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Impact of FAME on the performance of three Euro 4 light-duty diesel vehicles Part 1: Fuel consumption and regulated emissions

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Impact of FAME on the performance of three Euro 4 light-duty diesel vehicles Part 1: Fuel consumption and regulated emissions

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ABSTRACT

By 2020, EU legislation will require that 10% of the total transport fuel energy demand is met by the use of renewable energy, primarily by blending bio-components. Although many types of blending components for diesel fuels are being considered to achieve this requirement, Fatty Acid Methyl Esters (FAME) are the most likely to be used in significant volumes over the coming decade. FAME products have been used in Europe for many years, both as blends and as neat fuels, in certain niche markets.

One unanswered question concerning FAME/diesel fuel blends is the effect of FAME on fuel consumption. Since FAME has a slightly lower energy content compared to hydrocarbon-only fuels, a higher volumetric fuel consumption is expected unless the vehicle is able to compensate in some way for the energy loss associated with the bio-component in diesel fuel.

To answer this question, Concawe completed a vehicle study in which four diesel fuel blends with FAME (as Rapeseed Methyl Ester (RME)) were tested in three Euro 4 light-duty passenger cars, each equipped with different after-treatment technologies. The FAME contents of these fuels varied from 0% to 50% v/v in order to accentuate the effect of FAME on the energy content of the blended diesel fuels. The programme was statistically designed to give a robust and repeatable testing schedule so that fuel consumption and tailpipe emissions data could be reliably collected over regulatory and transient driving cycles. The vehicle study was conducted for Concawe by the Laboratory for Applied Thermodynamics of the Aristotle University of Thessaloniki, Greece.

Fuel consumption data for all three vehicles over all driving cycles show that the volumetric fuel consumption increases in direct proportion with increasing FAME content and the decreasing volumetric lower heating value (energy content) of the FAME/diesel fuel blends. There was no detectable change in the energy efficiency of the vehicles on different fuel blends and they were not able to compensate for the lower energy content of the FAME/diesel blends through improved performance.

Increasing the FAME content also reduced the PM but increased the NOx, HC, and CO emissions. The overall impact of FAME on tailpipe emissions was small when compared to the variations in emissions seen for different driving cycles and for different vehicles over the same driving cycle. No significant difference in emissions performance was observed for the two types of Diesel Particulate Filter (DPF) aftertreatment systems that were tested in these vehicles.

It is expected that these results will be of importance to those interested in the impact of FAME in diesel fuel on Well-to-Wheels fuel consumption and on tailpipe emissions from modern light-duty passenger cars.

KEYWORDS

Exhaust emissions, diesel fuel, engine technology, vehicles, fuel quality, NEDC, Euro 4, fuel consumption, particulate mass (PM), NOx, FAME, RME

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SUMMARY

Bio-components have been considered as alternative energy sources for road transport fuels for many years. Within the EU, higher renewable use has been mandated by the Renewable Energy Directive (RED, 2009/EC/28 [2]) with corresponding reductions in greenhouse gas (GHG) emissions (Fuel Quality Directive, (FQD, 2009/30/EC [28]). These mandates are driving the use of more bio-derived blend components for diesel fuels, especially Fatty Acid Methyl Esters (FAME). For this reason, it is of interest to understand the potential impact of FAME products on vehicle fuel consumption and tailpipe emissions.

Previous vehicle studies have investigated the effect of bio-diesel components on both fuel consumption and emissions performance. Most of these studies, however, focused on the effect of diesel fuel blends on regulated emissions from heavy duty engines, especially in hot start tests, while the effects on fuel consumption were less consistently addressed. The published literature also does not adequately report on the effects of bio-diesel blends on light duty diesel vehicles and on cold engine starting tests. For this reason, there is a gap in understanding on performance issues related to light duty vehicles that are of importance to the European market.

This vehicle study was designed by Concawe to investigate the effect of FAME on fuel consumption and tailpipe emissions from three Euro 4 light duty passenger cars. All vehicles had common rail turbocharged engines and were equipped with different exhaust aftertreatment technologies. Two of the three vehicles had Diesel Particulate Filters (DPF) that were regenerated using different strategies. All test work was carried out at the Laboratory of Applied Thermodynamics (LAT) of the Aristotle University of Thessaloniki, Greece.

Four fuels were evaluated in this study. One base diesel (B0 complying with the EN 590 specification [3]) was blended with commercially sourced Rapeseed Methyl Ester (RME) (complying with the EN 14214 specification [4]) to give three diesel/RME blends at 10%, 30% and 50% v/v RME. These concentrations were selected in order to anticipate future increases in biofuel blending levels for use in compatible vehicles and to accentuate the impact of RME on vehicle performance and emissions.

Measurements were performed according to the New European Driving Cycle (NEDC), which is the European regulatory procedure for vehicle emissions. Additionally, the ARTEMIS transient cycle was used to simulate more aggressive real world driving operation and compare results to those obtained over the NEDC. Some tests were also carried out at 50 and 120km/h constant speed conditions. All fuel/vehicle combinations were tested in a rigorously controlled and statistically designed test programme. Fuel consumption data were determined along with regulated and unregulated emissions, including particulate matter (PM) composition, particle number (PN) emissions, particle size distributions, and carbonyl emissions. This report focuses on fuel consumption and regulated emissions while the particle number (PN) and unregulated emissions results have been reported separately [1].

The fuel consumption data for all three vehicles over all driving cycles show that the volumetric fuel consumption increases in direct proportion to the increasing FAME concentration and the decreasing volumetric lower heating value (energy content) of the FAME/diesel fuel blends. There was no apparent change in the energy efficiency of the vehicles on different fuel blends and the vehicles were not able to compensate for the lower energy content of the FAME/diesel blends through improved performance.

Increasing the FAME content also reduced the particulate mass (PM) emissions and the number of solid particles but increased the NOx, HC, and CO emissions. The overall impact of FAME on emissions was small when compared to the variations in tailpipe emissions seen for different driving cycles and for different vehicles over the same driving cycle. No significant difference in emissions performance was observed for the two types of Diesel Particulate Filter (DPF) aftertreatment systems evaluated in this study.

1. INTRODUCTION

The Renewable Energy Directive (RED, 2009/28/EC) [2] will require 10% renewable energy in transport fuels by 2020 within the European Union while the Fuel Quality Directive (FQD, 2009/30/EC [28]) will require reductions in GHG emissions from transport fuels. Changes to the European gasoline and diesel fuel specifications have already been made to enable higher blending of bio-components into market gasoline and diesel fuels in order to enable these requirements.

In the near term, biofuel obligations for diesel fuels will most likely be fulfilled with FAME. In the longer term, bio-components from biomass and from other sources may become more readily available and will undoubtedly be required in order to achieve the EU ambitions. Although this is likely, the current test programme focussed on FAME bio-components only and alternatives to FAME, such as Hydrogenated Vegetable Oils (HVO) and Biomass-to-Liquids (BTL) blend components, may be considered for future studies.

FAME can be used as a neat fuel (B100) but is most widely used in low concentration blends with fossil diesel fuel. Currently, the EN 590 specification [3] allows up to 7% v/v FAME meeting the EN 14214 specification [4] to be blended into diesel fuel. Many different FAME types are commonly used throughout Europe and the rest of the world. Rapeseed Methyl Ester (RME) is the most frequently used, however, and a single batch of RME was chosen for this study (see **Section 2.2)**.

FAME use is an everyday practice in most EU Member States and its share in diesel fuel is rising year by year. B100 is allowed in some national legislation and some adapted vehicles, including those in captive fleets, can operate with high percentages of FAME, typically up to 30% v/v FAME (B30). As a result, any potential impact of biodiesel blends on vehicle emissions is already affecting vehicle fleet pollutant emission levels. These impacts could gain greater significance in view of the stricter emission standards (Euro 5) that are now in place [19].

Of special interest is the potential impact that higher FAME contents may have on vehicle fuel consumption and on regulated and unregulated emissions. Previous vehicle test programmes [5,6,7,8] have studied the effect of bio-components on both fuel consumption and regulated emissions but many of the more systematic studies have focused on heavy duty engines that were not yet equipped with exhaust aftertreatment systems. The most comprehensive assessment of heavy-duty vehicle emissions performance was published by the US EPA [9] which showed that NOx emissions increase and PM, CO, and HC emissions decrease as a function of increasing FAME content. The published literature does not adequately address the impact of FAME on modern light-duty diesel vehicle performance, however, and there is an overall gap in understanding on performance issues related to light-duty diesel vehicles that are important to the European marketplace.

The fuel consumption (FC) of light-duty vehicles operating on biodiesel blends is also an important question as attention increasingly focuses on the GHG reductions that can be achieved from these fuel blends. In most Well-to-Wheels (WTW) studies [10], the vehicle's efficiency is assumed not to change when the engine runs on an oxygenated fuel, that is, the same megajoules (MJ) of fuel are needed to complete a prescribed driving cycle for both hydrocarbon-only and oxygenated diesel fuels. This means, however, that a slightly higher volumetric FC is expected for oxygenated fuels because the volumetric energy content of these fuels is somewhat lower than that of hydrocarbon-only fuels. This effect is easily observed in gasoline vehicles fuelled with ethanol blends and will be more evident in diesel vehicles if the concentration of FAME in diesel were to increase.

For this reason, it is important to know whether modern vehicles are capable of recovering a portion of this volumetric penalty through better engine efficiency when running on oxygenated fuels. The published literature is not entirely clear on this point, in part because the energy content of FAME/diesel blends is only slightly lower than that of hydrocarbon-only diesel fuels. Detecting small differences in volumetric FC is difficult experimentally.

Accordingly, Concawe designed and carried out this statistically robust test programme to answer this question by generating new FC data from European diesel passenger cars. At the same time, this study provided an opportunity to re-evaluate the impact of oxygenate blends on vehicle exhaust emissions. Some results from this study have been published elsewhere [25].

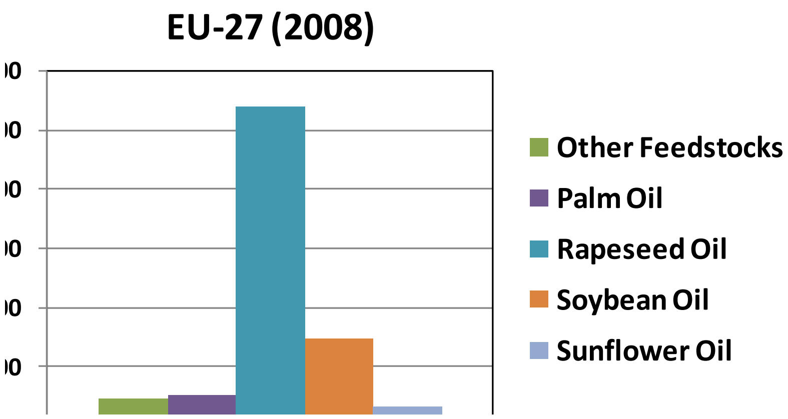
The objective of this test programme then was to generate definitive FC data and an emissions database on diesel fuels that contain varying concentrations of RME. This work was conducted on three diesel vehicles where our evaluation of recent literature indicates that there is a lack of reliable or consistent data.

Three vehicles complying with the Euro 4 emissions standard [18] were selected for this study. These vehicles were equipped with different exhaust aftertreatment systems and were chosen as representatives of the European diesel passenger car fleet. All vehicles used Exhaust Gas Recirculation (EGR) for NOx reduction and some form of Diesel Oxidation Catalyst (DOC). In addition, Vehicles 1 and 3 were equipped with Diesel Particulate Filters (DPF) that were regenerated using two different strategies. Details on the vehicles and their aftertreatment systems can be found in **Section 2.1**.

Four fuels were tested in this study. One base diesel fuel (Fuel B0 meeting the EN 590 specification) was blended with a single batch of commercial RME (meeting the EN 14214 specification) to give blends containing 10% v/v (B10), 30% v/v (B30) and 50% v/v (B50) RME. These RME concentrations were selected in order to anticipate future increases in biofuel blending levels for use in compatible vehicles and to accentuate the impact of RME on vehicle performance and emissions.

Details on the test fuels are given in **Section 2.2**. RME was chosen for this study because it is oxidatively more stable and is manufactured from a common feedstock used for FAME production in the EU-27 as shown in **Figure 1** [11]. The type of feedstock used to manufacture the FAME is not expected to play a large part in the fuel consumption and exhaust emissions results studied here. A summary of published literature related to this question is provided in **Appendix 2**.

Figure 1 Feedstocks for FAME production in EU-27 (2008) [11]



All vehicle/fuel combinations were tested five times on the B0 fuel and four times each on the three RME-containing fuels using a statistical design (see **Section 3.2**). A range of test cycles and steady state conditions were evaluated:

- New European Driving Cycle (NEDC), including the Urban Driving Cycle (UDC, also called the ECE-15) and the Extra Urban Driving Cycle (EUDC);
- ARTEMIS Urban and Road driving cycles [12]; and
- 120 and 50 km/h steady state conditions.

