Concawe
Environmental Science
for European Refining

Report

Report no. 2/19

Effect of Diesel Fuel Properties on Fuel Economy and Emissions of Three Passenger Cars

ISBN 978-2-87567-098-4

Effect of Diesel Fuel Properties on Fuel Economy and Emissions of Three Passenger Cars

Prepared for the Fuels and Emissions Management Group by Concawe Special Task Force STF-25:

R. Williams (Chair)
J. Ariztegui
T. Barsch
A.M.D. Carbonas
R. Clark
C. Fittavolini
L. Jansen
H. Kraft
L. Pellegrini
P. Van Heijning
D.J. Rickeard (Consultant)
H.D.C. Hamje (Concawe)
Pete Zemroch (Consultant)
Pauline Ziman (Consultant)

ABSTRACT

The objective of this project was to assess the effects of varying diesel fuel properties associated with increasing FAME content on pollutant emissions and fuel consumption of light-duty vehicles. To that aim three passenger cars were tested, each one of them equipped with a different exhaust after-treatment system and complying with different European emissions standards, - Euro 4, 5 and 6. Four diesel fuel properties were examined namely density, cetane number, biodiesel (FAME) content and Polycyclic Aromatic Hydrocarbon (PAH) content. The study focused on the effect of potentially increasing FAME content in the fuel above the current 7% limit to help meet the original renewable energy directive (RED) obligations. Tests included two driving cycles, the New European Driving Cycle (NEDC) and the Worldwide Harmonized Light Duty Test Cycle (WLTC), as well as a steady-state point for the characterization of particle emissions. Changes were then statistically modelled to look for trends in the data. Some established trends were confirmed but overall the effect of increasingly sophisticated after-treatment system, vehicle calibration and test cycle clearly dominated over fuel effects for emissions and efficiency in this study where changes in fuel properties were relatively small.

KEYWORDS

Density, cetane number, FAME, PAHs, emissions, fuel consumption, vehicle testing, NEDC, WLTC

INTERNET

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

CONTENTS

SUMMARY

Certain diesel fuel specification properties are considered to be environmental parameters according to the European Fuels Quality Directive (FQD, 2009/EC/30) and previous regulations. The limits for these properties included in the EN 590 specification were derived from the European Programme on Emissions, Fuels and Engine Technologies (EPEFE) which was carried out in the 1990's on diesel vehicles meeting Euro 2 emissions standards. These limits could potentially constrain FAME blending levels higher than 7% v/v which is the current EN590 limit although standards have recently been developed for B10 and B30, the former aimed at helping to meet the requirements of the renewable energy directive (RED). In addition, no significant work has been conducted since to investigate how changing these limits would affect performance, emissions or fuel consumption in more modern vehicles.

The objective of this test programme was to evaluate the impact of specific diesel properties related to increasing FAME content on emissions and fuel consumption in Euro 4, Euro 5 and Euro 6 light-duty diesel vehicle technologies. The tests were conducted using two driving cycles, the New European Driving Cycle (NEDC) and the World-wide harmonised Light duty Test Cycle (WLTC), which is considered closer to real driving and is the new type approval test. At the time that this programme wasdevised, the RDE test had not been developed so RDE tests were not conducted. Apart from FAME content, properties studied were Polycyclic Aromatic Hydrocarbon (PAH) content, density, and cetane number. Results of emissions testing are presented and discussed including effects of the above fuel properties on particulates, NOx emissions, fuel consumption, energy consumption and CO_2 emissions. Results can be summarized as follows:

Density: Increasing density above the current EN590 specification limit to allow for increased FAME content increases CO_2 in all cases, with varied effects observed for other regulated emissions. Increases observed in the latter could in part be mitigated by more advanced after-treatment systems coming into the market. However before considering increasing the density specification limit, the tailpipe CO_2 penalty would have to be weighed against benefits elsewhere of widening the diesel fuel envelope.

Cetane Number: CO_2 benefits were measured with higher cetane number only in the Euro 5 car under NEDC operation, whereas PM and NOx penalties were only measured in the Euro 4 NEDC and a NOx benefit was noted in the Euro 6 vehicle (WLTC only), indicating CN effects are vehicle and test cycle dependent. Overall there is no conclusive evidence in this programme that supports the reduction or increase in the current CN minimum specification level.

PAH: Effects of changing PAH levels were few and inconsistent and a tailpipe PM increase only observed in the non-DPF car would not be expected in Euro 5+ vehicles – there is overall little justification for reducing the PAH limit.

FAME: Increasing FAME content had the expected effect of increasing volumetric fuel consumption whereas it had no consistent negative or positive effects on emissions. NOx penalties and PM benefits were only observed in the oldest technology vehicle.

Overall the effect of increasingly sophisticated after-treatment system, vehicle calibration and test cycle clearly dominated fuel effects on emissions and efficiency in this study where changes in fuel properties were relatively small.

1. INTRODUCTION

The EN 590 specification allows up to 7% v/v FAME meeting the EN 14214 specification to be blended into conventional diesel fuel which can then be used in most light-duty diesel vehicles. At the time of the test programme design, the incumbent Renewable Energy Directive (RED) (2009/EC/28) [1] implied that higher FAME levels in automotive fuels would be desirable to help meet the 10% renewable energy targets for road transport particularly in light of increased demand for transportation fuel. In fact CEN specifications have been developed for B10 as well as B30. However, RED II alters this requirement in favour of encouraging more use of non-food-crop-derived advanced bio-fuels and biogas. There are a number of EN 590 specification properties considered to be environmental parameters according to the European Fuels Quality Directive (FQD, 2009/EC/30) [2] and previous regulations. These limits were derived from the European Programme on Emissions, Fuels and Engine (EPEFE) which was carried out in the 1990's on diesel vehicles meeting Euro 2 emissions standards [3].

These limits (shown in **Table 1**) could potentially constrain FAME blending levels higher than 7% v/v. On the other hand, no significant work has been conducted to investigate whether changing these limits would give rise to performance or emissions debits or fuel consumption benefits. For this reason, Concawe was interested in studying the impact of these parameters on performance and emissions in Euro 5+ vehicle technology. However, as stated above, the revisions in RED II may mean that higher crop –derived FAME volumes are no longer desired in road fuels.

Table 1 EN 590 properties specified as environmental parameters in the FQD (2009/EC/30) and their limits

Property	Limit
PAH	Max. 8% m/m
Density	Max. 845 g/m^3
T95	Max. 360°C
Cetane Number	Min. 51

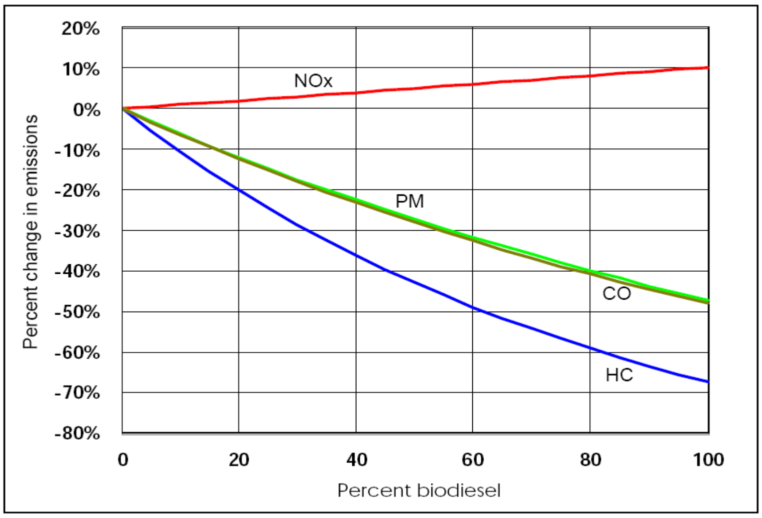
Literature on Diesel Property Effects on Emissions and Fuel Consumption

FAME effects

The addition of FAME into diesel fuel is well-known to reduce the PM emissions of diesel engines [4], [5], [7]. This effect is largely attributed to the addition of oxygen into the fuel which increases the local oxygen concentration in the rich area of the diesel flame [6] and by diluting aromatic hydrocarbons and especially polycyclic aromatic hydrocarbons in the diesel fuel with an aromatics-free blending component. Previous Concawe work confirmed that the addition of FAME in diesel fuel decreases the engine-out PM emission and noted a reduction in fuel consumption penalty associated with reducing the frequency of DPF regenerations [8]. Another study showed, however, that the vehicles were not able to compensate for the energy content deficit of RME/diesel blends through better engine efficiency on the oxygenated fuels [9].

Published literature was evaluated to identify the impact of FAME in diesel fuel on other regulated emissions. The majority of the published data refers to work carried out on heavy duty engines and covers an extensive range of fuel types, FAME concentrations, engines, and test protocols. In 2002, the US Environmental Protection Agency (EPA) published a comprehensive statistical analysis of all available data from which the following graph has been extracted [10].

Figure 1 Average percentage change in regulated emissions from heavy-duty engines with increasing biodiesel content



The effects shown in **Figure 1** represent the most widely reported view of biodiesel effects on regulated emissions. However, it should be remembered that these results are from a collection of published studies that are predominantly focused on heavy duty engines (and primarily on US market engines) that were not equipped with exhaust after-treatment and tested only over hot start test cycles. It may not be reasonable to assume that these results will be representative of modern European light duty vehicles that are equipped with a variety of after-treatment technologies and are certified over a cold start test cycle. There are considerably fewer publications related to modern light-duty diesel vehicles and the results that have been reported are generally less consistent than those from the heavy duty tests. One modern study on light duty engines [11] demonstrated that vehicle effects became stronger than fuel effects when emissions start to become very low.

Other property effects

Although there have been many studies focused on the effect of diesel fuel properties on emissions and fuel economy again many of them are heavy-duty vehicles studies and of the light-duty vehicles studies many of the earlier ones were focused on indirect injection vehicles which were more common in the 1990's. One of the first studies which included a vehicle with a direct injection engine was carried out by Tritthart et. al. [12]. While there were differences between fuels tested: density, aromatics and cetane number were highly correlated and the effects were not prescribed to any one property. The same study concluded that back-end volatility in the form of T90 did not affect any of the emissions. One of the findings from the EPEFE programme was that vehicles with electronic direct injection (DI) systems were generally more sensitive to fuel property changes than those with mechanically controlled systems, generally indirect injection (IDI).

Concawe carried out work in 1996 using a European DI engine to investigate the effect of density on engine controls and determined that fuel density affected the fuel pump setting, injection timing and EGR operation. The effect of density on particulates could be wholly or partially removed after engine settings were adjusted to take account of the density. It has also been shown in [13] that engine operation was a big factor in controlling emissions due to the change in density and this work was extended to other properties by [14]. They found that T95 and density were highly correlated and generally emissions improved as density decreased.

In a study carried out by JCAP [15] and [16] using a light duty DI engine, it was found that engine out emissions of PM, THC, CO and NOx could be reduced by reducing total aromatics, but fuel effects on tailpipe emissions could not be measured due to the low levels after various after-treatment systems were deployed.

Bielaczyc et. al. [17] studied the effect of cetane number on emissions and noted that increasing cetane number reduced emissions of HC, CO and NOx. Kumar et.al. [18] noted that increasing cetane reduced NOx and smoke although lowering T50 had a different affect. Hellier et.al. [19] studied the effect of keeping the ignition delay constant and also observed correlations between emissions and other properties of the fuel for example volatility and the adiabatic flame temperature. The latter studies were conducted using single cylinder engines.

Publication of this work

Aspects of this work have been published via TRA [20], SAE [21] and ETH [22] conference proceedings.

2. METHODOLOGY

2.1. TEST FUELS

Thirteen fuels were tested during this study. The base fuel for these tests was a typical European EN 590 diesel with maximum 10 mg/kg sulphur not containing FAME. Inspection test results versus EN 590 specifications were obtained for these fuels by the fuel blender including calorific values and carbon weight fraction data to evaluate the vehicle results (with the involvement of a statistician in the test design). The base fuel property variables were PAH (from 2 to 8% m/m, the latter being the current specification in EN590) and density (from 820 to 860kg/m^3, the current specification is 845 max) which are most likely to impact vehicle performance and emissions. FAME generally has a higher density than diesel fuel and cetane number around the current specification of 51. It was anticipated that T95 will vary with density of the base fuel. The effect of cetane number bracketing the specification (from 46 to 53) and FAME (from 0 to 10% v/v) which goes beyond the B7 EN590 specification was addressed by pair-wise comparisons. A Design of Experiments (DOE) approach was adopted to see if the number of fuels and tests could be reduced without compromising the results of the study.

FAME (RME) meeting EN 14214 specifications was used in blends designed to study FAME effects. A moderate dose of BHT was used to ensure stability throughout the test programme and the oxidation stability (Rancimat) was measured on representative samples at the start and end of the vehicle study.

Other than the fuel parameters that were evaluated, all other EN 590 specifications were met including lubricity, using a lubricity improver in the blends that did not contain FAME. A standard detergent treat was also used to ensure engine cleanliness throughout the test programme.

The cetane number targets were met using hydrocarbon blend components but some use of cetane improver (EHN) was used to trim the CN to the target values. Cetane number was derived through Ignition Quality Tester (IQT) data collected on all of the final blends.

Table 2 shows the target values for the four properties under examination for all the fuels considered in this study. The measured properties of all the fuels are shown in Appendix 1.

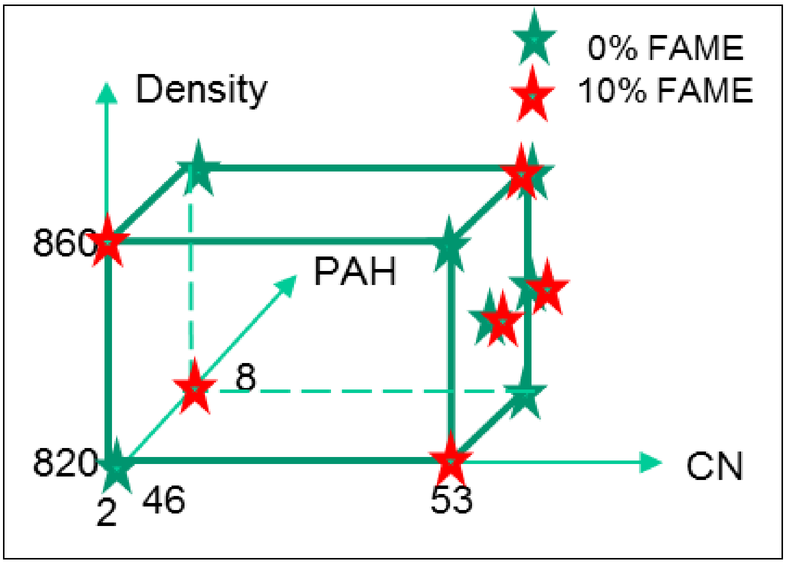
Table 2 Fuel Blend Property Target Matrix

Fuel	Density at 15°C (kg/m³)		Poly Aromatic Hydrocarbons (% m/m)		FAME (% v/v)		Cetane Number (minimum)	
	820	860	2% max	8% max	0%	10% max	46	53
F1	**X**		**X**		**X**		**X**	
F2		**X**	**X**			**X**	**X**	
F3		**X**	**X**		**X**			**X**
F4	**X**		**X**			**X**		**X**
F5		**X**		**X**	**X**		**X**	
F6	**X**			**X**		**X**	**X**	
F7	**X**			**X**	**X**			**X**
F8		**X**		**X**		**X**		**X**
F9		**X**		**X**	**X**			**X**

Fuel	Density at 15°C (kg/m³)	Poly Aromatic Hydrocarbons (% m/m)		FAME (% v/v)		Cetane Number (minimum)
	840	4% max	8% max	0%	10% max	53
F10	**X**		**X**	**X**		**X**
F11	**X**		**X**		**X**	**X**
F12	**X**	**X**		**X**		**X**
F13	**X**	**X**			**X**	**X**

Fuels 1 to 8 tested eight of the 16 possible combinations of levels in an orthogonal half-replicate of a 2^4 factorial design with the additional fuel No. 9 being one of the missing corners. Fuels 10 to 13 form a small 2×2 submatrix varying PAH and FAME with density and CN held constant. Figure 2 shows a pictorial representation of the fuel matrix.

Figure 2 Pictorial representation of target fuel matrix



The fuel matrix was completed with a reference fuel that was a typical European EN590 diesel fuel with maximum 10 mg/kg (10 ppm) sulphur. The FAME blending component was European Rapeseed Methyl Ester (RME) meeting the EN14214 specification and containing antioxidant additives to ensure oxidative stability over the course of the vehicle study. The fuels were tested in random order, which was different for each vehicle.

2.2. TEST VEHICLES

2.2.1 Vehicle selection and characteristics

The present study initially included tests on two diesel passenger car vehicles, a Euro 4 and a Euro 5 vehicle. However, during the course of the project, the study was expanded to testing a third vehicle, conforming to Euro 6. The tests were started with the Euro 5 vehicle, were continued with the Euro 4 and were completed with the Euro 6 vehicle. The first Euro 6 vehicle procured proved to be so problematic under test to such an extent that a replacement Euro 6 vehicle was obtained and tested. The second Euro 6 vehicle also proved challenging to test however the problems were overcome and a sufficient body of data was eventually generated. The challenges encountered in testing the Euro 6 vehicles and some mitigations are presented in Appendix 2. Descriptions of the vehicles are shown in Table 3:

Table 3 Vehicle properties

Vehicle property	Vehicle 1	Vehicle 2	Vehicle 3
Vehicle class	Upper Medium (D)	Medium (C)	Medium (C)
Category	M1	M1	M1
Emission standard	Euro 4	Euro 5	Euro 6
Engine Displacement (litres)	2.2	1.3	1.6
Max. Power (kW)	103	70	88
After-treatment device	DOC	DOC + DPF	DOC + DPF + SCR
EGR / Start-stop	Yes / No	Yes / Yes	Yes/Yes
Transmission	Manual 5-speed	Manual 5-speed	Manual 6-speed
Registration date	2004	2013	2015
Mileage at start of test (miles)	89,850	10,530	10,300

All three vehicles were equipped with high injection pressure common-rail diesel engines, which is now standard equipment. The exhaust after-treatment systems of the three vehicles increased in degrees of complexity as the Euro number increased. The Euro 4 vehicle was equipped with only a Diesel Oxidation Catalyst (DOC), which oxidizes CO and HC and the volatile fraction of PM, while the Euro 5 vehicle was equipped with both a DOC and a Diesel Particulate Filter (DPF), the latter for the control of PM emissions. The Euro 6 vehicle apart from a DOC and a DPF, was also equipped with a NOx control system, namely a Selective Catalytic Reduction (SCR) system, upstream of the DPF and using urea injection. The SCR catalyst is one of the two most common alternative after-treatment systems for NOx control, the other being the Lean NOx Trap (LNT) applied usually in smaller vehicles. The engines of all three vehicles used EGR (Exhaust Gas Recirculation) for the control of in-cylinder NOx formation.

All three vehicles tested were front wheel driven and were equipped with manual gearboxes. The Euro 4 was a D-class vehicle, while both the Euro 5 and Euro 6 belonged to the smaller C-class vehicle segment. In addition, these vehicle models covered an important share of the European car market. Finally, the Euro 5 and the Euro 6 had a low mileage at the beginning of the tests, while the Euro 4 was characterised by higher mileage, as it was an older vehicle.

2.2.2 Vehicle fueling

No back-to-back measurements on the same fuel were conducted to maximise the statistical robustness of the experiment. For this reason, an external fuel tank was used instead of the vehicle's fuel tank, as shown in Figure 3. This facilitated changing fuel every day, avoided any contamination between the previous and the next fuel, as well as ensured optimal flushing of the fuel lines and all the components of the vehicle's fuel system. In order not to affect the engine operation, the exact fueling system from the vehicle tank up to the engine was replicated. Therefore, if the vehicle was equipped with a low pressure fuel pump, then an equivalent, in terms of pressure and fuel flow, was applied in the external system. The information concerning the characteristics of the vehicle's low pressure fuel pump were provided by the manufacturers. This was the case with the Euro 5 and the Euro 6 vehicles, while in the Euro 4 vehicle a suction pump is integrated on the engine. In all cases, a fuel filter was fitted in the line between the external (low pressure) fuel pump and the high pressure pump of the engine. The supply and return fuel lines of the vehicle were bridged, therefore the fuel contained in the vehicle tank was continuously recirculating in order to prevent the vehicle's low pressure fuel pump from overheating.

Figure 3 External fuelling system (tank, filter, low pressure pump, pressure gauge)

2.2.3 Preparation of vehicles for testing

All three vehicles were prepared for testing on the chassis dynamometer according to manufacturer's instructions. For the Euro 6 vehicle only, the most important parameter that had to be adjusted was to switch to the so called "dyno mode". This is a function that many modern vehicles are equipped with and it is necessary in order to test these vehicles on the chassis dyno flawlessly. The main action of this function is to deactivate the ABS (Anti-lock Braking System) and ESP (Electronic Stability Programme) systems of the vehicle, while being tested on the chassis dyno, and at the same time to deactivate any speed sensors on the non-rotating wheels, provided that the tests are conducted on a single-axle chassis dyno. It is also assumed that the dyno mode function does not affect any other system of the vehicle and most importantly any other function or component that may affect fuel consumption and exhaust emissions, such as engine management and exhaust after treatment device control. A specific procedure is necessary to set the vehicle on "dyno mode" which is provided by the manufacturer. Overnight battery charging (during soaking) was applied to all vehicles to reduce the impact of battery state of charge on experimental repeatability.

2.2.4 DPF management

Another very important issue that had to be considered carefully was the DPF regeneration. In order to produce repeatable data for each fuel, as well as comparable results among the fuels, it is imperative that (uncontrolled) DPF regeneration does not occur during the tests. In addition, the experimental repeatability is enhanced if the DPF is in exactly the same fill state at the beginning of each testing day. In order to satisfy these two requirements, the official OEM diagnostic tool was used to regenerate the DPFs of the two DPF-equipped vehicles at the end of each test day.

2.2.5 Vehicle resistance-road load

All three vehicles were tested using the official inertia and road load (driving resistance) as provided by the manufacturer. These are the values used during the type approval procedure of the vehicles and correspond to the NEDC regulation (as described below). The chassis dyno was adjusted accordingly in order to reproduce precisely the corresponding coast-down times.

2.3 TEST PROTOCOL

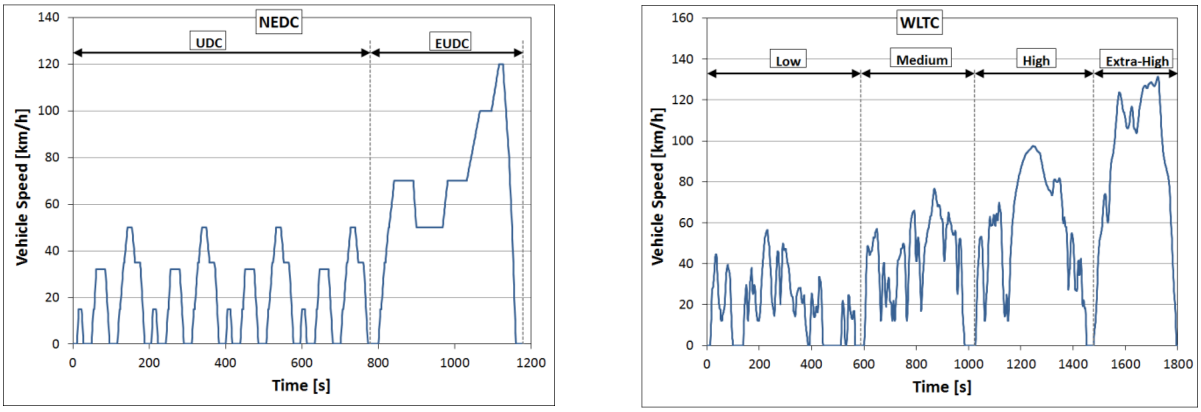
This section provides details concerning the test protocol and the procedures followed to maximise measurement quality and repeatability.

2.3.1 Driving cycles

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

The vehicle speed profiles of the two cycles considered in this study are shown in Figure 5. The WLTC represents the test cycle of the new regulation, the so called WLTP (Worldwide harmonized Light vehicles Test Procedure), which is different from NEDC in many aspects (vehicle mass, road load, test temperature etc.). However, it was not feasible to consider all these different aspects of the two cycles in the context of this testing activity, furthermore the WLTC tests were conducted from a hot start due to operational constraints rather than the cold start specified in the regulation. The inclusion of the driving cycle of the new regulation was deemed important and provided useful information concerning fuel effects on emissions and fuel consumption. In addition to the two driving cycles, a steady-state (constant vehicle velocity) point was included in the test protocol aiming at the detailed characterisation of particle emissions. This steady-state point was initially set at 120 km/h (that is the highest velocity in NEDC), but this was changed to 90 km/h during the project as some vehicles had difficulty running at this point. In the end it was decided to focus the analysis on the two transient drive cycles which were of more interest than the steady state. At the time that this programme was conceived the RDE (real driving emissions) test cycle was not yet fully developed although the WLTC should give a more realistic indication of on-road driving.

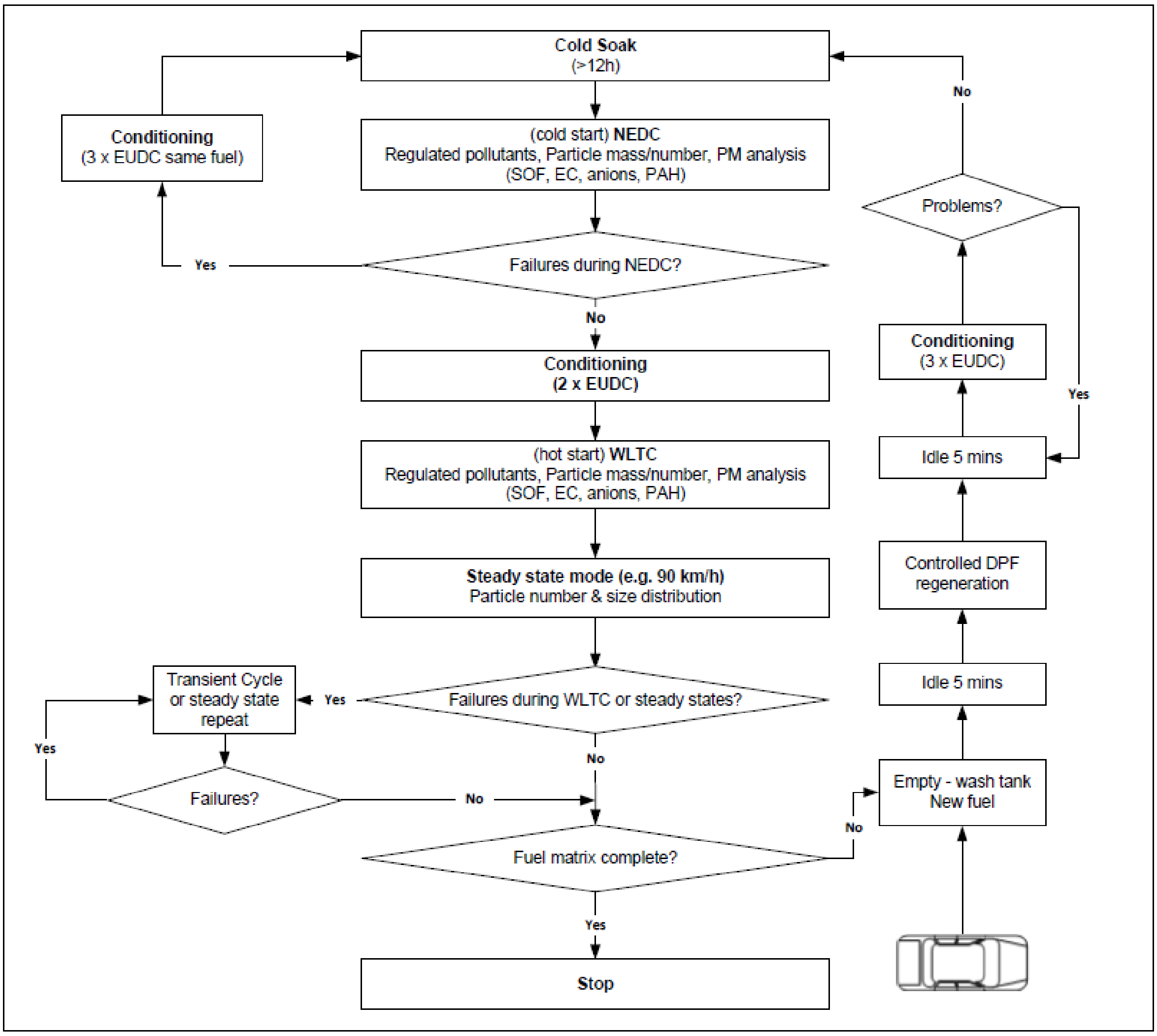
Figure 5 Speed profiles of the two driving cycles considered in this study (left: NEDC, right: WLTC).



2.3.2 Daily test protocol

The daily testing protocol started with the NEDC after a period of at least 12 hours cold soak. The NEDC is a cold-start cycle and comprises of the urban cycle (UDC) and the extra-urban cycle (EUDC), the former representing driving in the city and the latter aiming at simulating vehicle driving at higher speeds, e.g. when driving on highway and motorway. Immediately after completing the NEDC, the bag analysis was completed for the characterization of gaseous emissions as well as for the calculation of fuel consumption. Then, the vehicle and the whole test installation were conditioned for the WLTC. In order to fully warm-up all the components, two EUDCs were driven prior to the WLTC. The following WLTC was a hot-started cycle and comprises of four parts, Low, Medium, High and Extra-High. The first part is representative of urban driving conditions, the second is a transition phase from urban to suburban environment described in the third part, while the last part of WLTC is representative of motorway driving. As with the NEDC, immediately after the completion of WLTC the bag analysis was carried out. After the two driving cycles, the steady-state point was following, comprising of 5 min condition (warming) and 15 min of measurement, both at the same vehicle velocity. The specific target of this measurement was the characterization of particle emissions. After completing this measurement, the external fuel tank was filled with the fuel to be tested the following day. In order to clean the fuel lines from the previous fuel and avoid any mixing between the fuels, during the first 30 seconds of operation with the new fuel, the return fuel line was directed to another tank and the collected fuel was discarded, since it was a mixture of the previous and the new fuel. Then the vehicle was left to idle for 5 minutes and then the controlled DPF regeneration was performed (for the Euro 5 and Euro 6 cars). The vehicle was again left to idle for 5 minutes and then it was conditioned for the next day, driving 3 EUDCs as exactly prescribed by the NEDC regulation. After that the vehicle was left to soak at 25°C, which is also the testing temperature, for more than 12 h. A detailed flowchart of the daily testing and conditioning procedures is given in Figure 6, where all the intermediate steps and the alternatives in case of problems are presented.

Figure 6 Daily test protocol



2.4 EXPERIMENTAL SET-UP

Figure 7 presents the layout of the experimental installation where the test campaign was conducted. The chassis dyno is powered by an electric machine capable of operating either as a generator (braking operation of the dyno) or as a motor (motoring operation of the dyno). The dyno consists of two rollers where the moving wheels of the vehicle are placed and are either braked or rotated by the dyno. In the next sub-paragraphs the procedures and the equipment used in the measurement of regulated gaseous pollutants as well as for PM sampling are described.

2.4.1 Measurement of regulated emissions

The emissions of the three regulated gaseous pollutants, namely carbon monoxide (CO), unburnt hydrocarbons (HC) and oxides of nitrogen (NO_x - including both NO and NO_2) were recorded, together with the measurement of carbon dioxide (CO_2) emissions, which is the main component of combustion products and the major parameter in the calculation of fuel consumption. Table 4 provides information concerning the equipment used in the measurement of CO_2, CO, HC and NO_x.

Figure 7 Experimental set-up

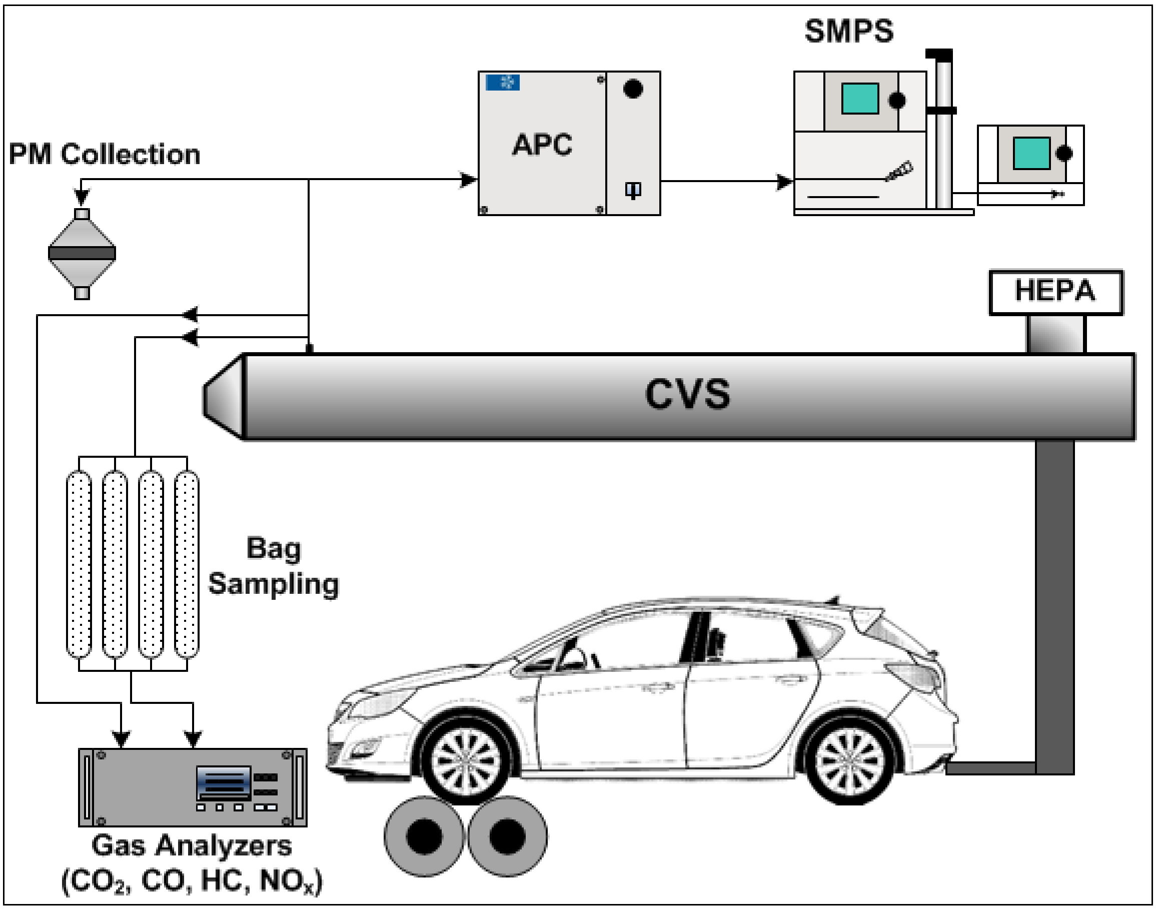


Table 4 Equipment used in the measurement of CO_2, CO, HC and NO_x.

Pollutant	Analyser	Measuring principle	Accuracy
CO_2	H&B	NDIR*	0.001%
CO	Horiba VIA510	NDIR	0.5 ppm
HC	Signal 3000HM	FID**	0.3 ppm
NO/NO_x	Signal 4000	CLD***	0.1 ppm

*NDIR: Non-Dispersive Infra-Red, **FID: Flame Ionization Detector, ***CLD: ChemiLuminescence Detection

Emissions measurements over NEDC and WLTC were conducted following the European regulations (Directive 70/220/EEC and amendments). The exhaust gas was primarily diluted and conditioned by means of Constant Volume Sampling (CVS). A 6 m long corrugated stainless steel tube transferred the exhaust from the tailpipe to the CVS tunnel inlet. The tube was insulated to minimize heat losses and particle thermophoresis and was clamped onto the vehicle exhaust pipe with a metallic tailpipe adaptor to avoid exposing the hot exhaust gas to any synthetic material connectors. The dilution air was filtered through a HEPA (High Efficiency Particulate Air) class H13/EN1822 filter at the inlet of the dilution tunnel. Proportional diluted exhaust gas samples were collected in bags for gaseous pollutants measurements.

