technologies. In addition to these two pollutants, the amount of primary nitrogen dioxide (the form of NOx important from an air quality perspective) emitted from vehicles was quantified. The metric used was f(NO_2), the percentage of the total NOx emitted as nitrogen dioxide (NO_2).

4.4.2 Impact of paraffinic diesel on the size of potential side effects

Nitrous oxide (N_2O) emissions, in absolute terms, varied from vehicle to vehicle. They were above 10 mg N_2O/km for four vehicles:

- Euro VI truck @ 73.5 mg N_2O/km from average of 3 cycles with baseline diesel
- Euro 6 van @ 34.6 mg N_2O/km from average of 4 hot starts with both fuels
- Euro VI bus @ 21.6 mg N_2O/km from average of 3 cycles with baseline diesel
- Euro 4 car @ 15.1 mg N_2O/km. from average of 4 hot starts with both fuels

A generalisation from the data are that the latest technology (SCR) has a tendency to significantly increase N_2O emissions. For the Euro VI truck and Euro 6 van their N_2O emissions amounted to 3.6% and 3.7%, respectively, in the greenhouse gas footprint of the vehicle.

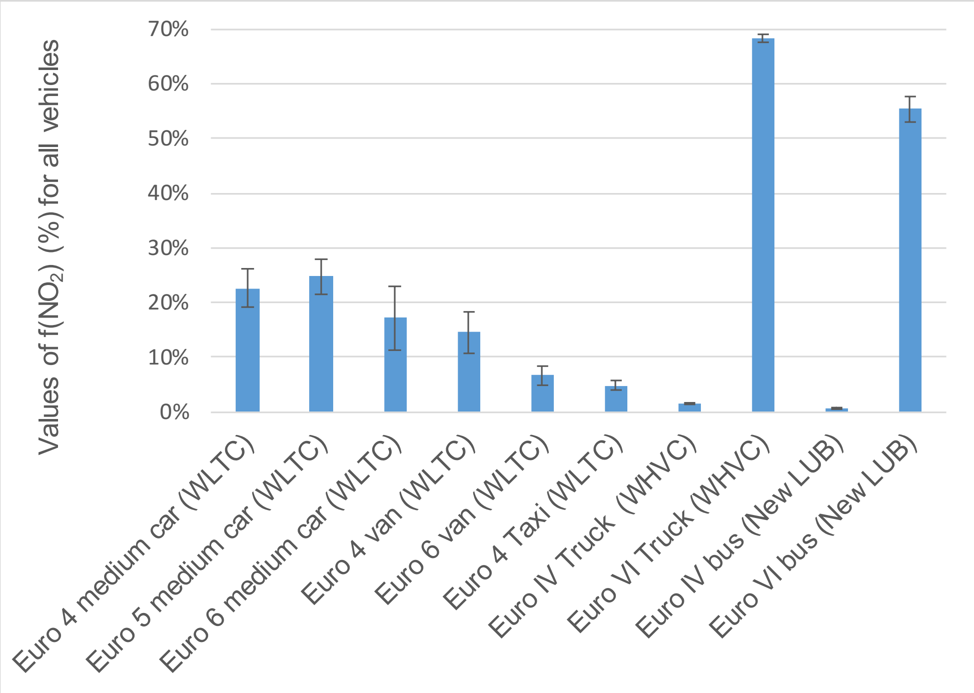
The impact of using paraffinic diesel on N_2O emissions was either too small to be measured within the data's standard deviation, or led to a small reduction in emissions. **Paraffinic diesel did not lead to significant increases in N_2O emissions.**

Ammonia emissions (NH_3) were generally low, < 2 mg NH_3 /km, with the one exception of the Euro VI truck where, using baseline diesel, they were 17 ± 3.8 mg NH_3/km. When using paraffinic diesel this dropped to 5.0 ± 0.0 mg NH_3/km. Therefore, again the results obtained indicate **paraffinic diesel did not lead to significant increases in ammonia emissions.**

Emissions of primary nitrogen dioxide relative to total emissions of nitrogen oxides (f(NO_2)) were very variable and are shown in Figure 24. They range from nearly 70% for the Euro VI truck, to <2% for the Euro IV truck and bus. It was 20% - 27% for all three cars.