These driving cycles allowed any differences between cold and hot start tests to be identified along with any changes as a result of transient versus steady state operation.

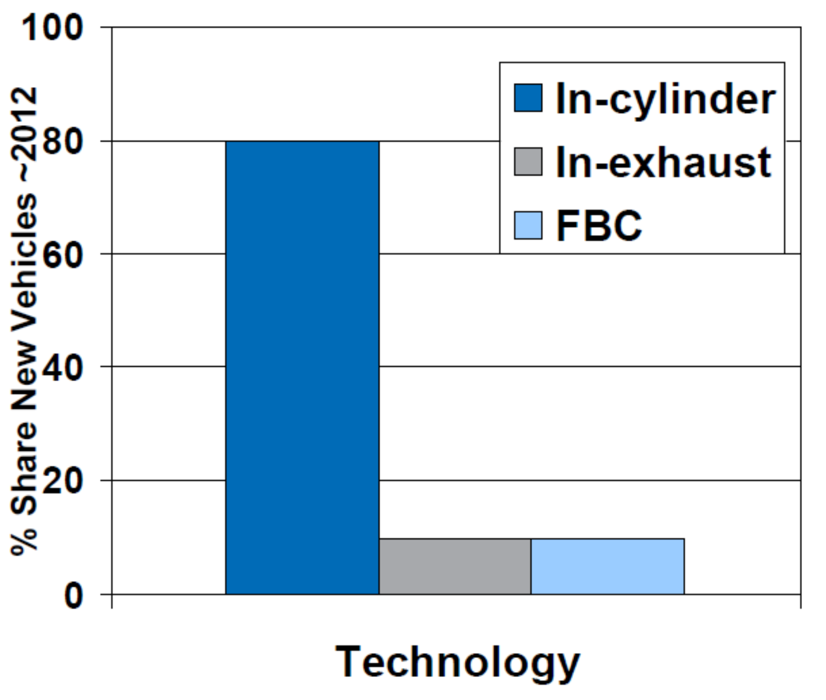
At each test condition, all regulated tailpipe emissions were measured (NOx, HC, CO, PM) along with CO_2 and FC data and these measurements are included in this report. For some test conditions, additional measurements were made of modal NO and NOx emissions and also of total particle number (PN). Additionally, particle size distributions were collected under steady-state driving conditions and these measurements were carried out in accordance with PMP[1] protocols. The results from both the NO and PN measurements are included in a second report [1] as well as the analysis of PM composition and carbonyl emissions. Over the course of the vehicle study, the oxidation stability of the RME/diesel blends was monitored and the results are included in **Appendix 11**.

Vehicles selected for this study were equipped with DPF aftertreatment systems to reduce particle emissions. Among the different types of DPF technologies in common use, the fuel-borne catalyst technology has a reasonable market share on the short- to medium-term but is not considered to be the favourite DPF option for the longer-term. In-cylinder post injection is expected to be the dominant DPF technology for the longer-term (**Figure 2)**. Diesel Particulate NOx Reduction (DPNR) technology is not widely used today and it has been noted that regeneration of the DPNR system occurs more frequently compared to standard DPF technology increasing overall fuel

[1] Particle Measurement Programme (PMP)

consumption. In this study, the DPF regeneration events were monitored to ensure that they did not occur during FC and emissions measurements.

Figure 2 Expected EU market share for different DPF regeneration strategies in 2012 for light-duty passenger cars (Source: Ricardo (2008))



Especially with the in-cylinder post-injection strategy, higher FAME levels in diesel fuel can increase the higher-boiling fuel components (including FAME) that appear in the lubricant. This is because DPF regeneration is achieved by periodically injecting extra fuel into the cylinder at the end of the combustion cycle. This can lead to changes in the lubricant performance and, in worse cases, damage to the oil pump and engine due to higher total lubricant volumes.

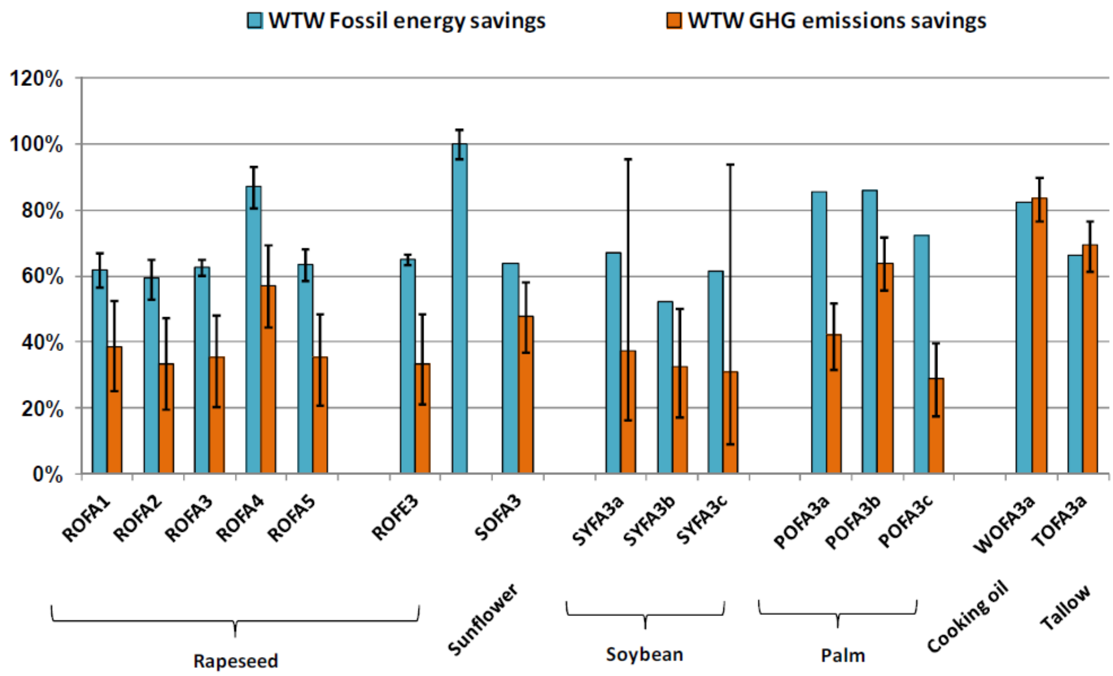
Among the three main types of DPF regeneration strategies, the in-cylinder post-injection strategy is the most commonly used for light-duty diesel vehicles today (**Figure 2**). This approach (used in Vehicle 1) and, to a *lesser* extent, the fuel-borne catalyst approach (used in Vehicle 3) are expected to be sensitive to this lubricant problem. The third DPF regeneration strategy, in-exhaust injection, is not expected to result in fuel accumulation in the lubricant because the fuel injector is mounted in the aftertreatment system, typically in front of the DPF. This approach is similar to non-DPF aftertreatment systems in terms of the impact of FAME in fuel on the lubricant system.

Diesel fuels having higher FAME contents have also been reported to increase the build-up of ash on the DPF leading to higher backpressure across the filter and the need for more frequent DPF regeneration cycles. There is some evidence that FAME can also reduce the balance point temperature for passive soot combustion. The different energy contents of FAME and FAME/diesel blends could also be an issue for engine calibration settings. There are interesting questions and an additional Concawe study has been conducted to investigate some of these effects.

In this study, Vehicle 2 was not equipped with a DPF and was included in order to give a clear indication of how the engine responded to fuel without complications from exhaust system regeneration. This also allowed read-across of the results to other Concawe studies that had been previously done on non-DPF vehicles [13,14,15,16].

FAME has about 14% (on a mass basis) less energy content compared to fossil diesel fuel. This lower energy content is expected to increase vehicle fuel consumption on a volumetric basis proportional to the FAME concentration. Well-to-Wheel (WTW) analyses [10] have shown the potential benefits in energy content and GHG emissions for various FAME products when used as neat fuels (**Figure 3)**. It is important to know from a Tank-to-Wheels (TTW) and WTW perspective whether the efficiency of modern engines changes when running on FAME-containing fuels.

Figure 3 WTW expended fossil energy and GHG emissions savings for 100% bio-diesel pathways compared to conventional diesel (2020+ DICI vehicle) [10]



Key to pathway codes

COD1	Conventional diesel
ROFA1	Rape (RME), meal to animal feed, glycerine as chemical
ROFA2	Rape (RME), meal to animal feed, glycerine to animal feed
ROFA3	Rape (RME), meal to animal feed, glycerine to fuel
ROFA4	Rape (RME), meal to biogas, glycerine to fuel
ROFA5	Rape (RME), meal to animal feed, glycerine to hydrogen
ROFE3	Rape (REE), meal to animal feed, glycerine to fuel
SOFA3	Sunflower (SME), meal to animal feed, glycerine to fuel
SYFA3a	Soy (SYME), no till, oil to EU, meal to animal feed, glycerine to biogas
SYFA3b	Soy (SYME), no till, beans to EU, meal to animal feed, glycerine to biogas
SYFA3c	Soy (SYME), conv. agriculture, oil to EU, meal to animal feed, glycerine to biogas
POFA3a	Palm (POME), meal to animal feed, no CH4 recovery, heat credit, glycerine to biogas
POFA3b	Palm (POME), meal to animal feed, CH4 recovery, heat credit, glycerine to biogas
POFA3c	Palm (POME), meal to animal feed, no CH4 recovery, no heat credit, glycerine to biogas
WOFA3a	FAME from waste cooking oil
TOFA3a	FAME from tallow

1.1. IMPACT OF FAME ON FUEL CONSUMPTION: PUBLISHED LITERATURE

Before beginning the vehicle study, a literature review was completed in order to evaluate the previously reported impacts of FAME on fuel consumption (see **Appendix 1**). Of the 99 papers examined in this review, 45 papers were selected as promising candidates for information on the impact of FAME-containing fuels on FC. Although these papers were studied in detail, it became apparent that none of the experiments reported in these papers were designed to look specifically at changes in engine efficiency. A best attempt has been made, however, to analyse them from this viewpoint but the robustness of the experimental design has led to the published efficiency data being of questionable value.

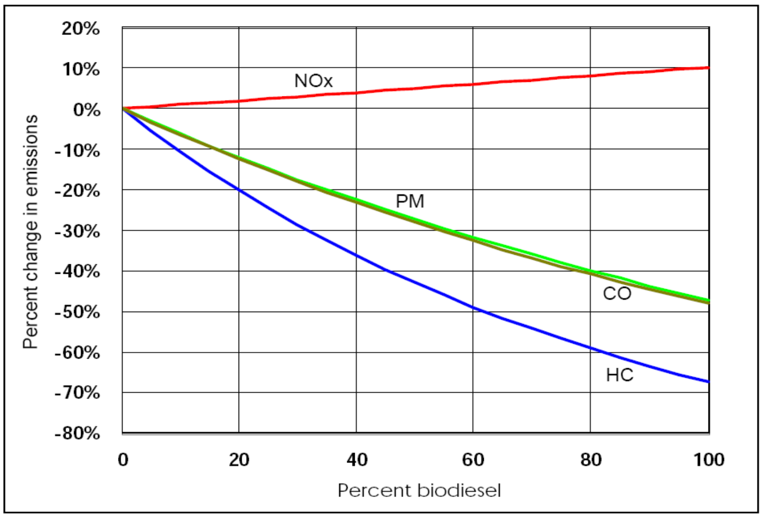
The key findings from the published literature are summarized here. First, there is little to no discrimination in FC effects for small changes in FAME content, e.g. from B0 to B10. Where papers have claimed an engine efficiency benefit when running on oxygenated fuels, the results are generally associated with a lack of discrimination between fuels. Analysing the data from these papers “second-hand” has required calculations of energy consumption or engine efficiency and these have had to rely on the Lower Heating Values (LHV) reported in the papers. Some of these LHVs are of questionable accuracy and represent another potential source of error in an analysis of published results.

The overall conclusion from this literature assessment on FC data is that no improvement in engine efficiency has been observed from the use of FAME and FAME blends compared to fossil diesel fuel. Although there is no evidence to suggest an improvement in engine efficiency, there is some tentative evidence suggesting that a reduction in engine efficiency is observed with FAME and FAME/diesel blends in some studies.

1.2. IMPACT OF FAME ON REGULATED EMISSIONS: PUBLISHED LITERATURE

The same published literature was evaluated to identify the impact of FAME in diesel fuel on regulated emissions (see **Appendix 3**). 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 [9] from which the following graph has been extracted.

Figure 4 Average percentage change in regulated emissions from heavy-duty engines with increasing biodiesel content [9]



The effects shown in **Figure 4** 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 predominantly focused on heavy duty engines (and primarily on US market engines) that were not equipped with exhaust aftertreatment and tested only over hot start test cycles. It may not be reasonable to assume that these results will be representative of modern European light duty vehicles that are equipped with a variety of aftertreatment technologies and are certified over a cold start test cycle. There are considerably fewer publications related to modern light-duty diesel vehicles and the results that have been reported are generally less consistent than those from the heavy duty tests. For this reason, it was important to include both regulated and unregulated exhaust emissions in this study.