The emissions of gaseous pollutants were measured with the laboratory analysers shown in Table 4, compliant with the prescriptions of the European legislation. Fuel consumption was derived by means of the exhaust-to-fuel carbon balance, taking into account the oxygen content of fuels, as described in section 2.5. In parallel to exhaust gas sample collection in bags, the instantaneous concentrations of gaseous pollutants (after the CVS) were also recorded using the same analysers.

2.4.2 Measurement and Analysis of PM Emissions

Particulate Matter (PM) sampling was performed following the specifications of the PMP protocol. One separate filter was used for each of the two driving cycles (NEDC, WLTC) for measuring PM emissions. In addition to the vehicle tests, a number of additional blank tests were performed for determining background levels for PM (particulate matter contained in the ambient air used for exhaust gas dilution). During these blank tests the sampling procedure for PM was the same as for vehicle measurements, but the transfer pipe of the CVS was disconnected from the vehicle's tailpipe. PM samples were collected on 47 mm PTFE-coated glass fibre filters (Pallflex TX40HI20) following the PMP specifications.

After weighing the filters and calculating the PM emissions, the filters were packed and stored in order to be used for determining the Soluble Organic Fraction (SOF) of PM, ions and elemental carbon (EC) by difference, as well as the Polycyclic Aromatic Hydrocarbon (PAH) compounds of the SOF. The PM filters were stored in a refrigerator and were sent for analysis either at the end of each repetition or at the end of testing each vehicle. The Environmental Pollution Control Laboratory (EPCL) from the Department of Chemistry of the Aristotle University of Thessaloniki has undertaken all the analyses conducted on PM filters.

2.4.2.1 Filter Preparation

The PM filter code number was always recorded. The particle sample filters were conditioned in a clean room, under controlled temperature (22±3°C) and humidity conditions (45±8%), according to PMP regulation. The filters were placed on a grounded aluminum plate during their conditioning period. Moreover, they were placed under a perforated aluminum cover in order to be protected from dust and be in contact with the environment at the same time. A reference filter (renewed after having been worn) was also kept in the clean room and was weighed at the same time as the PM filters, in accordance with the PMP regulation. The conditioning period was set to 2-80 h by the PMP procedure. In this study, because of the subsequent analyses (SOF, ions, EC, PAHs), the loaded filters were normally kept 24-48 h in the clean room and then immediately stored, in order to ensure that there will not be any change in the PM composition.

2.4.2.2 Microgram balance

The analytical balance used was Mettler-Toledo UMX2 with 0.1 μg resolution. The balance was grounded by its placement on an anti-static plate and the particulate filters on a grounded aluminum mat to avoid development of static charge. A reference mass was weighed during the testing period together with the reference filters. The balance precision (standard deviation) for the reference weight was 0.9 μg during the whole measuring period. Each sample filter was weighed until obtaining three measurements with deviation less than 0.9 μg.

2.4.2.3 Filter storage

After final weighing the filters were packed in order to be first stored and then sent for PM speciation analyses. Each filter was wrapped in aluminium foil and the foil-wrapped filter was placed in a suitably-sized self-sealing plastic bag. The plastic bag was stored in the chilled compartment of a refrigerator.

2.4.2.4 Chemical analysis of filter papers

Before the chemical analysis, the filters were kept outside the refrigerator for 24h in a controlled environment (20±1^{0}C and 50±5% relative humidity). The filters chosen for analysis (two for NEDC and two for WLTC, for each fuel) were then cut into 4 pieces and each piece was weighed in a microgram balance. Two new “hybrid” filters (consisting of two quarters of each of the original filters) for each cycle were formed, in order to optimize the validity of the results. One of the “hybrid” filters was used for the determination of the Soluble Organic Fraction (SOF), while half of the other “hybrid” filter was used for the analysis of Polycyclic Aromatic Hydrocarbons (PAHs) and half for the analysis for ions.

2.4.2.4.1 Determination of SOF

The determination of SOF was conducted according to IP 443/99, using a Soxhlet extraction. The SOF mass is determined by the filter mass difference before and after the extraction. After the 24h pre-treatment, the filter is placed in the flask of the Soxhlet device, which contains 100ml CH2Cl2 (dichloromethane) and is heated. The extraction takes around 3h and after the completion, the flask is left to cool down at room temperature. In the meantime, the filter is placed in the furnace at 50±5^{0}C for 30 min and then kept in a controlled environment (20±1^{0}C and 50±5% relative humidity) for 24 h. After that it is weighed in order to determine the SOF mass.

2.4.2.4.2 Determination of ion components

The ions were determined using ion chromatography. The filter is placed in a 5 ml volumetric flask and it is soaked with 0.3 ml methanol, which is used in order to limit the hydrophobic character of the sample due to the contained soot. 4.7 ml of ultrapure water are then added and the flask is placed in an ultrasonic bath for 30 min. At this stage the ion components are extracted to the aqueous phase. The extracts are placed in small flasks and are kept in the refrigerator in order to avoid thermal decomposition of the unstable nitrates. For the separation of the anions the chromatographic column Allsep Anion 7u (Alltech) is used. The conductometric detector CDD-6A is used for detecting the ions.

2.4.2.4.3 Calculation of elemental carbon (EC)

After SOF and ions determination, the elemental carbon (EC) is calculated by extracting SOF and ions from the total PM mass.

2.4.3 Particle Number And Size Distribution

Particle number (PN) measurement was performed during the two driving cycles (NEDC, WLTC), as well as during the steady-state point. The number concentration of solid particles with a diameter larger than 23 nm was measured with an AVL Particle Counter 489 (APC), which is an instrument in compliance with the relevant PN measurement regulations.

Further particle characterisation was conducted by measuring particle size distribution, which was possible only at the steady-state point. Particle size distribution was measured with an SMPS (Scanning Mobility Particle Sizer), which sampled the diluted and thermally treated aerosol at the APC output, as shown in Figure 7. The SMPS consisted of a TSI long DMA (Differential Mobility Analyser), operating at 15 l/min sheath flow and 1.5 l/min aerosol flow to provide sizing from 6 to 225 nm, and a TSI CPC (Condensation Particle Counter) 3776. With the experimental set up employed, the particle size distribution measurement could provide useful information only on the vehicle without DPF, i.e. the Euro 4 car. The presence of a DPF on the Euro 5 and 6 cars prevented any meaningful measurement of particle size distribution.

2.4.4 Recording of ECU (Engine Control Unit) data

During the tests and the conditioning phases, important ECU data were recorded, through the OBD (On-board Diagnositic) port of the vehicle and a universal OBD tool owned by LAT (not the OEM (Original Equipment Manufacturer) diagnostic tools used for DPF regeneration – the OEM tools do not have the necessary recording capabilities). The most important parameters monitored were the following:

- Engine rotating speed
- Vehicle velocity
- Air mass flow
- EGR rate
- Engine coolant temperature
- Intake air temperature & pressure
- Fuel rail pressure
- Battery voltage
- Catalyst temperature (if available)
- Engine oil temperature (if available)
- Battery voltage (if available)

In addition to the ECU data, two additional important parameters recorded were the battery and the alternator currents, using external sensors. Monitoring all these parameters allowed on the one hand ensuring the faultless operation of the vehicle and on the other the evaluation of the repeatability and the reproducibility of the results. Table 5 presents an overview of the recorded parameters and the corresponding testing conditions.

Table 5 Overview of the tests and parameters measured

	NEDC	WLTC	90 (or 120) km/h	Conditioning
CO_2	√	√	√	√
CO	√	√	√	√
HC	√	√	√	√
NO_x	√	√	√	√
PM	√	√		
PM analysis (SOF, PAHs, EC, ions)	√	√		
PN	√	√	√	
Particle size distribution			√	
ECU data	√	√	√	√

2.5 FUEL CONSUMPTION CALCULATIONS

According to the legislation, fuel consumption is calculated from the carbon balance in the exhaust gases. For this calculation, the regulation assumes a specific hydrocarbon with the ratio (C1:H1.86:O0.005) corresponding to diesel fuel with 5% biodiesel (B5) and no other blends of diesel with biodiesel are foreseen. However, in order to take into account the exact properties of the fuels considered in this study and calculate accurately fuel consumption, the relevant procedure should be revised. Equations (1) and (2) are used for the calculation of fuel consumption (FC) and dilution factor (DF) respectively. Coefficients A1 and A2, as well as the stoichiometric factor Fs are calculated for each individual fuel and are a function of fuel composition. Table 6 presents the fuel properties needed in the calculation of fuel consumption and dilution factor, while Table 7 gives the values of A1, A2 and Fs for each fuel.

It is important to note here that, although the values of these parameters do not present significant differences (for example, the difference between minimum and maximum value of A1 is less than 2%), their final effect on the calculated fuel consumption cannot be considered negligible. Besides, the effect of fuels on consumption is in the order of 5%, meaning that all parameters affecting the relevant calculations must be carefully taken into account.

Equation (1) $FC = A_1/D \times [(A_2 \times HC) + (0.429 \times CO) + (0.273 \times CO_2)]$

Where:

FC: fuel consumption in l/100km
A1: coefficient showing fuel carbon content (=10/carbon content)
A2: carbon content of HC (as C1)
D: fuel density in kg/l, @ 15°C
HC: measured HC emissions in g/km
CO: measured CO emissions in g/km
CO_2: measured CO_2 emissions in g/km

Equation (2) $DF = F_s / [CO_2 + (CO + HC) \times 10^{-4}$

DF: dilution factor
Fs: stoichiometric factor, different for each fuel
CO2: measured CO2 concentration in %
CO: measured CO concentration in ppm
HC: measured HC concentration in ppm

Table 6 Fuel properties used in the fuel consumption calculations

Fuel	Density [g/l]	Biodiesel content [%]	Carbon Content [%]	Hydrogen Content [%]	Oxygen Content [%]
D1	818.6	0.0	86.87	13.13	0.00
D2	856.9	9.6	86.58	12.36	1.06
D3	852.1	0.0	87.33	12.67	0.00
D4	818.1	9.6	85.88	13.06	1.06
D5	858.9	0.0	87.76	12.24	0.00
D6	823.7	9.0	85.95	13.06	0.99
D7	818.9	0.0	86.76	13.24	0.00
D8	855.5	9.4	86.21	12.76	1.03
D9	856.6	0.0	87.23	12.77	0.00
D10	839.6	0.0	87.17	12.83	0.00
D11	839.8	9.5	86.15	12.80	1.05
D12	839.1	0.0	87.03	12.97	0.00
D13	839.3	9.5	86.10	12.85	1.05
D14-Ref	834.2	4.9	86.42	13.04	0.54

Table 7 Coefficients and factors used in equations 1 and 2.

Fuel	A_1	A_2	F_s
D1	0.1151	0.8687	13.60
D2	0.1155	0.8751	13.90
D3	0.1145	0.8733	13.79
D4	0.1164	0.8680	13.60
D5	0.1139	0.8776	13.98
D6	0.1163	0.8681	13.60
D7	0.1153	0.8676	13.55
D8	0.1160	0.8711	13.73
D9	0.1146	0.8723	13.75
D10	0.1147	0.8717	13.73
D11	0.1161	0.8706	13.71
D12	0.1149	0.8703	13.67
D13	0.1161	0.8701	13.69
D14-Ref	0.1157	0.8689	13.62

3. RESULTS – VEHICLE AND TEST CYCLE EFFECTS

This section compares the results for the three vehicles on the reference fuel over both test cycles, i.e. the effect of vehicle type and test cycle on emissions and fuel consumption. In addition, any phenomena that might have affected the tests are discussed here. Fuel effects are discussed in section 4. The exact values of all the parameters used in the analysis are provided in tables in Appendix 3. In order to compare the overall performance of the three vehicles on the two test cycles, the results presented here are for the Reference fuel D14 only as this is a standard diesel fuel meeting the EN590 specification. The test fuels were blended to explore the limits of the specification and hence are not always representative of fuels available in the market. The means for all test fuels are tabulated and charted in Appendix 3.The error bars shown on the charts below are ±1 Standard Deviation based on the pooled standard deviation across all fuels after any adjustments for step changes and trends. They therefore indicate the overall test-to-test variation as used in the statistical analysis.

3.1. TEST SEQUENCE

The test sequences for all three vehicles involved three sets of replications for each vehicle which were each fully randomized. All replications started with reference fuel (D14) testing for bracketing reasons, i.e. to ensure that the vehicle remains at the same condition throughout the test campaign. For the same reason, a D14 test was included around the middle of each replication. From time to time for logistical reasons testing was stopped and if this occurred the reference fuel was tested before starting with the test fuels again.

3.2. CO_2 EMISSIONS AND FUEL CONSUMPTION

Carbon dioxide emissions and fuel consumption are discussed together, since CO_2 is the main exhaust gas component from which fuel consumption is calculated (according to eq. (1)). These two parameters can also be used to evaluate the energy efficiency of the vehicle. Figure 8 shows the results of CO_2 emissions and Figure 9 shows fuel consumption for cold NEDC and hot WLTC.

Figure 8 Reference fuel (D14) CO2 emissions for Euro 4, Euro 5 and Euro 6 vehicles

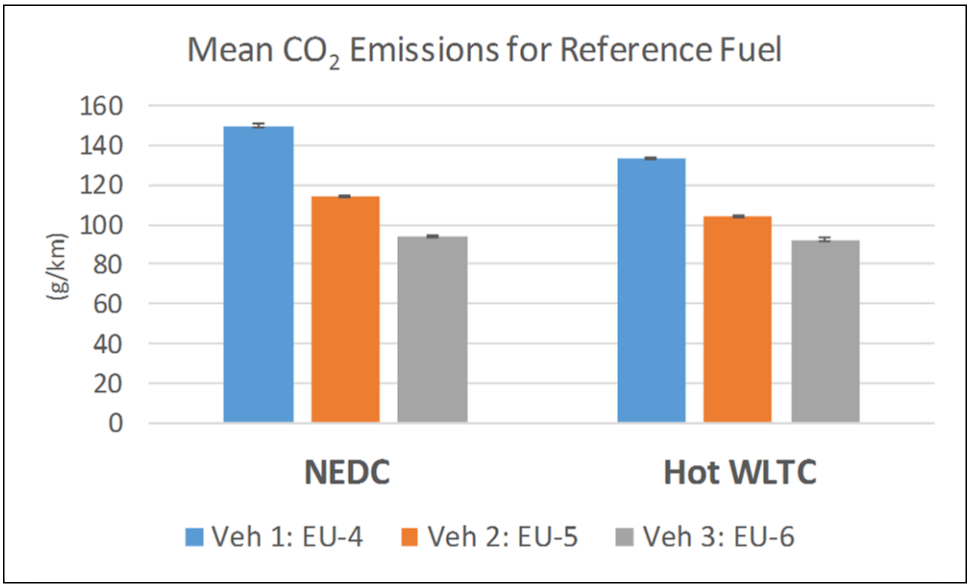
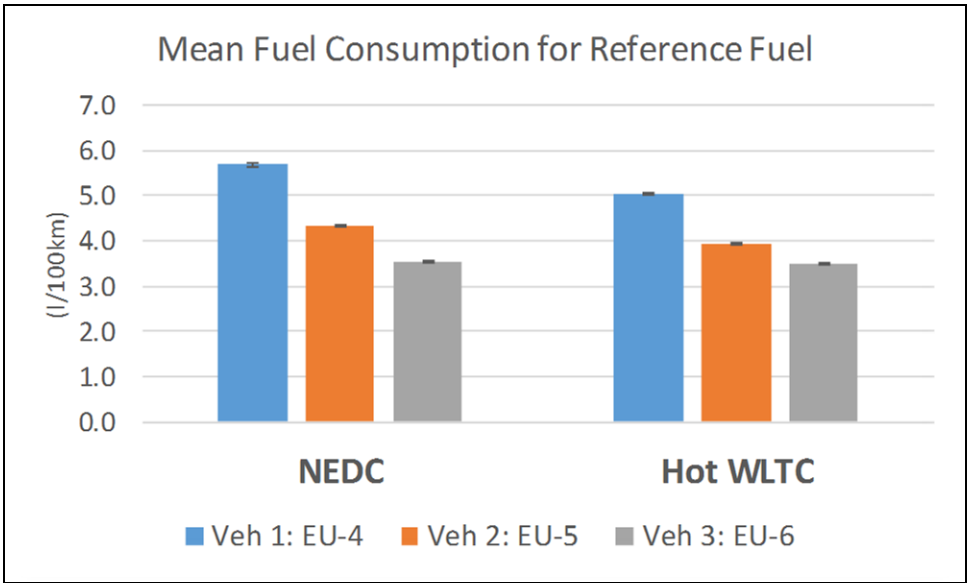


Figure 9 Reference fuel (D14) Fuel consumption for Euro 4, Euro 5 and Euro 6 vehicles



CO_2 emissions of cold NEDC are around 150g/km in the Euro 4 vehicle, compared with around 135g/km in the hot WLTC. CO_2 emissions were lower in WLTC in all three vehicles, as both cycles are run with the same road load and the engine operates in more efficient areas during WLTC, albeit at higher mean loads. In addition, NEDC contains a cold start (i.e. start temperatures equal to soak temperature), while WLTC was run with a hot start. In both test cycles, for the Euro 4 car the test variability is very good - standard deviation 0.74% in the cold NEDC and 0.54% in the hot WLTC. For the Euro 5 vehicle, the CO_2 emissions were less than the Euro 4 with cold NEDC emissions around 115g/km. In WLTC, CO_2 emissions were 104g/km. In both test cycles, the variability is again very good - standard deviation being 0.75% in the NEDC and 0.73% in the WLTC. In the Euro 6 vehicle the CO_2 emissions of cold NEDC are 94g/km and around 2g/km lower at 92g/km in the WLTC.

In both test cycles, the variability is again low with a standard deviation of 0.66% in NEDC and 0.80% in WLTC.

The Euro 4 vehicle returned fuel consumption of 5.7 l/100km in NEDC and 5.0 l/100km in WLTC. In the Euro 5 vehicle, the fuel consumption was less than for the Euro 4 vehicle being 4.3 l/100km in NEDC and 3.9 l/100km in WLTC. For the Euro 6 vehicle, the fuel consumption was less than the Euro 5 vehicle with the fuel consumption of 3.55 l/100km in NEDC and 3.50 l/100km in WLTC. In all three vehicles and both test cycles, the overall standard deviation is virtually identical to that for CO_2 emissions in percentage terms and hence well below 1%.

3.3 CO AND HC EMISSIONS

Carbon monoxide (CO) and unburnt hydrocarbons (HC) are two of the regulated pollutants studied here (the others being NOx and PM/PN). Both these pollutants are products of incomplete combustion and, in general, they are found in very low concentrations in the exhaust of a diesel engine (engine-out emissions). However, in order to meet the emissions standards, generally it is necessary to use a diesel oxidation catalyst (DOC) so that tailpipe emissions are below the limit.

Figure 10 Reference fuel (D14) CO emissions from Euro 4, Euro 5 and Euro 6 vehicles

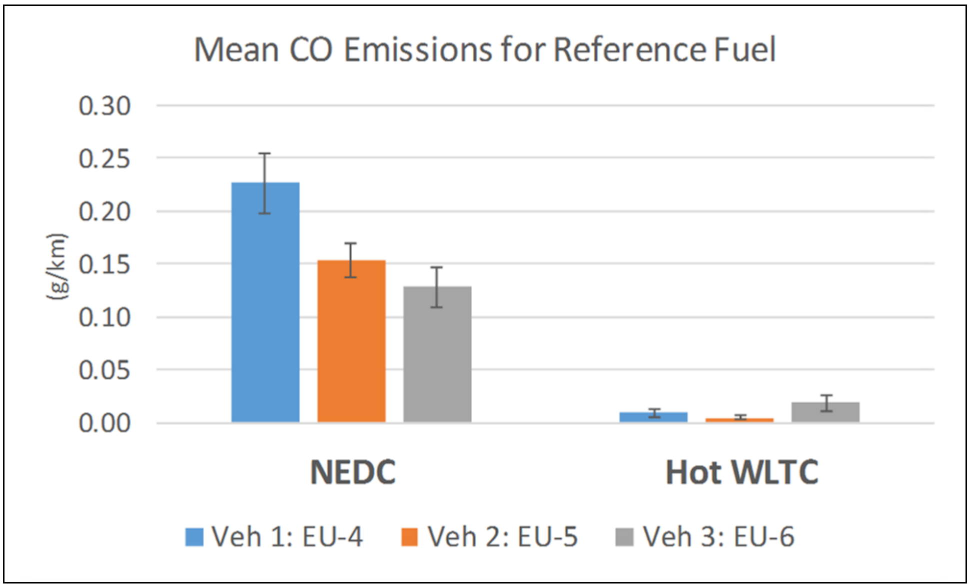
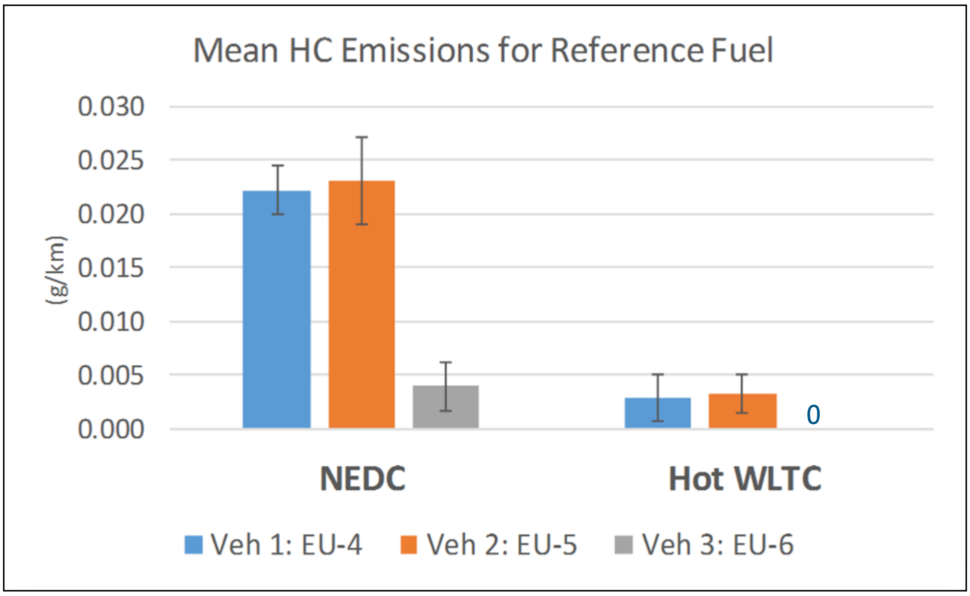


Figure 11 Reference fuel (D14) HC emissions from Euro 4, Euro 5 and Euro 6 vehicles. Note: that zero HC was measured for all WLTCs with reference fuel on the Euro 6 car.



Both CO and HC emissions are around one order of magnitude lower in hot WLTC as compared to cold NEDC in all three vehicles due to DOC effectiveness in different thermal conditions during the two driving cycles. The obvious reason for this is the cold start of NEDC, where the catalyst is cold and does not operate efficiently. On the other hand, WLTC starts with the engine and all the vehicle components in warm condition in this programme, thus DOC has exceeded its light-off temperature.

For all vehicles CO is well below the relevant limit of 0.5 g/km in the NEDC. There is no limit for HC alone, as this is combined with NOx. Variability is generally good for these emissions in the cold start NEDC where emissions values are higher, however variability was worse in the WLTC due to the low absolute emissions levels. In the WLTC tests on the Euro 6 vehicle, the vast majority of the HC results were zero and this included all of the measurements on reference fuel D14. It is therefore not meaningful to present HC results for the Euro 6 vehicle in this cycle.

3.4 NOX/NO/NO_2 EMISSIONS

Nitrogen oxides (NOx) emissions have become the most important pollutant of modern diesel engines, as particulate emissions are effectively controlled with the application of DPFs. Technologies that reduce in-cylinder NOx formation, such as injection timing adjustment (retard) and EGR, are now commonplace. However, modern vehicles need additional control means in order to comply with the emission limits of current legislation. Modern diesel vehicle tailpipe NOx emissions are primarily composed of NO and NO2. The latter is the main pollutant of concern when it comes to human health.

Figure 12 Reference fuel (D14) NOx emissions from Euro 4, Euro 5 and Euro 6 vehicles

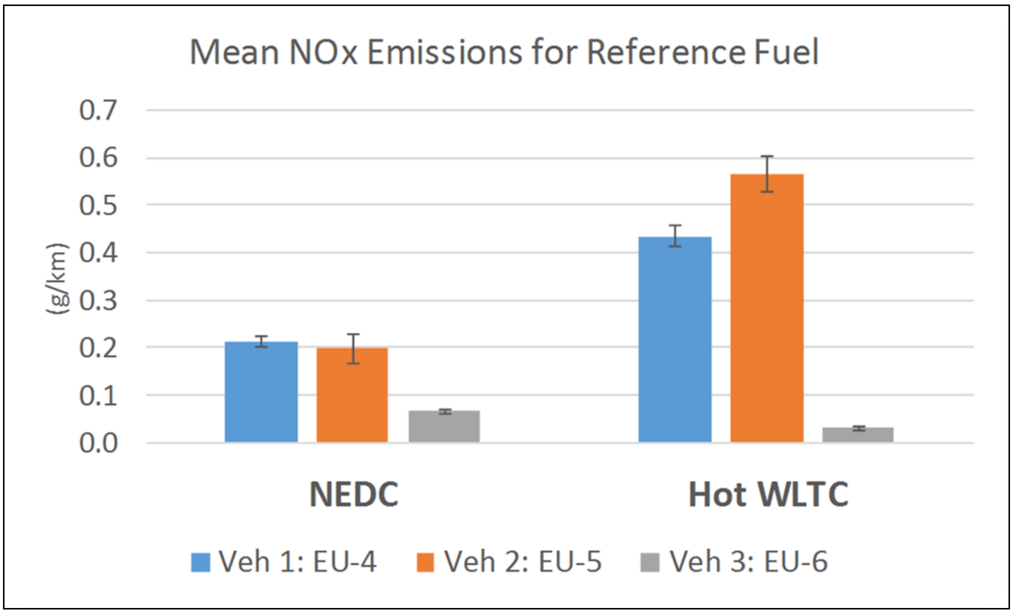


Figure 13 Reference fuel (D14) NO emissions from Euro 4, Euro 5 and Euro 6 vehicles

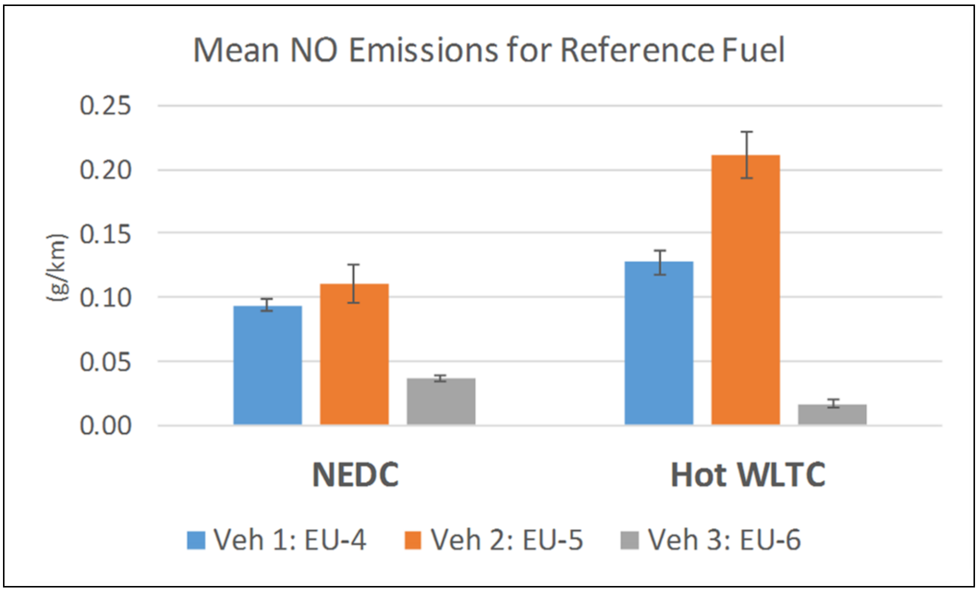
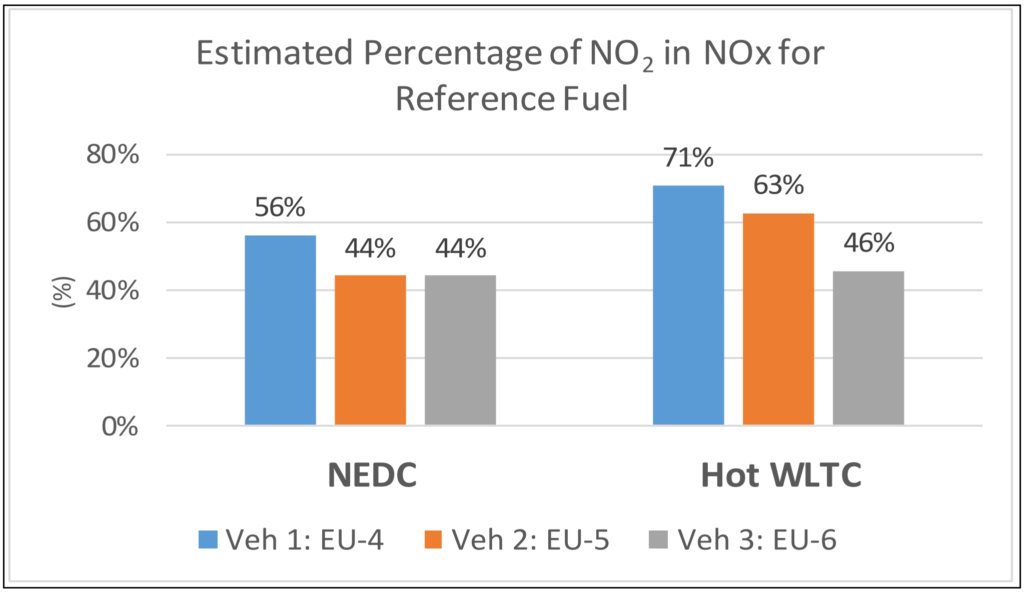


Figure 14 Estimated fraction of NO_2 in NOx for Reference fuel (D14)



Figures 12 and 13 show NOx and NO emissions for cold start NEDC and hot start WLTC. NO_2 emissions can be calculated by subtraction of the measured NO from the total NOx and Figure 14 shows the estimated proportion of NO_2 as a fraction of NOx based on the difference in the Reference fuel means for NOx and NO.

For the Euro 4 vehicle, NOx emissions were below the Euro 4 limit of 0.25 g/km in cold start NEDC. This constitutes an important criterion in the evaluation of a fuel on a vehicle without any after-treatment devices for NOx control. NOx emissions were significantly higher in WLTC as compared to NEDC, since the former cycle operates at higher loads (leading to higher combustion temperatures where NOx tends to form) and less EGR and injection timing retard is likely to be applied given that the vehicle emissions calibration is tailored to the NEDC. In NEDC, NO_2 constitutes around 56% of tailpipe NOx emissions, while in WLTC the respective percentage is 71%. For the Euro 5 vehicle NOx emissions were only slightly lower than the Euro 4 vehicle in the NEDC and the average is above the Euro 5 limit of 0.18 g/km. Emissions were higher than the Euro 4 vehicle in the WLTC. The reasons for this are likely to be similar to those explained for the Euro 4 vehicle above. Of the NOx produced from the Euro 5 vehicle run in NEDC, 44% is NO_2, while in WLTC NO_2 constitutes 63% of tailpipe NOx emissions for the reference fuel.

In the Euro 6 vehicle fitted with SCR, NOx and NO emissions for cold NEDC and hot WLTC were significantly lower than for the Euro 4 and Euro 5 vehicles. NOx emissions were on average below the Euro 6 limit of 0.08 g/km in cold NEDC. Contrary to the other two vehicles, lower NOx emissions are observed in WLTC. Although engine-out NOx emissions may be higher in hot WLTC, due to the higher temperatures developed, the SCR performs better at the higher temperature. Concerning NOx composition, in NEDC 44% is NO_2, while in WLTC NO_2 constitutes 46% of tailpipe NOx emissions for the reference fuel.

In these results, the fraction of NO_2 is highest from the Euro 4 car and lowest for the Euro 6 car. If this were a trend generally applicable across the vehicle fleet then the contribution of primary NO_2 from diesel passenger car exhausts to ambient NO_2 would improve with fleet turnover faster than would be predicted by reduction in NOx alone and this could translate to accelerated improvements in urban air quality. However, these results are not consistent with conventional wisdom expressed in the literature which suggests that the fraction of NO_2 in the tailpipe NOx from diesel cars is generally higher when DPFs are fitted and higher again when SCR catalysts are used [23,24]. However evidence from latter works suggests that there is no clear correlation between emissions control equipment and fraction of NO_2 in tailpipe NOx, rather that this is dependent on the individual OEM/vehicle application [25-27].

3.5 PM EMISSIONS

Another regulated pollutant considered in this study is particulate matter (PM), measured with the filter paper method and expressed in mass units. Particles emitted by a diesel engine consist mainly of elemental carbon (soot) and constitute its most characteristic pollutant. Soot is a product of fuel pyrolysis in the engine cylinder, following a number of steps during formation and being affected, among other factors, by fuel properties. The issue of PM emissions has been successfully dealt with by the use of the DPF, as will be shown in the results of the Euro 5 and 6 vehicles.

Figure 15 Reference fuel (D14) PM emissions from Euro 4, Euro 5 and Euro 6 vehicles

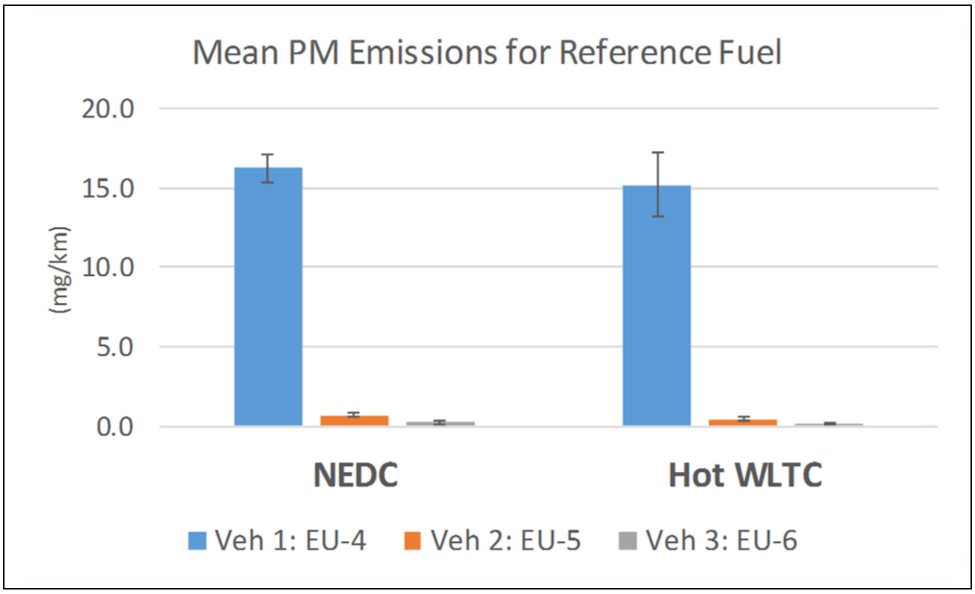


Figure 15 shows PM emissions for cold NEDC and hot WLTC. PM emissions from the Euro 4 vehicle were substantially below the Euro 4 limit of 25 mg/km in the cold NEDC test despite having no DPF and the relatively high mileage of the vehicle.