The figures may be misleading because absolute emissions of NO_2 depend on the product of the NOx emissions and f(NO_2) ratios. For the vehicles tested, the highest primary NO_2 emissions were from the Euro 4 car (225 mg NO_2/km). The Euro VI bus and truck emit 125 mg NO_2/km and ~40 mg NO_2/km, respectively, despite their very high f(NO_2) ratios because of their lower overall NOx emissions. The Euro IV bus with its high NOx emissions but low f(NO_2) ratio emitted around 50 mg NO_2/km.

Figure 24: Values of f(NO_2), percentage of NOx emitted as NO_2 for all ten vehicles over whole drive cycles



The impact of using paraffinic diesel on $f(NO_2)$ ratios was always relatively small, statistically insignificant, with the exception of the Euro VI bus, where an increase was seen.

Key Conclusion 6:

For the Euro VI truck and bus vehicles tested emissions of ammonia and nitrous oxide are high, and for the latter can add several percent to the vehicle's GHG emissions. Also, emissions of primary nitrogen dioxide can be a high proportion of the NOx emitted for both the paraffinic and baseline diesels. This is a consequence of vehicle exhaust treatment technology, and is largest for the more recent technologies.

Key Conclusion 7:

When driven with paraffinic diesel emissions of ammonia, nitrous oxide and primary nitrogen dioxide do not increase significantly for any vehicles. I.e. the use of paraffinic diesel was not observed to have detrimental side effects within the levels of certainty to which these additional pollutants were measured.

4.5 Trends/issues

Whilst some key conclusions from the overall study were:

- When driven with paraffinic diesel NOx emissions are generally lower than when driven with baseline diesel (in 8 of 10 vehicles thoroughly studied), i.e. the paraffinic diesel is reducing NOx emissions.
- The differences are generally smaller than the cycle to cycle reproducibility (error bars) such that in isolation they are not significant
- The data is consistent with earlier data reported by ASFE.

At the outset of the emissions testing various specific hypotheses were tested:

Hypothesis 1: The paraffinic diesel will have a smaller influence on later technology (i.e. Euro VI and Euro 6 HDVs and LDVs)

Result: In relative terms the data displayed in Figure 17 does not support this, the percentage reductions of Euro VI/6 vehicles often being greater than their earlier technology counterparts.

However, Figure 15 and Figure 16 does support this because the absolute NOx emissions from the later technology is much less than for the older technologies, making the absolute NOx reduction (in terms of a difference in mg NOx emitted /km driven) smaller for the later technologies.

Hypothesis 2: For vehicles whose peak power is much greater than that required to drive a cycle the paraffinic diesel will have a smaller influence.

Result: This hypothesis was tested with the Euro 5 car, i.e. the 170 hp vehicle relative to the other two medium cars. The evidence in Figure 2 does not support this.

Hypothesis 3: The ASFE data, the lower half of Figure 17, shows little systematic reduction in NOx emissions as a function of vehicle category and emissions standard from the use of paraffinic diesel for different emissions standards. But it does show a larger systematic reduction in NOx emissions brought about by the use of paraffinic diesel for HDVs relative to LDVs.

Result: The analysis presented in this report does support this.

4.6 Recommendations regarding Tranche 2 testing

From the results obtained it might be worth testing the following vehicles to proceed to Tranche 2 testing, (**on-road testing** of vehicle emissions to check for NOx reductions in real-world conditions mirror those seen from dynamometer testing.)

Vehicle	Reasons
Euro 5 car	Both relatively large overall reduction in NOx emissions when using paraffinic diesel, and evidence that reduction is greater for urban driving
Euro 6 car	Large overall reduction in NOx emissions when using paraffinic diesel for urban driving, though overall change is small
Euro IV truck	Relatively large overall reduction in NOx emissions when using paraffinic diesel
Van from a different mass manufacturer	Recommend testing a different van make/model to investigate whether the results from the single manufacturer's vans tested were truly representative of the van fleet.

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