2. EXPERIMENTAL

2.1. DIESEL VEHICLES

Three light-duty diesel passenger cars complying with the Euro 4 emission regulations [17,18] were selected for this test programme. The choice of vehicles was made in order to cover the most prominent engine and exhaust aftertreatment technologies currently present in the European fleet. For this reason, all three vehicles were equipped with direct injection, high injection pressure common rail and turbocharged engines. All vehicles used EGR for NOx control and a DOC for reducing CO and HC emissions. Vehicles 1 and 3 were also equipped with a DPF for controlling PM emissions. Previous results have shown that DPFs can be effective at reducing PN emissions, namely those ultrafine particles that have aerodynamic mobility diameters less than about 0.1μm.

Two different types of DPF were chosen for this study based on their regeneration strategy. Vehicle 1 was equipped with a catalysed DPF (CDPF) while Vehicle 3 used a fuel-borne additive to regenerate the DPF. As shown in **Figure 2**, these two DPF regeneration technologies are likely to be the most widely used options for DPF regeneration in the European light-duty diesel fleet. The vehicles and their characteristics are shown in **Table 1**.

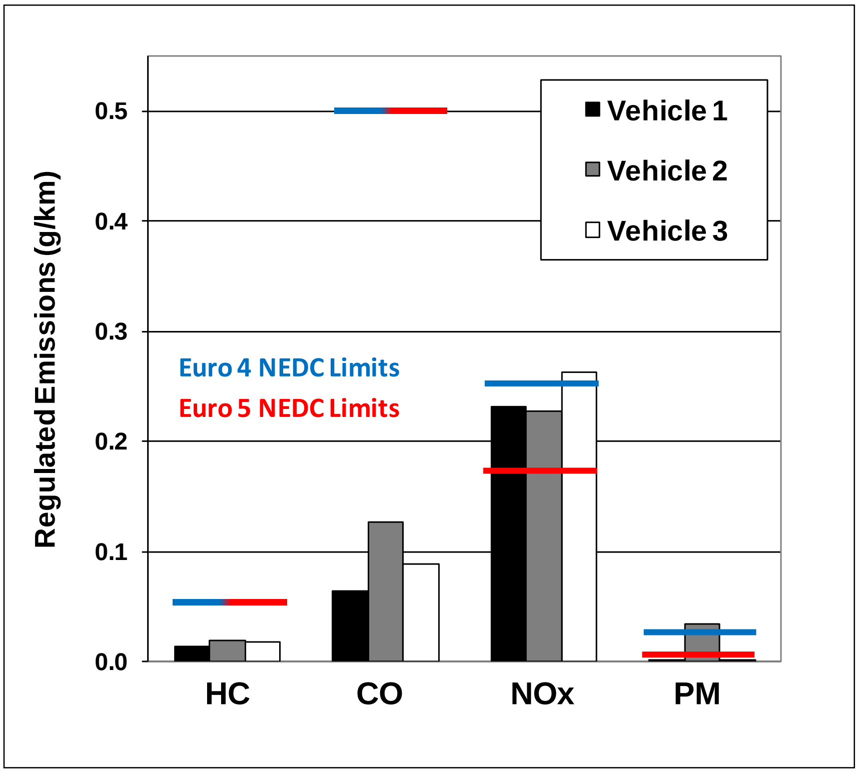
Table 1 Technical Characteristics of the Light-duty Diesel Passenger Cars

Vehicle Characteristics	Units	Vehicle 1	Vehicle 2	Vehicle 3[2]
Model Year	Year	2009	2004	2005
Cylinders		4	4	4
Displacement	cm^3	2148	2200	1997
Maximum Power	kW	110	100	98
Injection System		Common Rail DI	Common Rail DI	Common Rail DI
Transmission		Automatic	Manual	Manual
Euro Certification		Euro 4	Euro 4	Euro 4
Exhaust Aftertreatment				
• **EGR**		Yes	Yes	Yes
• **DOC**		Yes	Oxidation pre-catalyst plus 2-stage DOC with DeNOx characteristics	Yes
• **DPF**		Yes, regenerated by in-cylinder fuel injection and catalyzed DPF	None	Yes, regenerated by in-cylinder injection of fuel-borne catalyst
Mileage at start of testing	km	3,487	62,118	27,603

The average regulated emissions from these vehicles over the NEDC are shown in **Figure 5** for all five tests on the hydrocarbon-only diesel fuel (B0). Compared to the Euro 4 and 5 emissions limits shown by the horizontal bars, all three vehicles complied with the Euro 4 limits, although the NOx emissions for Vehicle 3 and the PM emissions for Vehicle 2 were borderline. The DPF-equipped vehicles reduced the PM emissions to levels that were substantially lower than that required even by the upcoming Euro 5 emissions regulation [19].

2 Vehicle 3 is the 'golden vehicle' that was previously used as the round-robin test vehicle in the European Particle Measurement Programme (PMP) [20,21]

Figure 5 Average regulated emissions over the NEDC on the B0 fuel



2.2. BIODIESEL TEST FUELS

Although some European countries, mainly Germany and Austria have marketed B100 fuels (that is, 100% FAME), low level blends of FAME in diesel fuel are more commonly used across the European market. Provided that the FAME blend stock meets the EN 14214 standard [4], up to 7% v/v FAME can be blended into conventional diesel fuels according to the European EN 590 standard [3]. CEN is also working to produce a specification for a fuel with FAME content in diesel fuel up to 10% v/v FAME (B10) for compatible vehicles. For fleet applications, there is also some use of mid-range blends, typically 20-30% v/v FAME in diesel fuel.

In principle, FAME, either neat or in blends with diesel fuel, can be used in normal diesel engines. The cetane number of FAME is typically above 50 and the product distils within the normal diesel distillation range, although on the high end of this range. The properties of FAME are sufficiently different from conventional diesel, however, that some impacts on combustion can be expected.

Diesel fuel containing up to 7% v/v FAME and meeting the EN 590 standard can be used in all conventional diesel vehicles, according to warranty information provided by the auto manufacturers. At higher FAME levels in diesel fuel, FAME has been reported to affect engine and aftertreatment performance and some materials, such as fuel system seals and gaskets. Auto manufacturers have expressed some concerns about whether the composition and oxidative stability of FAME, as specified in EN 14214, are adequate to avoid these problems and this is the subject of on-going work within CEN.

Four fuels were specially blended for this study: a reference diesel fuel (B0) and 3 blends of this diesel fuel with FAME. The base fuel complied with the European EN 590 standard and had a maximum 10 mg/kg sulphur content.

The FAME was a European Rapeseed Methyl Ester (RME) complying with the European EN 14214 standard and contained 1,000ppm of a commercial antioxidant additive (butylated hydroxy toluene (BHT)) to ensure oxidation stability. The Rancimat oxidation stability was monitored throughout the study (see **Appendix 11**).

The RME was blended into the EN 590 diesel fuel at three different concentrations, resulting in the following four test fuels:

- B0: Base diesel fuel
- B10: 10% v/v RME in B0
- B30: 30% v/v RME in B0
- B50: 50% v/v RME in B0

By extending the fuel matrix up to B50, any changes in either FC or emissions performance resulting from the RME could be more easily identified.

Finally, a fully-formulated diesel performance additive package[3] that is widely used in Europe was added to all test fuels at the same concentration in order to ensure consistent fuelling performance throughout the vehicle test programme. An ester-type lubricity additive was also added to all fuels.

The properties of these four test fuels are presented in **Appendix 3**. **Table 2** lists the fuel parameters that are most important for the fuel consumption evaluation.

Table 2 Analytical results on diesel test fuels[4]

Fuel Property	Units	Test Method	B0	B10	B30	B50
Derived Cetane Number (DCN)		**IP 498**	**55.5**	**56.1**	**56.3**	**58.1**
Carbon	**% m/m**	**ASTM D5291**	**85.84**	**84.97**	**82.99**	**81.11**
Hydrogen	**% m/m**	**ASTM D5291**	**13.73**	**13.50**	**13.20**	**12.84**
Oxygen	**% m/m**	**MT/MCR/21**	**<0.04**	**1.1**	**3.3**	**5.4**
Lower Heating Value (LHV)	**MJ/kg**	**ASTM D240/IP12**	**42.89**	**42.32**	**41.22**	**40.06**
Volumetric LHV (VLHV)	**MJ/l**	**Calculated**	**35.30**	**35.09**	**34.66**	**34.17**

As shown in **Table 2**, increasing the FAME content from B0 to B50 resulted in a small (~7%) reduction in LHV. For this reason, the test protocol was carefully designed with sufficient statistical power in order to control experimental variability and to differentiate between small differences in FC and regulated emissions.

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3 HiTEC® 4678

4 Average of two or more measurements conducted at Concawe Member Companies

2.3. LUBRICANT SELECTION

A single lubricant was used in all three vehicles in order to avoid the influence of different lubricants on engine performance and emissions. The selection was made after consulting with the manufacturers of all three test vehicles. The lubricant was an SAE grade 0W-30 for diesel engines (ACEA class B3-B5) with low sulphur, phosphorus and ash contents.

3. METHODOLOGY

From the analysis of the published literature and the small change in LHV for the RME/diesel blends, it was apparent that repeatable, reliable and consistent measurements would be required in order to interpret the impact of RME concentration on fuel consumption and emissions. For this reason, a robust and statistical experimental design was required.

3.1. TEST PROTOCOL

Before starting a test on a given vehicle, the lubricant was changed and the vehicle was driven for at least 1000km in order to condition the lubricant. During this mileage accumulation, information was collected on the DPF-equipped Vehicles 1 and 3 to identify the indicators for the onset of DPF regeneration. This ensured that DPF regenerations would be observed if they occurred during the daily measurement protocol.

From this information, the mileage interval at which the DPF regeneration would occur could be determined and steps taken to avoid regeneration during testing. An additional step was included in the vehicle conditioning to assess how close the vehicle was to regeneration and, if required, a ‘forced’ regeneration was carried out to ensure that regeneration did not occur during the next day’s testing. More information on DPF regeneration is given in **Section 4.4.1**.

Figure A4-1 in **Appendix 4** shows the complete daily procedure for vehicle preparation and testing which consisted of the following steps:

- Pre-condition the vehicle on the designated test fuel, including a controlled DPF regeneration, if required;
- Cold soak the vehicle overnight;
- Complete fuel consumption and emissions measurements in the following sequence:
  - NEDC on the cold vehicle consisting of the UDC (also called the ECE-15) and the EUDC,
  - ARTEMIS Urban and Road transient cycles [12],
  - 120km/h steady-state with some measurements also collected at a 50km/h steady-state condition.

Strict adherence to this protocol ensured that all vehicle preparation, fuel changes, and fuel consumption and emissions measurements were carried out in a repeatable manner for each vehicle/fuel combination.

The RME/diesel blends (B10, B30, and B50) were tested four times in each vehicle while the base fuel (B0) was tested five times in order to improve estimates of baseline performance and engine drift with time. A typical test order is shown below:

Test	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Fuel	B0	B10	B50	B30	B0	B10	B30	B50	B0	B50	B30	B10	B0	B10	B50	B30	B0

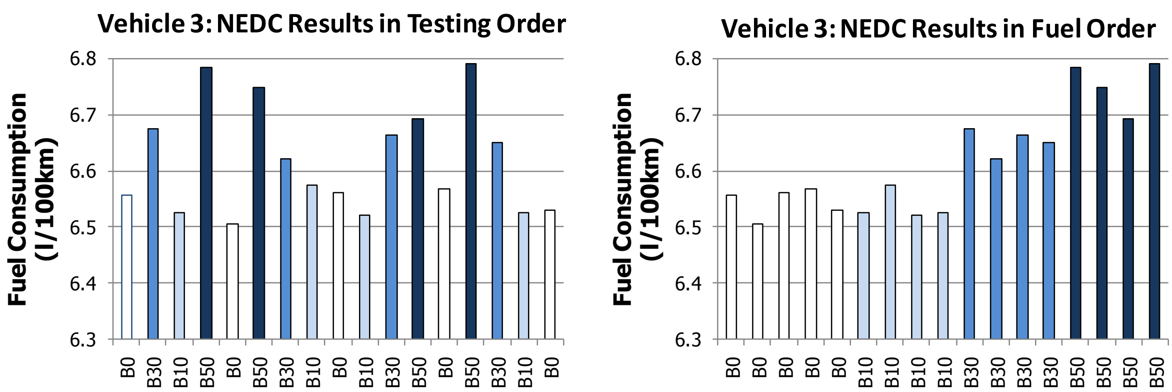
In this example, the three RME/diesel blends are tested in four randomized blocks and the five B0 tests are positioned between adjacent blocks and at the start and end of the testing.