The Euro 5 vehicle equipped with a DPF showed PM emissions for cold NEDC and hot WLTC that were significantly lower than the Euro 4 vehicle and barely visible on the chart in Figure 15. PM emissions remained below the Euro 5 limit, which is 5 mg/km, in cold NEDC. Lower PM values are observed in WLTC as compared to NEDC also for the DPF-equipped vehicles. The Euro 6 (also equipped with DPF) showed PM emissions even lower than the Euro 5 vehicle and remaining below the Euro 6 limit, which is 5mg/km, in the cold NEDC test.

Overall measurement variability was satisfactory, with lower variability in the Euro 4 measurements due to the much higher absolute values.

3.6 PARTICLE NUMBER (PN) AND PARTICLE SIZE DISTRIBUTION

3.6.1 Particle Number

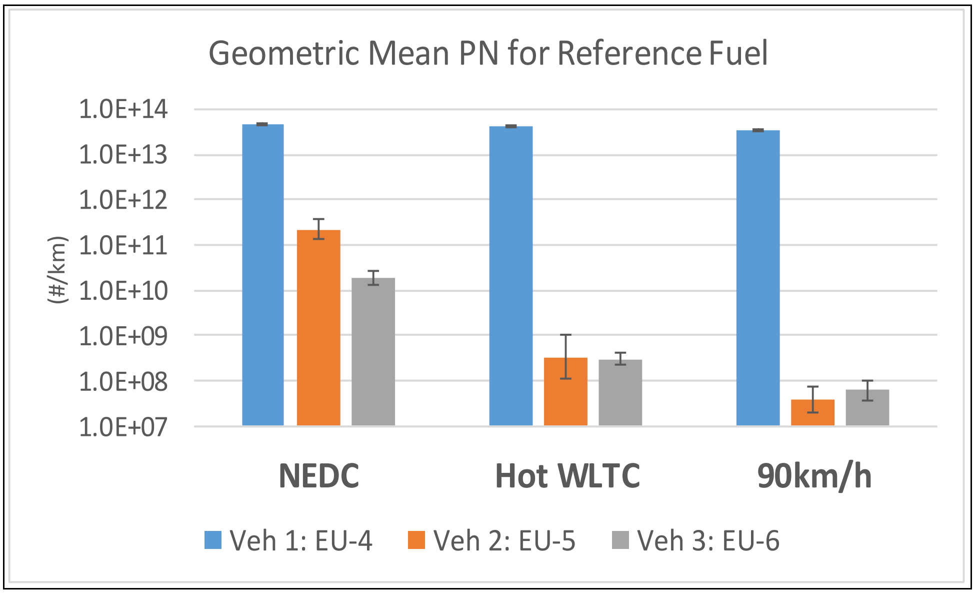
Particle number became a regulated emission parameter for diesel vehicles when the Euro 5b standard came into force (September 2011). Figure 16 shows PN during cold NEDC, hot WLTC and hot steady state 90 km/h respectively for the three vehicles. These are geometric means which are generally used to summarise PN emissions and they are plotted with the y-axis on a logarithmic scale.

With respect to these data, the following is observed:

In all vehicles, PN follows the same pattern as the corresponding PM emissions in that PN values are higher in NEDC compared to WLTC owing to the cold start of the former. Emissions from the Euro 6 vehicle were lower than those from the Euro 5 vehicle which was lower than those from the Euro 4 vehicle for NEDC. For the WLTC and steady state at 90 km/h the Euro 5 and Euro 6 were lower than Euro 4 but equivalent to each other within experimental error.

For the Euro 5 and Euro 6 vehicles, PN remained below the Euro 5 limit of $6x10^{11}$#/km. Emissions from the steady state condition were lower than those from the WLTC as this too had a hot start and lacks the WLTC's transients where more particles will form.

Figure 16 Reference fuel (D14) PN emissions from Euro 4, Euro 5 and Euro 6 vehicles

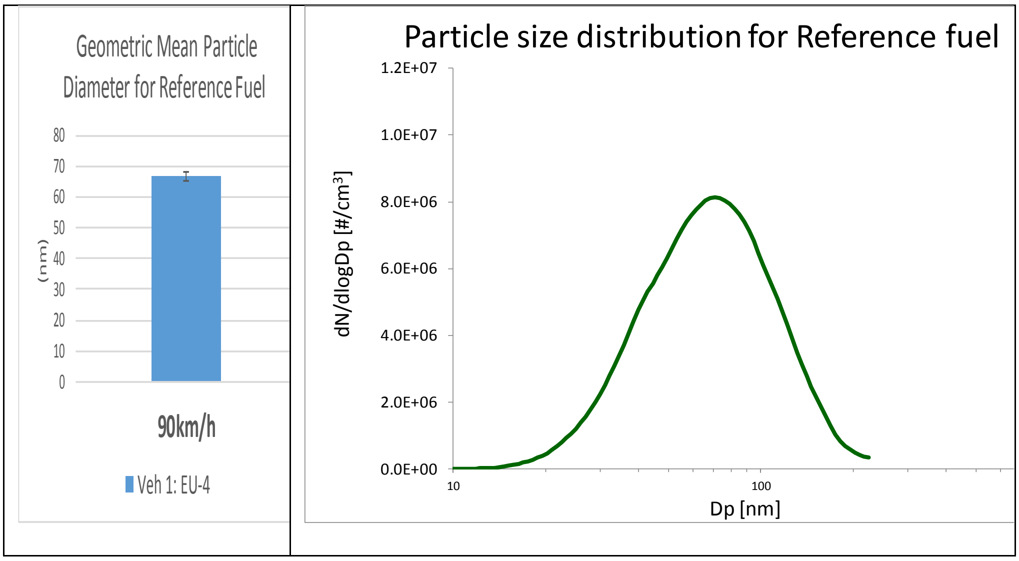


3.6.2 Particle size distribution

The primary reason for the steady state condition during which PN was measured was to obtain the size distribution of the emitted particles. Figure 17a) shows the mean geometric particle diameter and Figure 17b) shows the size distribution for the reference fuel in the Euro 4 vehicle which gave enough particulates to be able to conduct the analysis. It was not possible to collect any reliable particle size distribution data from the DPF-equipped cars with the experimental set up employed. The analysis of the effect of fuel properties on these results is discussed in the next chapter.

Figure 17 a) Reference fuel (D14) Geometric mean particle diameter and

b) Reference fuel (D14) particle distribution for the Euro 4 vehicle

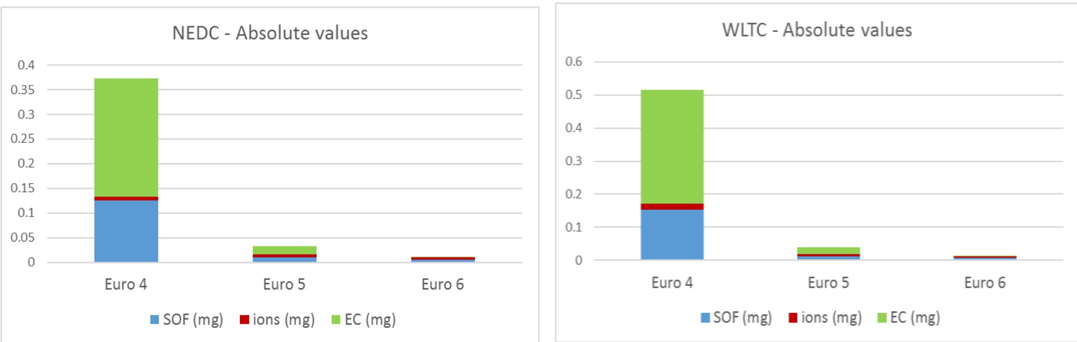


3.7 PM FILTER PAPER ANALYSIS

The last part of the assessment of fuel effects on emissions is the analysis of the PM filter papers. This analysis included the determination of SOF (Soluble Organic Fraction), ions and EC (Elemental Carbon), as well as the characterisation of PAHs. The tables of results shown in Appendix 4 present the analysis, in terms of mass, of filter papers in NEDC and WLTC, respectively for the three vehicles. Figure 18 shows absolute values of soluble organic fraction, ions and elemental carbon on average for papers from the NEDC and WLTC test cycles showing that the total values are greater for the WLTC than the NEDC and that far more total material is present for the Euro 4 vehicle than the later vehicles.

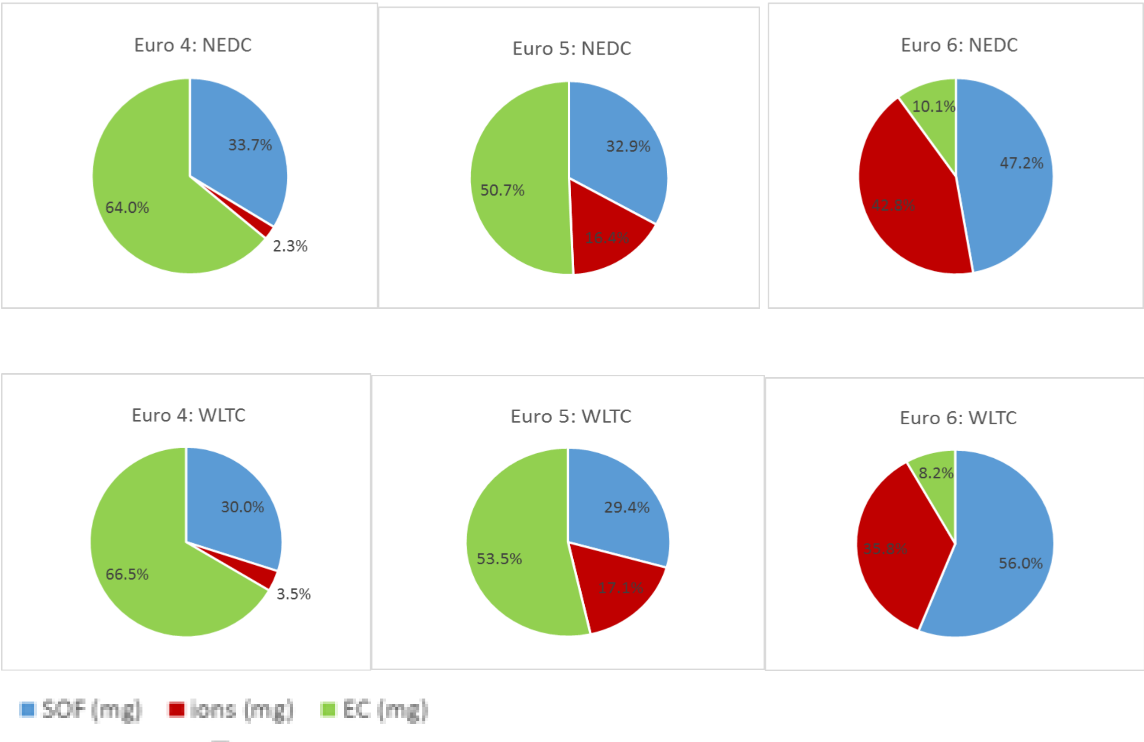
It was decided that nothing further could be gleaned from statistical analysis of the filter paper analysis data in combination with the fuel property matrix as the papers were combinations of several tests particularly for the Euro 6 vehicle for which there was very little material to work with. No analysis was carried out on the PAH analysis as it was not deemed useful without the PAH breakdown of the original fuels.

Figure 18 Absolute values of soluble organic fraction, ions and elemental carbon for reference fuel (D14)



The average percentage breakdown for the different vehicle technologies is shown in Figure 19. This demonstrates that there is a bigger difference in the breakdown between the technologies than between the two test cycles on average. The equivalent charts for the individual fuels are shown in Appendix 4 demonstrating that in general the vehicle technology differences are bigger than either cycle to cycle differences or fuel differences.

Figure 19 Average %ages for NEDC and WLTC for Euro 4, Euro 5 and Euro 6



4. RESULTS – MODELLED EFFECTS OF FUEL PROPERTY CHANGES ON HC, PM, PN, NOX, CO, CO2 EMISSIONS, FUEL & ENERGY CONSUMPTION

4.1 DATA HANDLING AND ANALYSIS

Recognised data evaluation and analysis techniques were employed to identify corrupted data points, outliers and trends. Data points identified through engineering reasoning to be invalid have been rejected from the data analysis, as have gross statistical outliers which would obscure real fuel effects in the analysis if retained. Trend correction has been limited to minimise data treatment and has only been applied where deemed necessary to correct for drift in the data which would otherwise obscure real fuel effects.

Estimated effects on emissions of changes in fuel properties for each vehicle and cycle are tabulated in this section and plotted in Appendix 5. The effects have been estimated by fitting a simple multiple regression model to each emission with linear terms in the four properties. These models are then used to estimate emissions across ranges representative of the properties actually measured across the 14 fuels.

Data handling and analysis is discussed in detail in the Statistical Methodology Appendix 6.

4.2 ESTIMATES OF DENSITY EFFECTS

Table 8 Estimates of density effects

DENSITY (820 - 855 kg/m^3)[a]	Vehicle 1		Vehicle 2		Vehicle 3	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
CO_2 (g/km)	148.8 - 151.5 ***	132.9 - 135.2 ***	113.8 - 116.2 ***	103.4 - 105.1 ***	93.4 - 95.2 ***	91.9 - 93.6 ***
Energy consumption (MJ/100km)	202.8 - 204.1 *	180.9 - 181.2 NS	155.4 - 156.6 *	140.7 - 140.9 NS	127.4 - 127.9 NS	125.1 - 125.5 NS
Fuel consumption (l/100km)	5.742 - 5.594 ***	5.121 - 4.966 ***	4.400 - 4.291 ***	3.986 - 3.861 ***	3.608 - 3.505 ***	3.542 - 3.439 ***
NOx (g/km)	0.213 - 0.218 NS	0.450 - 0.448 NS	0.178 - 0.222 **	0.576 - 0.586 NS	0.0672 - 0.0655 NS	0.0339 - 0.0267 ***
PM (mg/km)	15.49 - 17.47 ***	13.47 - 15.94 **	0.830 - 0.696 NS	0.416 - 0.428 NS	0.292 - 0.259 NS	0.192 - 0.163 NS
PN (#)	4.50E+13 - 4.65E+13 **	3.78E+13 - 4.10E+13 ***	4.68E+11 - 1.67E+11 ***	1.28E+09 - 2.59E+08 ***	2.79E+10 - 1.72E+10 **	3.07E+08 - 3.45E+08 NS
HC (g/km)	0.022 - 0.030 ***	0.002 - 0.002 NS	0.029 - 0.041 ***	0.006 - 0.003 **	0.0038 - 0.0058 *	Too low to model
CO (g/km)	0.244 - 0.336 ***	0.011 - 0.008 NS	0.173 - 0.253 ***	0.005 - 0.006 NS	0.122 - 0.149 **	0.018 - 0.020 NS

[a] Estimated responses over the density range 820 – 855 kg/m^3 with CN = 50, PAH = 4.75%m/m and FAME = 4.75%v/v
Significance of effects: *** P<0.1%, **P<1%, * P<5%, NS not significant at P<5%.
Significant increasing effects are shown in red, significant decreasing effects are shown in green.

Fuel Consumption: Volumetric fuel consumption decreases as density increases: this is observed in all three vehicles and both test scenarios and is expected to be due to the higher energy content injected per unit volume of fuel.

Energy Consumption: Energy consumption is statistically unchanged as density changes, except in NEDC tests in the Euro 4 and 5 vehicles where there is a slight increase with density and the lack of signal in the WLTC tests highlights the dependency of fuel effects on test cycle. This indicates that the injected volume is largely being adjusted via the Accelerator Pedal Position (APP) to compensate for the change in injected mass. This is happening because the vehicles are operating at part load (road load) and maintaining the same APP for a high density fuel would result in higher mass injection and therefore an increase in speed.

CO2: There is a tendency for CO_2 to increase with density which is observed in all three vehicles and test cycles. This could indicate that the difference in injected mass is not compensated for entirely for the higher density fuels; however is probably predominantly due to the higher C/H ratio of heavier components comprising the high density fuels.

HC & CO: In the NEDC results, higher density is associated with increased HC and CO which could be due to the slight mixture enrichment and higher C/H ratio corroborated by the increased CO_2. This relationship is not apparent during the WLTC cycle when the oxidation catalyst is fully warm and HC and CO levels are inherently very low and this highlights the dependency of fuel effects on test cycle. In fact in the case of the Euro 5, HC tends to be lower with high density fuels over the WLTC.

PM & PN: PM & PN increases with density in the Euro 4 vehicle in both test cycles, again expected to be linked to slight enrichment and higher C/H ratio. This vehicle is not fitted with a DPF, therefore it is unsurprising that fuel effects on PM are more apparent than in the Euro 5 and Euro 6 test vehicles and this highlights the influence of vehicle technology on fuel effects. Fewer particles were produced in the DPF-equipped cars with higher density fuels in some cases.

NOx: An increase in NO_x was associated with increased density only in the Euro 5 NEDC tests. This could be due to elevated peak combustion temperatures. The opposite effect was seen in the WLTC tests in the Euro 6 vehicle, although in this vehicle, SCR is likely to influence the results at the tailpipe.

Summary of density effects: The increases primarily exemplified in CO_2 emissions observed with the current in-market vehicle technologies tested suggest that some environmental penalties would result from relaxing the current diesel density upper limit. Some of the negative effects are likely to be largely mitigated by increased sophistication of exhaust after-treatment and fuel injection hardware and calibration as vehicle technology evolves through the current Euro 6 phase and beyond. However the higher CO_2 emissions are likely to persist as a result of increased C/H ratio associated with heavy components and the penalty of increased tailpipe CO_2 emissions associated with increased density fuels would have to be weighed against the benefits of widening the usable diesel fuel envelope.

No fuels tested fell substantially below the current lower density limit, however, by extrapolation the data indicate that reducing the density lower limit somewhat would have no negative effects on emissions, though it would have negative impacts on volumetric fuel consumption and potentially maximum power.

4.3 ESTIMATES OF CETANE NUMBER EFFECTS

Table 9 Estimates of cetane number effects

CETANE NUMBER (46 - 54)[b]	Euro 4		Euro 5		Euro 6	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
CO_2 (g/km)	150.2 - 150.2 NS	134.2 - 133.9 NS	115.5 - 114.6 **	104.5 - 104.0 NS	94.3 - 94.3 NS	92.9 - 92.6 NS
Energy consumption (MJ/100km)	203.6 - 203.3 NS	181.1 - 181.0 NS	156.6 - 155.3 **	141.1 - 140.5 NS	127.6 - 127.7 NS	125.3 - 125.2 NS
Fuel consumption (l/100km)	5.669 - 5.667 NS	5.043 - 5.045 NS	4.362 - 4.329 **	3.930 - 3.918 NS	3.554 - 3.560 NS	3.491 - 3.491 NS
NOx (g/km)	0.212 - 0.220 *	0.453 - 0.444 NS	0.196 - 0.205 NS	0.590 - 0.573 NS	0.0662 - 0.0665 NS	0.0325 - 0.0281*
PM (mg/km)	14.79 - 18.17 ***	13.46 - 15.95 **	0.786 - 0.740 NS	0.416 - 0.429 NS	0.317 - 0.234 NS	0.205 - 0.150 NS
PN (#)	4.24E+13 - 4.93E+13 ***	3.73E+13 - 4.16E+13 ***	3.00E+11 - 2.61E+11 NS	6.62E+08 - 5.01E+08 NS	2.72E+10 - 1.77E+10 **	3.05E+08 - 3.48E+08 NS
HC (g/km)	0.031 - 0.021 ***	0.002 - 0.002 NS	0.044 - 0.025 ***	0.005 - 0.004 NS	0.0058 - 0.0039 *	Too low to model
CO (g/km)	0.359 - 0.222 ***	0.010 - 0.009 NS	0.260 - 0.166 ***	0.005 - 0.005 NS	0.153 - 0.118 ***	0.021 - 0.017 NS

[b] Estimated responses over the CN range 46 – 54 with density = 837.5 kg/m^3, PAH = 4.75%m/m and FAME = 4.75%v/v

Significance of effects: *** P<0.1%, **P<1%, * P<5%, NS not significant at P<5%.

Significant increasing effects are shown in red, significant decreasing effects are shown in green.

Fuel consumption, energy consumption and CO2: Increased cetane number is associated with decreased CO_2, energy consumption and fuel consumption in the Euro 5 vehicle NEDC data, though the effects are very small. This is expected to be due to the higher CN fuels advancing combustion to a more thermodynamically efficient phasing. It is postulated that this correlation is not evident in the Euro 4 vehicle because of the less retarded - therefore less sensitive - combustion phasing employed to favour efficiency over NOx abatement, as well as to the higher EGR rate likely to be applied in the Euro 5 vehicle. It is postulated that in some Euro 6+ technology vehicles where exhaust after-treatment rather than in-cylinder NOx abatement strategies are common that the CN - CO_2 link would be less prevalent and this appears to be demonstrated in the Euro 6 vehicle in which the link is also not apparent. The lack of these benefits in either the Euro 5 WLTC data or any of the Euro 4 and Euro 6 data demonstrates the influence of both test cycle and vehicle calibration on fuel effects.

PM, PN and NOx: In the Euro 4 vehicle, a PM and PN (as well as a NOx) increase is associated with increasing CN. This is likely to be due to high CN fuels reducing ignition delay and therefore limiting air-fuel pre-mixing time. The PM effect is not observed in the Euro 5 nor the Euro 6 vehicle, probably due to the use of a DPF and is therefore unlikely to be a first order concern in other Euro 5+ technology vehicles. Increasing CN also tended to produce higher PN in the non-DPF Euro 4 car but fewer particles from the DPF-equipped Euro 6 vehicle in the NEDC. Higher engine out PM in DPF equipped vehicles (Euro 5+) could lead to higher fuel consumption and CO_2 due to increased engine pumping work and fuel required for active DPF regeneration. A decrease in NOx was seen in the Euro 6 vehicle but only in the WLTC test cycle.

HC and CO: In all three vehicles higher CN is associated with lower CO and HC in the NEDC. In the Euro 6 vehicle the reduction was statistically significant for the CO in the NEDC. This could be due to the cold start where the longer ignition delay is countered by reduced ignition delay of the increase in cetane providing more optimal combustion phasing and also due to the oxidation catalyst not operating efficiently during the cold start. The trend in HC and CO is not observed in the hot start WLTC probably because of the inherently lower HC and CO levels commensurate with the oxidation catalyst working more efficiently at higher temperatures, again showing the influence of test cycle. In the Euro 6, the WLTC HC levels were too low to enable modelling.

Summary of cetane number effects: CO_2 benefits were measured with higher cetane number only in the Euro 5 car under NEDC operation, whereas PM and NOx penalties were only measured in the Euro 4 NEDC and a NOx benefit was noted in the Euro 6 vehicle (WLTC only), indicating CN effects are vehicle and test cycle dependent. Benefits in CO and HC emissions were observed in all 3 vehicles but only observed in the cold start NEDC where HC and CO levels are in the measurable range. Overall there is no conclusive evidence in this programme that supports the reduction or increase in the current CN minimum specification level and in fact an increase in PM and PN in the non-DPF equipped vehicle was observed with higher cetane number.

4.4 ESTIMATES OF PAH EFFECTS

Table 10 Estimates of PAH effects

PAH (2.0 - 7.5%m/m)[c]	Euro 4		Euro 5		Euro 6	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
CO_2 (g/km)	150.3 - 150.0 NS	133.7 - 134.4 *	115.2 - 114.9 NS	104.3 - 104.3 NS	94.1 - 94.5 NS	92.7 - 92.8 NS
Energy consumption (MJ/100km)	203.9 - 203.0 NS	180.7 - 181.4 *	156.4 - 155.6 NS	140.9 - 140.8 NS	127.5 - 127.9 NS	125.3 - 125.2 NS
Fuel consumption (l/100km)	5.679 - 5.657 NS	5.031 - 5.057 *	4.354 - 4.337 NS	3.923 - 3.924 NS	3.549 - 3.565 NS	3.490 - 3.491 NS
NOx (g/km)	0.215 - 0.216 NS	0.449 - 0.448 NS	0.203 - 0.198 NS	0.578 - 0.585 NS	0.0665 - 0.0662 NS	0.0304 - 0.0302 NS
PM (mg/km)	15.93 - 17.03 *	13.92 - 15.49 *	0.720 - 0.806 NS	0.442 - 0.402 NS	0.295 - 0.255 NS	0.184 - 0.171 NS
PN (#)	4.51E+13 - 4.64E+13 *	3.83E+13 - 4.05E+13 **	2.18E+11 - 3.58E+11 *	4.21E+08 - 7.88E+08 NS	2.18E+10 - 2.21E+10 NS	3.26E+08 - 3.25E+08 NS
HC (g/km)	0.026 - 0.027 NS	0.002 - 0.002 NS	0.035 - 0.034 NS	0.004 - 0.005 *	0.0048 - 0.0049 NS	Too low to model
CO (g/km)	0.289 - 0.292 NS	0.009 - 0.010 NS	0.222 - 0.204 NS	0.005 - 0.005 NS	0.136 - 0.135 NS	0.019 - 0.019 NS

[c] Estimated responses over the PAH range 2.0 – 7.5%m/m with density = 837.5 kg/m³, CN = 50 and FAME = 4.75%v/v
Significance of effects: *** P<0.1%, **P<1%, * P<5%, NS not significant at P<5%.
Significant increasing effects are shown in red, significant decreasing effects are shown in green.

PM & PN: There are few significant effects of PAH on the test metrics and none of these were consistent across the vehicle/test combination except for a significant increase in PM & PN in both test cycles in the Euro 4 vehicle. This could be linked with slower burning of heavy, carbon rich species impeding complete combustion. This association is not evident in the Euro 5 and Euro 6 vehicles possibly because of the DPF greatly reducing PM levels, hence suppressing any fuel related signals in the PM data. This is unlikely to be a first order concern in other Euro 5+ technology vehicles due to the pervasive use of DPFs. However, higher engine out PM in DPF equipped vehicles (Euro 5+) could lead to higher fuel consumption and CO_2 due to increased engine pumping work and fuel required for active DPF regeneration.

Fuel consumption, energy consumption and CO2: There were significant increases in CO_2, energy and fuel consumption in the Euro 4 WLTC data only, again illustrating the influence of both test cycle and vehicle calibration on fuel effects.

HC: There was also a slightly significant difference in HC for the WLTC in the Euro 5 car although the values were very low.

Summary of PAH effects: Effects of higher PAH levels were few and inconsistent and the tailpipe PM and PN increase only observed in the non-DPF car would not be expected in Euro 5+ vehicles – there is overall little evidence for reducing the PAH limit.

4.5 ESTIMATES OF FAME EFFECTS

Table 11 Estimates of FAME effects

FAME (0.0 - 9.5%v/v)[d]	Euro 4		Euro 5		Euro 6	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
CO_2 (g/km)	150.1 - 150.2 NS	134.0 - 134.1 NS	115.0 - 115.0 NS	104.1 - 104.4 NS	94.1 - 94.5 NS	92.7 - 92.8 NS
Energy consumption (MJ/100km)	203.5 - 203.4 NS	181.2 - 180.9 NS	156.2 - 155.7 NS	140.8 - 140.8 NS	127.6 - 127.8 NS	125.4 - 125.2 NS
Fuel consumption (l/100km)	5.629 - 5.708 ***	5.012 - 5.076 ***	4.321 - 4.370 ***	3.895 - 3.952 ***	3.528 - 3.585 ***	3.469 - 3.512***
NOx (g/km)	0.212 - 0.219 *	0.441 - 0.457 *	0.200 - 0.201 NS	0.572 - 0.591 NS	0.0656 - 0.0671 NS	0.0311 - 0.0294 NS
PM (mg/km)	17.55 - 15.41 ***	16.11 - 13.30 ***	0.799 - 0.727 NS	0.442 - 0.402 NS	0.299 - 0.251 NS	0.188 - 0.167 NS
PN (#)	4.68E+13 - 4.47E+13 ***	4.06E+13 - 3.81E+13 ***	2.97E+11 - 2.63E+11 NS	5.15E+08 - 6.44E+08 NS	1.87E+10 - 2.58E+10 *	2.95E+08 - 3.59E+08 NS
HC (g/km)	0.026 - 0.026 NS	0.002 - 0.003 NS	0.037 - 0.033 *	0.003 - 0.005 *	0.0053 - 0.0044 NS	Too low to model
CO (g/km)	0.302 - 0.279 NS	0.010 - 0.009 NS	0.222 - 0.204 *	0.005 - 0.005 NS	0.143 - 0.129 *	0.021 - 0.017 NS

[d] Estimated responses over the FAME range 0.0 – 9.5%v/v with density = 837.5 kg/m^3, CN = 50 and PAH = 4.75%m/m

Significance of effects: *** P<0.1%, **P<1%, * P<5%, NS not significant at P<5%.

Significant increasing effects are shown in red, significant decreasing effects are shown in green.

Fuel consumption, energy consumption and CO2: As expected, higher FAME levels are associated with increased volumetric fuel consumption due to the replacement of hydrocarbon species with lower energy content oxygenate species, and this is observed in both vehicles and test data sets; however there is no significant effect on energy consumption or CO_2.

PM, PN & NOx: PM & PN is reduced with higher FAME content fuels in the Euro 4 vehicle in both test cycles, whereas NOx increases, again as has been observed in previous studies. The PM effect is not evident in the Euro 5 and Euro 6 vehicle data possibly because of the DPF greatly reducing PM levels, hence suppressing any fuel related signals in the PM data. NOx penalties were also not evident in the Euro 5 and 6 vehicles and this in particular highlights the differences in sensitivities between older and newer vehicle technologies. Lower engine out PM in DPF equipped vehicles (Euro 5+) could lead to lower fuel consumption and CO_2 due to reductions in engine pumping work and the fuel quantity required for active regeneration associated with DPF operation. This could partially offset the increased volumetric fuel consumption associated with FAME containing fuels as well as low level effects on engine power.

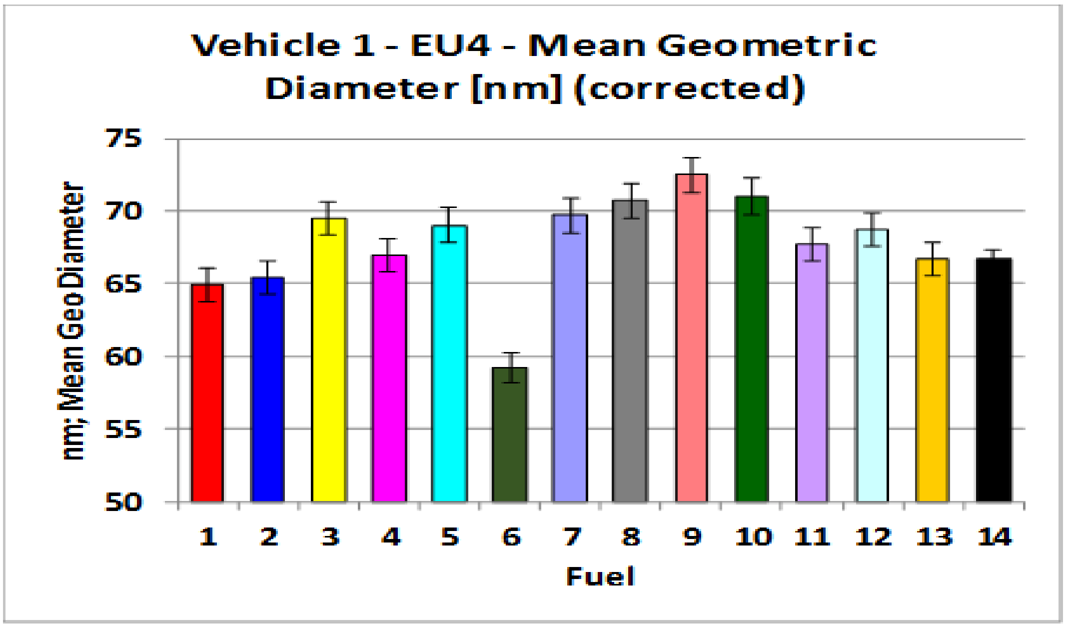
HC & CO: There is a significant increase in HC associated with FAME in the Euro 5 WLTC data which is somewhat unexpected and could be an indirect effect of the negative correlation between FAME and density although the HC emissions were very low. There are reductions in HC and CO in the Euro 5 NEDC data which are more in line with expectations of FAME effects on emissions although these reductions were not observed in the Euro 4. The Euro 6 shows a slightly significant reduction in CO which is consistent with the Euro 5 vehicle.

Summary of FAME effects: Increasing FAME content had the expected effect of increasing volumetric fuel consumption whereas it had no consistent negative or positive effects on emissions. NOx penalties and PM and PN benefits were only observed in the oldest technology vehicle.

5. RESULTS - FUEL PROPERTY EFFECTS ON PARTICLE SIZE DISTRIBUTION

Analysis of fuel effects on particle size distribution from the 90 km/h steady state testing was only attempted for the Euro 4 car due to the low particle numbers from the Euro 5 and 6 cars due to their DPFs.

Figure 20 Geometric mean particle diameter for all fuels in the Euro 4 car over 90km/h steady state testing. Error bars denote ±1 standard deviation



It can be seen from the data in Figure 20 that some fuel effects are apparent on mean particle size.

Figure 21 Mean particle size distribution for all fuels in the Euro 4 car over steady state testing

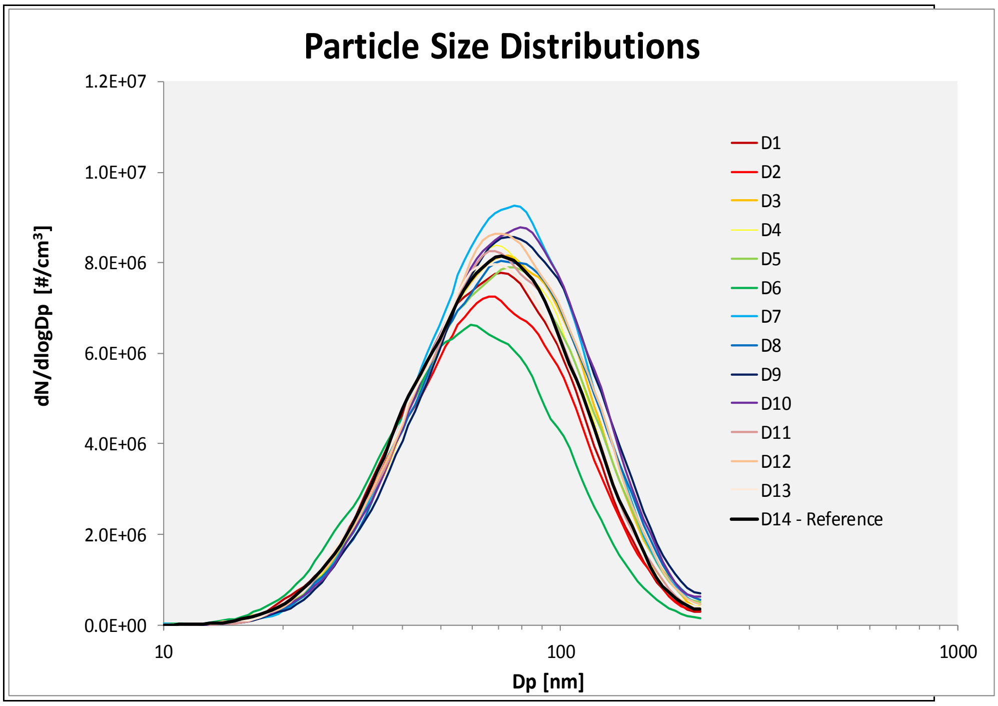


Table 12 Estimates of fuel property effects on mean particle size in the Euro 4 over 90km/h steady state testing

Fuel property	Range	Modelled mean particle diameter range (nm)
Density	820-855kg/m^3	64.11 - 68.18***
Cetane number	46-54	63.70 - 68.59***
PAH	2.0-7.5% m/m	66.07 - 66.23 NS
FAME	0.0-9.5% v/v	67.53 - 64.77***

Significance of effects: *** P<0.1%, **P<1%, * P<5%, NS not significant at P<5%.
Significant increasing effects are shown in red, significant decreasing effects are shown in green.