The block design approach reduces the risk that fuel effects will be confounded by potential extraneous sources of variability while the absence of back-to-back measurements ensures that the results are truly independent. Different randomized orders were used for each vehicle (see **Appendix 4**). Seventeen days of testing were required to complete testing on one vehicle and a single driver was used for all vehicle tests.

A repeat test criterion was included in the test protocol. If the ratio of the highest to the lowest FC measurements over the cold NEDC for a particular vehicle and fuel combination exceeded 1.05, then a repeat test was to be conducted on that vehicle and fuel as soon as possible or at the end of the test programme. This criterion was based on historical repeatability data from various sources. In this study, the variation in FC results did not exceed this ratio and no repeat tests were required. Similar criteria were not set for the other tailpipe emissions and cycles.

An example is shown in **Figure 6** for FC results for Vehicle 3 over the NEDC. The left-hand chart shows the FC results in the actual daily testing order while the right-hand chart shows the same results rearranged according to the fuel tested. The results of this type were statistically analyzed as described in **Section 3.2**.

Figure 6 FC results for Vehicle 3 over the NEDC in actual testing order and in fuel order



From work carried out by PMP, it is known that the extent of particle fill on the DPF can affect results with measured PN decreasing as the DPF fills [20,21]. However, there was little scope to take this into account within the test protocol without severely increasing the length of the study. From the analysis of the PN emissions [1], no significant discontinuities were observed between PN measurements made before and after a DPF regeneration event.

The following exhaust emissions were measured:

- CO_2 emissions and FC;
- Emissions of HC, CO, NOx, NO, and PM;

- Particle number (PN), both solid (carbonaceous) and total particle counts, for all cycles and the particle size distribution for the steady state tests [1];
- Analysis of PM composition from selected test conditions. The composition analysis included the percentage of Soluble Organic Fraction (SOF) by Gas Chromatography (GC); sulphate and nitrate anions by Ion Chromatography (IC); and elemental carbon (EC) by difference. The fuel- and lube-derived fractions of the SOF were also estimated by GC. The results of these measurements are included in [1];
- Analysis of carbonyl (aldehyde and ketone) unregulated emissions from selected cycles [22].

Table 3 summarises all of the measurements that were completed over each test condition.

Table 3 Summary of all measurements carried out in this Part 1 study

	UDC	EUDC	NEDC	ARTEMIS Urban	ARTEMIS Road	50 km/h	120 km/h	Vehicle Conditioning
ECU data			X	X	X	X	X	X
CO_2	X	X	X	X	X	*	*	*
CO	X	X	X	X	X	*	*	*
HC	X	X	X	X	X	*	*	*
NO	X	X	X	X	X			
NOx	X	X	X	X	X	*	*	*
Modal NOx			X					
PM total			X	X	X			
PM speciation+			X	X				
PN total+			X	X	X	X	X	
PN solid+			X	X	X	X	X	
Particle size distribution+						X	X	
Carbonyl compounds+			X	X				

* Modal data for these emissions were collected for quality control purposes only and used for calculating indicative emissions at the 120 km/h steady state operating point.

+ See Part 2 Study [1] for these results

The total number of solid particles was measured according to the PMP protocol. A schematic and a full description of the equipment and protocol are given in [20,21].

This report focuses on the results obtained from both FC and regulated emissions measurements, including the analysis of NO/NOx ratio as a tool for understanding catalyst and vehicle effects. The composition of filtered PM samples and unregulated emissions, including PN, PN size distribution, and carbonyl emissions, are summarized in [1].

3.2. STATISTICAL ANALYSIS

This section describes the statistical methods used to analyse the data from this programme. These are similar to those used in earlier Concawe studies [13,14,15,16]. More details can be found in **Appendix 5**.

Each FC and emissions measurement (CO_2, HC, CO, NOx, NO, NO/NOx, and PM) was examined separately on a vehicle-by-vehicle and cycle-by-cycle basis.

In the EPEFE gasoline project [23] and in the other emission and particulate studies cited above, the variability in emissions and particulate measurements has typically been found to follow a lognormal distribution with the degree of scatter increasing as the emission level increases.

The standard deviation vs. mean plots in **Appendix 7** show that HC, CO, NOx, NO, and PM measurements behaved in this way in the present study in those cycles where there were noticeable differences in emissions between fuels (note these plots were plotted before outliers had been removed or the results had been trend corrected). This assumption is harder to verify rigorously for CO_2 and FC because the measurements differ little from fuel to fuel in absolute terms on any particular vehicle. Nevertheless, all subsequent statistical analyses are based on the assumption of lognormality because the physical mechanisms suggest that this is the most plausible model for emissions (and therefore FC) data.[5]

The data were examined for outliers by inspecting studentized residuals (residuals divided by their Standard Errors (SE)). Less than 1% of the measured emissions values were rejected (see **Appendix 5** for details).

Consistent with previous Concawe studies, arithmetic means have been used to summarize all fuel consumption, gaseous emission and PM measurements, despite the lognormality in the data. This is because logarithmic (i.e. geometric means) underestimate total emissions to the atmosphere (see **Appendix 5**). Therefore in the various plots in subsequent sections, all measurements are plotted on the original g/km or l/100km scale. SEs and error bars were computed using weighted analysis of (co)variance techniques (see **Appendix 5**).

In the bar charts presented in **Section 4**, the error bars show the mean value ±1.4 x SE of the mean value. The factor 1.4 in this equation was selected for consistency with EPEFE [23] and with previous Concawe studies [13,13,14,16]. Emissions from two fuels will not be significantly different from one another at $P<5\%$[6] unless there is a sizeable gap between their error bars.

Statistically significant time trends (at $P<1\%$[7]) were found in 22[8] of the 114 data sets (3 vehicles × 7 measurements × up to 6 cycles[9]) for HC, CO, NOx, NO, PM, CO_2, and FC. These sets of data points can be adjusted to what they might have been if all of the tests had been conducted halfway through the test programme using statistical "analysis of covariance" techniques. Trends were corrected on the natural and not the logarithmic scale using an appropriately weighted analysis (see **Appendix 5**).

Both the uncorrected and corrected means are shown in **Appendix 6**. It can be seen that trend correction generally had little effect on mean emissions because a statistically robust randomised block design was used to set the test order (see

5 If NO and NOx are both lognormal, then so is the NO/NOx ratio.

6 P<5% = the probability that such an event could be observed by chance when no real effect exists is less than 5%. In other words, we are 95% confident that the effect is real.

7 P<1% = the probability that such an event could be observed by chance when no real effect exists is less than 1%. In other words, we are 99% confident that the effect is real.

8 This includes one NEDC data set where the time trend for NO was not significant but was corrected in order to be consistent with the contributing EUDC data set that was trend corrected. NO/NOx values were not trend corrected.

9 PM was not measured at the 120 km/h steady-state condition or over the separate UDC and EUDC cycles.

Section 3.1). Nevertheless, the correction reduced SEs and error bars helped to improve the discrimination between different fuels. For this reason, corrected means are shown for these variables in **Figures 8** to **15**.

4. RESULTS AND DISCUSSION

All regulated emissions measurements were made according to the procedures described in **Appendix 4**. The average CO_2, FC, regulated gaseous emissions (HC, CO, and NOx), and PM emissions for each vehicle and cycle are tabulated in **Appendix 6** along with the NO and NO/NOx ratio.

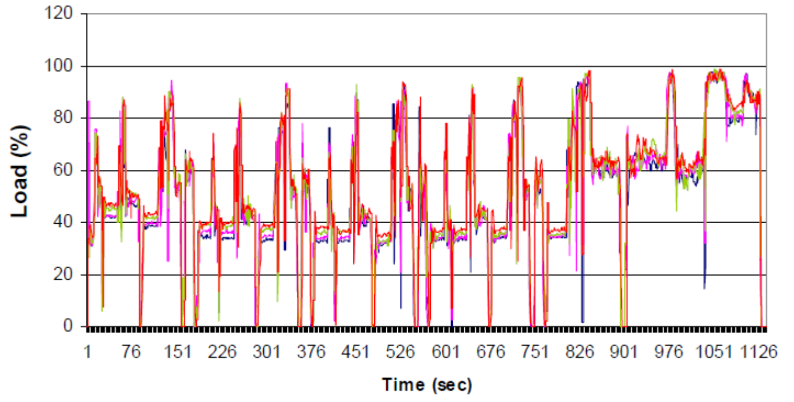
The following sections summarize the results of measurements conducted on the three vehicles during this study. The results are divided in sections corresponding to engine operating data, CO_2/FC, and the other regulated emissions. An additional section discusses catalyst effects and DPF regeneration events. This data is also the subject of a published paper [29}.

4.1. ENGINE OPERATION DATA

Appendix 10 shows the actual engine speed record from each vehicle's Engine Control Unit (ECU) regarding calculated engine load (as provided by the On-Board Diagnostics (OBD)). As expected, for every vehicle, the engine speed following the predefined cycle profile and gearshift strategy did not vary with different fuels.

However, a clear increase in the average calculated engine load (as reported by the OBD) is observed with different fuels for all cycles (**Figure 7**). In this figure, the B0 fuel is shown in blue (bottom) while the B50 fuel is shown in red (top). The engine management system (EMS) calculates the load on the basis of the fuel volume injected into the cylinder.

Figure 7 Calculated engine load from the ECU for Vehicle 2 over the NEDC



The reduction in the fuel's energy content with increasing RME resulted in an increase of the fuel volume injected into the cylinder. This is interpreted by the ECU as an increase in the engine load (by means of the ECU-calculated engine load). However, the power output (actual load) does not change.

Table 4 summarizes the engine load data recorded from the vehicle's ECU. The B10 fuel caused an increase of about 1% in the ECU-calculated engine load reflecting the lower volumetric energy content of this B10 blend. The corresponding reductions were about 3% for B30 and about 5% for B50. The reductions for the B10 and B30 fuels are considered to be small and most probably do not affect the engine control strategy. It is possible, however, that the increase in the ECU-calculated engine load with B50 is large enough to affect the EMS resulting in slightly different operating strategies. However, a definitive conclusion could only be drawn after consultation with the engine manufacturers.

Table 4 Differences in average engine load compared to results on the B0 fuel

Cycle	Fuel	Vehicle 1	Vehicle 2	Vehicle 3	*Average*
NEDC	B10	-0.5%	1.8%	0.3%	***0.5%***
	B30	2.0%	3.5%	2.3%	***2.6%***
	B50	4.0%	4.9%	5.1%	***4.7%***
ARTEMIS Urban	B10	1.2%	3.2%	-0.4%	***1.3%***
	B30	1.1%	6.0%	2.1%	***3.1%***
	B50	4.6%	7.0%	5.9%	***5.8%***
ARTEMIS Road	B10	2.0%	1.1%	0.8%	***1.3%***
	B30	6.8%	2.1%	0.6%	***3.2%***
	B50	4.7%	2.9%	6.8%	***4.8%***

4.2. CO_2 EMISSIONS, FUEL CONSUMPTION AND ENGINE EFFICIENCY

The primary objective of this study was to determine whether modern vehicles improve their efficiency when running on FAME/diesel fuels. If this were to occur, the volumetric FC should be lower than would be predicted from the volumetric Lower Heating Value (VLHV) of the RME/diesel fuel blend. Since the change in VLHV is not large, higher RME contents and a rigorous test protocol were used in this study as described previously.

The energy consumption of a vehicle is reported in different ways depending on how the data will be used. For example, consumers purchase fuel by the litre and, therefore, are primarily interested in the vehicle's volumetric FC (in litres/100km). Vehicle manufacturers are required to measure and report TTW CO_2 emissions over the regulatory NEDC driving cycle using a single certification fuel. At this time, the certification fuel is a B5 fuel having average chemical and physical properties.

For planning purposes, however, the vehicle's efficiency or energy consumption (in MJ/100km) is more important so that CO_2 emissions can be evaluated over the entire WTW fuel production and use chain. Because GHG emissions are linked to energy consumption, CO_2 emissions from the vehicle also depend on the composition of the fuel, especially the hydrogen to carbon (H/C) ratio of the fuel. Energy consumption is generally more informative for comparing the WTW performance of different fuels in vehicles over a prescribed driving cycle.

In this study, tailpipe emissions measurements were made for CO_2, CO and HC[10]. These measurements, together with the H/C of the test fuel, allowed the FC to be calculated by carbon balance (see **Appendix 8** for details). Because the RME contains oxygen, its energy content per litre (or per kilogram) is lower than the energy content of a litre (or kilogram) of fossil diesel fuel. Therefore, for the same vehicle efficiency, the volume of fuel needed to complete a given driving cycle will be slightly higher for an RME-containing fuel than it will be for a fossil diesel fuel.