Increasing density and cetane number tended to produce particles of larger mean diameter, whereas PAH had no significant effect. Increasing FAME tended to produce smaller mean diameter particles.

6. SUMMARY AND CONCLUSIONS

The current specification governing automotive diesel fuel in Europe, EN590, has been developed taking into consideration environmental and economic effects of fuel sourcing, manufacturing and finished fuel quality as well as maximising the efficient operability of diesel fired vehicles. As vehicle technology evolves along with the diversification of fuel stocks, it may be prudent to re-evaluate the fuel specification to ensure it remains fit-for-purpose and not unnecessarily constraining in terms of fuel supply or vehicle operability. To this end, a test programme was conducted to evaluate the impact of specific diesel properties related to a potential increase in FAME content to meet the requirements of the original renewable energy directive (RED) on emissions and fuel consumption from Euro 5 and Euro 6 light-duty diesel vehicles. Tests were also carried out in a Euro 4 vehicle to provide comparison with previous work as well as earlier technology. Apart from changing Fatty Acid Methyl Ester (FAME) content, properties studied were Poly-Aromatic Hydrocarbon (PAH) content, density, and cetane number.

Traditional correlations between emissions and fuel properties (such as density and CO_2) were clearly evident in the data, confirming that the test programme was capable of discerning real fuel effects on emissions.

Results of emissions testing delivered the following findings:

Density: Increasing density above the current EN590 spec limit, which would be needed to allow an increase in FAME content increases CO_2 in all cases, with varied effects observed for other regulated emissions including increases in cold start HC and CO. Increases observed in the latter could in part be mitigated by more advanced after-treatment systems coming into the market, however before considering increasing the density spec limit, the tailpipe CO_2 penalty would have to be weighed against benefits elsewhere of widening the diesel fuel envelope.

Cetane Number: CO_2, energy consumption and fuel consumption benefits were measured with higher cetane number only in the Euro 5 car under NEDC operation, whereas PM and NOx penalties were only measured in the Euro 4 NEDC and a NOx benefit was noted in the Euro 6 vehicle (WLTC only), indicating CN effects were vehicle and test cycle dependent. Benefits in CO and HC emissions were observed in all 3 vehicles but only observed in the cold start NEDC where HC and CO levels are in the measurable range. Overall there is no conclusive evidence in this programme that supports the reduction or increase in the current CN minimum specification level and in fact an increase in PM and PN in the non-DPF equipped vehicle was observed with higher cetane number.

PAH: Effects of changing PAH levels were few and inconsistent and the tailpipe PM and PN increase only observed in the non-DPF car would not be expected in Euro 5+ vehicles – there was overall little justification for reducing the PAH limit.

FAME: Increasing FAME content had the expected effect of increasing volumetric fuel consumption whereas it had no consistent negative or positive effects on emissions. NOx penalties and PM and PN benefits were only observed in the oldest technology vehicle.

Overall the effect of increasingly sophisticated after-treatment system, vehicle calibration and test cycle clearly dominated fuel effects on emissions and efficiency in this study where changes in fuel properties were relatively small.

7. GLOSSARY

ABS	Anti-lock Braking System
APP	Accelarator Pedal Position
CLD	Chemi-luminescence detection
CN	Cetane Number
CO	Carbon monoxide
CO_2	Carbon dioxide
CPC	Condensation Particle Counter
DI	Direct Injection
DMA	Differential Mobility Analyser
DOC	Diesel Oxidation Catalyst
DOE	Design of Experiment
DPF	Diesel Particulate Filter
EC	Elemental Carbon
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EHN	Ethyl hexyl nitrate
EN590	European specification for diesel fuel
EN14214	European specification for fatty acid methyl esters
EPA	(US) Environmental Protection Agency
EPEFE	European Programme on Emissions, Fuels and Engine Technologies
ESP	Electronic Stability Programme
EUDC	Extra-urban Drive Cycle
FAME	Fatty acid methyl ester
FID	Flame Ionisation Detector
FQD	Fuel Quality Directive
HC	Hydrocarbons
IDI	Indirect Injection

IQT	Ignition Quality Tester
JCAP	Japanese Clean Air Programme
LNT	Lean NOx Trap
NDIR	Non-dispersive Infra-Red
NEDC	New European Drive Cycle
NOx	Nitrogen oxides
OBD	On-board Diagnostics
OEM	Original Equipment Manufacturer
PAH	Polyaromatic hydrocarbons
PM	Particulate Matter
PMP	Particle Measurement Programme
PN	Particle Number
RED	Renewable Energy Directive
RME	Rapeseed methyl ester
SCR	Selective Catalytic Reduction
SMPS	Scanning Mobility Particle Sizer
SOF	Soluble Organic Fraction
Tx	Temp. (°C) at which x% of the fuel has been distilled
UDC	Urban Drive Cycle
WLTC	Worldwide Harmonized Light Duty Test Cycle

8. ACKNOWLEDGEMENTS

The members of Concawe FE/STF-25 would like to acknowledge the contribution of Professor Zissis Samaras, Dr Athanasis Dimaratos and other staff of Laboratory of Applied Thermodynamics, Aristotle University of Thessaloniki for their contribution to this work. They would also like to thank Coryton Advanced Fuels, Coryton, UK for the fuel blending.

9. REFERENCES

1. EU (2009) Renewable Energy Directive, European Commission Directive 2009/EC/28

2. EU (2009) Fuel Quality Directive, European Commission Directive 2009/EC/30

3. Hublin,M., Gadd, P.G.,Hall, D.E and Schindler, K.P. (1995) European Programmes on Emissions, Fuels and Engine Technologies (EPEFE) Light Duty Diesel Study. SAE Paper 961073, 1995. Warrendale PA: Society of Automotive Engineers

4. Williams, A., McCormick, R. L., Hayes, R. R., Ireland, J. et al (2006) Effect of Biodiesel Blends on Diesel Particulate Filter Performance. SAE Technical Paper 2006-01-3280, 2006. Warrendale PA: Society of Automotive Engineers

5. Bhardwaj, O., Kremer, K., Pischinger, S., Lüers, B. et al (2013) Impact of Biomass-Derived Fuels on Soot Oxidation and DPF Regeneration Behavior. SAE Technical Paper 2013-01-1551, 2013. Warrendale PA: Society of Automotive Engineers

6. Lamharess, N., Starck, L., Millet, C. N., and Da Costa, P. Effect of Biofuels on Catalyzed Diesel Particulate Filter Regeneration. Topics in Catalysis, 56: *462-466*, 2013.

7. Czerwinski, J., Bürki, S., Bonsack, P., Mayer, A. et al DPF's Regeneration Procedures and Emissions with RME Blend Fuels. SAE Technical Paper 2012-01-0844, 2012. Warrendale PA: Society of Automotive Engineers

8. Rose, K.D., Hamje H., Jansen, L., Fittavolini, C et.al. Impact of FAME Content on the Regeneration Frequency of Diesel Particulate Filters. SAE Technical Paper 2014-01-1605, 2014. Warrendale PA: Society of Automotive Engineers

9. CONCAWE Report 6/14: Impact of FAME on the performance of three Euro 4 light duty vehicles: Part 1 fuel consumption and regulated emissions, Brussels, May 2014.

10. EPA420-P-02-001: A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions, October 2002

11. Nikanjam, M. Rutherford, J & Morgan, P., Performance and Emissions of Diesel and Alternative Diesel Fuels in Modern Light-Duty Diesel Vehicles. SAE Technical Paper 2011-24-0198, 2011. Warrendale PA: Society of Automotive Engineers

12. Tritthart, P., Chichocko, R. and Cartellieri, W., Fuel Effects on Emissions in Various Test Cycles in Advanced Passenger Car Diesel Vehicles. SAE Paper 932684, 1993. Warrendale PA: Society of Automotive Engineers

13. Mann, N., Kvinge, F. and Wilson, G., Diesel Fuel Effects on Emissions – Towards a Better Understanding. SAE Paper 982486, 1998. Warrendale PA: Society of Automotive Engineers

14. Kwon, Y., Mann, N., Rickeard, D.J., Haugland, R., et. al., Fuel Effects on Diesel Emissions – A New Understanding. SAE Paper 2001-01-3522, 2001. Warrendale PA: Society of Automotive Engineers

15. Hara, S., Kaneko, T., Kakegawa, T., Senbokuya, S., et.al Effects of Fuel Properties on the Performance of Advanced Diesel NOx Aftertreatment Devices. SAE Paper 2006-01-3443, 2006. Warrendale PA: Society of Automotive Engineers

16. Kakegawa, T., Kaneko, T., Hara, S., Sembokuya, S., et.al., Summary Report of Japan Clean Air Program Diesel and Diesel Fuel Activities. SAE Paper 2007-01-1952 or JSAE Technical Paper No. 20077342. Warrendale PA: Society of Automotive Engineers

17. Bielaczyc, P., Kozak, M. and Merkisz, J., Effects of Fuel Properties on Exhaust Emissions From the Latest Light Duty DI Diesel Engine. SAE Paper 2003-01-1882 or JSAE Technical Paper No. 20030355. Warrendale PA: Society of Automotive Engineers

18. Kumar, S. et.al. The Effect of Diesel Fuel Properties on Engine-out Emissions and Fuel Efficiency at Mid-Load Conditions. SAE Paper 2009-01-2697.

19. Hellier, P., Ladommatos, N., Allan, R., Payne, M., et.al The Impact of Saturated and Unsaturated Fuel Molecules on Diesel Combustion and Exhaust Emissions. JSAE Paper 201191.

20. Williams, R., Hamje, H. et al Effect of fuel properties on emissions from Euro 4 and Euro 5 diesel passenger cars. TRA 6th European Transport Research Conference, 2016.

21. Williams, R., Hamje, H., Rickeard, D., Bartsch, T. et al Effect of Diesel Properties on Emissions and Fuel Consumption from Euro 4, 5 and 6 European Passenger Cars. SAE Technical Paper 2016-01-2246, 2016, https://doi.org/10.4271/2016-01-2246. Warrendale PA: Society of Automotive Engineers

22. Williams, R., Hamje, H. et al, Effect of diesel properties on emissions and fuel consumption from Euro 4, 5, & 6 European passenger cars. ETH Combustion Generated Nanoparticles Conference 2017

23. Bishop, G. A. & Stedman, D. H., Emissions of nitrogen dioxide from modern diesel vehicles, Air Pollution XVI, doi:10.2495/AIR080261

24. Alvarez, R., Weilenmann, M., & Favez, J., Evidence of increased mass fraction of NO2 within real-world NOx emissions of modern light vehicles — derived from a reliable online measuring method. Atmospheric Environment, 42, 4699-4707, http://dx.doi.org/10.1016/j.atmosenv.2008.01.046

25. O'Driscoll, R. et al, A Portable Emissions Measurement System (PEMS) study of NOx and primary NO2 emissions from Euro 6 diesel passenger cars and comparison with COPERT emission factors, Atmospheric Environment Vol. 145, 81-91, https://doi.org/10.1016/j.atmosenv.2016.09.021

26. Degraeuwe et al, Impact of passenger car NOx emissions and NO2 fractions on urban NO2 pollution – Scenario analysis for the city of Antwerp, Belgium, Atmospheric Environment Vol. 126, 218-224, https://doi.org/10.1016/j.atmosenv.2015.11.042

27. Williams, R., Andersson, J., Hamje, H., Ziman, P. et al., "Impact of Demanding Low Temperature Urban Operation on the Real Driving Emissions Performance of Three European Diesel Passenger Cars," SAE Technical Paper 2018-01-1819, 2018, doi:10.4271/2018-01-1819.

APPENDIX 1 – MEASURED FUEL PROPERTIES

CORYTON
advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/278	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 1	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	08/08/2013

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		46.0	-	47.5
Cetane Number IQT	ASTM D6890		Report		49.1
Cetane Index	EN ISO 4264		Report		44.8
2-EHN Cetane Improver	Blending	mg/L	Report		0
Density @ 15°C	EN ISO 3675	kg/L	~0.820		0.8186
Flash Point	ASTM D7236	°C	Report		64.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	2	1.6
Total Aromatics	EN 12916 mod	% m/m	Report		22.8
Sulfur	EN ISO 20846	mg/kg	Report		0.3
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.01
Ash	EN ISO 6245	% m/m	Report		0.001
Water Content	EN ISO 12937	mg/kg	Report		30.0
Total Contamination	EN ISO 12662	mg/kg	Report		<6
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	0.1	<0.1
Oxidation Stability	EN ISO 12205	g/m^3	Report		<1
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		154
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		1.736
CFPP	EN 116	°C	Report		<-46
Carbon	ASTM D5291	% m/m	Report		86.87
Hydrogen	ASTM D5291	% m/m	Report		13.13
Oxygen	EN 14078	% m/m	Report		0.00
Gross Calorific Value	IP 12	MJ/kg	Report		46.15
Net Calorific Value	IP 12	MJ/kg	Report		43.463
Distillation					
E250	EN ISO 3405	% v/v	Report		75.2
E350	EN ISO 3405	% v/v	Report		94.0
IBP	EN ISO 3405	°C	Report		178.4
5% Volume Evaporated	EN ISO 3405	°C	Report		189.1
10% Volume Evaporated	EN ISO 3405	°C	Report		191.4
15% Volume Evaporated	EN ISO 3405	°C	Report		193.2
20% Volume Evaporated	EN ISO 3405	°C	Report		195.3
30% Volume Evaporated	EN ISO 3405	°C	Report		199.5
40% Volume Evaporated	EN ISO 3405	°C	Report		204.5
50% Volume Evaporated	EN ISO 3405	°C	Report		211.2
60% Volume Evaporated	EN ISO 3405	°C	Report		220.3
70% Volume Evaporated	EN ISO 3405	°C	Report		235.2
80% Volume Evaporated	EN ISO 3405	°C	Report		274.5
85% Volume Evaporated	EN ISO 3405	°C	Report		311.7
90% Volume Evaporated	EN ISO 3405	°C	Report		338.1
95% Volume Evaporated	EN ISO 3405	°C	Report		352.9
FBP	EN ISO 3405	°C	Report		359.3
Residue	EN ISO 3405	% v/v	Report		1.5

Date:	08/08/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

CORYTON
advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/264	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 2	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	22/07/2013

Test	Method	Unit	Limit		Result
			Min	Max	
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		46.0	-	46.3
Cetane Number IQT	ASTM D6890		Report		47.2
Cetane Index	EN ISO 4264		Report		46.0
2-EHN Cetane Improver	Blending	mg/L	Report		0
Density @ 15°C	EN ISO 3675	kg/L	~0.860		0.8569
Flash Point	ASTM D7236	°C	Report		67.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	2	2.1
Total Aromatics	EN 12916 mod	% m/m	Report		30.6
Sulfur	EN ISO 20846	mg/kg	Report		5.3
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.01
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	EN ISO 12937	mg/kg	Report		80.0
Total Contamination	EN ISO 12662	mg/kg	Report		7.6
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	10.0	9.6
Oxidation Stability	EN ISO 12205	g/m^3	Report		<1
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		173
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		2.812
CFPP	EN 116	°C	Report		-5
Carbon	ASTM D5291	% m/m	Report		86.58
Hydrogen	ASTM D5291	% m/m	Report		12.36
Oxygen	EN 14078	% m/m	Report		1.06
Gross Calorific Value	IP 12	MJ/kg	Report		45.03
Net Calorific Value	IP 12	MJ/kg	Report		42.40
Distillation					
E250	EN ISO 3405	% v/v	Report		31.3
E350	EN ISO 3405	% v/v	Report		92.8
IBP	EN ISO 3405	°C	Report		165.2
5% Volume Evaporated	EN ISO 3405	°C	Report		190.1
10% Volume Evaporated	EN ISO 3405	°C	Report		202.6
15% Volume Evaporated	EN ISO 3405	°C	Report		215.7
20% Volume Evaporated	EN ISO 3405	°C	Report		226.5
30% Volume Evaporated	EN ISO 3405	°C	Report		247.4
40% Volume Evaporated	EN ISO 3405	°C	Report		267.6
50% Volume Evaporated	EN ISO 3405	°C	Report		285.9
60% Volume Evaporated	EN ISO 3405	°C	Report		302.2
70% Volume Evaporated	EN ISO 3405	°C	Report		316.3
80% Volume Evaporated	EN ISO 3405	°C	Report		329.1
85% Volume Evaporated	EN ISO 3405	°C	Report		335.7
90% Volume Evaporated	EN ISO 3405	°C	Report		343.6
95% Volume Evaporated	EN ISO 3405	°C	Report		357.5
FBP	EN ISO 3405	°C	Report		367.5
Residue	EN ISO 3405	% v/v	Report		1.3

Date:	22/07/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

CORYTON advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/265	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 3	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	24/07/2013

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		53.0	-	52.4
Cetane Number IQT	ASTM D6890		Report		54.7
Cetane Index	EN ISO 4264		Report		48.0
2-EHN Cetane Improver	Blending	mg/L	Report		800
Density @ 15°C	EN ISO 3675	kg/L	~0.860		0.8521
Flash Point	ASTM D7236	°C	Report		70.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	2	2.9
Total Aromatics	EN 12916 mod	% m/m	Report		30.7
Sulfur	EN ISO 20846	mg/kg	Report		6.8
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.01
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	EN ISO 12937	mg/kg	Report		30.0
Total Contamination	EN ISO 12662	mg/kg	Report		<6
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	0.1	<0.1
Oxidation Stability	EN ISO 12205	g/m^3	Report		<1
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		312
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		3.002
CFPP	EN 116	°C	Report		-6
Carbon	ASTM D5291	% m/m	Report		87.33
Hydrogen	ASTM D5291	% m/m	Report		12.67
Oxygen	EN 14078	% m/m	Report		0.00
Gross Calorific Value	IP 12	MJ/kg	Report		45.57
Net Calorific Value	IP 12	MJ/kg	Report		42.88
Distillation					
E250	EN ISO 3405	% v/v	Report		30.1
E350	EN ISO 3405	% v/v	Report		91.7
IBP	EN ISO 3405	°C	Report		169.1
5% Volume Evaporated	EN ISO 3405	°C	Report		196.9
10% Volume Evaporated	EN ISO 3405	°C	Report		211.0
15% Volume Evaporated	EN ISO 3405	°C	Report		222.6
20% Volume Evaporated	EN ISO 3405	°C	Report		232.8
30% Volume Evaporated	EN ISO 3405	°C	Report		249.8
40% Volume Evaporated	EN ISO 3405	°C	Report		265.4
50% Volume Evaporated	EN ISO 3405	°C	Report		280.8
60% Volume Evaporated	EN ISO 3405	°C	Report		294.5
70% Volume Evaporated	EN ISO 3405	°C	Report		308.7
80% Volume Evaporated	EN ISO 3405	°C	Report		324.3
85% Volume Evaporated	EN ISO 3405	°C	Report		333.5
90% Volume Evaporated	EN ISO 3405	°C	Report		345.3
95% Volume Evaporated	EN ISO 3405	°C	Report		362.0
FBP	EN ISO 3405	°C	Report		374.2
Residue	EN ISO 3405	% v/v	Report		1.5

Date:	24/07/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

CORYTON advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/279	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 4	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	15/08/2013

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		53.0	-	53.7
Cetane Number IQT	ASTM D6890		Report		55.4
Cetane Index	EN ISO 4264		Report		49.5
2-EHN Cetane Improver	Blending	mg/L	Report		0
Density @ 15°C	EN ISO 3675	kg/L	~0.820		0.8181
Flash Point	ASTM D7236	°C	Report		76.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	2	1.5
Total Aromatics	EN 12916 mod	% m/m	Report		21.0
Sulfur	EN ISO 20846	mg/kg	Report		0.5
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.01
Ash	EN ISO 6245	% m/m	Report		0.003
Water Content	EN ISO 12937	mg/kg	Report		70.0
Total Contamination	EN ISO 12662	mg/kg	Report		<6
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	10.0	9.6
Oxidation Stability	EN ISO 12205	g/m^3	Report		1
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		151
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		1.894
CFPP	EN 116	°C	Report		-28
Carbon	ASTM D5291	% m/m	Report		85.88
Hydrogen	ASTM D5291	% m/m	Report		13.06
Oxygen	EN 14078	% m/m	Report		1.06
Gross Calorific Value	IP 12	MJ/kg	Report		45.52
Net Calorific Value	IP 12	MJ/kg	Report		42.75
Distillation					
E250	EN ISO 3405	% v/v	Report		67.0
E350	EN ISO 3405	% v/v	Report		96.4
IBP	EN ISO 3405	°C	Report		192.4
5% Volume Evaporated	EN ISO 3405	°C	Report		201.3
10% Volume Evaporated	EN ISO 3405	°C	Report		203.3
15% Volume Evaporated	EN ISO 3405	°C	Report		205.5
20% Volume Evaporated	EN ISO 3405	°C	Report		207.4
30% Volume Evaporated	EN ISO 3405	°C	Report		212.6
40% Volume Evaporated	EN ISO 3405	°C	Report		218.3
50% Volume Evaporated	EN ISO 3405	°C	Report		226.2
60% Volume Evaporated	EN ISO 3405	°C	Report		237.0
70% Volume Evaporated	EN ISO 3405	°C	Report		257.0
80% Volume Evaporated	EN ISO 3405	°C	Report		296.5
85% Volume Evaporated	EN ISO 3405	°C	Report		320.7
90% Volume Evaporated	EN ISO 3405	°C	Report		334.1
95% Volume Evaporated	EN ISO 3405	°C	Report		344.6
FBP	EN ISO 3405	°C	Report		352.4
Residue	EN ISO 3405	% v/v	Report		1.4

Date:	15/08/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

CORYTON
advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/318	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 5	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	08/08/2013

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		46.0	-	46.7
Cetane Number IQT	ASTM D6890		Report		48.8
Cetane Index	EN ISO 4264		Report		46.8
2-EHN Cetane Improver	Blending	mg/L	Report		0
Density @ 15°C	EN ISO 3675	kg/L	~0.860		0.8589
Flash Point	ASTM D7236	°C	Report		87.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	8	8.3
Total Aromatics	EN 12916 mod	% m/m	Report		35.8
Sulfur	EN ISO 20846	mg/kg	Report		4.7
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		<0.01
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	EN ISO 12937	mg/kg	Report		50.0
Total Contamination	EN ISO 12662	mg/kg	Report		<6
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	0.1	<0.1
Oxidation Stability	EN ISO 12205	g/m^3	Report		1
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		204
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		3.211
CFPP	EN 116	°C	Report		-5
Carbon	ASTM D5291	% m/m	Report		87.76
Hydrogen	ASTM D5291	% m/m	Report		12.24
Oxygen	EN 14078	% m/m	Report		0.00
Gross Calorific Value	IP 12	MJ/kg	Report		45.61
Net Calorific Value	IP 12	MJ/kg	Report		43.01
Distillation					
E250	EN ISO 3405	% v/v	Report		29.6
E350	EN ISO 3405	% v/v	Report		89.9
IBP	EN ISO 3405	°C	Report		196.2
5% Volume Evaporated	EN ISO 3405	°C	Report		216.5
10% Volume Evaporated	EN ISO 3405	°C	Report		222.7
15% Volume Evaporated	EN ISO 3405	°C	Report		229.0
20% Volume Evaporated	EN ISO 3405	°C	Report		235.2
30% Volume Evaporated	EN ISO 3405	°C	Report		250.8
40% Volume Evaporated	EN ISO 3405	°C	Report		266.7
50% Volume Evaporated	EN ISO 3405	°C	Report		281.8
60% Volume Evaporated	EN ISO 3405	°C	Report		297.7
70% Volume Evaporated	EN ISO 3405	°C	Report		313.5
80% Volume Evaporated	EN ISO 3405	°C	Report		330.4
85% Volume Evaporated	EN ISO 3405	°C	Report		339.6
90% Volume Evaporated	EN ISO 3405	°C	Report		350.1
95% Volume Evaporated	EN ISO 3405	°C	Report		364.8
FBP	EN ISO 3405	°C	Report		373.0
Residue	EN ISO 3405	% v/v	Report		1.5

Date:	08/08/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

CORYTON advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/266	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 6	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	22/07/2013

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		46.0	-	46.6
Cetane Number IQT	ASTM D6890		Report		48.3
Cetane Index	EN ISO 4264		Report		44.6
2-EHN Cetane Improver	Blending	mg/L	Report		0
Density @ 15°C	EN ISO 3675	kg/L	~0.820		0.8237
Flash Point	ASTM D7236	°C	Report		59.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	8	6.6
Total Aromatics	EN 12916 mod	% m/m	Report		15.4
Sulfur	EN ISO 20846	mg/kg	Report		1.1
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.01
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	EN ISO 12937	mg/kg	Report		60.0
Total Contamination	EN ISO 12662	mg/kg	Report		6.7
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	10.0	9.0
Oxidation Stability	EN ISO 12205	g/m^3	Report		3
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		168
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		1.769
CFPP	EN 116	°C	Report		-41
Carbon	ASTM D5291	% m/m	Report		85.95
Hydrogen	ASTM D5291	% m/m	Report		13.06
Oxygen	EN 14078	% m/m	Report		0.99
Gross Calorific Value	IP 12	MJ/kg	Report		45.43
Net Calorific Value	IP 12	MJ/kg	Report		42.65
Distillation					
E250	EN ISO 3405	% v/v	Report		73.1
E350	EN ISO 3405	% v/v	Report		95.6
IBP	EN ISO 3405	°C	Report		169.1
5% Volume Evaporated	EN ISO 3405	°C	Report		183.8
10% Volume Evaporated	EN ISO 3405	°C	Report		186.8
15% Volume Evaporated	EN ISO 3405	°C	Report		189.6
20% Volume Evaporated	EN ISO 3405	°C	Report		193.4
30% Volume Evaporated	EN ISO 3405	°C	Report		200.7
40% Volume Evaporated	EN ISO 3405	°C	Report		208.1
50% Volume Evaporated	EN ISO 3405	°C	Report		217.5
60% Volume Evaporated	EN ISO 3405	°C	Report		227.5
70% Volume Evaporated	EN ISO 3405	°C	Report		242.2
80% Volume Evaporated	EN ISO 3405	°C	Report		282.9
85% Volume Evaporated	EN ISO 3405	°C	Report		318.7
90% Volume Evaporated	EN ISO 3405	°C	Report		336.5
95% Volume Evaporated	EN ISO 3405	°C	Report		348.1
FBP	EN ISO 3405	°C	Report		354.6
Residue	EN ISO 3405	% v/v	Report		1.5

Date:	22/07/2013
Signed: C L Goodfellow Director	[signature]

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

CORYTON advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/280	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 7	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	15/08/2013

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		53.0	-	55.9
Cetane Number IQT	ASTM D6890		Report		55.0
Cetane Index	EN ISO 4264		Report		50.2
2-EHN Cetane Improver	Blending	mg/L	Report		0
Density @ 15°C	EN ISO 3675	kg/L	~0.820		0.8189
Flash Point	ASTM D7236	°C	Report		75.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	8	6.9
Total Aromatics	EN 12916 mod	% m/m	Report		15.5
Sulfur	EN ISO 20846	mg/kg	Report		0.3
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.01
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	EN ISO 12937	mg/kg	Report		30.0
Total Contamination	EN ISO 12662	mg/kg	Report		<6
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	0.1	<0.1
Oxidation Stability	EN ISO 12205	g/m^3	Report		1
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		248
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		2.032
CFPP	EN 116	°C	Report		-40
Carbon	ASTM D5291	% m/m	Report		86.76
Hydrogen	ASTM D5291	% m/m	Report		13.24
Oxygen	EN 14078	% m/m	Report		0.00
Gross Calorific Value	IP 12	MJ/kg	Report		46.20
Net Calorific Value	IP 12	MJ/kg	Report		43.39
Distillation					
E250	EN ISO 3405	% v/v	Report		69.1
E350	EN ISO 3405	% v/v	Report		94.2
IBP	EN ISO 3405	°C	Report		190.6
5% Volume Evaporated	EN ISO 3405	°C	Report		204.6
10% Volume Evaporated	EN ISO 3405	°C	Report		206.8
15% Volume Evaporated	EN ISO 3405	°C	Report		209.4
20% Volume Evaporated	EN ISO 3405	°C	Report		211.7
30% Volume Evaporated	EN ISO 3405	°C	Report		217.7
40% Volume Evaporated	EN ISO 3405	°C	Report		222.5
50% Volume Evaporated	EN ISO 3405	°C	Report		229.1
60% Volume Evaporated	EN ISO 3405	°C	Report		237.8
70% Volume Evaporated	EN ISO 3405	°C	Report		251.6
80% Volume Evaporated	EN ISO 3405	°C	Report		282.4
85% Volume Evaporated	EN ISO 3405	°C	Report		309.3
90% Volume Evaporated	EN ISO 3405	°C	Report		334.4
95% Volume Evaporated	EN ISO 3405	°C	Report		352.9
FBP	EN ISO 3405	°C	Report		360.2
Residue	EN ISO 3405	% v/v	Report		1.5

Date:	15/08/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

CORYTON
advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/319	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 8	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	08/08/2013

Test	Method	Unit	Limit		Result
			Min	Max	
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		53.0	-	54.5
Cetane Number IQT	ASTM D6890		Report		46.0
Cetane Index	EN ISO 4264		Report		48.8
2-EHN Cetane Improver	Blending	mg/L	Report		1500
Density @ 15°C	EN ISO 3675	kg/L	~0.860		0.8555
Flash Point	ASTM D7236	°C	Report		90.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	8	7.9
Total Aromatics	EN 12916 mod	% m/m	Report		28.6
Sulfur	EN ISO 20846	mg/kg	Report		4.2
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.04
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	EN ISO 12937	mg/kg	Report		100.0
Total Contamination	EN ISO 12662	mg/kg	Report		<6
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	10.0	9.4
Oxidation Stability	EN ISO 12205	g/m^3	Report		3
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		177
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		3.098
CFPP	EN 116	°C	Report		-20
Carbon	ASTM D5291	% m/m	Report		86.21
Hydrogen	ASTM D5291	% m/m	Report		12.76
Oxygen	EN 14078	% m/m	Report		1.03
Gross Calorific Value	IP 12	MJ/kg	Report		45.07
Net Calorific Value	IP 12	MJ/kg	Report		42.36
Distillation					
E250	EN ISO 3405	% v/v	Report		28.5
E350	EN ISO 3405	% v/v	Report		91.4
IBP	EN ISO 3405	°C	Report		200.3
5% Volume Evaporated	EN ISO 3405	°C	Report		218.8
10% Volume Evaporated	EN ISO 3405	°C	Report		225.5
15% Volume Evaporated	EN ISO 3405	°C	Report		231.2
20% Volume Evaporated	EN ISO 3405	°C	Report		237.2
30% Volume Evaporated	EN ISO 3405	°C	Report		252.3
40% Volume Evaporated	EN ISO 3405	°C	Report		268.4
50% Volume Evaporated	EN ISO 3405	°C	Report		285.1
60% Volume Evaporated	EN ISO 3405	°C	Report		302.0
70% Volume Evaporated	EN ISO 3405	°C	Report		317.7
80% Volume Evaporated	EN ISO 3405	°C	Report		332.0
85% Volume Evaporated	EN ISO 3405	°C	Report		339.3
90% Volume Evaporated	EN ISO 3405	°C	Report		347.3
95% Volume Evaporated	EN ISO 3405	°C	Report		360.1
FBP	EN ISO 3405	°C	Report		366.7
Residue	EN ISO 3405	% v/v	Report		1.4

Date:	08/08/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

Certificate of Analysis

Fuel Blend No:	CAF-G13/320	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 9	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	08/08/2013

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		53.0	-	53.6
Cetane Number IQT	ASTM D6890		Report		56.2
Cetane Index	EN ISO 4264		Report		47.8
2-EHN Cetane Improver	Blending	mg/L	Report		1500
Density @ 15°C	EN ISO 3675	kg/L	~0.860		0.8566
Flash Point	ASTM D7236	°C	Report		88.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	8	8.5
Total Aromatics	EN 12916 mod	% m/m	Report		32.5
Sulfur	EN ISO 20846	mg/kg	Report		4.8
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.04
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	EN ISO 12937	mg/kg	Report		70.0
Total Contamination	EN ISO 12662	mg/kg	Report		<6
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	0.1	<0.1
Oxidation Stability	EN ISO 12205	g/m^3	Report		1
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		177
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		3.222
CFPP	EN 116	°C	Report		-20
Carbon	ASTM D5291	% m/m	Report		87.23
Hydrogen	ASTM D5291	% m/m	Report		12.77
Oxygen	EN 14078	% m/m	Report		0.00
Gross Calorific Value	IP 12	MJ/kg	Report		45.57
Net Calorific Value	IP 12	MJ/kg	Report		42.86
Distillation					
E250	EN ISO 3405	% v/v	Report		28.0
E350	EN ISO 3405	% v/v	Report		90.0
IBP	EN ISO 3405	°C	Report		199.6
5% Volume Evaporated	EN ISO 3405	°C	Report		218.7
10% Volume Evaporated	EN ISO 3405	°C	Report		224.9
15% Volume Evaporated	EN ISO 3405	°C	Report		231.0
20% Volume Evaporated	EN ISO 3405	°C	Report		238.2
30% Volume Evaporated	EN ISO 3405	°C	Report		253.0
40% Volume Evaporated	EN ISO 3405	°C	Report		268.1
50% Volume Evaporated	EN ISO 3405	°C	Report		281.8
60% Volume Evaporated	EN ISO 3405	°C	Report		296.1
70% Volume Evaporated	EN ISO 3405	°C	Report		312.3
80% Volume Evaporated	EN ISO 3405	°C	Report		329.4
85% Volume Evaporated	EN ISO 3405	°C	Report		338.5
90% Volume Evaporated	EN ISO 3405	°C	Report		350.0
95% Volume Evaporated	EN ISO 3405	°C	Report		364.4
FBP	EN ISO 3405	°C	Report		371.4
Residue	EN ISO 3405	% v/v	Report		1.5

Date:	08/08/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

CORYTON
advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/289	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 10	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	08/08/2013

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		53.0	-	53.9
Cetane Number IQT	ASTM D6890		Report		55.0
Cetane Index	EN ISO 4264		Report		51.1
2-EHN Cetane Improver	Blending	mg/L	Report		0
Density @ 15°C	EN ISO 3675	kg/L	~0.840		0.8396
Flash Point	ASTM D7236	°C	Report		89.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	8	7.5
Total Aromatics	EN 12916 mod	% m/m	Report		25.8
Sulfur	EN ISO 20846	mg/kg	Report		2.8
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.01
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	EN ISO 12937	mg/kg	Report		40.0
Total Contamination	EN ISO 12662	mg/kg	Report		<6
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	0.1	<0.1
Oxidation Stability	EN ISO 12205	g/m^3	Report		<1
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		262
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		2.745
CFPP	EN 116	°C	Report		-12
Carbon	ASTM D5291	% m/m	Report		87.17
Hydrogen	ASTM D5291	% m/m	Report		12.83
Oxygen	EN 14078	% m/m	Report		0.00
Gross Calorific Value	IP 12	MJ/kg	Report		45.80
Net Calorific Value	IP 12	MJ/kg	Report		43.08
Distillation					
E250	EN ISO 3405	% v/v	Report		40.2
E350	EN ISO 3405	% v/v	Report		92.4
IBP	EN ISO 3405	°C	Report		202.9
5% Volume Evaporated	EN ISO 3405	°C	Report		221.1
10% Volume Evaporated	EN ISO 3405	°C	Report		225.2
15% Volume Evaporated	EN ISO 3405	°C	Report		227.8
20% Volume Evaporated	EN ISO 3405	°C	Report		232.3
30% Volume Evaporated	EN ISO 3405	°C	Report		241.6
40% Volume Evaporated	EN ISO 3405	°C	Report		249.8
50% Volume Evaporated	EN ISO 3405	°C	Report		261.2
60% Volume Evaporated	EN ISO 3405	°C	Report		275.4
70% Volume Evaporated	EN ISO 3405	°C	Report		295.1
80% Volume Evaporated	EN ISO 3405	°C	Report		316.7
85% Volume Evaporated	EN ISO 3405	°C	Report		328.9
90% Volume Evaporated	EN ISO 3405	°C	Report		342.6
95% Volume Evaporated	EN ISO 3405	°C	Report		359.1
FBP	EN ISO 3405	°C	Report		367.5
Residue	EN ISO 3405	% v/v	Report		1.5

Date:	08/08/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

CORYTON
advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/290	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 11	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	15/08/2013

Test	Method	Unit	Limit		Result
			Min	Max	
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		53.0	-	53.8
Cetane Number IQT	ASTM D6890		Report		55.0
Cetane Index	EN ISO 4264		Report		50.5
2-EHN Cetane Improver	Blending	mg/L	Report		0
Density @ 15°C	EN ISO 3675	kg/L	~0.840		0.8398
Flash Point	ASTM D7236	°C	Report		89.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	8	7.2
Total Aromatics	EN 12916 mod	% m/m	Report		22.6
Sulfur	EN ISO 20846	mg/kg	Report		3.0
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.01
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	EN ISO 12937	mg/kg	Report		70.0
Total Contamination	EN ISO 12662	mg/kg	Report		<6
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	10.0	9.5
Oxidation Stability	EN ISO 12205	g/m^3	Report		1
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		153
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		2.266
CFPP	EN 116	°C	Report		-28
Carbon	ASTM D5291	% m/m	Report		86.15
Hydrogen	ASTM D5291	% m/m	Report		12.80
Oxygen	EN 14078	% m/m	Report		1.05
Gross Calorific Value	IP 12	MJ/kg	Report		45.21
Net Calorific Value	IP 12	MJ/kg	Report		42.49
Distillation					
E250	EN ISO 3405	% v/v	Report		43.1
E350	EN ISO 3405	% v/v	Report		93.9
IBP	EN ISO 3405	°C	Report		203.4
5% Volume Evaporated	EN ISO 3405	°C	Report		220.2
10% Volume Evaporated	EN ISO 3405	°C	Report		224.0
15% Volume Evaporated	EN ISO 3405	°C	Report		225.8
20% Volume Evaporated	EN ISO 3405	°C	Report		229.6
30% Volume Evaporated	EN ISO 3405	°C	Report		237.7
40% Volume Evaporated	EN ISO 3405	°C	Report		247.0
50% Volume Evaporated	EN ISO 3405	°C	Report		258.8
60% Volume Evaporated	EN ISO 3405	°C	Report		276.8
70% Volume Evaporated	EN ISO 3405	°C	Report		301.2
80% Volume Evaporated	EN ISO 3405	°C	Report		323.3
85% Volume Evaporated	EN ISO 3405	°C	Report		332.2
90% Volume Evaporated	EN ISO 3405	°C	Report		340.8
95% Volume Evaporated	EN ISO 3405	°C	Report		353.3
FBP	EN ISO 3405	°C	Report		360.9
Residue	EN ISO 3405	% v/v	Report		1.4

Date:	15/08/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

CORYTON advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/291	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 12	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	15/08/2013

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		53.0	-	54.5
Cetane Number IQT	ASTM D6890		Report		53.4
Cetane Index	EN ISO 4264		Report		51.6
2-EHN Cetane Improver	Blending	mg/L	Report		0
Density @ 15°C	EN ISO 3675	kg/L	~0.840		0.8391
Flash Point	ASTM D7236	°C	Report		87.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	4	4.1
Total Aromatics	EN 12916 mod	% m/m	Report		25.4
Sulfur	EN ISO 20846	mg/kg	Report		3.1
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.01
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	EN ISO 12937	mg/kg	Report		40.0
Total Contamination	EN ISO 12662	mg/kg	Report		<6
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	0.1	<0.1
Oxidation Stability	EN ISO 12205	g/m^3	Report		1
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		277
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		2.781
CFPP	EN 116	°C	Report		-13
Carbon	ASTM D5291	% m/m	Report		87.03
Hydrogen	ASTM D5291	% m/m	Report		12.97
Oxygen	EN 14078	% m/m	Report		0.00
Gross Calorific Value	IP 12	MJ/kg	Report		45.82
Net Calorific Value	IP 12	MJ/kg	Report		43.07
Distillation					
E250	EN ISO 3405	% v/v	Report		37.5
E350	EN ISO 3405	% v/v	Report		92.2
IBP	EN ISO 3405	°C	Report		197.0
5% Volume Evaporated	EN ISO 3405	°C	Report		215.8
10% Volume Evaporated	EN ISO 3405	°C	Report		220.0
15% Volume Evaporated	EN ISO 3405	°C	Report		225.1
20% Volume Evaporated	EN ISO 3405	°C	Report		229.5
30% Volume Evaporated	EN ISO 3405	°C	Report		240.3
40% Volume Evaporated	EN ISO 3405	°C	Report		253.0
50% Volume Evaporated	EN ISO 3405	°C	Report		266.2
60% Volume Evaporated	EN ISO 3405	°C	Report		281.3
70% Volume Evaporated	EN ISO 3405	°C	Report		299.9
80% Volume Evaporated	EN ISO 3405	°C	Report		319.8
85% Volume Evaporated	EN ISO 3405	°C	Report		331.2
90% Volume Evaporated	EN ISO 3405	°C	Report		344.0
95% Volume Evaporated	EN ISO 3405	°C	Report		359.2
FBP	EN ISO 3405	°C	Report		367.7
Residue	EN ISO 3405	% v/v	Report		1.5

Date:	15/08/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

CORYTON advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/292	**Contact:**	Ken Rose
Fuel Type:	Diesel Fuel 13	**Order No:**	201303190
Customer:	CONCAWE	**Date:**	15/08/2013

Test	Method	Unit	Limit		Result
			Min	Max	
Appearance	Visual Rating		Report		C&B
Cetane Number	EN ISO 5165		53.0	-	54.2
Cetane Number IQT	ASTM D6890		Report		54.2
Cetane Index	EN ISO 4264		Report		51.2
2-EHN Cetane Improver	Blending	mg/L	Report		0
Density @ 15°C	EN ISO 3675	kg/L	~0.840		0.8393
Flash Point	ASTM D7236	°C	Report		86.0
Polycyclic Aromatics	EN 12916 mod	% m/m	-	4	4.2
Total Aromatics	EN 12916 mod	% m/m	Report		22.5
Sulfur	EN ISO 20846	mg/kg	Report		2.4
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	Report		0.01
Ash	EN ISO 6245	% m/m	Report		<0.001
Water Content	EN ISO 12937	mg/kg	Report		70.0
Total Contamination	EN ISO 12662	mg/kg	Report		<6
Copper Corrosion	EN ISO 2160	Rating	Report		1a
FAME	EN 14078	% v/v	-	10.0	9.5
Oxidation Stability	EN ISO 12205	g/m^3	Report		2
Oxidation Stability Rancimat	EN 15751	h	Report		>20
Lubricity Correct WSD	EN ISO 12156-1	micron	Report		148
Viscosity at 40°C	EN ISO 3104	mm^2/s	Report		2.675
CFPP	EN 116	°C	Report		-16
Carbon	ASTM D5291	% m/m	Report		86.10
Hydrogen	ASTM D5291	% m/m	Report		12.85
Oxygen	EN 14078	% m/m	Report		1.05
Gross Calorific Value	IP 12	MJ/kg	Report		45.27
Net Calorific Value	IP 12	MJ/kg	Report		42.54
Distillation					
E250	EN ISO 3405	% v/v	Report		40.5
E350	EN ISO 3405	% v/v	Report		93.3
IBP	EN ISO 3405	°C	Report		197.1
5% Volume Evaporated	EN ISO 3405	°C	Report		215.6
10% Volume Evaporated	EN ISO 3405	°C	Report		219.0
15% Volume Evaporated	EN ISO 3405	°C	Report		222.8
20% Volume Evaporated	EN ISO 3405	°C	Report		227.1
30% Volume Evaporated	EN ISO 3405	°C	Report		237.9
40% Volume Evaporated	EN ISO 3405	°C	Report		249.3
50% Volume Evaporated	EN ISO 3405	°C	Report		265.0
60% Volume Evaporated	EN ISO 3405	°C	Report		284.8
70% Volume Evaporated	EN ISO 3405	°C	Report		307.6
80% Volume Evaporated	EN ISO 3405	°C	Report		326.6
85% Volume Evaporated	EN ISO 3405	°C	Report		334.7
90% Volume Evaporated	EN ISO 3405	°C	Report		342.8
95% Volume Evaporated	EN ISO 3405	°C	Report		355.6
FBP	EN ISO 3405	°C	Report		362.8
Residue	EN ISO 3405	% v/v	Report		1.4

Date:	15/08/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

CORYTON advanced fuels

Certificate of Analysis

Fuel Blend No:	CAF-G13/117	**Contact:**	Ken Rose
Fuel Type:	CEC RF-06-08 B5	**Order No:**	TBA
Customer:	CONCAWE	**Date:**	12/09/2013

Test	Method	Unit	Limit		Result
			Min	Max	
Appearance	Visual		Report		C&B
Cetane Number	EN ISO 5165		52.0	54.0	53.2
Cetane Number IQT	ASTM D6890		Report		53.2
Cetane Index	EN ISO 4264		Report		51.9
2-EHN Cetane Improver	Blending	mg/L	Report		0
Density @ 15°C	EN ISO 3675	kg/L	0.833	0.837	0.8342
Flash Point	ASTM D7236	°C	55	-	78.0
Polycyclic Aromatics	EN 12916 mod	% m/m	Report		3.3
Total Aromatics	EN 12916 mod	% m/m	Report		19.8
Sulphur Content	EN ISO 20846	mg/kg	-	10.0	2.1
Carbon Residue (on 10% DR)	EN ISO 10370	% m/m	-	0.2	0.01
Ash Content	EN ISO 6245	% m/m	-	0.01	<0.001
Water Content	EN ISO 12937	% m/m	-	0.02	0.005
Total Contamination	EN ISO 12662	mg/kg	Report		10.5
Copper Corrosion (3h @ 50°C)	EN ISO 2160	Rating	Class 1	-	1a
FAME	EN 14078	% v/v	4.5	5.5	4.9
Oxidation Stability	EN ISO 12205	g/m^3	-	25	1
Oxidation Stability Rancimat	EN 15751	h	20	-	>20
Lubricity Correct WSD	ISO 12156-1	micron	-	400	233
Viscosity @ 40°C	EN ISO 3104	mm^2/s	2.3	3.3	2.519
CFPP	EN 116	°C	-	-15	-36
Carbon	ASTM D5291	% m/m	Report		86.42
Hydrogen	ASTM D5291	% m/m	Report		13.04
Oxygen	EN 14078	% m/m	Report		0.54
Gross Calorific Value	IP 12	MJ/kg	Report		45.71
Net Calorific Value	IP 12	MJ/kg	Report		42.94
Distillation					
E250	EN ISO 3405	% v/v	Report		41.4
E350	EN ISO 3405	% v/v	Report		95.7
IBP	EN ISO 3405	°C	Report		182.6
5% Volume Evaporated	EN ISO 3405	°C	Report		204.8
10% Volume Evaporated	EN ISO 3405	°C	Report		210.8
15% Volume Evaporated	EN ISO 3405	°C	Report		216.6
20% Volume Evaporated	EN ISO 3405	°C	Report		222.6
30% Volume Evaporated	EN ISO 3405	°C	Report		235.2
40% Volume Evaporated	EN ISO 3405	°C	Report		248.2
50% Volume Evaporated	EN ISO 3405	°C	245.0	-	261.8
60% Volume Evaporated	EN ISO 3405	°C	Report		275.1
70% Volume Evaporated	EN ISO 3405	°C	Report		289.5
80% Volume Evaporated	EN ISO 3405	°C	Report		306.5
85% Volume Evaporated	EN ISO 3405	°C	Report		317.8
90% Volume Evaporated	EN ISO 3405	°C	Report		330.5
95% Volume Evaporated	EN ISO 3405	°C	345.0	350.0	346.8
FBP	EN ISO 3405	°C	-	370.0	355.8
Residue	EN ISO 3405	% v/v	Report		1.3

Date:	12/09/2013
Signed: C L Goodfellow Director	

Coryton Advanced Fuels Ltd
The Manorway
Stanford-le-Hope
Essex SS17 9LN, UK

Tel: +44 (0)1375 665707
Fax: + 44 (0)1375 678904
Email: admin@corytonfuels.co.uk
Website: www.corytonfuels.co.uk

10. APPENDIX 2 - INSIGHTS FROM CHASSIS DYNAMOMETER TESTING OF EURO 6 DIESEL PASSENGER CARS

SUMMARY

The additional complexity and new systems employed on modern vehicles can present obstacles when testing such vehicles on a chassis dynamometer. The purpose of this appended report is to record some of the challenges and learning from testing two Euro 6 diesel passenger cars to inform other vehicle testers. It should be noted that the issues described for vehicle A appeared to be the result of a malfunction which was very random and there was no evidence of deliberate unusual calibration of the vehicle system. For vehicle B the issues were more due to the wheel speed discrepancy threshold and the information is provided to share knowledge of the general challenges of testing vehicles with electrical systems.

It was originally intended to procure a single Euro 6 vehicle for the Concawe STF/25 diesel fuel specification property study, however the vehicle initially procured (identified as vehicle A) was problematic under test conditions. Despite deploying considerable effort and expertise, along with some limited support from the relevant OEM, proceeding with the vehicle was deemed unviable and a replacement Euro 6 car from a different OEM (identified as vehicle B) was sourced as an alternative test platform. The second vehicle also presented substantial obstacles to producing a test database on the chassis dynamometer however a viable data base was eventually generated.

The challenges and learning from testing two Euro 6 diesel passenger cars are summarised as:

- Vehicle A appeared to switch on an exhaust heating mode part way in to cold start NEDC tests but only after the initial 5 tests were completed. Symptomatic of this behaviour were large electrical load draw, high AdBlue consumption, post injection activation, start stop & EGR deactivation.
- Vehicle B had a very low wheel speed discrepancy threshold in dyno mode which was exceeded due to wheel slip under WLTC accelerations. This could not be solved via reprogramming or system deactivation but was solved by increasing traction at the CD roller through use of special tyres.
- Vehicle B exhibited erratic electrical system charging and start stop deployment behaviour. Start stop can be easily deactivated. Fitting a new battery temporarily solved the erratic charging behaviour, however this had to be repeated on approximately a monthly basis.

INTRODUCTION

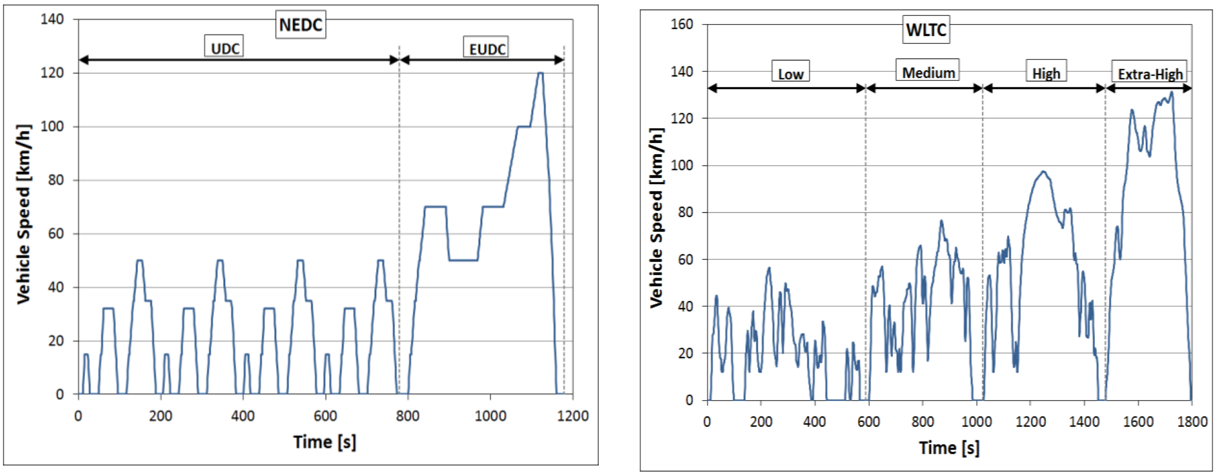
Both the Euro 6 vehicle which was initially tested without success and its replacement featured similar exhaust after-treatment configuration including DOC, DPF & urea-SCR and both originated from large European OEMs. For the purposes of this appendix, the initial vehicle on which testing was unsuccessful is labelled as Vehicle A and the replacement which was eventually tested with success labelled as Vehicle B.

Table 1 Brief description of test vehicles

Vehicle	Vehicle A (testing abandoned)	Vehicle B (testing completed)
Engine configuration / displacement	4L / 2.0L	4L 1.6L
Gearbox	Manual 6-speed	Manual 6-speed
First registered	02/2015	02/2015
Mileage as received	19,000km	10,300km

Fuels from the test fuel set were run during the work described in this appendix and tests were driven over the NEDC and WLTC cycles as described in the main report.

Figure A2.1 The two driving cycles considered in this study (left: NEDC, right: WLTC)



VEHICLE A: CHALLENGES AND INSIGHTS

Overview

The problem that was experienced with Vehicle A consisted of a number of engine control parameters changing for a specific time period during the test. Interestingly the problem was not present from the beginning of the tests. Although this peculiar behaviour was quite repeatable after its first appearance, and one could suggest that it would not affect the comparative analysis of the fuel effects on fuel consumption and emissions, it was decided not to run the tests with this vehicle, for the following two reasons:

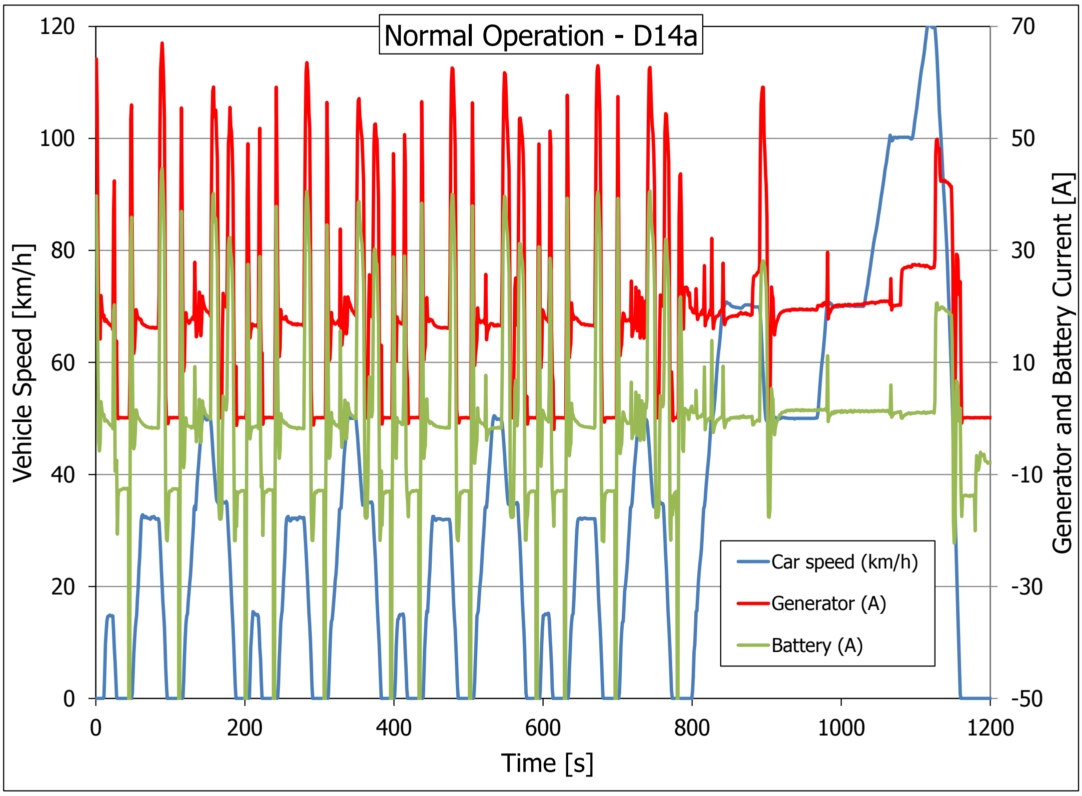
- The phenomena observed were deviating significantly from the normal operation and what the manufacturer specifies for this vehicle in terms of emissions performance, as also confirmed by the local OEM service agent.
- The abnormal behaviour appeared suddenly, without any apparent cause and the mechanism behind it could not be fully investigated and understood with the available means and time. Thus, the specific behaviour was fully uncontrollable and there was equally high probability that the abnormal behaviour could disappear within some days after its first appearance. This would render the tests before and after the switch in behaviour incomparable and would jeopardise the whole testing campaign.

This behaviour was later postulated as being attributable to an exhaust heating strategy employed to raise the SCR system temperature to its normal operating temperature range following cold start.

Behaviour during initial tests

Figures A2.2-2.4 depict key parameters under what is deemed to be normal operation. Figure A2.2 depicts the normal behaviour of the electrical components of the vehicle, i.e. the generator and the battery.

Figure A2.2 Generator and battery currents during the normal operation of Vehicle A



As Figure A2.3 shows in a closer view in, the vehicle is equipped with start-stop and BERS (Brake Energy Regeneration System), both used to reduce fuel consumption. The former stops the engine when the vehicle stands still, eliminating fuel consumption during idling, which is significant in NEDC. The latter activates the generator during deceleration of the vehicle in order to charge the battery, so that it is kept above a critical state of charge, preventing generator activation during acceleration that would impose extra load on the engine. Conversely, generator activation during deceleration does not impose any additional load to the engine (that would cause extra fuel consumption), provided that engine speed is within the fuel cut-off limits.

Each manufacturer may select a different strategy concerning the coverage of electrical consumption, accounting for various parameters such as the battery State of Charge (SoC) and the level of current requirements. As can be seen in Figure A2.3, the constant electrical consumptions, which are around 17 A, are covered by the generator, while during stop phases the battery provides the necessary energy for the electrical consumption (around 13 A). In addition, regenerative braking is activated during each deceleration of the vehicle and the current produced is used to charge the battery (after covering the electrical consumptions). Further, after each engine start, the generator operates at a high load for a very short period in order to replenish the energy consumed by the battery due to the activation of the starter. This practice is used by a number of manufacturers. However, different strategies may also be followed, and this is the case with the Vehicle 2, where, at normal operation, the generator was activated only during regenerative braking charging the battery, which covered the constant electrical consumption of the vehicle throughout the test. Figure A2.4 presents the engine speed profile and the EGR level during the normal operation of the vehicle at NEDC testing, where EGR is between 40% and 60% during constant speed driving.

Figure A2.3 Closer view of the electrical behaviour of Vehicle A

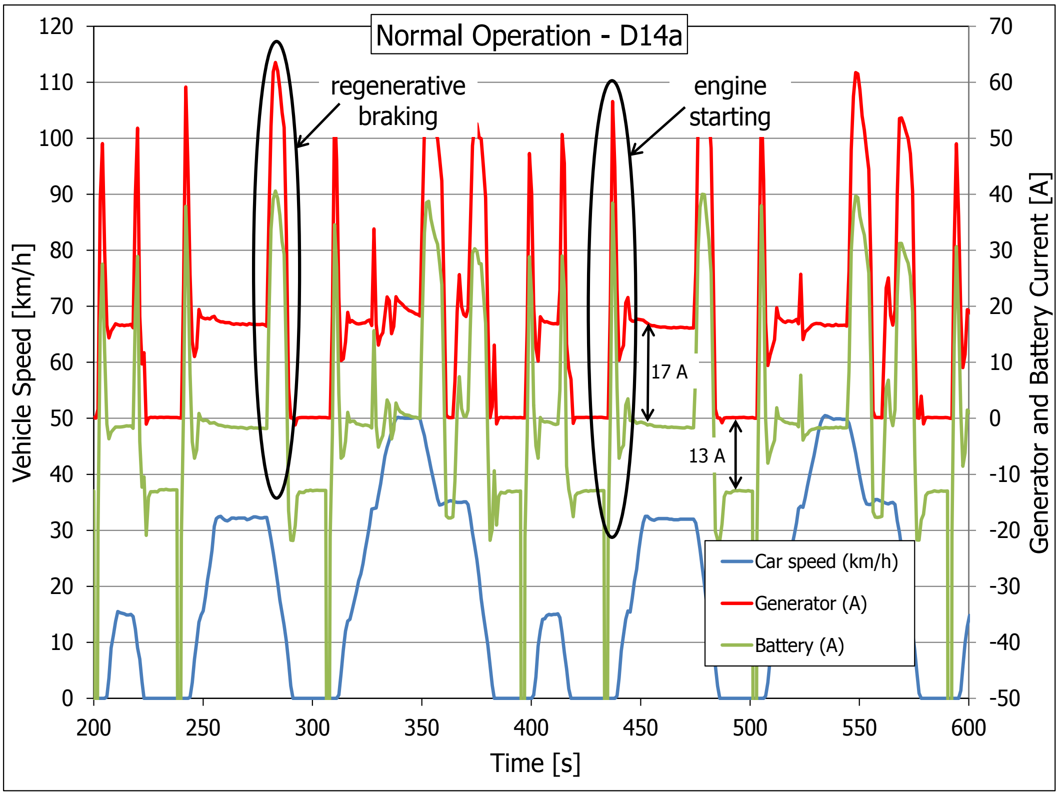
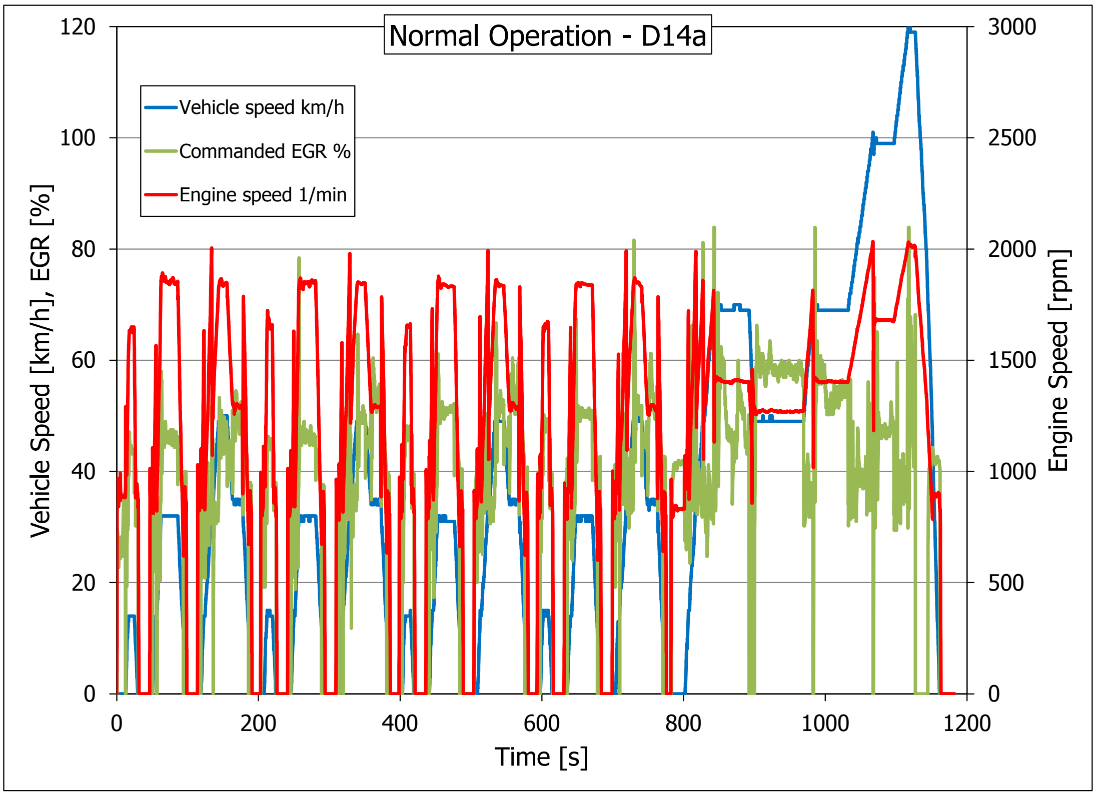


Figure A2.4 Engine speed and EGR level during the normal operation of Vehicle A



Altered behaviour

The abnormal operation of Vehicle A appeared for the first time at the 6th day of testing, while the first five tests were run without any problem. The first symptom of this malfunction (and the only one that could be noticed by the driver) was the deactivation of start-stop for a specific period within NEDC testing, resulting in missing two engine stops (out of 13 in total for the NEDC). However, after thorough investigation, it was found that many other phenomena were occurring during the same period within NEDC testing. In summary, the following appeared from ~150s to ~265s during the (cold start) NEDC:

- **the generator operates at high load**, producing high current (in the order of 50 A), much higher than the constant electrical consumptions of the vehicle (17 A). Most importantly, this current is not used to charge the battery, as can be clearly seen in
-
- Figure *A2.5*, but for the heated rear windscreen and the heated external mirrors of the vehicle (this was found out by touching these components). The reason why these two systems were activated during this phase was not determined. Nevertheless, it must be noted that other systems that consume electrical energy may have also been activated during this phase, without being identified.
- **start-stop deactivates**
- **EGR is deactivated**, as can be seen in

- Figure *A2.6*.
- **Post injection is activated**. The injection system of this engine can apply up to three post injections. During the malfunction phase, the first and the second were activated.

At first appearance, the symptoms were considered random and further investigation was necessary in order to find out if this was systematic behaviour. After some days of testing, it was proven that it was systematic and repeatable, but considered abnormal and uncontrollable.

Figure A2.5 Generator and battery currents during the abnormal operation of Vehicle A

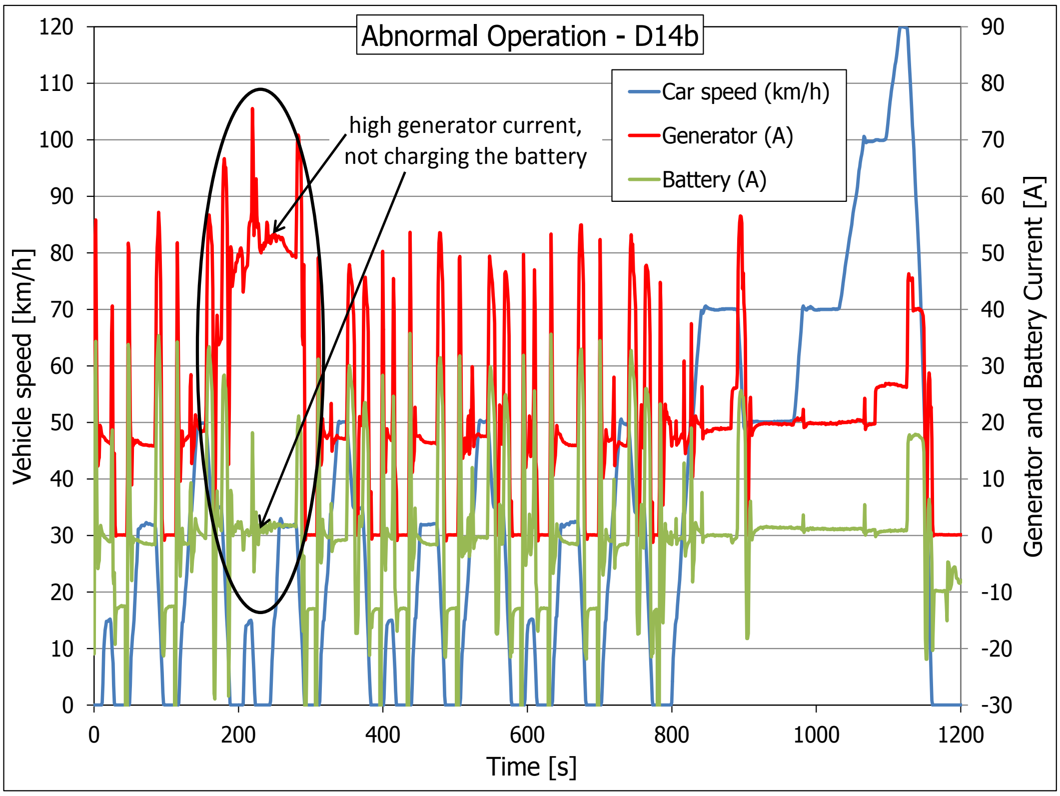
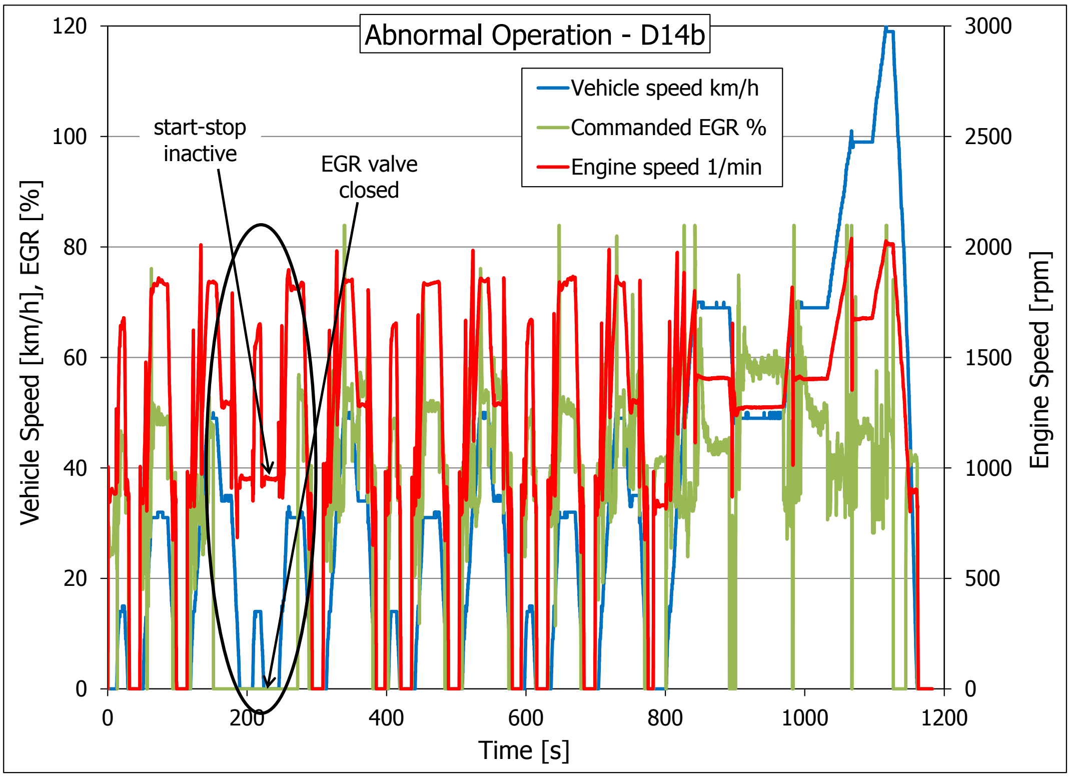
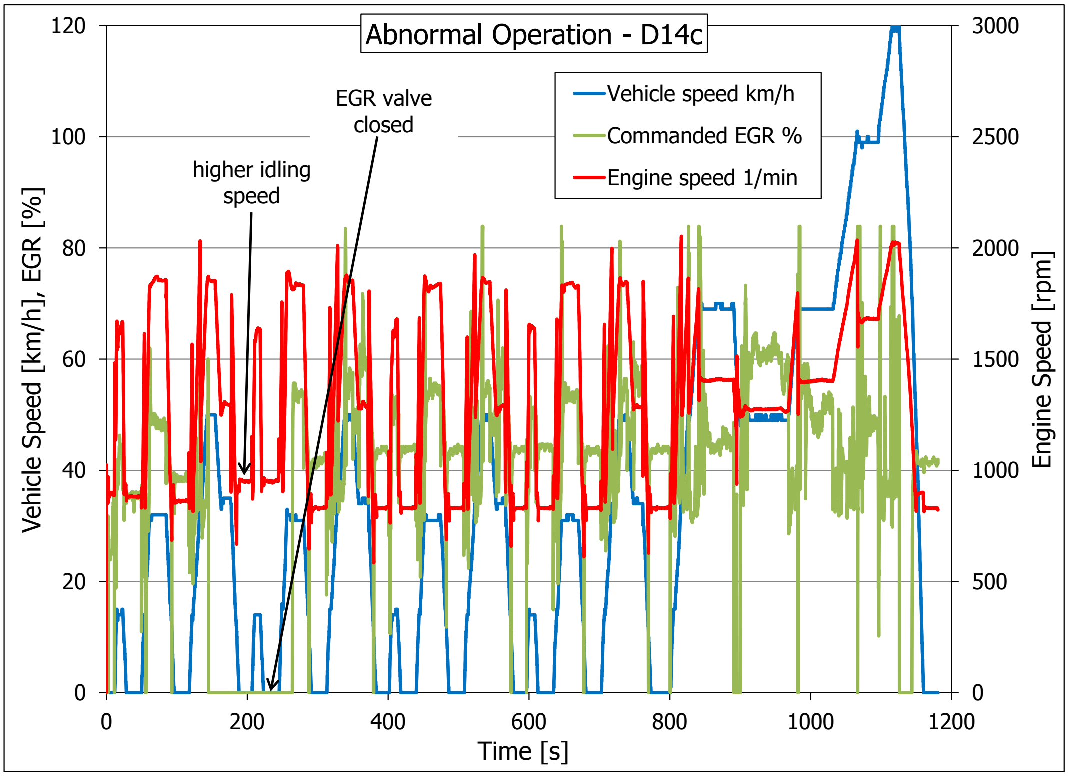


Figure A2.6 Engine speed and EGR level during the abnormal operation of Vehicle A



Overall it appears that these phenomena constitute an exhaust heating strategy to heat up the SCR system into the optimal operating range more quickly following cold start, (though activation of heated rear window and mirrors is not explained by this theory). A number of subsequent tests were run with reference fuel and the behaviour was found to be repeatable. One of the tests was run with the start-stop system deactivated and revealed a new finding: higher engine idling speed during the malfunctioning period (Figure A2.7), owing to the generator load.