To calculate the energy consumption or vehicle efficiency, the LHV of the fuel blend must also be known by direct measurement. Because all of the fuel and vehicle measurements have some degree of experimental uncertainty, a carefully designed study must be completed with multiple repeat tests in order to unambiguously identify

[10] In comparison to the CO_2 emissions, the CO and HC emissions are very small.

fuel-related effects. Randomised testing of different fuels is also important in order to minimise short- and long-term effects.

Although CO_2 emissions are important and can be measured directly, they cannot be directly compared with energy consumption if the fuel compositions are different. As was the case in this study, however, the variation in H/C ratio between different fuels was not very large so the correlation between CO_2 emissions and energy consumption is quite close.

Figures 8 and **9** show the CO_2 emissions and FC, respectively, for all vehicles and all driving cycles. In all of the bar charts shown in this report, the error bars represent ±1.4 x SE of the mean value for the indicated fuel and vehicle (see **Section 3.2** for an explanation). Emissions from two different fuels will not be significantly different from one another at P<5% unless there is a sizeable gap between their error bars.

Figure 8 Average CO_2 emissions for all vehicles and driving cycles

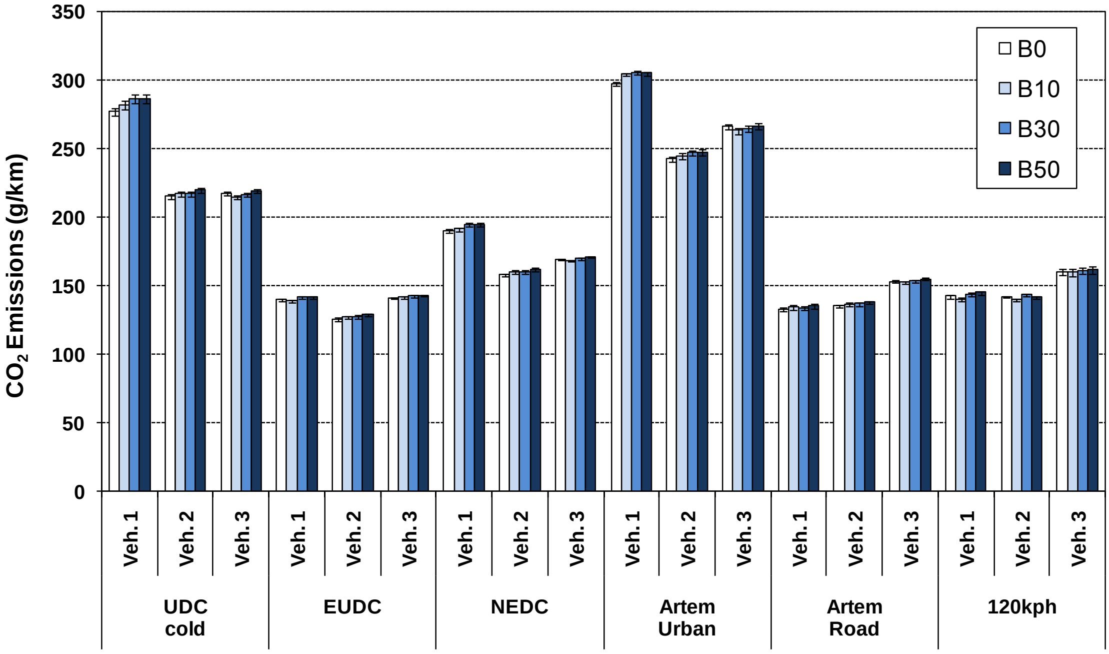
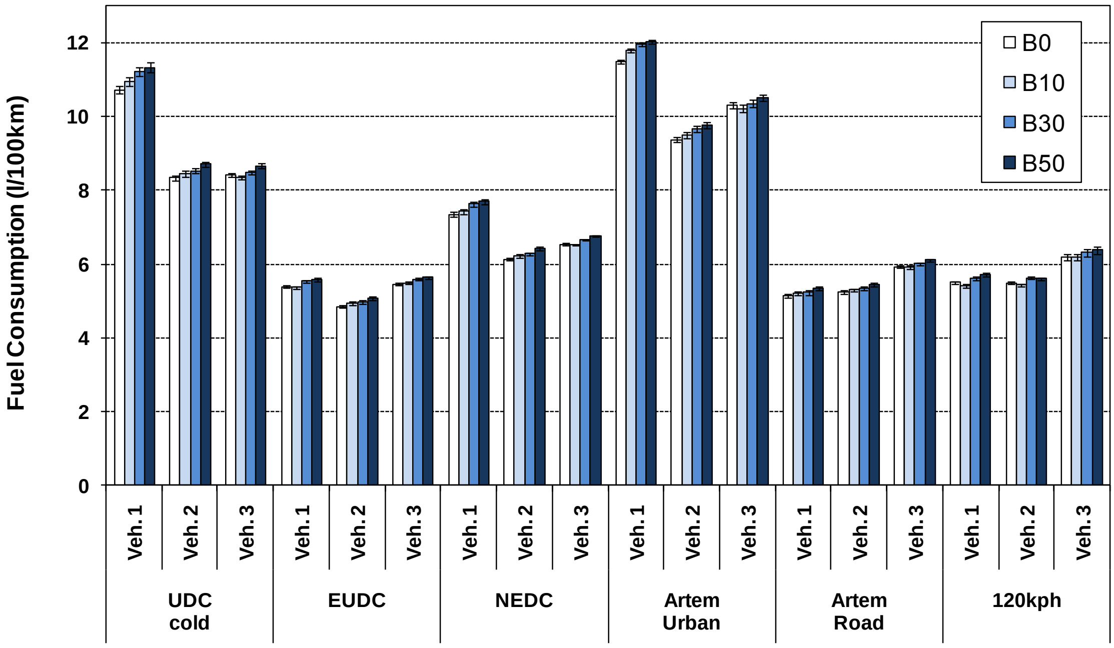


Figure 9 Average volumetric FC for all vehicles and driving cycles



As shown in **Figures 8** and **9**, both the CO_2 emissions and the calculated volumetric FC increase with increasing RME content as expected from the slightly lower energy content of the RME/diesel blends. The same trends are observed for all vehicles and cycles. Repeat measurements of CO_2 emissions on the same vehicle, fuel, and driving cycle varied by up to ± 3% about their mean which was within the range of expected variation. It is very clear, however, that the changes in CO_2 emissions and volumetric FC are much larger between different driving cycles and vehicles than they are from changes in the fuel composition.

Focusing on the fuel variations only, however, the CO_2 emissions generally increased as the RME content increased. The CO_2 emissions with the B50 fuel were on the order of 1 to 3% higher than for the B0 fuel in most cases. All vehicles responded in a similar way for CO_2 emissions and volumetric FC with increasing RME content.

Over the NEDC, the vehicle is driven according to a prescribed cycle of speed versus time (see **Figure A4-1** in **Appendix 4**). For fuels having different LHVs, this means that different masses of fuel will be consumed over the regulatory NEDC and converted to CO_2 exhaust emissions through combustion.

As the RME content increases, the mass of fuel consumed increases because the LHV of the RME (and therefore the LHV of the RME/diesel blend) decreases. Much of this additional mass, however, comes from the oxygen in the RME which does not affect CO_2 emissions directly.

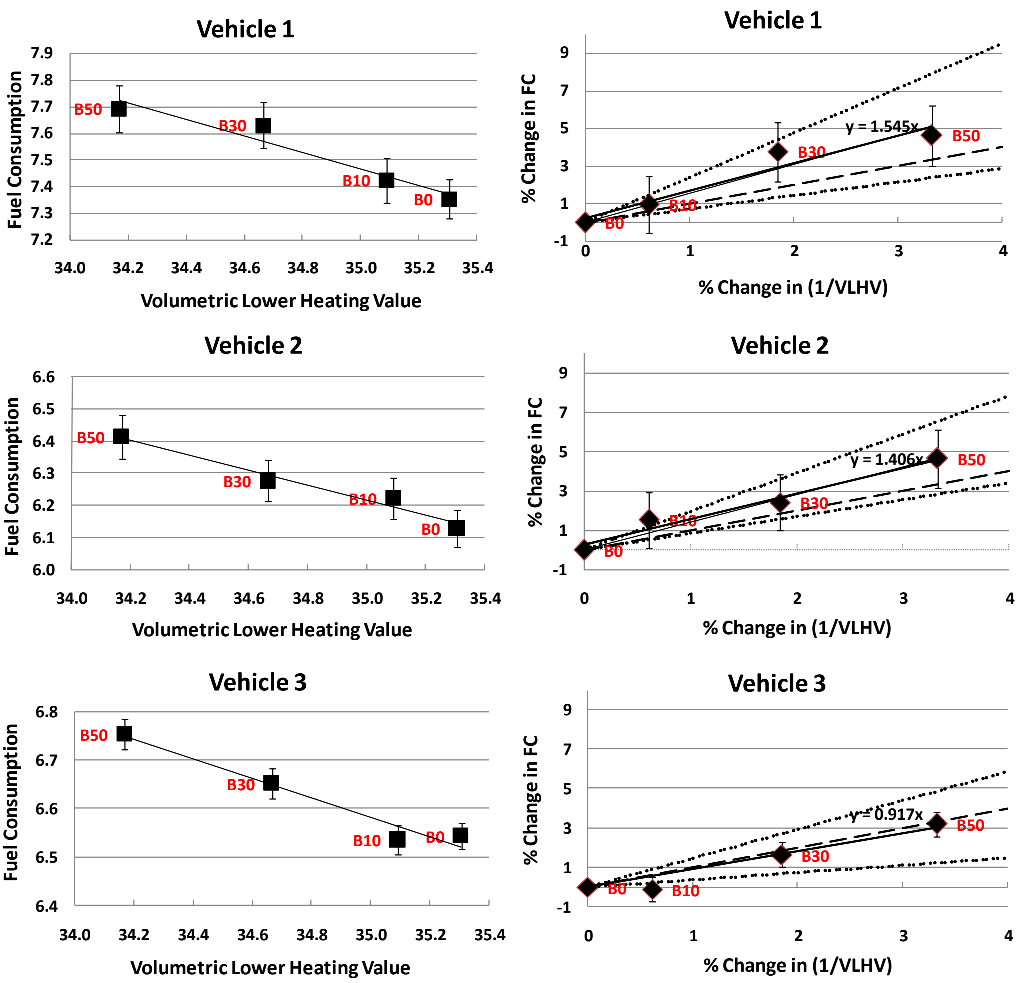
On the other hand, CO_2 emissions are affected by the fraction of fuel energy that comes from carbon compared to hydrogen, that is, the mass H/C ratio of the fuel. For the fuels used in this study, the mass H/C ratio varied very little so we would not expect to see any differences in CO_2 emissions between fuels if the energy efficiency of the vehicle did not change when running on different fuels.

A plot of the % change in calculated FC versus the % change in [1/VLHV] can be used to compare the calculated FC changes to the predicted FC changes for different fuels since the predicted FC depends on the VLHV. Details on the FC calculations for RME/diesel fuel blends are provided in **Appendix 8**. Based on the earlier discussion in this section, the FC measurement is expected to be more sensitive to the FAME content than the CO_2 measurement.

This analysis was completed for the NEDC and the results are shown in **Figure 10**. The left-hand charts show the measured FC (in l/100km) versus the VLHV (in MJ/l) of the test fuel for all three vehicles over the NEDC. The error bars show 95% confidence limits for the average FC values plotted and the solid line is a best fit through the data points. The correlation between the FC and VLHV is obviously very good.

In the right-hand figures, the percent change in FC is plotted versus the percent change in [1/VLHV] using the B0 results for each vehicle as the basis. The error bars again represent 95% confidence limits and the solid line is a best fit through the data points. The slope of this best fit line is also reported in each figure. The dotted lines are the 95% confidence limits around the best fit line and the dashed line is a one-to-one correlation line.