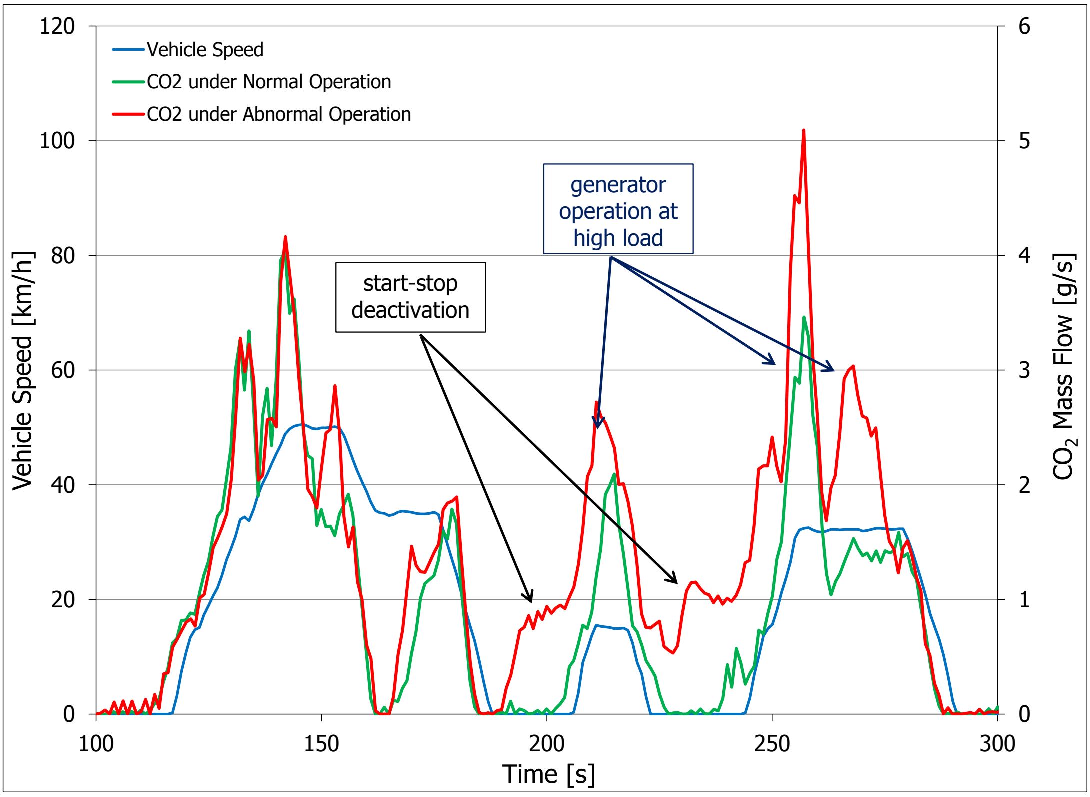
Figure A2.7 Engine speed and EGR level during the abnormal operation of Vehicle A with the start-stop system deactivated



The above described altered behaviour had a significant effect on fuel consumption and emissions over NEDC testing. In absolute numbers, CO_2 emissions increased by 7 g/km and 18 g/km in NEDC and UDC respectively compared to the initial tests. In EUDC there was not any effect, since the abnormal behaviour was occurring only for a specific part of UDC. Figure A2.8 presents the instantaneous CO_2 emissions during the malfunctioning period and the comparison with the normal operation case. Furthermore, NO_x emissions increased, mainly by the full absence of EGR at the malfunctioning case. It is obvious that two measurements with that much different vehicle operation are not comparable. Finally, after some investigation, a number of peculiar OBD recordings were observed that do not make sense (e.g. vehicle speed of some thousands km/h), a fact that may suggest faulty ECU, although no errors were recorded in the diagnostic tool.

A further interesting finding regarded the consumption of AdBlue, the urea solution used in the SCR catalyst. According to the OEM, the 16-litre AdBlue tank of the vehicle is sufficient for approximately 15,000 km, which means that the foreseen AdBlue consumption is around 1 l/1,000km. However, it was observed that after 1,500 km of driving, including the first five normal testing days and a number of malfunctioning tests, 4.5 l AdBlue were consumed. This was an indication of a possible malfunction of the SCR system, although there were not any fault recordings in the diagnostic tool.

Figure A2.8 Instantaneous CO_2 emissions during normal and abnormal operation of Vehicle A



Actions taken to address the problems

After having fully observed the phenomenon and found out that it was a repeatable behaviour of the vehicle during NEDC testing, a number of actions were taken attempting to resolve the problem. Since it was impossible to determine one specific cause for this malfunction, the steps followed were based on logical assumptions, starting from the simplest actions:

- Firstly the car battery was replaced with a brand new, original equipment part. A brand new battery with better storage capacity might prevent start-stop deactivation, which was the first observation and was assumed that it was caused by a damaged battery. This action was taken before finding out the other symptoms of the malfunction (alternator operation, EGR valve closure, post injection etc.).
- After observing the problem at its full extent, a deeper investigation and diagnosis was conducted, with the assistance of the local OEM service agent. All the vehicle systems and components were tested and checked but no fault recordings were found in the diagnostic tool.
- After that, the vehicle was removed from the chassis dyno and was driven on the road (without the “dyno mode”, which is necessary for vehicle testing on the chassis dyno) for about 250km. However, after these actions the problem was not resolved and the malfunction continued to appear at the same phase of NEDC testing.
- The next step was to proceed to the reset of some ECU functions and components that were accessible through the diagnostic tool. The O_2 sensor, the injector controller and the start-stop controller were reset, but did not bring the desired result and the malfunction continued to appear. A possible further step to the same direction could be the ECU re-programming, but this was not a simple action, as it would require the involvement of the manufacturer. This action would be equivalent to replacing the ECU, without, however, ensuring that the problem would be fully resolved.

- There was a suspicion that the ECU did not count in its internal counter the forced DPF regenerations performed daily on the chassis dyno through the diagnostic tool. This might be a reason why at the first part of the cold-start NEDC the ECU tried to warm-up the exhaust, so as to be able to activate DPF regeneration, but after collecting the signals of pressure drop across the DPF and calculating soot loading aborted this action (and the malfunction stopped). In order to exclude this possibility, the vehicle was driven on the road for a long distance, in order to activate by itself some DPF regenerations. The vehicle was driven around 1,200 km. Three DPF regenerations took place during the trip (the DPF regenerations were recognized by recording tailpipe temperature and OBD data).
- A calibration Engineer in the OEM was consulted via Concawe company member contacts, however the suggestions made by the OEM Engineer did not solve the problem.
- The vehicle underwent a full service at the local OEM service agent and all the systems and components were checked.
- Data collected with an OBD logging tool during NEDC testing was analysed but no explanation of the behaviour was evident.

After completing these actions and returning to the laboratory, the same vehicle behaviour was observed during the same phase of NEDC testing.

VEHICLE B: CHALLENGES AND INSIGHTS

Wheel slip and dyno mode deactivation

A major issue encountered with Vehicle B was the low wheel speed discrepancy threshold which ultimately resulted in deactivation of the dyno mode during the test. The dyno mode function is used to deactivate the ABS/ESP as well as the speed sensors of the rear wheels, which do not rotate on the dyno. The deactivation of the dyno mode made it impossible to successfully complete the driving cycle, since a number of errors (e.g. rear wheels not rotating, while vehicle moving) were recorded in the ECU, which in turn limited drastically the operating range of the engine (the engine was allowed to accelerate only up to maximum 2000 rpm, without being able to respond to load demands) for safety reasons. The speed discrepancy between the front wheels, which was the cause of this problem, was determined by the ECU using the inputs of the speed sensors located at each of the front wheels for the ABS/ESP functions, as well as for the Tyre Pressure Monitoring System (TPMS). The specific vehicle was proven to be very sensitive to front wheel slip (when tested on the dyno), as it is the first time that such a problem was encountered by the test provider.

The critical parameter in this case was the very limited speed discrepancy allowed between the front wheels. It was suspected that the tolerance of wheel slip allowed on the dyno (under dyno mode) is very low compared to the one on the road, and this was confirmed officially by the OEM. Even with support from the local OEM service agent, it was not possible to change or adjust this tolerance to the desired range. When this (very low) tolerance was exceeded, the dyno mode was deactivated, and the ESP/ABS and the speed sensors of the rear wheels were activated. In parallel, the TPMS indicating lamp turned on in the instruments panel, since it translated the speed difference as a tyre failure. Also the ECU recorded additional errors, since the rear wheels were not rotating while the vehicle was moving. As a result, a “SERVICE” message appeared in the instruments panel and the test could not be continued. It is important to underline here that the slip tolerance between the front wheels was exceeded only in WLTC tests, as NEDC does not include strong accelerations. Obviously, with the adoption of WLTC as the type approval driving cycle, the value of the slip tolerance should be revisited by the OEM.

Wheel slip problem - remedial actions

In order to overcome this problem, various solutions were tried, starting from the simplest one and moving to the more complex and costly. The following three solutions were tested:

1. Deactivation of the speed sensors (or unplug them)
2. Bridge the two sensors together (so that an identical speed signal is indicated for both driven wheels)
3. Adjust (increase) wheel traction on the dyno rollers

The first and easiest solution was to deactivate the speed sensors of the front wheels, so that the slip is not measured at all. This is an action often taken in other vehicles; therefore, it was considered a feasible solution. The deactivation was tried through an OBD tool. However, it was not possible to deactivate the speed sensors of the front wheels by any means. After contacting the OEM, this finding was also confirmed officially by the manufacturer. Unplugging the speed sensors was also tried, but this was translated as sensor failure by the ECU, as expected, and the test could not be run.

The second solution tested was to bridge the two sensors together, so that the ECU sees identical rotational speed for both front wheels. This could be done by unplugging one sensor and using the signal from the other for both ECU readings. In order to realise this solution, some spare parts were purchased (mainly the electrical plugs). Numerous alternatives with different electrical connections were tested, either using directly the signal from one speed sensor or amplifying it before feeding it to the ECU or even using resistors and capacitors in order to filter the signal. In all cases the control unit was diagnosing that one speed sensor was missing and the relevant errors could not be erased from the ECU's memory.

The third, and successful, solution tested was to increase the wheel traction on the dyno rollers so as to minimise the slip of the front wheels. This meant that the quality of the contacting surfaces (tyres and rollers) should be modified and the best option was to use other wheels with special tyres (***Figure A2.9***, left) that enhanced the traction on the dyno. Great care was taken in order to ensure the following:

i. The new wheel/tyre combination had the same circumference as the original one. This was very important in order to maintain the same rotational speed of the wheels, which in turn affects the operating point of the engine throughout the driving cycles.

ii. The new wheels/tyres had the same inertia as the original parts, in order to avoid extra or less vehicle loading.

iii. The dyno was reprogrammed and readjusted in order to account for the different friction when the new tyres were used. This way the total vehicle (and thus engine) loading remained exactly the same and was fully consistent with the road load values provided officially by the OEM.

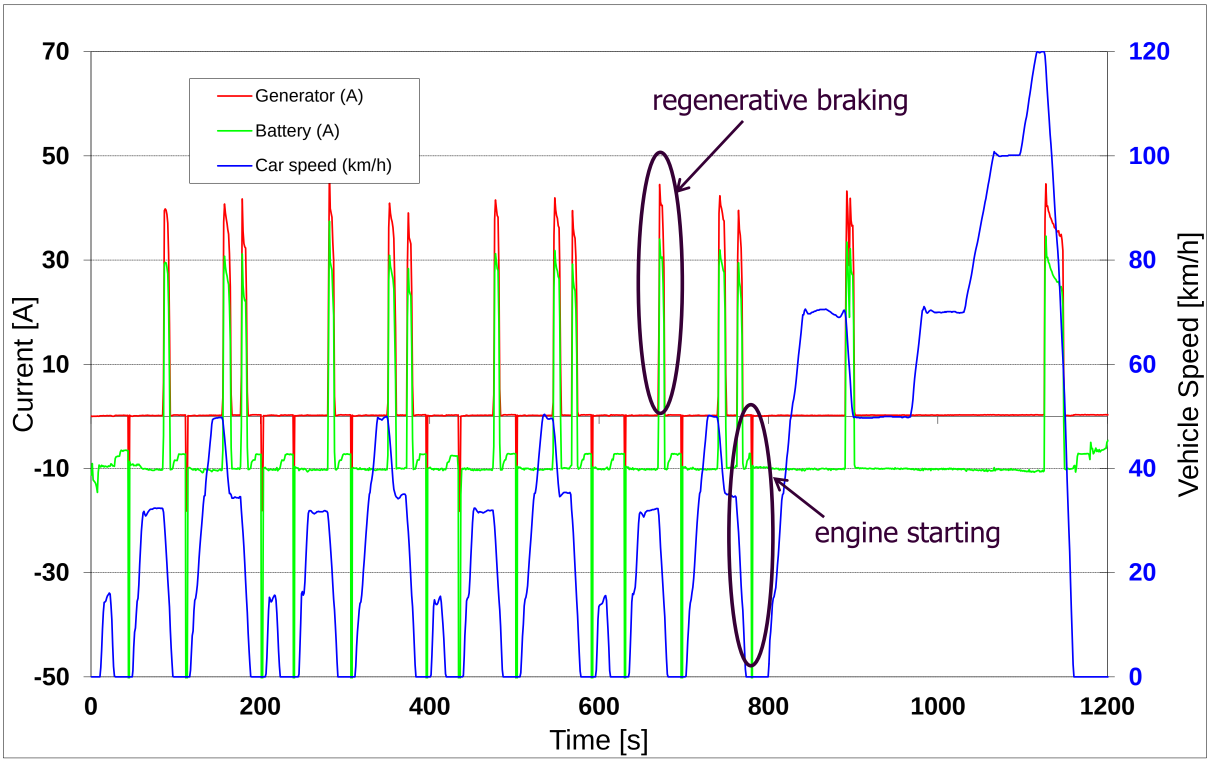
As the new wheels were not specified for the test vehicle, special adaptors (***Figure A2.9***, middle & right) were manufactured in the workshop for correctly fitting them to the vehicle's hubs. After that, a number of trials indicated that both NEDC and WLTC could be tested successfully, without any excessive slip between the front wheels and the subsequent deactivation of the dyno mode.

Figure A2.9 Left: The new wheels and tyres, Middle & right: The adaptors manufactured for fitting the new wheels to Vehicle B.

Inconsistent electrical system behaviour

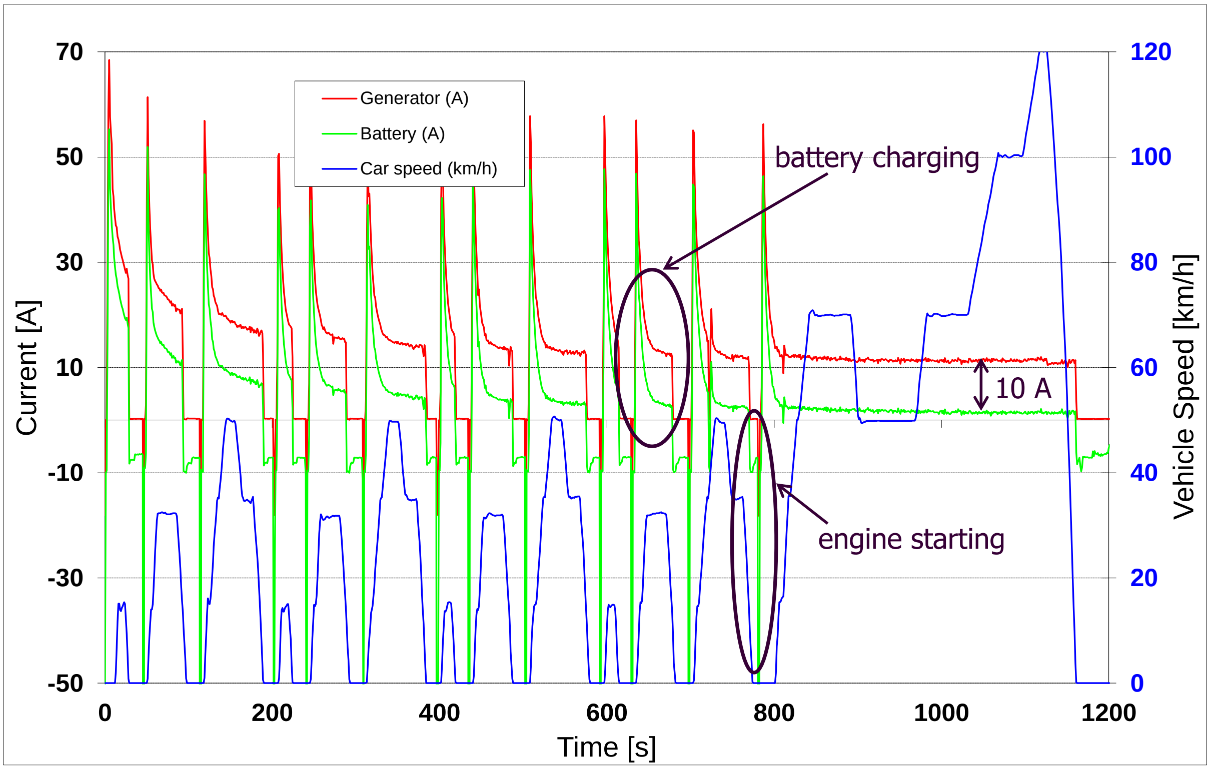
The second problem faced with Vehicle B was the unstable electrical behaviour, mainly during NEDC testing. The vehicle is equipped with start-stop and BERS systems, to reduce fuel consumption. The start-stop stops the engine when the vehicle stands still, eliminating fuel consumption during idling. BERS activates the generator during the deceleration of the vehicle in order to charge the battery, so that it is kept above a critical state of charge, preventing generator activation during acceleration that would impose extra load on the engine. Generator activation during deceleration does not impose any additional load to the engine (that would cause extra fuel consumption), provided that engine speed is within the fuel cut-off limits. Figure A2.10 presents the normal (ideal) behaviour of the battery and the generator.

Figure A2.10 Normal (ideal) generator and battery behaviour during NEDC testing of Vehicle B



As Figure A2.10 shows, the battery covers the constant electrical consumption of the vehicle (10 A, the minus sign means that current is provided by the battery) and the generator is activated only during deceleration, through the regenerative braking function. This is the ideal operation that the manufacturer targets during type approval testing, starting the test with a fully charged battery (being charged during the previous night). On the other hand, Figure A2.11 presents an abnormal behaviour of the electrical system of the vehicle, where the generator is constantly active throughout the cycle in order to charge the battery, which again was fully charged the previous night using an external charger. The positive sign in the battery current signals that current is absorbed by the battery, while the difference between generator and battery currents is constant and equal to 10 A (this can be clearly seen at the end of the cycle where battery current tends to zero), which corresponds to the constant electrical consumption of the vehicle.

Figure A2.11 Abnormal generator and battery behaviour during NEDC testing of Vehicle B



It is obvious that a measurement during which the vehicle presents the normal electrical behaviour (as in Figure A2.10) is not comparable with a measurement where the vehicle presents the electrical behaviour of Figure A2.11 and no conclusions can be drawn concerning fuel effects on consumption and emissions. Given that the vehicle's charging behaviour was observed to switch between the two operating modes illustrated in Figure A2.10 and Figure A2.11 in initial testing, which was also accompanied by erratic deployment of start-stop, remedial action was taken to address the problem.

Inconsistent electrical system behaviour – remedial actions

In order to overcome the issue of different electrical charging strategies affecting fuel test results in the post-processing stage, a correction methodology applicable only to fuel consumption and CO_2 emissions, was developed by the test supplier. The detailed description and the application of this correction methodology is included in the main body of the project report.

In order to avoid any corrections during data processing that might introduce some inaccuracy, this problem was finally overcome at the testing stage by **renewing the battery at the beginning of each test fuel run** and in any other instance that this was found necessary. It was finally concluded that even a brand new battery presents a step drop in its performance after a short period of time (less than a month), something that has been also observed by the official local OEM service agent.

APPENDIX 3 – TEST DATA: TABLES OF MEANS

CO2 Emissions (g/km)

Fuel	Vehicle 1: Euro 4		Vehicle 2: Euro 5		Vehicle 3: Euro 6	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
	Uncorrected	Corrected	Corrected	Uncorrected	Corrected	Corrected
D1	148.73	132.85	113.98	103.72	92.88	92.19
D2	152.64	135.20	117.38	105.55	95.52	93.96
D3	150.98	134.71	115.93	104.23	94.82	93.16
D4	149.18	132.73	113.90	103.24	94.32	92.01
D5	151.49	135.96	117.04	105.10	95.67	93.85
D6	148.86	133.15	114.17	103.92	93.68	91.90
D7	149.48	132.63	113.34	102.57	93.68	91.62
D8	151.79	135.33	115.23	105.92	95.25	93.68
D9	151.30	136.03	115.21	105.61	95.85	94.03
D10	149.60	133.95	115.01	103.42	94.12	93.10
D11	149.89	135.42	114.57	104.27	94.95	92.77
D12	150.64	133.89	114.96	103.92	93.73	92.10
D13	150.16	133.58	115.27	103.99	94.72	92.83
D14 (Ref)	149.67	133.22	114.05	103.93	93.70	92.42

Fuel Consumption (l/100km)

Fuel	Vehicle 1: Euro 4		Vehicle 2: Euro 5		Vehicle 3: Euro 6	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
	Uncorrected	Corrected	Corrected	Uncorrected	Corrected	Corrected
D1	5.728	5.100	4.392	3.983	3.575	3.539
D2	5.648	4.976	4.348	3.885	3.525	3.459
D3	5.557	4.942	4.274	3.824	3.485	3.419
D4	5.806	5.156	4.435	4.011	3.668	3.576
D5	5.515	4.923	4.261	3.805	3.474	3.399
D6	5.759	5.133	4.418	4.006	3.619	3.543
D7	5.702	5.099	4.366	3.943	3.608	3.521
D8	5.637	5.010	4.279	3.921	3.533	3.469
D9	5.544	4.969	4.224	3.858	3.510	3.436
D10	5.594	4.996	4.301	3.858	3.517	3.474
D11	5.672	5.112	4.336	3.936	3.591	3.502
D12	5.648	5.006	4.312	3.885	3.511	3.444
D13	5.686	5.046	4.367	3.928	3.584	3.507
D14 (Ref)	5.683	5.045	4.331	3.936	3.555	3.500

Energy Consumption (MJ/100km)

Fuel	Vehicle 1: Euro 4		Vehicle 2: Euro 5		Vehicle 3: Euro 6	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
	Uncorrected	Corrected	Corrected	Uncorrected	Corrected	Corrected
D1	203.80	181.46	156.27	141.70	127.19	125.93
D2	205.22	180.80	157.96	141.13	128.06	125.67
D3	203.04	180.59	156.17	139.72	127.35	124.92
D4	203.05	180.33	155.10	140.28	128.30	125.02
D5	203.72	181.85	157.42	140.58	128.34	125.56
D6	202.32	180.33	155.19	140.74	127.13	124.48
D7	202.59	181.19	155.13	140.12	128.19	125.14
D8	204.26	181.57	155.06	142.09	128.03	125.71
D9	203.54	182.44	155.10	141.63	128.87	126.12
D10	202.34	180.71	155.56	139.54	127.20	125.64
D11	202.38	182.40	154.71	140.46	128.14	124.97
D12	204.13	180.91	155.83	140.41	126.89	124.48
D13	203.03	180.15	155.91	140.25	127.96	125.18
D14 (Ref)	203.58	180.71	155.12	140.99	127.36	125.38

NO Emissions (g/km)

Fuel	Vehicle 1: Euro 4		Vehicle 2: Euro 5		Vehicle 3: Euro 6	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
	Corrected	Corrected	Corrected	Corrected	Corrected	Corrected
D1	0.090	0.125	0.106	0.212	0.0383	0.0200
D2	0.097	0.131	0.112	0.224	0.0362	0.0137
D3	0.100	0.135	0.126	0.204	0.0357	0.0140
D4	0.093	0.140	0.098	0.214	0.0365	0.0137
D5	0.095	0.128	0.115	0.220	0.0356	0.0150
D6	0.098	0.143	0.106	0.216	0.0379	0.0200
D7	0.090	0.124	0.091	0.202	0.0363	0.0172
D8	0.100	0.131	0.106	0.206	0.0383	0.0146
D9	0.096	0.130	0.140	0.212	0.0371	0.0116
D10	0.092	0.128	0.105	0.194	0.0346	0.0144
D11	0.098	0.131	0.120	0.215	0.0351	0.0130
D12	0.096	0.129	0.114	0.219	0.0373	0.0165
D13	0.099	0.141	0.134	0.206	0.0365	0.0130
D14 (Ref)	0.094	0.127	0.111	0.211	0.0373	0.0170

CO Emissions (g/km)

Fuel	Vehicle 1: Euro 4		Vehicle 2: Euro 5		Vehicle 3: Euro 6	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
	Uncorrected	Uncorrected	Uncorrected	Uncorrected	Corrected	Uncorrected
D1	0.266	0.0101	0.207	0.0048	0.145	0.0171
D2	0.472	0.0095	0.362	0.0055	0.162	0.0199
D3	0.270	0.0077	0.235	0.0080	0.123	0.0238
D4	0.153	0.0054	0.134	0.0056	0.087	0.0139
D5	0.456	0.0061	0.315	0.0061	0.175	0.0195
D6	0.293	0.0117	0.201	0.0044	0.126	0.0196
D7	0.176	0.0176	0.116	0.0042	0.107	0.0139
D8	0.254	0.0060	0.177	0.0000	0.118	0.0130
D9	0.260	0.0092	0.221	0.0051	0.156	0.0182
D10	0.213	0.0084	0.142	0.0065	0.108	0.0246
D11	0.202	0.0076	0.150	0.0080	0.119	0.0176
D12	0.246	0.0097	0.182	0.0039	0.116	0.0220
D13	0.224	0.0086	0.176	0.0047	0.111	0.0085
D14 (Ref)	0.227	0.0092	0.154	0.0050	0.128	0.0187

HC Emissions (g/km)

Fuel	Vehicle 1: Euro 4		Vehicle 2: Euro 5		Vehicle 3: Euro 6	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
	Uncorrected	Uncorrected	Uncorrected	Corrected	Uncorrected	Uncorrected
D1	0.0224	0.0024	0.0348	0.0069	0.0063	.
D2	0.0373	0.0020	0.0621	0.0031	0.0076	0.0002
D3	0.0259	0.0023	0.0359	0.0011	0.0030	.
D4	0.0139	0.0013	0.0188	0.0037	0.0011	.
D5	0.0374	0.0019	0.0526	0.0030	0.0058	.
D6	0.0280	0.0018	0.0343	0.0035	0.0038	0.0001
D7	0.0159	0.0019	0.0177	0.0041	0.0032	0.0009
D8	0.0239	0.0025	0.0253	0.0051	0.0044	.
D9	0.0250	0.0026	0.0346	0.0023	0.0056	.
D10	0.0198	0.0007	0.0230	0.0030	0.0026	.
D11	0.0214	0.0030	0.0241	0.0056	0.0047	.
D12	0.0218	0.0003	0.0288	0.0014	0.0047	.
D13	0.0228	0.0028	0.0248	0.0087	0.0041	.
D14 (Ref)	0.0222	0.0029	0.0231	0.0033	0.0040	.

NOx Emissions (g/km)

Fuel	Vehicle 1: Euro 4		Vehicle 2: Euro 5		Vehicle 3: Euro 6	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
	Uncorrected	Uncorrected	Corrected	Corrected	Corrected	Corrected
D1	0.211	0.443	0.186	0.564	0.0690	0.0376
D2	0.218	0.456	0.200	0.605	0.0653	0.0264
D3	0.223	0.456	0.239	0.566	0.0633	0.0260
D4	0.217	0.462	0.177	0.585	0.0686	0.0264
D5	0.203	0.437	0.204	0.586	0.0627	0.0278
D6	0.219	0.470	0.184	0.601	0.0680	0.0359
D7	0.213	0.430	0.159	0.558	0.0656	0.0307
D8	0.232	0.447	0.192	0.598	0.0716	0.0277
D9	0.221	0.431	0.266	0.593	0.0670	0.0226
D10	0.221	0.448	0.192	0.526	0.0629	0.0271
D11	0.225	0.449	0.225	0.602	0.0648	0.0242
D12	0.216	0.437	0.202	0.587	0.0674	0.0308
D13	0.223	0.466	0.251	0.537	0.0642	0.0250
D14 (Ref)	0.214	0.434	0.198	0.565	0.0666	0.0313

PM Emissions (mg/km)

Fuel	Vehicle 1: Euro 4		Vehicle 2: Euro 5		Vehicle 3: Euro 6	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
	Uncorrected	Uncorrected	Corrected	Corrected	Uncorrected	Uncorrected
D1	15.61	13.08	0.867	0.470	0.336	0.194
D2	15.14	13.86	0.637	0.333	0.391	0.203
D3	18.42	16.60	0.793	0.488	0.330	0.168
D4	16.59	12.95	0.845	0.471	0.280	0.155
D5	18.16	17.11	0.836	0.503	0.263	0.154
D6	12.54	11.12	0.705	0.383	0.273	0.222
D7	19.95	18.35	0.985	0.382	0.280	0.137
D8	19.15	16.85	0.750	0.491	0.140	0.060
D9	21.53	20.86	0.775	0.452	0.237	0.191
D10	21.34	18.15	0.894	0.408	0.211	0.134
D11	18.74	17.46	0.654	0.309	0.250	0.177
D12	18.25	16.50	0.527	0.365	0.256	0.176
D13	16.47	10.87	0.718	0.517	0.161	0.122
D14 (Ref)	16.22	15.20	0.690	0.471	0.236	0.163

PN (#/km)

Fuel	Vehicle 1: Euro 4		Vehicle 2: Euro 5		Vehicle 3: Euro 6	
	NEDC	WLTC	NEDC	WLTC	NEDC	WLTC
	Corrected	Corrected	Uncorrected	Uncorrected	Corrected	Corrected
D1	4.397E+13	3.759E+13	4.692E+11	1.198E+09	2.905E+10	2.271E+08
D2	4.234E+13	3.811E+13	6.702E+10	1.520E+08	2.306E+10	4.514E+08
D3	4.837E+13	4.110E+13	2.533E+11	3.265E+08	9.412E+09	3.049E+08
D4	4.750E+13	3.658E+13	4.276E+11	1.280E+09	4.223E+10	7.139E+08
D5	4.639E+13	4.255E+13	2.978E+11	3.869E+08	1.803E+10	2.909E+08
D6	4.017E+13	3.410E+13	4.757E+11	1.488E+09	3.452E+10	3.074E+08
D7	5.218E+13	4.438E+13	5.247E+11	1.194E+09	1.677E+10	2.765E+08
D8	5.045E+13	4.314E+13	2.299E+11	3.416E+08	1.587E+10	3.406E+08
D9	5.162E+13	4.635E+13	2.354E+11	3.879E+08	1.599E+10	3.729E+08
D10	5.213E+13	4.346E+13	2.090E+11	5.250E+08	1.196E+10	4.026E+08
D11	5.004E+13	4.408E+13	2.744E+11	6.552E+08	2.056E+10	4.977E+08
D12	5.021E+13	4.250E+13	1.895E+11	2.438E+08	1.439E+10	3.495E+08
D13	4.787E+13	3.962E+13	3.095E+11	9.782E+08	1.873E+10	1.555E+08
D14 (Ref)	4.749E+13	4.022E+13	2.248E+11	3.296E+08	1.926E+10	3.084E+08

PN Steady State 90km/hr (#/km)

Fuel	Vehicle 1: Euro 4	Vehicle 2: Euro 5	Vehicle 3: Euro 6
	90km/h	90km/h	90km/h
	Corrected	Uncorrected	Uncorrected
D1	3.278E+13	7.358E+07	8.473E+07
D2	3.113E+13	1.072E+08	8.168E+07
D3	3.614E+13	1.426E+08	4.488E+07
D4	3.528E+13	8.155E+07	5.423E+07
D5	3.436E+13	7.417E+07	5.942E+07
D6	2.752E+13	3.725E+07	8.301E+07
D7	3.869E+13	6.113E+07	4.463E+07
D8	3.679E+13	9.719E+07	6.730E+07
D9	3.772E+13	1.573E+08	1.322E+08
D10	3.756E+13	2.630E+07	4.338E+07
D11	3.489E+13	9.606E+07	5.481E+07
D12	3.639E+13	6.229E+07	1.064E+08
D13	3.455E+13	7.800E+07	1.024E+08
D14 (Ref)	3.492E+13	3.849E+07	6.231E+07

Mean Geometric Diameter (nm) Euro 4 vehicle only in 90km/h steady state

Fuel	Vehicle 1: Euro 4
	Corrected
D1	64.92
D2	65.41
D3	69.51
D4	66.96
D5	69.05
D6	59.24
D7	69.72
D8	70.71
D9	72.51
D10	71.02
D11	67.73
D12	68.73
D13	66.70
D14 (Ref)	66.73

APPENDIX 4 – FILTER PAPER ANALYSIS

As stated in the main body, no attempt was made to evaluate the effect of fuel properties on filter paper content due to the lack of repeat samples. Given below are observations on the differences between fuels, vehicles and test cycles based on the filter paper analyte, followed by the tabulated data and pie charts showing the contributions of SOF, ions and EC for each fuel-vehicle-test combination.

For the Euro 4 vehicle for most fuels, SOF is higher in absolute terms in the WLTC rather than in the NEDC results. For the ions, specifically nitrates (NO_3^-) and sulphates (SO_4^{2-}) with the only exception fuel being D9, in all cases ions mass is higher in WLTC than NEDC. Fuels D12 and D14 are by far the ones with the highest amount of ions produced in WLTC, while fuel D1 produced very low levels of ions in both NEDC and WLTC. The result for D3 in WLTC should not be taken into consideration, since it was not possible to detect the exact level of ions mass. It is observed that ions have very little contribution to the total PM mass.

For EC, which is calculated by extracting SOF and ion mass from the total PM mass, it was observed that EC mass is higher in WLTC, owing to the longer duration of this cycle, although the cycle does contain a hot start. In addition, fuels D9 and D10 produce the highest levels of EC, while fuel D6 gives the lowest EC mass in both test cycles. One property that might affect this observation significantly is the biodiesel content of the fuels – D9 and D10 are B0 while fuel D6 is B10. The presence of biodiesel enhances carbon oxidation, owing to the fuel bound oxygen. The latter, although found in low concentration (maximum up to 1% m/m, see Table 11) is in close proximity with the hydrocarbons – actually it is in the fuel molecule. This is further confirmed for other fuels also, for example D3 and D5 that do not contain biodiesel.

For the Euro 5 vehicle compared to the Euro 4 vehicle, both the PM and the SOF masses are one order of magnitude lower, since the Euro 5 was equipped with a DPF. Here, fuels D3 and D5 produce the highest SOF, in terms of both mass units and percentage values. On the other hand, fuel D12 produces one of the lowest SOF mass in both test cycles. Contrary to the Euro 4 vehicle, there is not a clear trend for the ions mass between the two test cycles – for 5 fuels ions mass is higher in NEDC, while for the others ions mass is higher in WLTC. It must be noted however, that ions mass is much lower compared to the respective values for the Euro 4.

With the only exception being fuel D7, it is observed that EC mass is higher in WLTC for the Euro 5 vehicle. Compared to the Euro 4 vehicle, EC values are one order of magnitude lower, due to the presence of a DPF in the Euro 5. For this reason, it is very difficult to derive solid conclusions. For example, fuel D6 that was found to produce the lowest EC mass in the Euro 4 vehicle, gives one of the highest EC masses in the Euro 5. The ion contribution to the total PM mass is not negligible, as it was in the Euro 4 vehicle. It is found that the total PAH mass is lower than the respective value for the Euro 4 – by around 20% in average in both cycles. The presence of the DPF enhances further oxidation of hydrocarbons and this may contribute to this result.

The analysis of the PM filter papers from the Euro 6 vehicle took much longer, compared to the other two vehicles, owing to the extremely low masses and concentration of some components, due to re-adjustment and re-calibration of the equipment necessary to meet the lowest possible measuring ranges. Complete analysis of the filter papers was not possible, as some components were below the detectable limits (marked in red). Compared to the Euro 4 vehicle, both the PM and the SOF masses are one order of magnitude lower, since, like the Euro 5 vehicle the Euro 6 is equipped with a DPF. In addition, the Euro 6 vehicle gave lower PM and SOF mass values than the Euro 5, which could be due to a more efficient DPF or better in-cylinder soot management. In the NEDC test all fuels seem to produce the same quantity of SOF, while in WLTC D1 and D10 present higher SOF mass values, which remain in any case in very low levels.

Similarly to the Euro 5 vehicle, there is not a clear trend for the ions mass between the two test cycles for the Euro 6. The result for D10 in NEDC should not be taken into consideration, since it was not possible to detect the exact level of ions mass. In general, the mass of ions is higher in WLTC, with fuels D6, D9, D12 and D14 showing the highest values. Compared to the other two vehicles, the mass of ions is much lower than for the Euro 4 vehicle and is in the same order of magnitude, but slightly lower, compared to that of the Euro 5 vehicle. Fuels D6, D9 and D13 seem to produce the highest EC mass during WLTC. Compared to the Euro 4 vehicle for the WLTC, EC values are one order of magnitude lower, while they are within the same range with the Euro 5 vehicle, obviously due to the presence of a DPF. Therefore, it is again very difficult to derive solid conclusions.

It was again observed for the Euro 6 vehicle that ion contribution to the total PM mass is not negligible. The total PAH mass is lower than for the Euro 4 and in the same order as the Euro 5 vehicle.

Figure A4.1 Analysis of filter papers from NEDC test (Euro 4)

Fuel	PM weight [mg]	SOF [mg]	ions [mg]	EC [mg]	Σ16PAHs [mg]
D1	0.3254	0.1290	0.0058	0.1905	0.00016
D2	0.3102	0.1210	0.0056	0.1836	0.00013
D3	0.3805	0.0940	0.0074	0.2791	0.00015
D4	0.3514	0.1160	0.0100	0.2254	0.00013
D5	0.3703	0.1090	0.0098	0.2515	0.00015
D6	0.2605	0.0990	0.0054	0.1560	0.00012
D7	0.4171	0.1640	0.0124	0.2407	0.00013
D8	0.4033	0.1570	0.0140	0.2323	0.00014
D9	0.4376	0.1440	0.0131	0.2805	0.00016
D10	0.4370	0.0870	0.0109	0.3392	0.00014
D11	0.3897	0.1340	0.0046	0.2511	0.00013
D12	0.3796	0.1220	0.0080	0.2496	0.00013
D13	0.3428	0.1360	0.0078	0.1990	0.00017
D14	0.4900	0.1460	0.0051	0.3389	0.00015
average	0.3753	0.1267	0.0083	0.2403	0.00014

Figure A4.2 Analysis of filter papers from WLTC tests (Euro 4)

Fuel	PM weight [mg]	SOF [mg]	ions [mg]	EC [mg]	Σ16PAHs [mg]
D1	0.4429	0.1720	0.0081	0.2629	0.00019
D2	0.4248	0.1600	0.0136	0.2512	0.00015
D3	0.5499	0.1180	0.0004	0.4315	0.00018
D4	0.4374	0.1160	0.0158	0.3056	0.00013
D5	0.5782	0.1470	0.0154	0.4159	0.00017
D6	0.3735	0.1340	0.0113	0.2282	0.00017
D7	0.5294	0.1850	0.0177	0.3267	0.00013
D8	0.5750	0.1750	0.0188	0.3812	0.00015
D9	0.7303	0.1830	0.0100	0.5373	0.00019
D10	0.5980	0.1130	0.0269	0.4581	0.00017
D11	0.5391	0.1370	0.0143	0.3878	0.00014
D12	0.5534	0.1740	0.0488	0.3306	0.00017
D13	0.4311	0.1350	0.0117	0.2843	0.00017
D14	0.5414	0.2200	0.0415	0.2799	0.00017
average	0.5090	0.1577	0.0198	0.3319	0.00016

Figure A4.3 Analysis of filter papers from NEDC test (Euro 5)

Fuel	PM weight [mg]	SOF [mg]	ions [mg]	EC [mg]	Σ16PAHs [mg]
D1	0.035	0.0100	0.0084	0.0164	0.00010
D2	0.033	0.0130	0.0067	0.0138	0.00010
D3	0.035	0.0140	0.0120	0.0087	0.00013
D4	0.036	0.0120	0.0019	0.0222	0.00011
D5	0.041	0.0180	0.0021	0.0206	0.00013
D6	0.035	0.0090	0.0025	0.0237	0.00011
D7	0.046	0.0110	0.0083	0.0265	0.00010
D8	0.033	0.0110	0.0089	0.0134	0.00012
D9	0.027	0.0090	0.0025	0.0151	0.00012
D10	0.030	0.0100	0.0052	0.0150	0.00010
D11	0.023	0.0080	0.0060	0.0087	0.00010
D12	0.021	0.0060	0.0038	0.0112	0.00010
D13	0.029	0.0110	0.0047	0.0137	0.00011
D14	0.035	0.0140	0.0030	0.0176	0.00011
average	0.034	0.0109	0.0053	0.0174	0.00011

Figure A4.4 Analysis of filter papers from WLTC test (Euro 5)

Fuel	PM weight [mg]	SOF (mg)	ions (mg)	EC (mg)	Σ16PAHs (mg)
D1	0.031	0.0070	0.0055	0.0181	0.00011
D2	0.025	0.0090	0.0032	0.0133	0.00013
D3	0.047	0.0180	0.0166	0.0124	0.00014
D4	0.045	0.0140	0.0061	0.0252	0.00012
D5	0.054	0.0190	0.0072	0.0280	0.00012
D6	0.044	0.0090	0.0067	0.0279	0.00013
D7	0.037	0.0080	0.0044	0.0243	0.00012
D8	0.046	0.0130	0.0058	0.0271	0.00010
D9	0.033	0.0090	0.0057	0.0182	0.00015
D10	0.049	0.0140	0.0069	0.0277	0.00012
D11	0.033	0.0100	0.0056	0.0169	0.00012
D12	0.033	0.0090	0.0058	0.0186	0.00014
D13	0.046	0.0140	0.0056	0.0265	0.00013
D14	0.038	0.0110	0.0087	0.0183	0.00015
average	0.039	0.0115	0.0070	0.0207	0.00013

Figure A4.5 Analysis of filter papers from NEDC test (Euro 6)

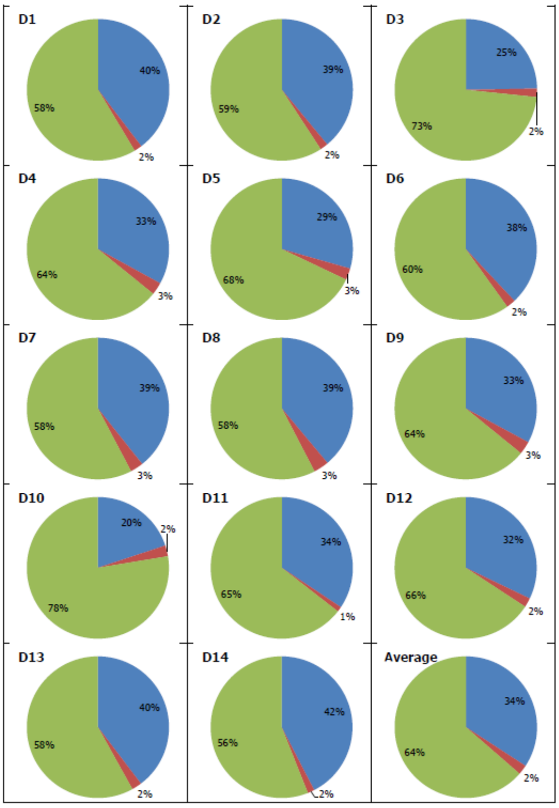
Fuel	PM weight [mg]	SOF [mg]	ions [mg]	EC [mg]	Σ16PAHs [mg]
D1	0.014	0.006	0.00741	0.000590	0.0001339
D2	0.008	0.004	0.00389	0.000110	0.0001327
D3	0.010	0.004	0.00490	0.001100	0.0001351
D4	0.014	0.006	0.00641	0.001590	0.0001347
D5	0.011	0.006	0.00315	0.001850	0.0001312
D6	0.013	0.004	0.00731	0.001690	0.0001295
D7	0.012	0.007	0.00419	0.000810	0.0001310
D8	0.011	0.006	0.00416	0.000840	0.0001311
D9	0.014	0.007	0.00460	0.002400	0.0001330
D10	0.003	0.001	Non-detectable	Non-detectable	0.0001314
D11	0.010	0.005	0.00400	0.001000	0.0001312
D12	0.010	0.005	0.00465	0.000350	0.0001307
D13	0.011	0.005	0.00424	0.001760	0.0001329
D14	0.012	0.006	0.00438	0.001620	0.0001310
average	0.011	0.005	0.00487	0.001208	0.0001320

Figure A4.6 Analysis of filter papers from WLTC test (Euro 6)

Fuel	PM weight [mg]	SOF [mg]	ions [mg]	EC [mg]	Σ16PAHs [mg]
D1	0.019	0.014	0.0043	0.0007	0.0001316
D2	0.010	0.007	0.0026	0.0004	0.0001395
D3	0.013	0.006	0.0058	0.0012	0.0001406
D4	0.014	0.008	0.0049	0.0011	0.0001372
D5	0.016	0.011	0.0039	0.0011	0.0001316
D6	0.024	0.012	0.0091	0.0029	0.0001359
D7	0.011	0.006	0.0041	0.0009	0.0001324
D8	0.006	0.002	0.0037	0.0003	0.0001327
D9	0.019	0.008	0.0080	0.0030	0.0001390
D10	0.019	0.013	0.0059	0.0001	0.0001352
D11	0.011	0.006	0.0041	0.0009	0.0001356
D12	0.013	0.005	0.0079	0.0001	0.0001339
D13	0.018	0.012	0.0035	0.0025	0.0001326
D14	0.016	0.005	0.0091	0.0019	0.0001400
average	0.015	0.008	0.0055	0.0012	0.0001356

Figure A4.7 Contribution of elemental carbon (green), ions (red) and SOF (blue) in the filter paper analyte

Euro 4 - NEDC



Euro 4 - WLTC

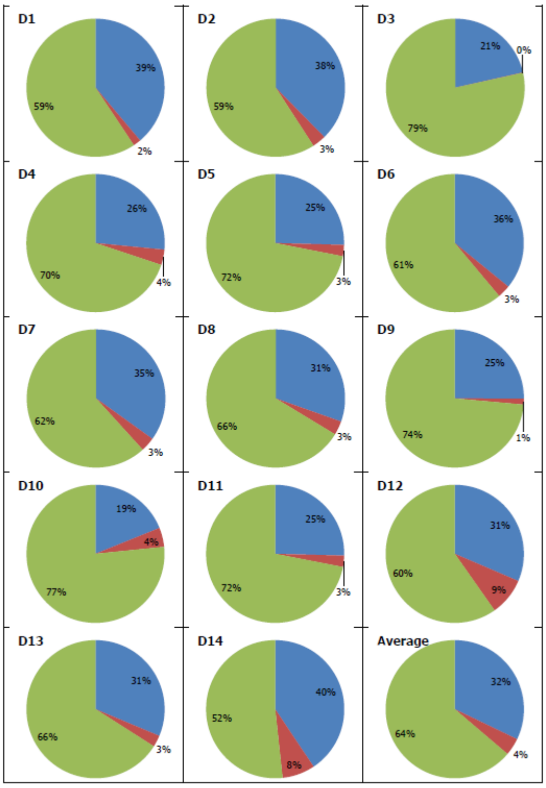
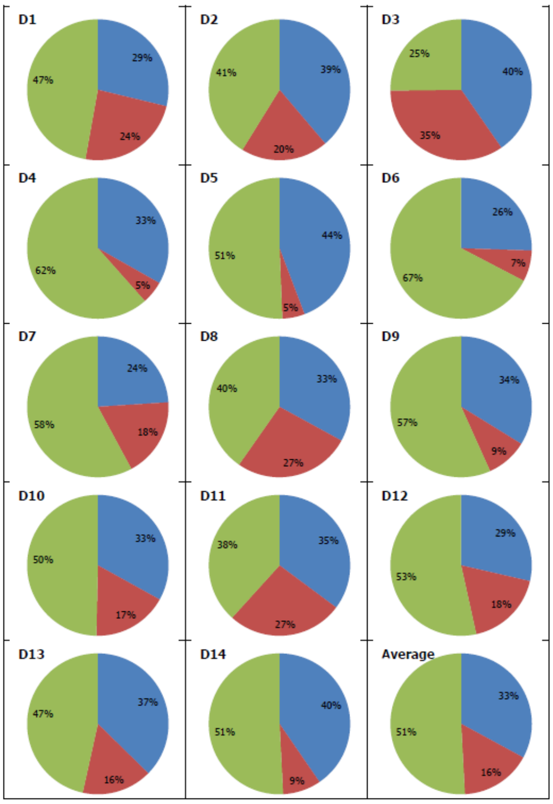


Figure A4.8 Contribution of elemental carbon (green), ions (red) and SOF (blue) in the filter paper analyte

Euro 5 – NEDC



Euro 5 - WLTC

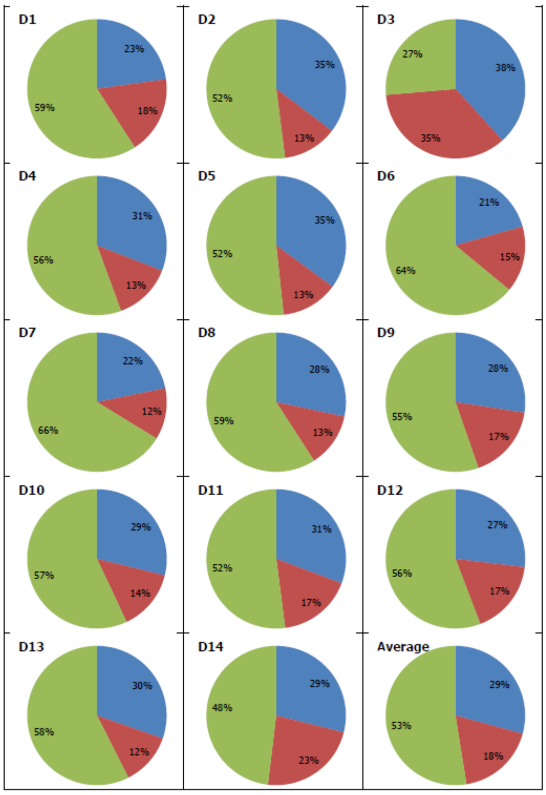
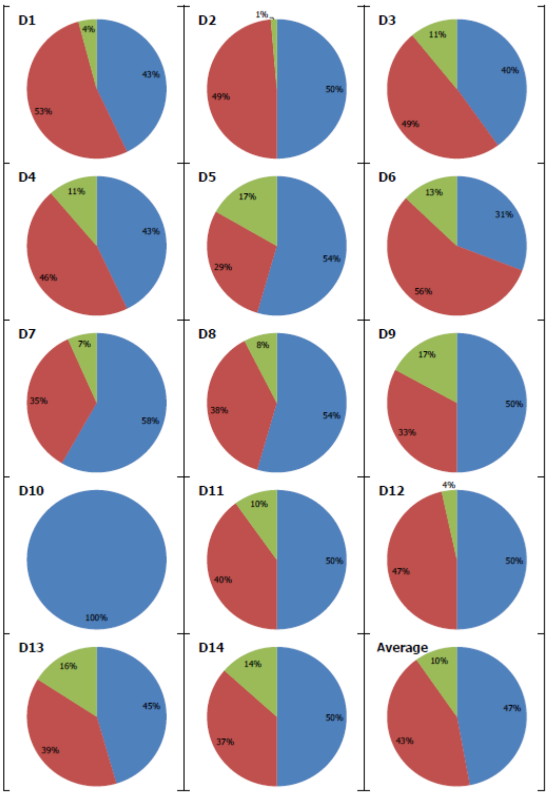
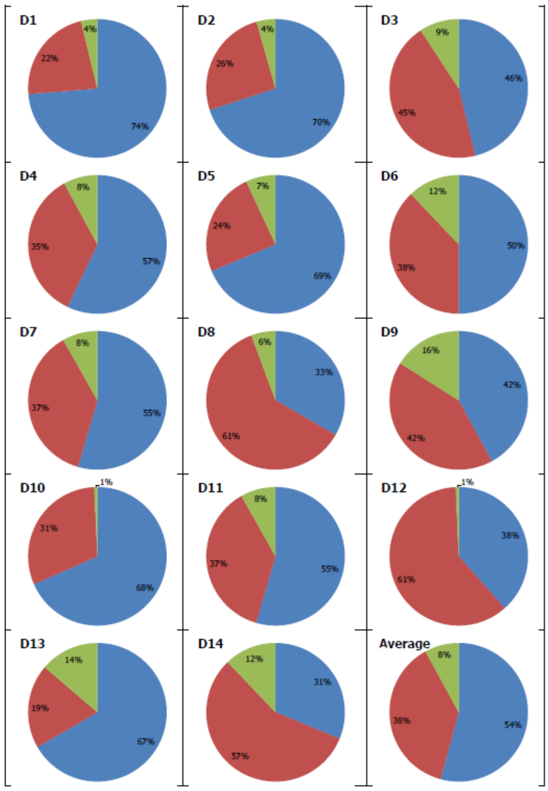


Figure A4.9 Contribution of elemental carbon (green), ions (red) and SOF (blue) in the filter paper analyte

Euro 6 - NEDC



Euro 6 - WLTC



APPENDIX 5 - ESTIMATES OF FUEL EFFECTS

Statistically significant fuel effects at P < 0.05 are illustrated in the charts below which plot the fuel means (open circles) and the fitted values from section 4. Where there is no statistically significant fuel effect (at P < 0.05) the model is not shown. Error bars on the fitted values correspond to 1.4 x standard error.

A5.1 DENSITY

Figure A5.1 The effect of density on fuel consumption

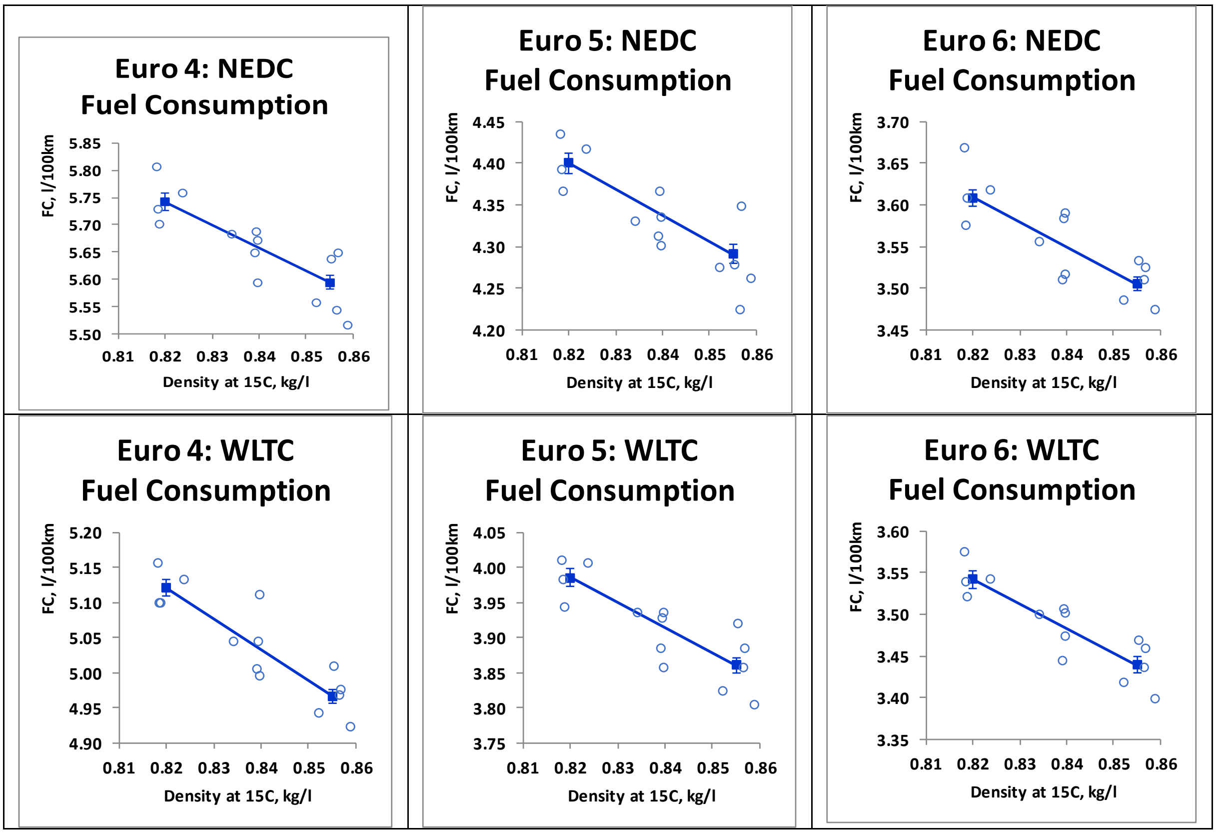


Figure A5.2 The effect of density on energy consumption showing the two cases where statistically significant fuel effects were observed

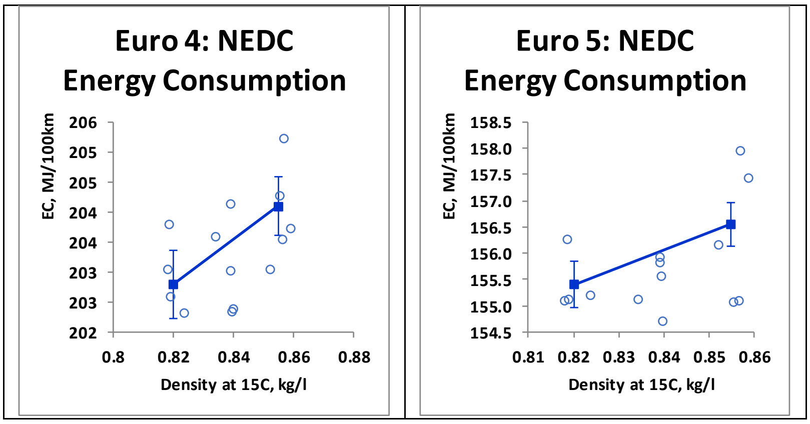


Figure A5.3 The effect of density on CO_2 emissions

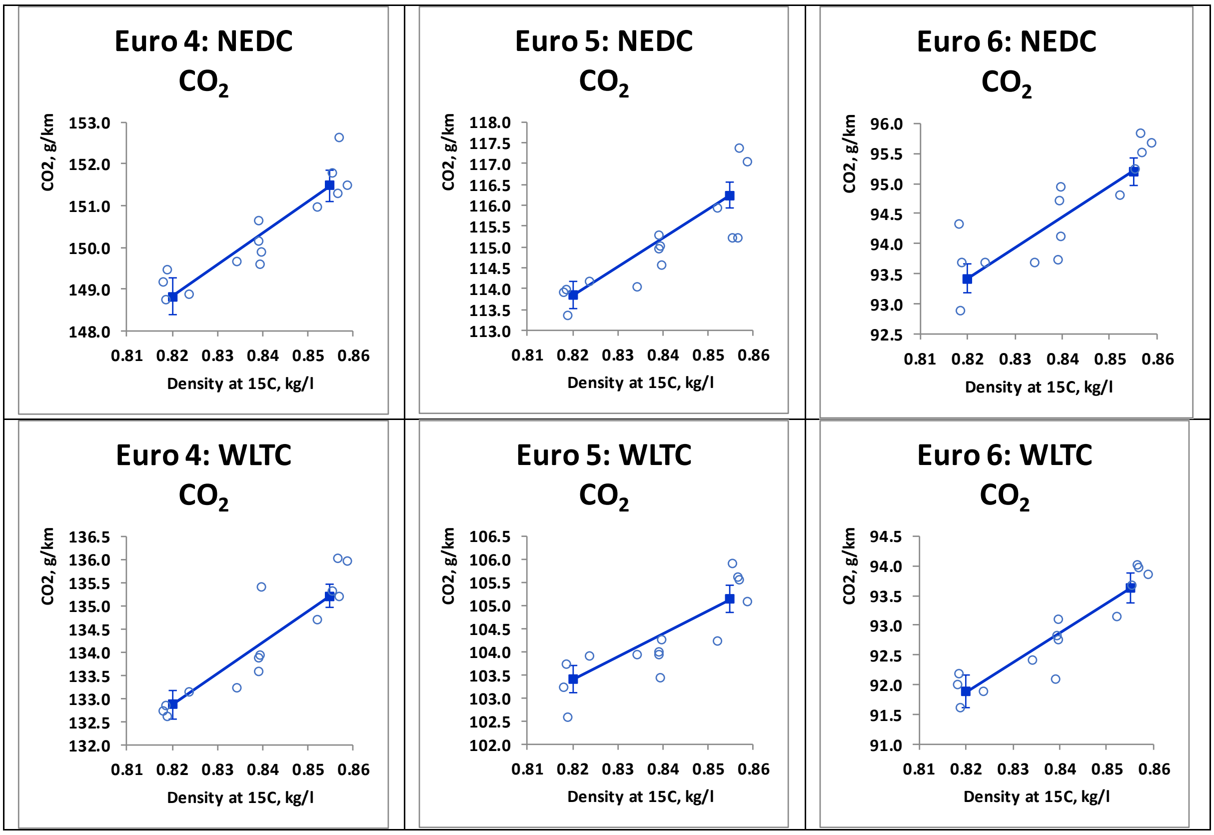
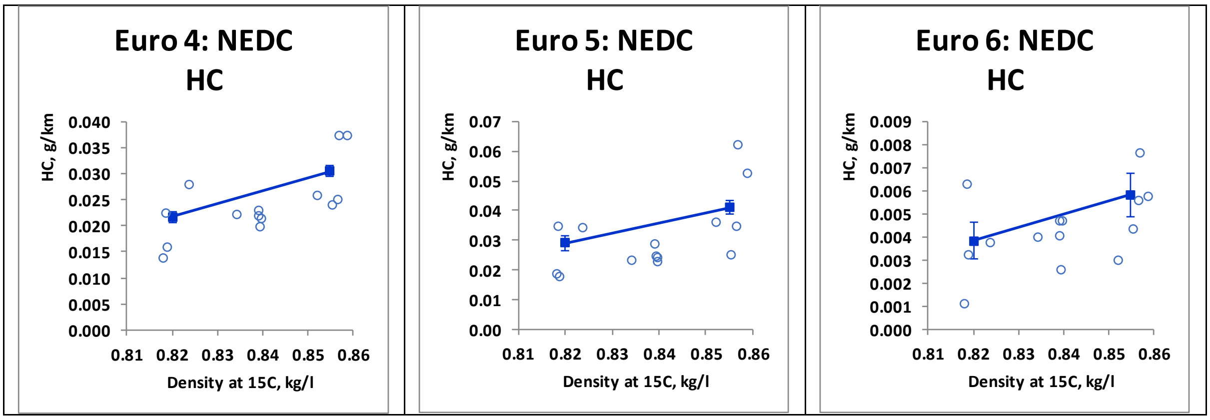


Figure A5.4 The effect of density on HC emissions



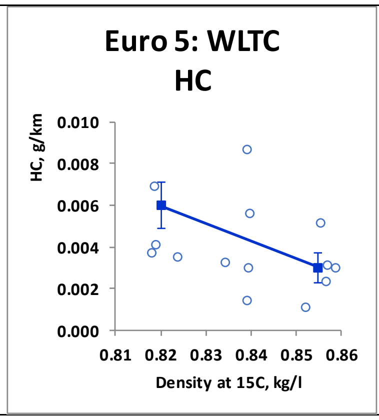


Figure A5.5 The effect of density on CO emissions

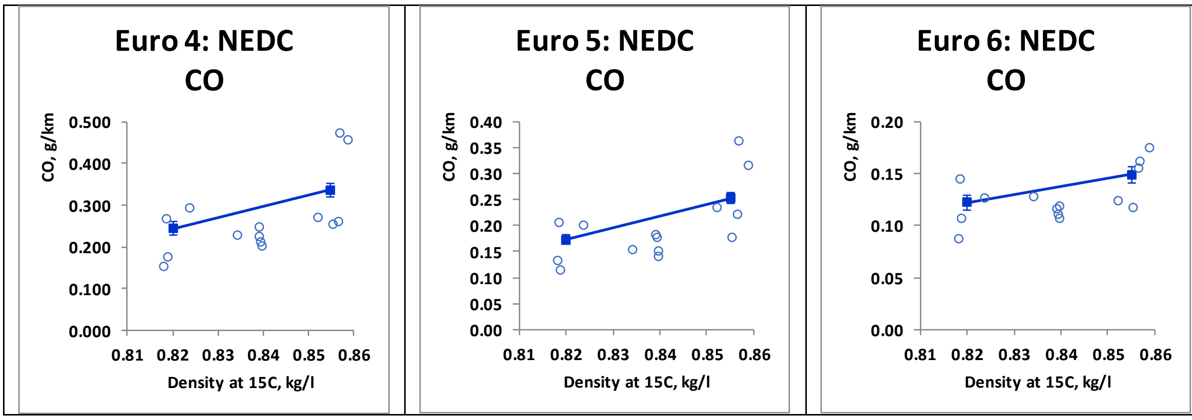


Figure A5.6 The effect of density on PM emissions

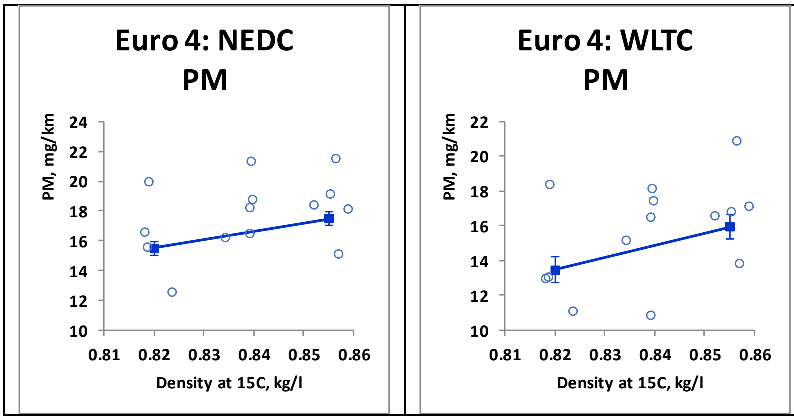


Figure A5.7 The effect of density on NOx emissions

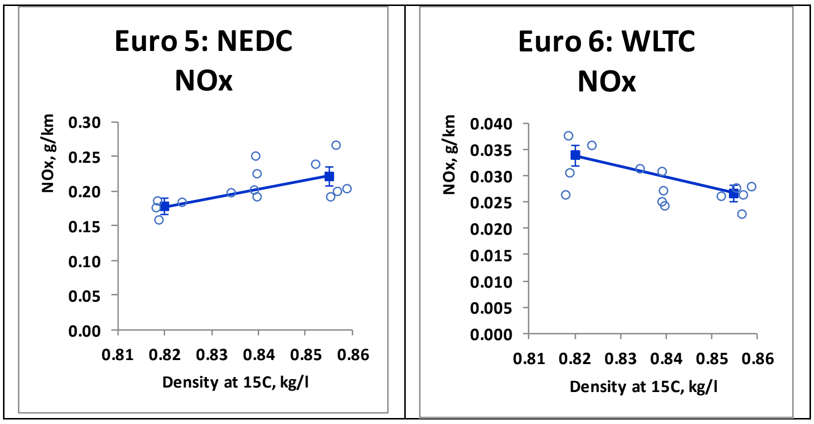
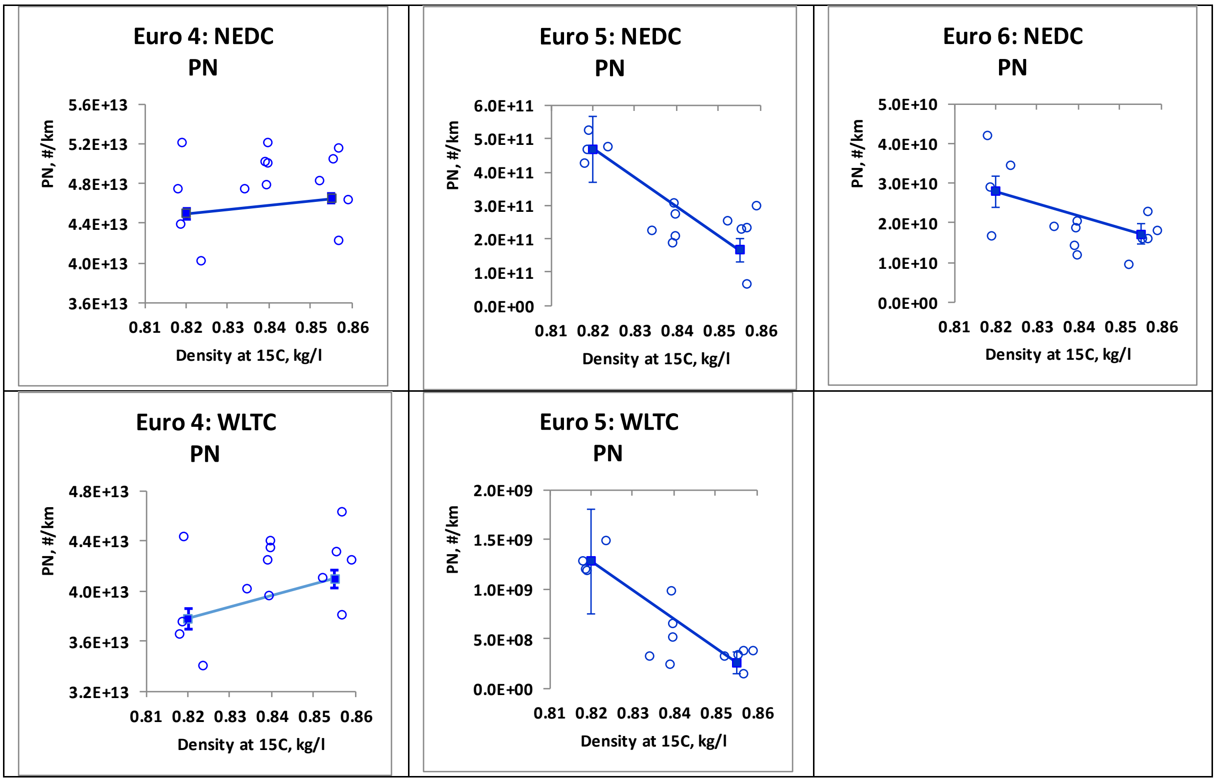


Figure A5.8 The effect of density on PN



A5.2 CETANE NUMBER

Figure A5.9 The effect of cetane number on CO_2 emissions, energy consumption and fuel consumption

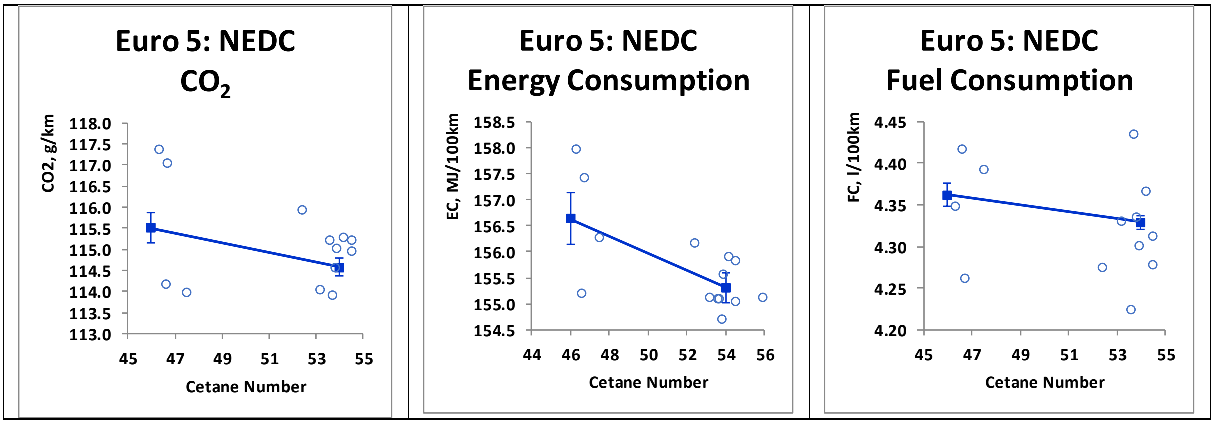


Figure A5.10 The effect of cetane number on PM emissions.