Figure 10 Change in FC as a function of the fuel's VLHV over the NEDC



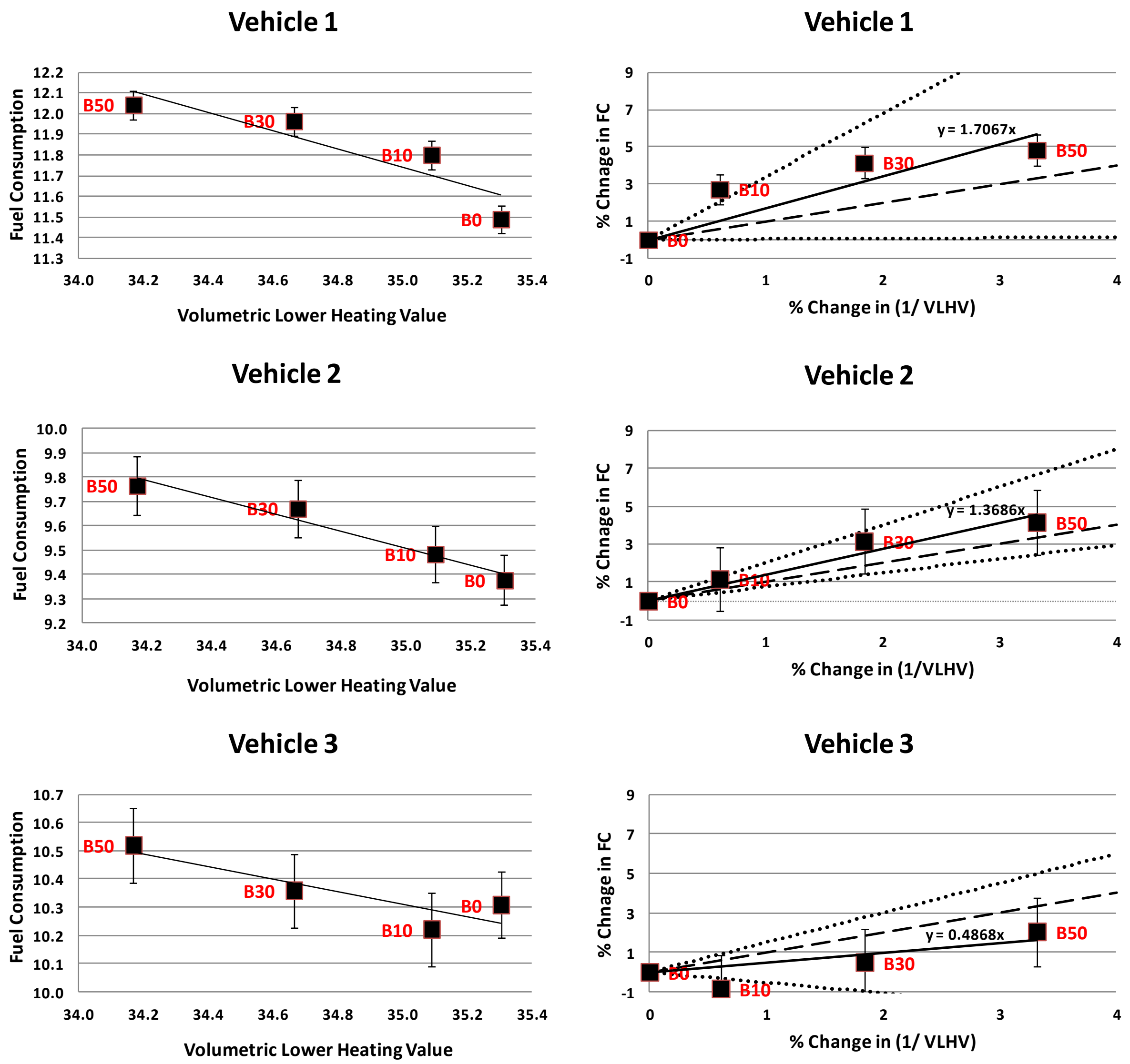
The best fit lines lie above the one-to-one correlation lines for Vehicles 1 and 2, suggesting that the engine efficiency over the NEDC is actually lower on the higher RME fuels. However, these correlation lines are not outside the 95% confidence limits. This means that the change in FC can be simply explained by the loss in energy content of the RME-containing fuels, within the experimental uncertainty inherent in the measurements.

Within the statistical precision, the data show that the volumetric FC increases in direct proportion to the decrease in the VLHV of the RME/diesel fuel blends over the NEDC. There is no evidence that the use of RME as a blending component provides an engine efficiency benefit and the vehicles are not able to compensate for the lower energy content of the FAME/diesel blends through better engine efficiency on the oxygenated fuels. Although a recent study [27] suggests that future engines could be further engineered to adapt to differences in fuel composition, this is clearly not the case with the vehicles tested in this study.

As was noted previously, the volumetric FC is usually reported by vehicle manufacturers and researchers because it is a regulated number intended to provide consumers with an understandable indicator of a vehicle's efficiency over a single driving cycle. Tailpipe CO_2 emissions are also of interest to vehicle manufacturers as a regulated parameter but do not provide information on a fuel's sustainability and environmental impact which requires a WTW analysis.

Similar trends in FC vs. VLHV were found for the same vehicles and fuels over the ARTEMIS Urban cycle (**Figure 11**). Comparable data for the UDC and EUDC portions of the NEDC and for the 120 km/h steady-state condition are shown in **Appendix 9**.

Figure 11 Change in FC as a function of the fuel's VLHV over the ARTEMIS Urban cycle



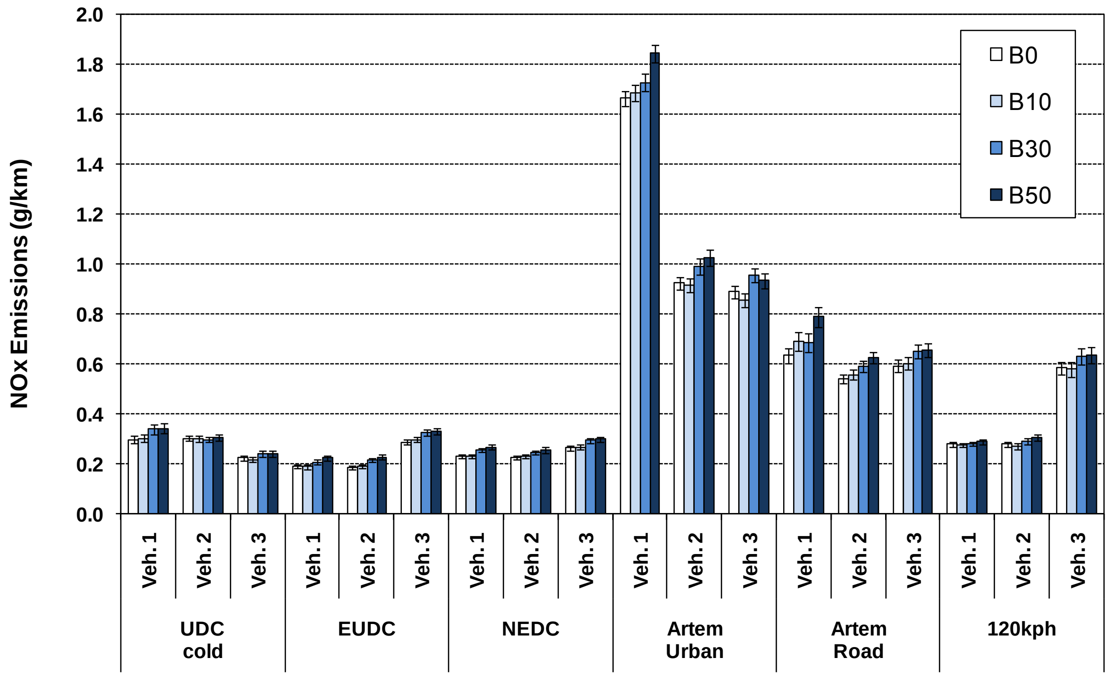
4.3. REGULATED EMISSIONS

This section presents the results from the regulated emissions measurements. In each case, the absolute average values recorded over each cycle are provided with error bars that represent 1.4 x the standard error of the measurements.

4.3.1. NOx Emissions

Figure 12 shows the average NOx emissions measured for each vehicle over all driving cycles and demonstrates the effect of driving cycle, vehicle, and fuel on NOx emissions.

Figure 12 Average NOx emissions for all vehicles and driving cycles



The Euro 5 and 6 emissions regulations may present some engine calibration and aftertreatment challenges, especially with respect to controlling NOx emissions under all operating conditions. NOx emissions are the sum of NO and NO_2 in the exhaust gas. Although diesel engines emit mainly NO, the aftertreatment system, especially the DOC, increases the oxidation of the engine-out NO to NO_2. The NO emissions and NO/NOx ratio are discussed in **Section 4.4**.

From the NOx emissions results shown in **Figure 12**, it is observed that RME has a consistent effect on NOx emissions over all cycles and in all three vehicles. The NOx emissions increased linearly with increasing RME content in the fuel blend. For most vehicles and cycles, the increases were in the 1-10% range but increases up to 20% were observed in some casces for the B50 fuel.

Over the NEDC, all three vehicles responded in a similar way with the NOx emissions increasing as the RME content of the fuel increased. Over the NEDC sub-cycles, however, Vehicles 1 and 3 responded quite differently, with Vehicle 1 giving higher

NOx emissions over the UDC and Vehicle 3 giving higher NOx emissions over the EUDC.

These differences were much larger than the effects found with changing RME content. In Vehicle 2, however, the NOx emissions over the UDC were essentially unchanged with increasing RME content but did increase slightly over the EUDC with increasing RME content. Since the differences found in the sub-cycles gave similar results for all vehicles across the NEDC, it is possible that the sub-cycle differences are associated with different EMS strategies in all three vehicles.

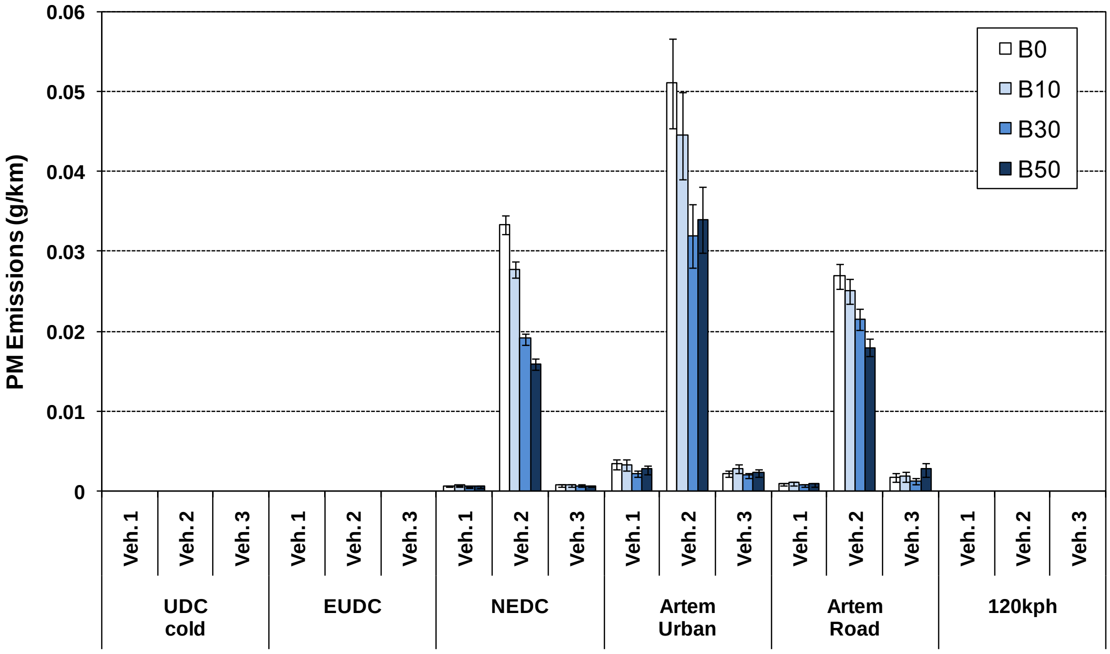
Over the ARTEMIS cycles, all vehicles gave broadly similar trends with respect to NOx emissions. Significant differences in NOx emission levels were observed between legislated and non-legislated cycles; in some cases, emissions over the ARTEMIS cycles were almost 10 times higher than over the NEDC.

Overall, the effect of increasing RME content on NOx emissions from the light-duty diesel vehicles in this study is consistent with that reported previously for heavy-duty vehicles [9]. Literature relating to the effect in light duty applications is less consistent, although generally it is observed that NOx emissions increase with increases in FAME content. However, it has also been reported that a reduction in NOx emissions was observed as the FAME content of the diesel fuel increased [24].

4.3.2. PM Emissions

Figure 13 shows the Particulate Mass (PM) emissions for all vehicles and for three driving cycles. PM emissions were not measured over the NEDC sub-cycles or over the 120kph steady-state condition.

Figure 13 Average PM emissions for all vehicles and applicable driving cycles



A single filter was used to collect the PM over each complete cycle, including the NEDC. From **Figure 13**, it can be seen that the absolute PM emissions from the DPF-equipped Vehicles 1 and 3 were very low and in some cases close to the measured background. No statistically significant differences were observed from these vehicles with changes in the RME content.

For Vehicle 2, the PM emissions were more than 10 times higher than those from the DPF-equipped vehicles and decreased with increasing RME content. Over the NEDC, reductions of up to 50% were observed with the B50 fuel. Increasing the RME content was somewhat more beneficial over the NEDC than over the ARTEMIS cycles.

The effect of increasing RME concentration on PM emissions from light-duty diesel vehicles is generally consistent with those reported in the existing literature. Selected PM filters were analyzed and the results of these measurements are included in [1].

4.3.3. CO and HC Emissions

The carbon monoxide (CO) and hydrocarbon (HC) emissions from each vehicle are shown in **Figures 14** and **15**, respectively.

Figure 14 Average CO emissions for all vehicles and driving cycles

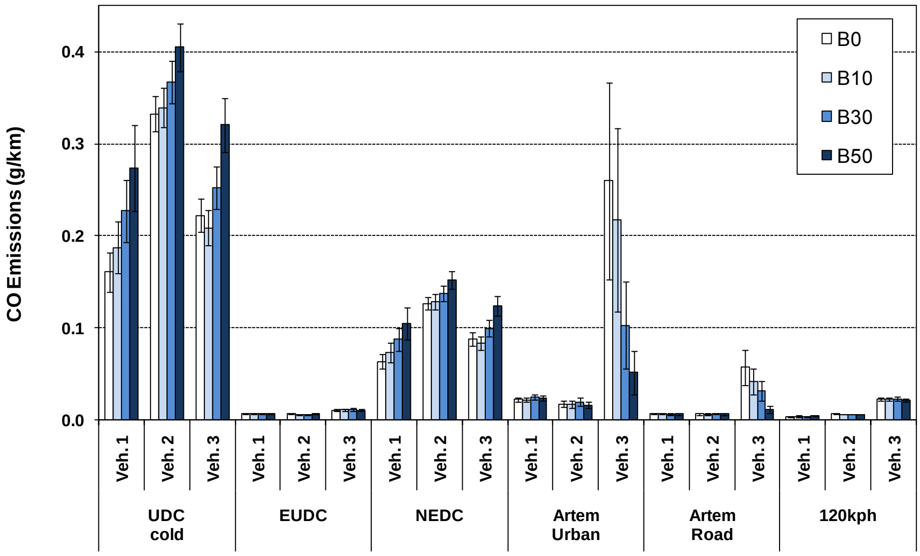
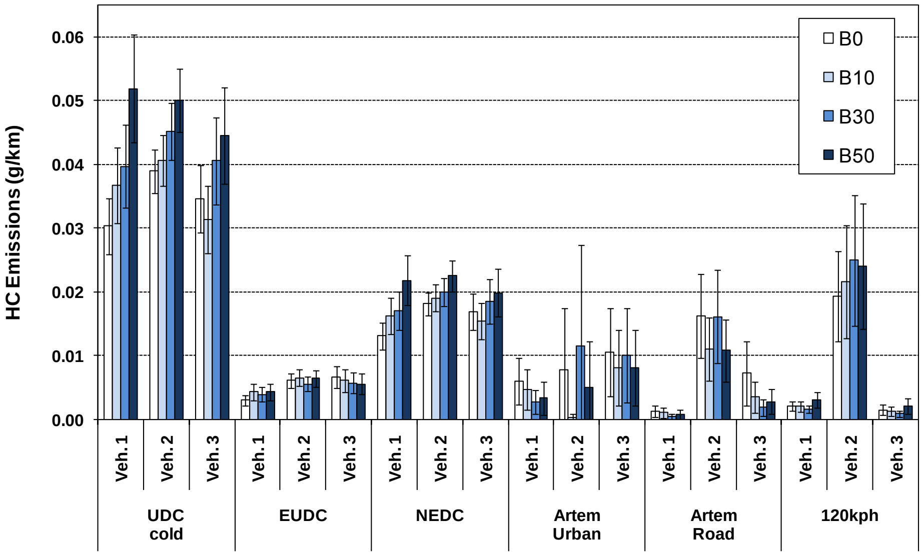


Figure 15 Average HC emissions for all vehicles and driving cycles



As shown in these figures**,** the absolute emissions levels for both HC and CO were very low for all vehicles and considerably lower than the Euro 4 regulatory limits. For all hot start cycles, the absolute values for HC were very close to background levels and no statistically significant differences were seen between fuels.

The highest concentrations of both CO and HC emissions were seen over the cold start UDC, with lower CO and HC emissions observed over the EUDC after the DOC had fully warmed up. Thus, over the NEDC, the CO and HC emissions are primarily due to emissions occurring over the UDC. No significant differences in the HC measurements were observed over the EUDC. For all vehicles, RME significantly increased the CO emissions over the cold start UDC while emissions were low over the EUDC with no clear patterns. For a few driving cycles, the increase in CO and HC emissions was statistically significant between the B0 and B50 fuels.

Over the ARTEMIS Urban and Road cycles, Vehicle 3 showed higher CO emissions than Vehicles 1 and 2. A significant reduction in CO emissions was observed with increasing RME content in this case and a smaller effect was observed for HC emission. For this vehicle, RME appeared to have a positive effect on both CO and HC emissions.

Similar observations regarding cold start emissions performance are mentioned in other studies and contradict the usual expectation that biodiesel always reduces CO and HC emissions. RME may reduce engine-out emissions but this effect can be masked by the performance of the DOC. From the results presented here, RME may have a short-term negative impact on oxidation catalyst efficiency particularly over cold start conditions, increasing the tailpipe CO and HC emissions with increasing RME content.

4.4. EFFECT OF AFTERTREATMENT SYSTEM

4.4.1. DPF Regeneration Events

As previously mentioned, the DPF-equipped vehicles were tested before starting the test programme in order to understand their DPF regeneration frequency. This was important to ensure that no DPF regeneration events occurred during a single day’s testing. The DPF-equipped vehicles were constantly monitored for possible regeneration events that could occur during the measurements and, when they were found to be close in mileage to the next regeneration event, they were ‘forced’ into a regeneration event following the completion of the day’s testing. Thus, all measurements taken over the complete programme were unaffected by DPF regeneration.

In the test sequence followed, the DPF in Vehicle 1 regenerated three times while the DPF in Vehicle 3 regenerated twice. Typical evidence of a regeneration event compared to standard operation is provided in **Figures 16** and **17**.

Figure 16 Catalyst temperatures for a DPF regeneration event (23-2 series) for Vehicle 1 compared to standard (average) operation over 3 driving cycles

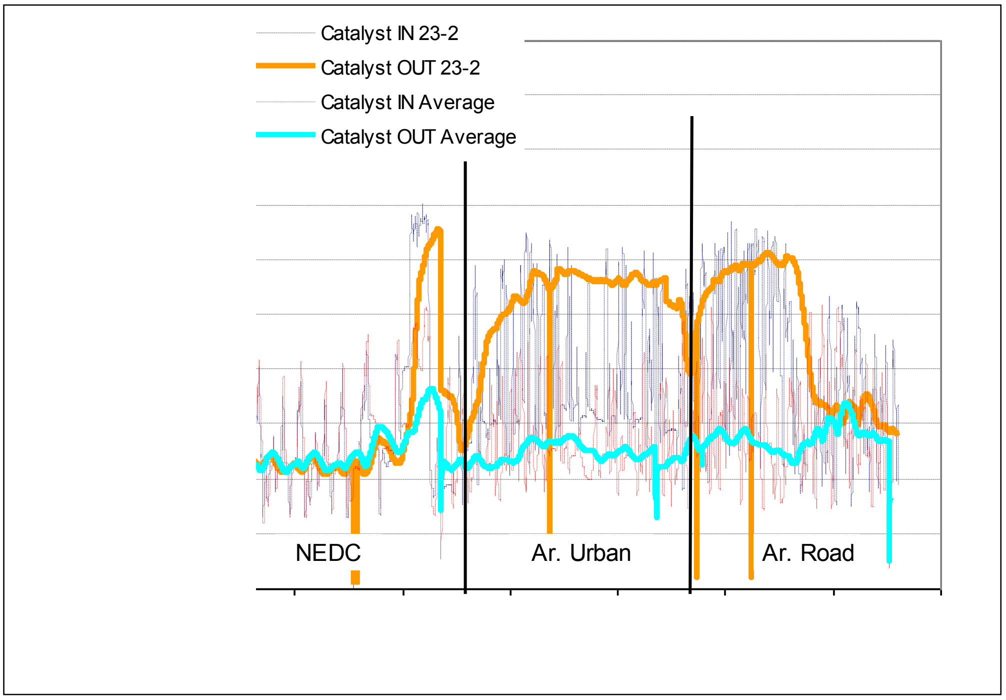
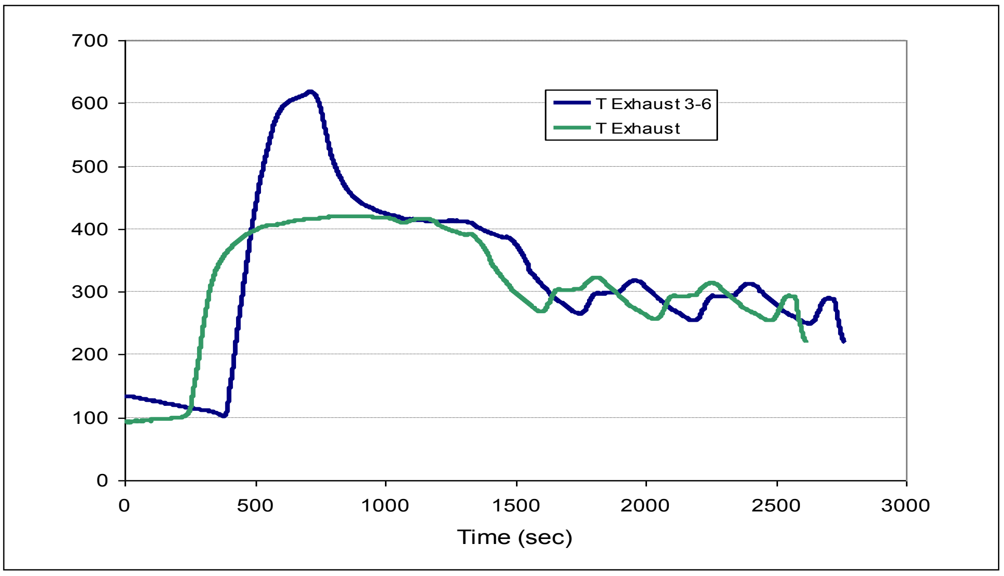


Figure 17 Exhaust temperature during a DPF regeneration event ($T_{exhaust}$ 3-6) compared to standard operation ($T_{exhaust}$) for Vehicle 3



From previous PMP work, it is known that the extent of particle fill on the DPF can affect results with measured particle numbers decreasing as the DPF fills [20]. However, within the test protocol there was little scope to take this into account without severely extending the length of the study.

4.4.2. Effect of Aftertreatment on Emissions

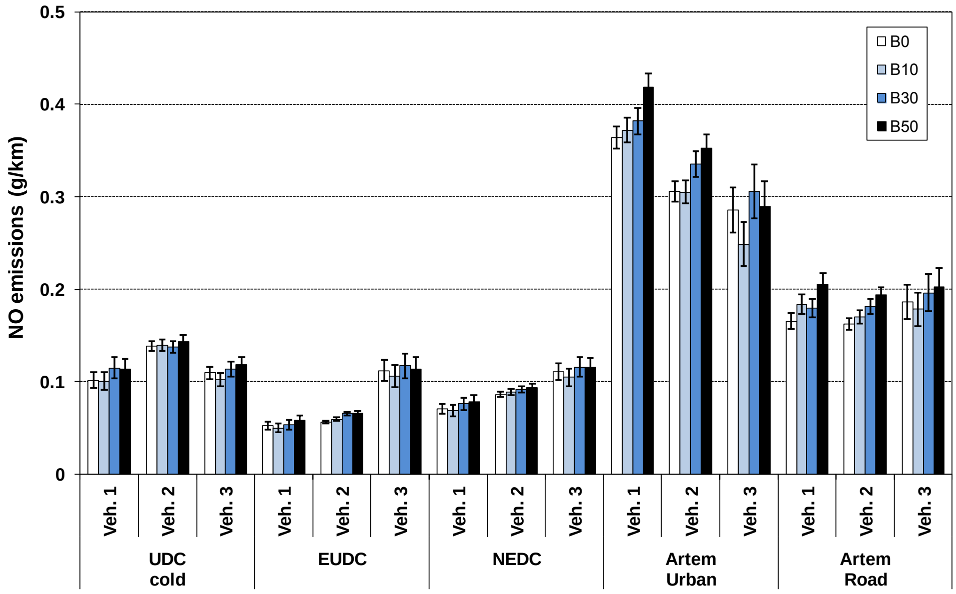
4.4.2.1. NO Emissions

During the study, NO emissions were measured separately from the legislated bag emissions for NOx. In a vehicle without a DOC, the majority of the NOx emissions are emitted as NO. In the presence of a DOC, however, a larger fraction of the NO will be oxidised to NO_2 and emitted at the tailpipe. These NO_2 emissions are of increasing concern for local air quality and human health.

The measurement of NO and also the investigation of the NO/NOx ratio allowed the effects due to the different aftertreatment technologies to be measured and compared when operating on different RME/diesel blends.

Figure 18 shows the NO emissions measured from each vehicle over all driving cycles. NO emissions data were not collected at the steady-state conditions.