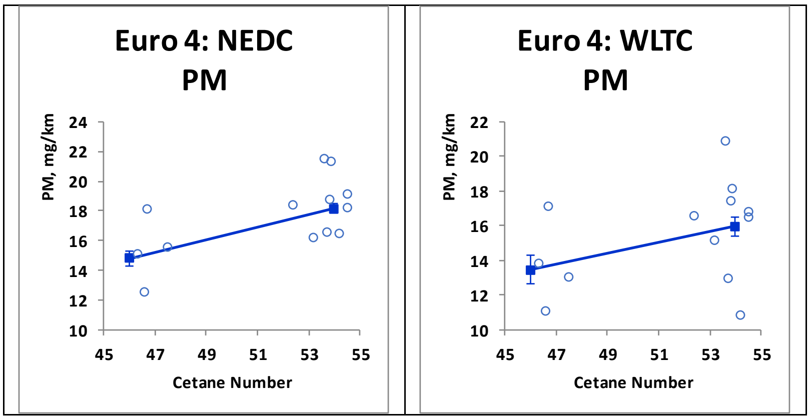


Figure A5.11 The effect of cetane number on NOx emissions.

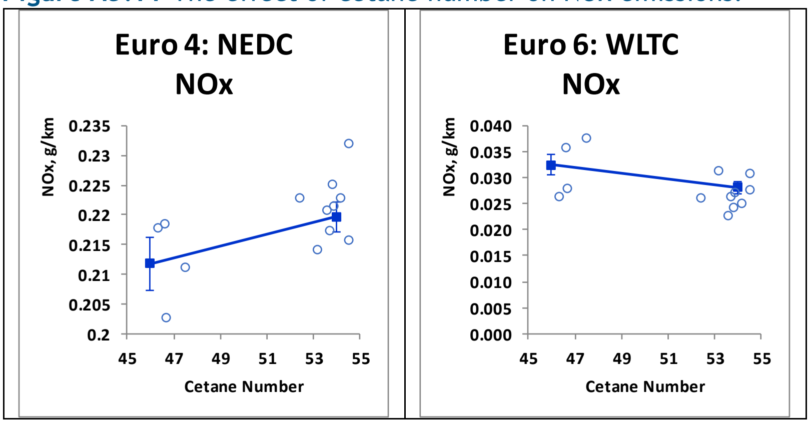


Figure A5.12 The effect of cetane number on HC emissions

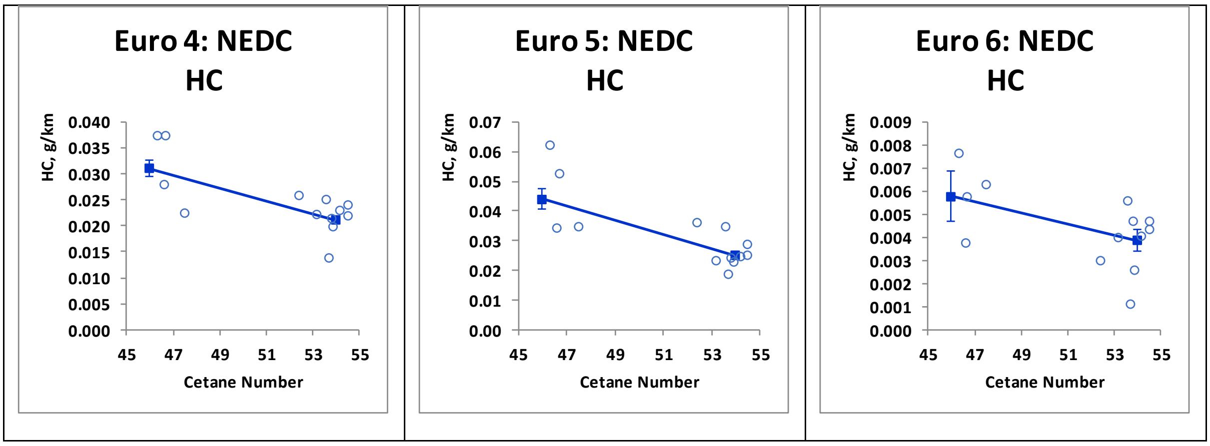


Figure A5.13 The effect of cetane number on CO emissions.

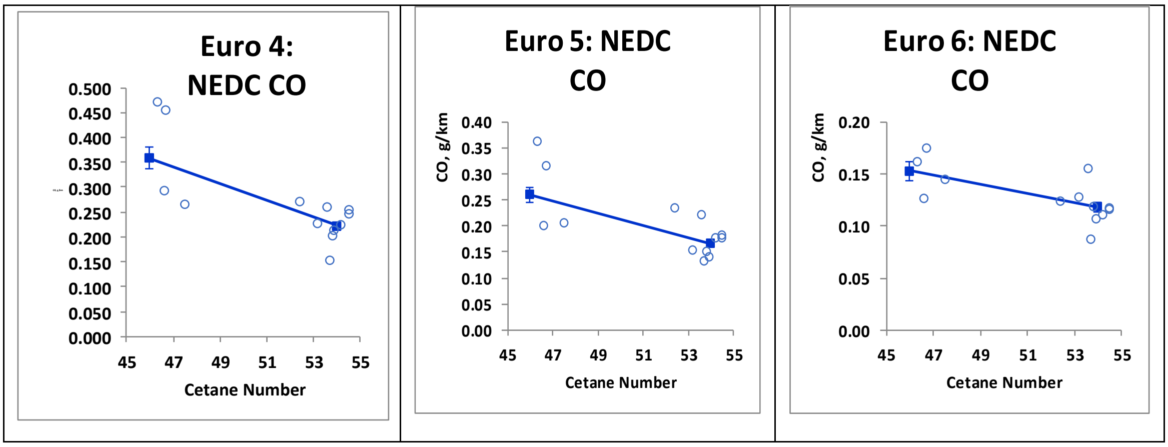
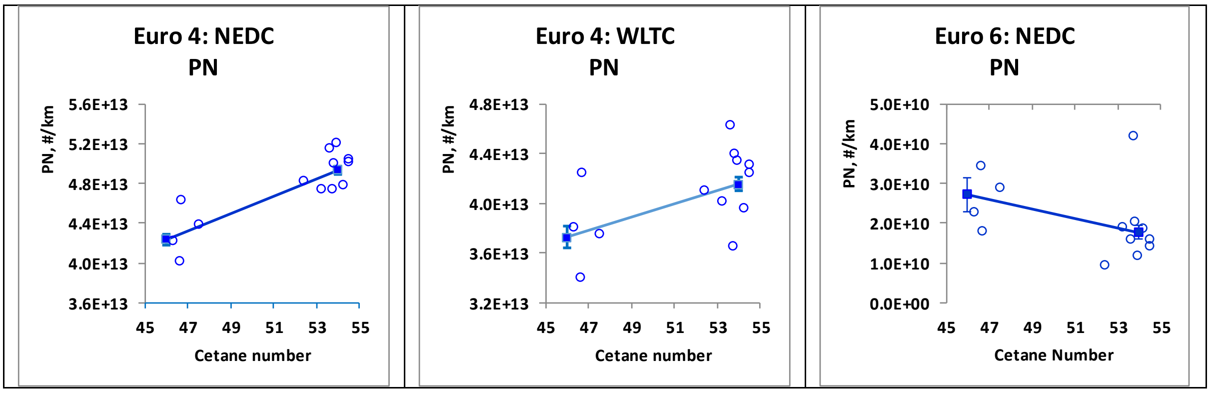


Figure A5.14 The effect of cetane number on PN



A5.3 PAH

Figure A5.15 The effect of PAH on PM emissions.

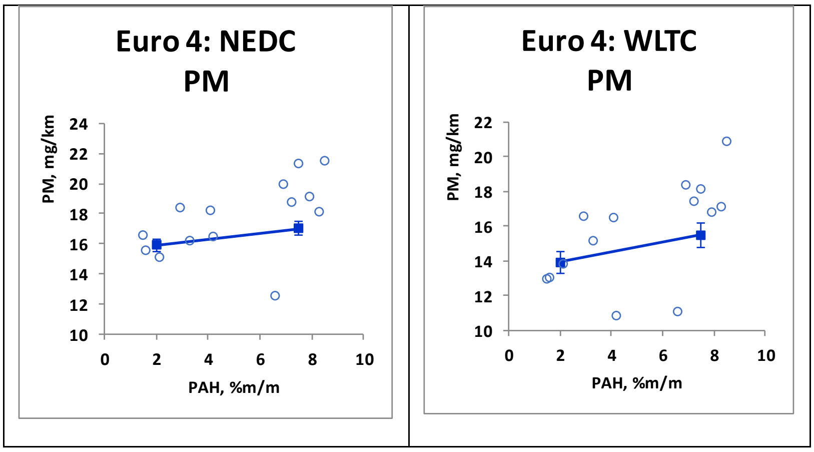


Figure A5.16 The effect of PAH on CO_2 emissions, energy consumption and fuel consumption

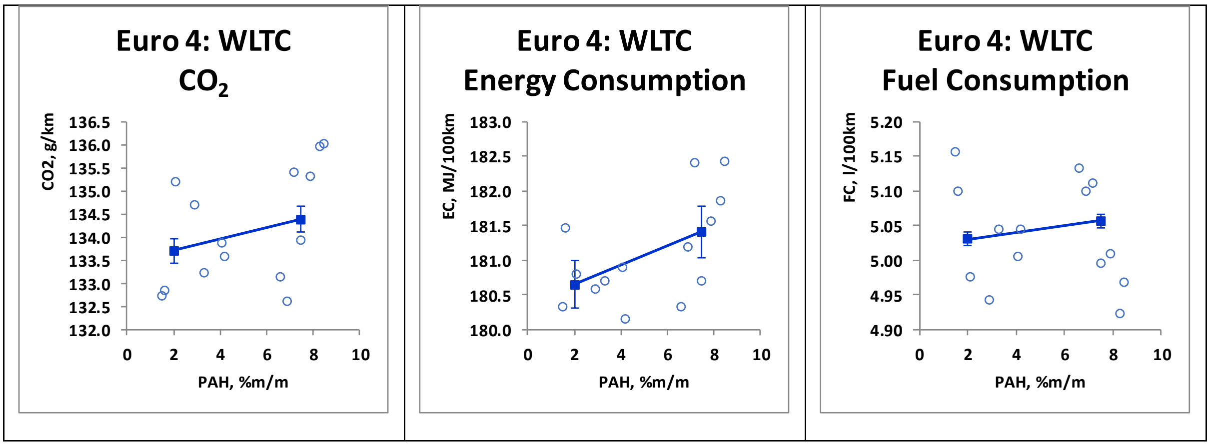


Figure A5.17 The effect of PAH on HC emissions

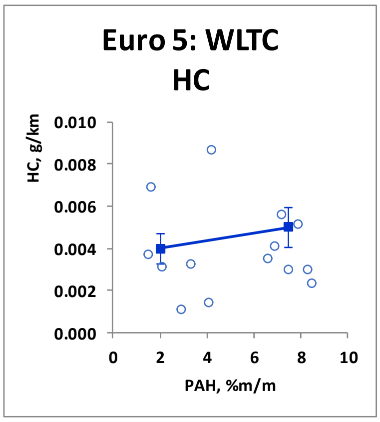
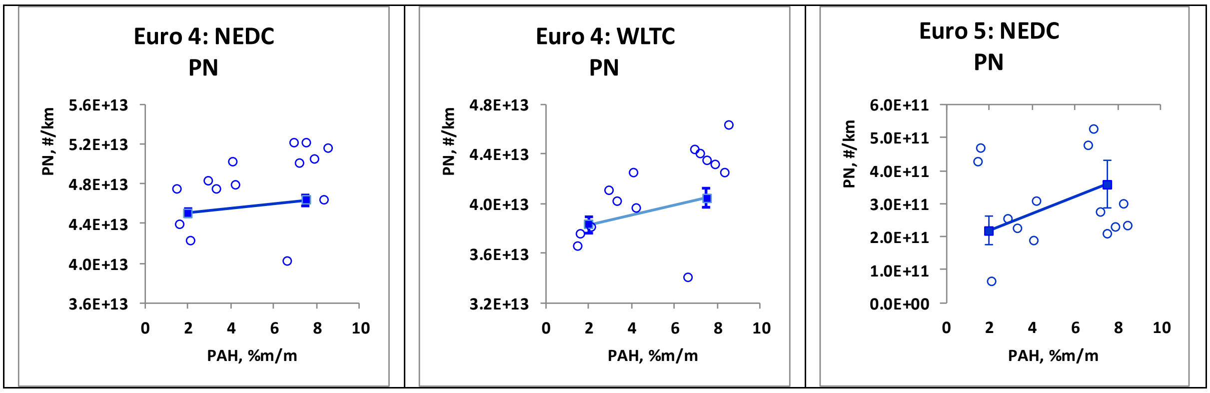


Figure A5.18 The effect of PAH on PN



A5.4 FAME

Figure A5.19 The effect of FAME on fuel consumption.

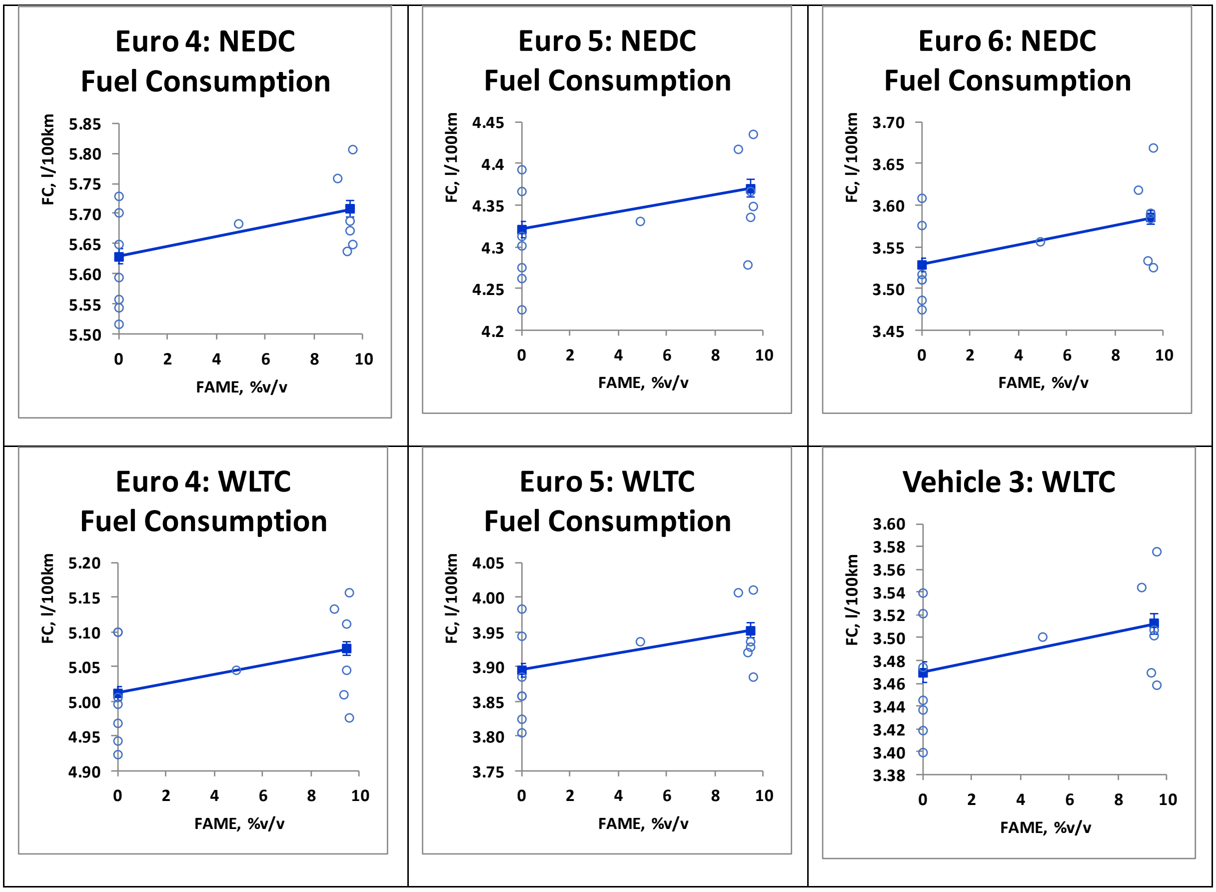


Figure A5.20 The effect of FAME on PM emissions in the Euro 4 vehicle only.

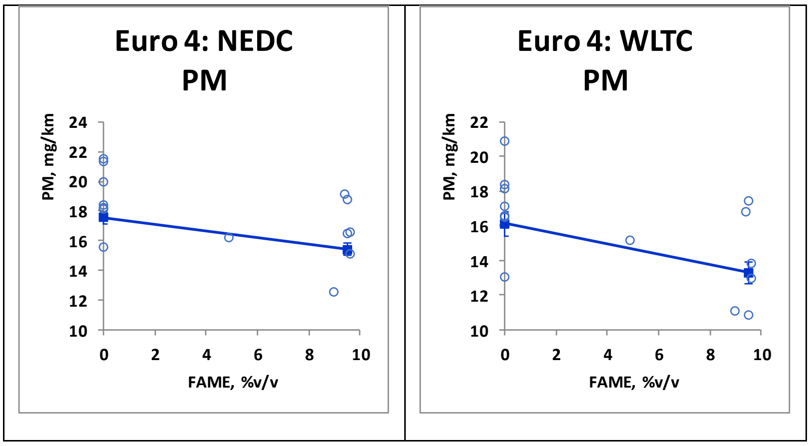


Figure A5.21 The effect of FAME on NOx emissions, significant in the Euro 4 vehicle only.

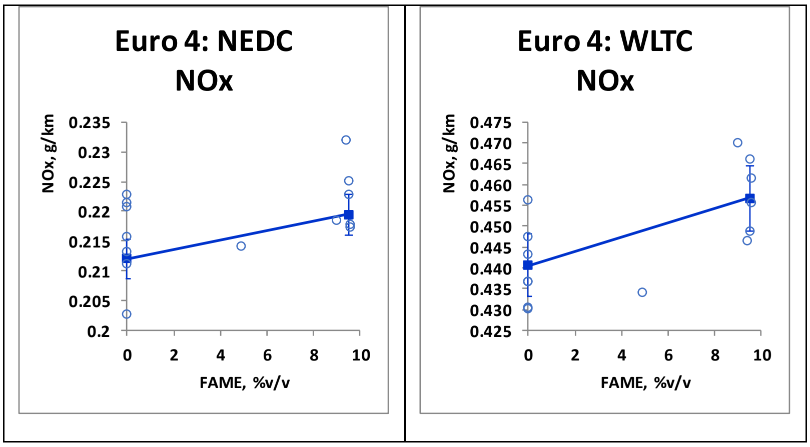


Figure A5.22 The effect of FAME on HC emissions in the Euro 5 vehicle only

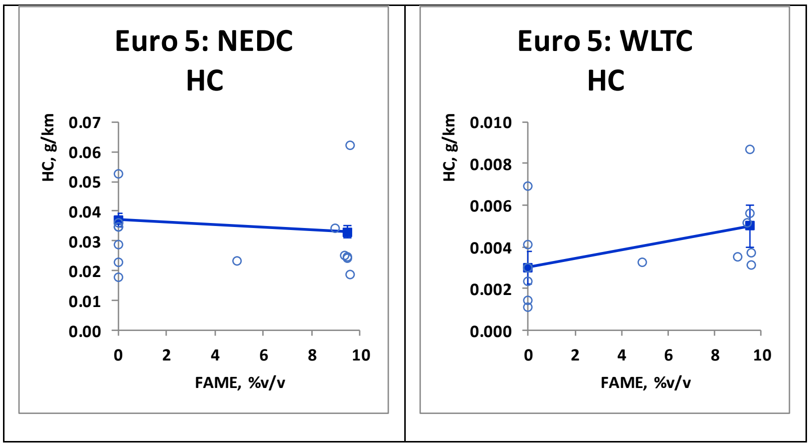


Figure A5.23 The effect of FAME on CO emissions

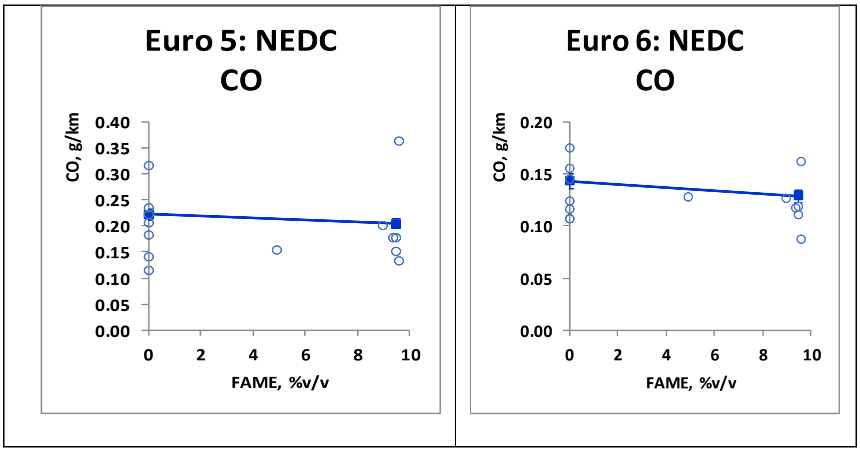
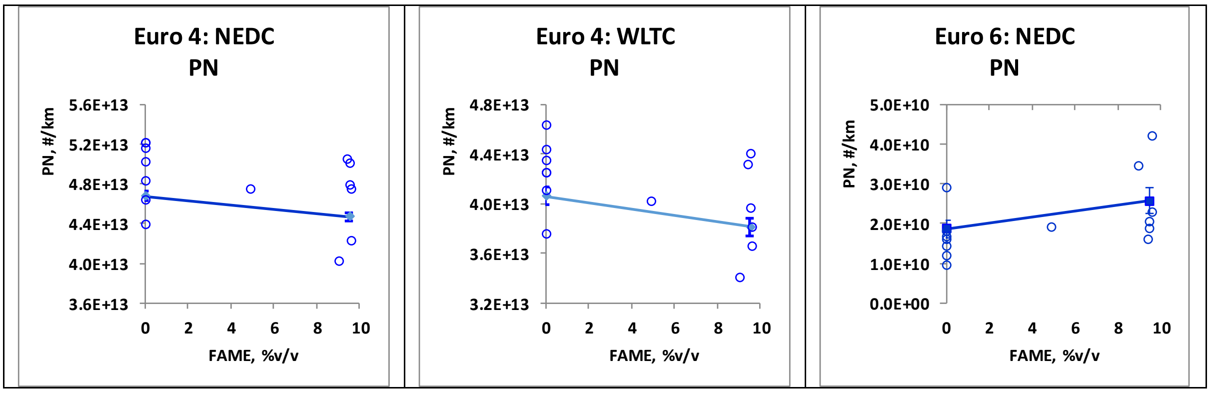


Figure A5.24 The effect of FAME on PN



APPENDIX 6 – STATISTICAL DATA ANALYSIS

This Appendix provides additional information on the statistical analysis methods outlined in Section 4. Note: in the context of this appendix EC is Energy Consumption and FC is Fuel Consumption.

Outlier and trend detection

The emissions data were checked for possible outliers by examining studentized residuals (residuals divided by their standard errors) in an analysis of (co)variance models fitted to the measured emissions for a particular vehicle and cycle on the natural scale for all emissions except PN and on the log-transformed scale for PN. A one-way ANOVA (Analysis Of Variance) model was fitted to each vehicle x cycle x emission combination with emission or ln(PN) as the response variable and fuel as the classifying factor. Time trends were sought by treating the test order as a covariate but, in some cases, there were step changes between the blocks of replications and it was more appropriate to adjust the data by including a block effect. Significant trends were identified in the following cases and adjusted for as described:

Vehicle	Cycle	Variable	Description
1 - EU4	WLTC	CO2, EC & FC	Step change after Test 16 following a break in testing. Treat as two blocks, Tests 1-16 and Tests 17-48
1 - EU4	NEDC & WLTC	NO	Block correction based on breaks in testing after Test 16 (between Reps 1 & 2) and again after Test 40 (Christmas break)
1 - EU4	NEDC, WLTC & 90km/h	PN	Simple linear trend correction
2 - EU5	NEDC	NOx & NO	Simple linear trend correction
2 - EU5	NEDC	PM	Block correction treating tests 52-56 as separate blocks
2 - EU5	NEDC	CO2, EC & FC	Quadratic trend correction
2 - EU5	WLTC	HC, NOx & NO	Simple linear trend correction
2 - EU5	WLTC	PM	Quadratic trend correction
3 - EU6	NEDC	CO2, EC & FC	Block correction using replications as blocks
3 - EU6	NEDC	CO, NOx & NO	Simple trend correction
3 - EU6	WLTC	CO2, EC & FC	Block correction using replications as blocks
3 - EU6	WLTC	NOx & NO	Simple trend correction
3 - EU6	NEDC & WLTC	PN	Block correction using replications as blocks

The trend correction adjusts the data points to the value they might have had if they had all been conducted midway through the test programme. As this test programme was designed with a statistically robust randomised block design for fuel testing order, the average test position of each fuel was quite close to the midway point and hence trend corrections have only a small effect on the mean emissions for each fuel. Their main benefit is to reduce the impact of the random variation making it easier to identify significant fuel effects.

Some tests were identified as potentially invalid by LAT at the time of testing and, in some cases, repeat tests were scheduled to replace them. Tests declared invalid by LAT were omitted prior to any further examination of the data. Statistical outliers were sought by comparing the studentized residuals against the upper 5% and 1% points of statistical tables. Outliers are classed as points significant at $P < 1\%$ and stragglers as points significant at $P < 5\%$. Questionable results were queried with the test laboratory but were not normally rejected unless there were sound engineering reasons to believe that something unexpected had occurred with that particular test. However, since the purpose of this study is to explore the effects of fuel properties, outliers can have a high degree of influence in regression modelling and, in some cases, were omitted to ensure that real fuel effects were not masked or distorted by one highly unusual data point.

Vehicle 1 - Euro 4

The following outliers were omitted from the data:

Cycle	Test	Variable	Description
WLTC	39	HC	Very high value (outlier)
WLTC	43	HC	Very high value (straggler)
WLTC	17	CO	Very high value (outlier)
NEDC	36	NO	Data missing

In fuel property modelling only, presumably because it was an influential low value, the following data point was additionally omitted:

Cycle	Test	Variable	Description
WLTC	9	PM	Low suspect point - omitted in fuel property modelling only

Vehicle 2 - Euro 5

The following tests were declared invalid and omitted:

Cycle	Test	Reason
NEDC & WLTC	17	Tests following vehicle service
NEDC & WLTC	18	
WLTC	30	High temperature in WLTC
WLTC	31	
WLTC	32	
WLTC	34	
WLTC	35	
WLTC	36	
WLTC	41	High temperature for part of WLTC only
WLTC	42	High temperature in WLTC
NEDC & WLTC	43	EGR drop off in NEDC; High temperature in WLTC
WLTC	44	High temperature in WLTC
NEDC & WLTC	45	High start of test temperature in NEDC; High temperature in WLTC
NEDC & WLTC	46	
NEDC & WLTC	47	
NEDC & WLTC	48	
NEDC & WLTC	49	
NEDC & WLTC	50	High start of test temperature in NEDC; WLTC missing
NEDC & WLTC	51	High start of test temp in NEDC. Very low CO2 in WLTC.

PN measurements were omitted in accordance with the above cycles with the 90 km/h condition being omitted whenever the WLTC was omitted. There was one exception to this which was Test 41 where the high temperature occurred for part of the WLTC only and all PN measurements were retained.

In Replication 1, the steady state was run at 120 km/h and subsequently reduced to 90 km/r. The 120 km/h PN data from Replication 1 has not been analysed.

The following data points were omitted for Vehicle 2:

Cycle	Test	Variable	Description
NEDC	3	PM	PM data missing
WLTC	22	PM	Filter paper damaged
NEDC & WLTC	9	PN	No source data

Vehicle 3 - Euro 6

The following tests were declared invalid and omitted:

Cycle	Test	Reason
NEDC & WLTC	1-3	Isolated from and out of line with bulk of data
NEDC & WLTC	4-12	Declared invalid by LAT
NEDC	17	Declared invalid by LAT
WLTC	21	
WLTC	22	
WLTC	26	
NEDC	31	Stop-Start issues - removal recommended by LAT
NEDC	32	
WLTC	33	Declared invalid by LAT
WLTC	36	
WLTC	40	
WLTC	43	No test on WLTC
WLTC	46	Declared invalid by LAT
WLTC	53	
WLTC	57	
WLTC	60	

Vehicle 3 - Euro 6

Cycle	Test	Variable	Description
NEDC & WLTC	23	PM	PM data missing
NEDC & WLTC	25	PM	PM data missing
NEDC	33	NOX	Statistical outlier - High value
NEDC	43	PM	PM data missing
NEDC	43	NOX & NO	NOx & NO DL missing for this test
NEDC	16	PN	No measurement

Arithmetic and Geometric means and error bars

As in previous Concawe studies, arithmetic means have been used in this report to summarize mean emissions of CO_2, CO, HC, NOx, NO & PM and mean fuel consumption. Arithmetic means are preferred to geometric (i.e. logarithmic) means because the latter have the disadvantage of underestimating the total emissions to the atmosphere. Although some of these emissions might be expected to follow a log-normal distribution, the effect is mitigated because each vehicle has been analysed separately and its emissions span only the limited range attributable to fuel effects.
However, again in line with previous Concawe studies, geometric means have been used to summarize the PN measurements because these can differ by one or more orders of magnitude. Arithmetic means can be dominated by one or two very high values and hence be unrepresentative of the main body of data.

The data set for each vehicle x cycle x emission measurement was analysed separately. For all emissions except PN, the arithmetic means and their standard errors were estimated for all fuels from an iteratively re-weighted analysis of variance in which each measurement was assigned a weight equal to:

Weight = 1 /(fitted mean emission from the previous iteration for that vehicle x fuel x cycle)^2

to take account of any lognormality in the data.

The weights for the first iteration were set to 1. This approach is similar to weighting by 1/(mean emission)^2 but allows for the means to be updated in successive iterations if they are being adjusted for trends.
In the case of PN, the geometric means and their standard error were estimated from an analysis of variance with Ln(PN) as the dependent variable.

In the bar charts presented in Section 3 , the error bars show the

Mean ± 1 x Pooled Standard deviation.

where the standard deviation is after any adjustments for trend or block corrections and is pooled across all the fuels. The error bars are therefore representative of the overall test variability that was achieved for use in the statistical analysis.

Appendix 3 tabulates the means for all fuels.

Modelling of Fuel Property effects

Modelling of the four fuel properties - density, PAH, FAME and Cetane number (CN) - was carried out using a similar methodology to that used for estimating the fuel means as described above. Each vehicle x cycle was analysed separately. For all emissions and fuel consumption except PN, iteratively re-weighted least squares regression was carried out on the raw measurements. For PN, the regression was carried out on the log scale using Ln(PN) as the dependent variable.

The results presented in this report are derived from a linear regression model containing all four fuel properties, regardless of their statistical significance and without any additional or interaction terms. The estimates of fuel effects in section 4 were obtained by applying this model to obtain the estimated values at the low and high extremes of each fuel properties whilst the other three properties were held constant at their midpoint.

For example, to obtain the effect of density on CO_2 emissions, the regression model in all four fuel properties for CO_2 emissions was applied to estimate CO_2 emissions at a density of 820 kg/m^3 (FAME=4.75%v/v, PAH=4.75%m/m, CN = 50) and again at a density of 855 kg/m^3 with the other three properties remaining at the same values. The effect is flagged as significant based on the direction and significance of the coefficient of the fuel property concerned. In the above example, density had a positive coefficient significant at P<0.1% as tabulated in section 4, using red text to indicate increasing CO_2 with density and *** to indicate significance at P < 0.1%.

Concawe

Environmental Science for European Refining

Concawe
Boulevard du Souverain 165
B-1160 Brussels
Belgium

Tel: +32-2-566 91 60
Fax: +32-2-566 91 81
e-mail: info@concawe.org
http://www.concawe.eu

ISBN 978-2-87567-098-4