Figure 18 NO emissions for all vehicles

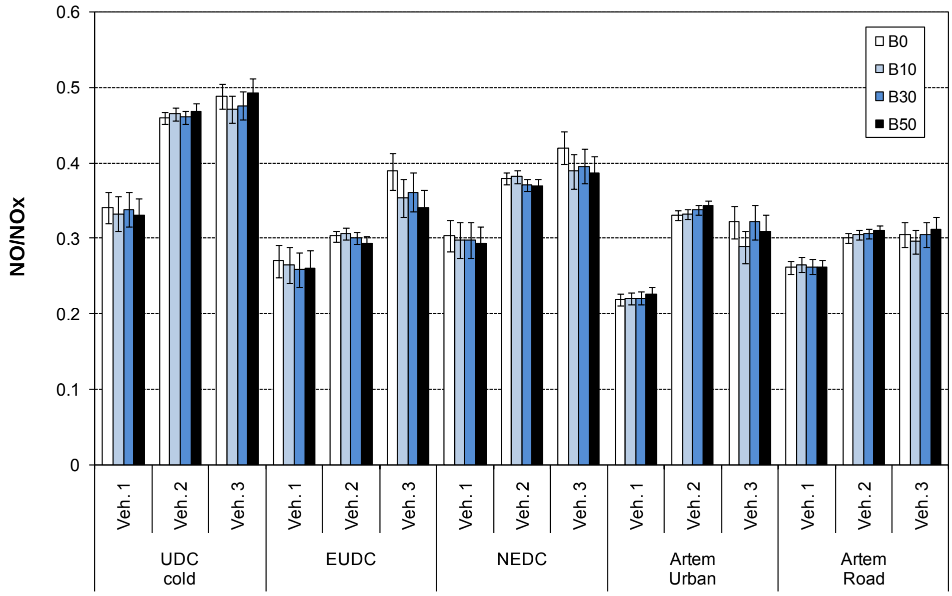


From this figure, it can be seen that the effect of increasing RME concentration on NO emissions follows similar trends to those already presented in **Section 4.3.1** for NOx emissions. Over the UDC, the NO emissions were similar for Vehicles 1 and 3 while they were much higher for Vehicle 3 over the EUDC. Consequently, the NO emissions for Vehicle 3 were also higher over the NEDC. Compared to the NEDC and its sub-cycles, the NO emissions were much higher over the ARTEMIS cycles and more sensitive to changes in the RME concentration.

4.4.2.2. NO/NOx Ratio

NOx emissions are the sum of NO and NO_2 emitted from the vehicle tailpipe and, as mentioned previously, a diesel engine primarily emits NO. The presence of a DOC aftertreatment system increases the conversion of NO to NO_2 which is then emitted at the tailpipe, increasing the respirable NO_2 concentration. This has potential impacts on local air quality and on human health. In the framework of these measurements, it was attempted to investigate whether there was any impact of RME content on the NO/NOx ratio. **Figure 19** shows the normalized NO/NOx ratio as measured over the legislated cycles. The NO and NO/NOx ratio data are tabulated in **Appendix 6**. The NO/NOx ratio is not shown for the 120 kph steady-state because the NO emissions were not measured at this condition.

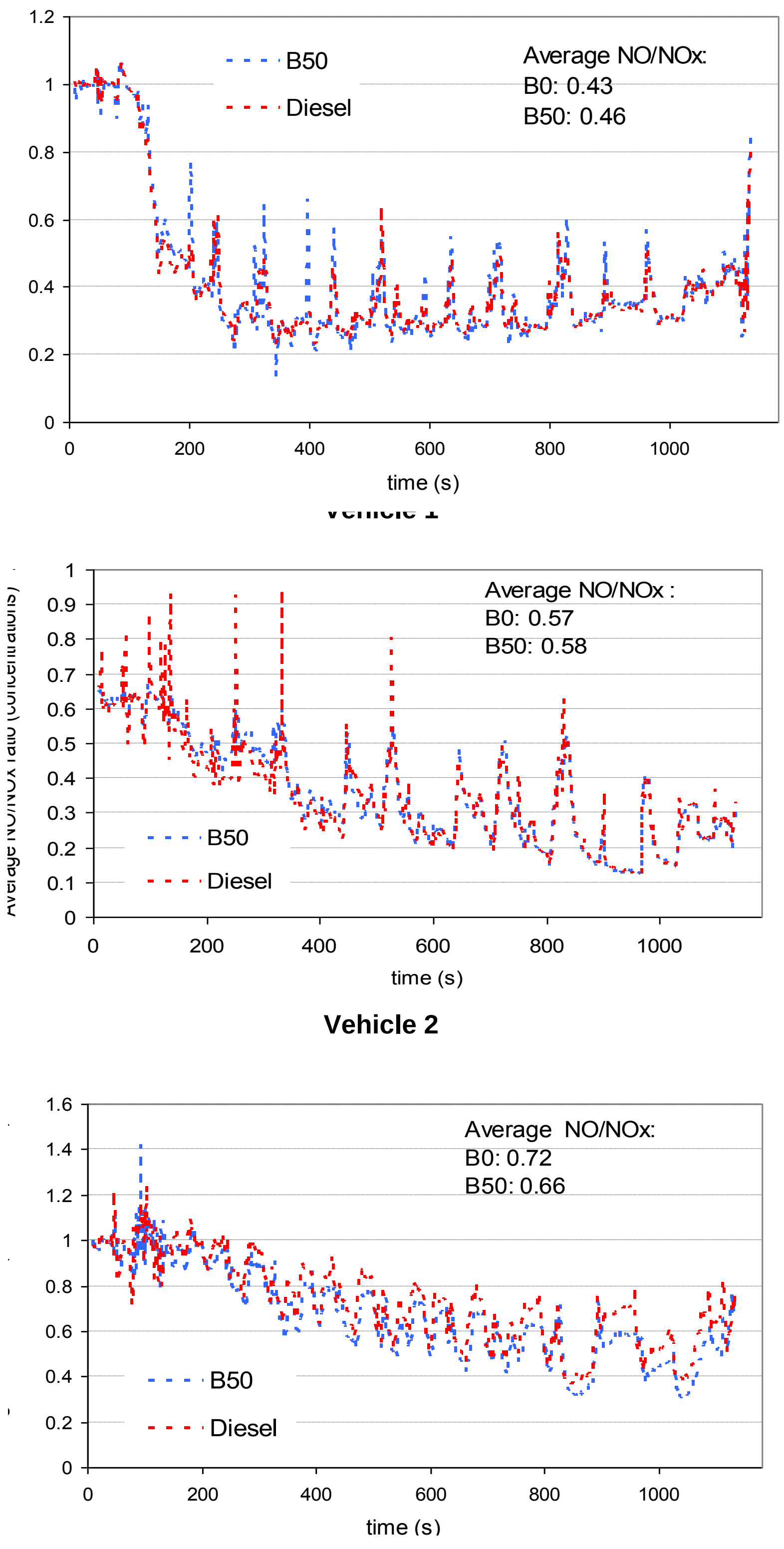
Figure 19 NO/NOx emissions ratio for all vehicles and driving cycles



As shown in **Figure 19**, the NO/NOx ratio depends strongly on the vehicle and driving cycle but there is very little effect of RME concentration. Over the EUDC (hot portion), all vehicles show a trend to lower NO/NOx ratio with increasing biodiesel concentration. This trend is most pronounced for Vehicle 3 with the NO/NOx ratio over the EUDC being approximately 10% lower for the three biodiesel blends compared to the reference fuel. As a result, the NO/NOx ratio is about 8% lower over the NEDC for this vehicle indicating a shift towards slightly more NO_2 when biodiesel is present.

Analysis of the NO from the regulated bag emissions procedure is not the best way to measure the NO/NOx ratio, however, because the elapsed time between bag sampling and analysis can change the NO concentrations in a way that is not repeatable or controllable. For this reason, the average instantaneous NO/NOx ratio was also measured using a fast response NOx analyser in addition to the bag emissions measurements. The results of these measurements are shown in **Figure** 20.

Figure 20 Average instantaneous NO/NOx ratio over NEDC as recorded using the fast NOx analyzer for B0 and B50 fuels



Generally, the results of the analysis made with the fast NOx analyser are consistent with those from the bag samples. The instantaneous measurements indicate that the use of B50 does not affect the NO/NOx ratio in the case of Vehicles 1 and 2. However, the use of B50 on Vehicle 3 led to an approximately 8.5% lower NO/NOx ratio over the NEDC compared to the B0 fuel. The differentiation between the B0 and the B50 NO/NOx ratio begins at the start of the EUDC (800 seconds) and onwards.

One explanation for this observation may be related to the exhaust aftertreatment systems of the 3 vehicles. RME, due to its oxygen content, tends to enhance the oxidation of certain pollutants such as CO, HC, PM, and NO. However, the oxidation catalysts on the first two vehicles masked these oxidation effects in the case of CO and HC (**Section 4.3.3)**. The difference in exhaust gas oxidation in Vehicle 3 may be due to a smaller DOC, a different type of catalyst, or different optimisation to the other vehicles. In the CO and HC case, biodiesel use led to reductions in these pollutants. It is therefore expected that increasing FAME use in this vehicle would have the same impact on NO, increasing its conversion to NO_2 and lowering the NO/NOx ratio, as is observed. Although the difference is not large, more study on NO/NOx engine-out emissions with FAME/diesel blends would be appropriate in order to better understand the effects of engines, fuel, and aftertreatment system.

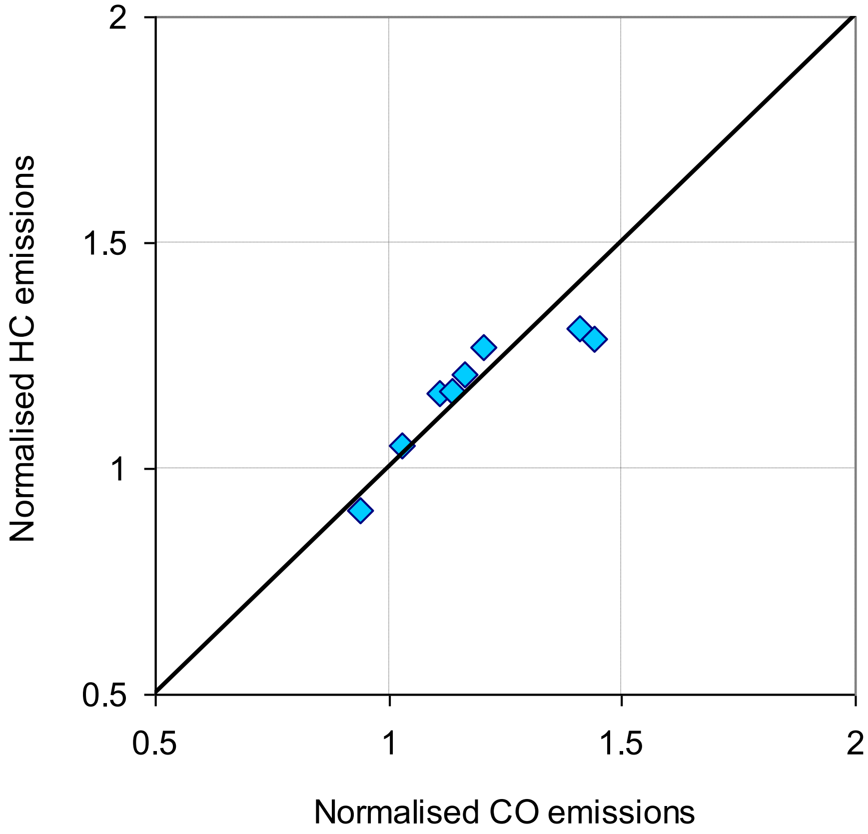
4.4.2.3. HC and CO Emissions

Published literature on the effect of FAME concentration on HC and CO emissions generally shows a beneficial effect as the FAME concentration increases. However, the majority of this work was carried out on heavy duty engines that were not equipped with exhaust aftertreatment. The published literature on the effect on light duty CO/HC emissions is less clear. This test work clearly demonstrated an increase in both CO and HC emissions, although the absolute concentrations were very low.

It is possible that the presence of the RME interacts with the DOC in some way, either by affecting the light-off period (which would be especially noticeable over the UDC) or by affecting the efficiency of the catalyst as it warms up. Interactions between fuel species and catalyst operation have been seen before. From the EPEFE programme [23], it was shown that the removal of 2-3 ring PAH from the fuel resulted in a reduction in catalyst efficiency. From this observation, it was surmised that higher molecular weight hydrocarbons are oxidised more easily compared to lower molecular weight molecules. While the effect seen here suggests the opposite with respect to higher molecular weight hydrocarbons, the presence of an oxygenated fuel may also play a part. These interactions are not clearly understood and more information on the interaction between fuel components and catalyst performance is needed in order to fully interpret the results.

Figure 21 attempts to identify whether HC or CO is affected more strongly by RME use by comparing the normalised HC and CO emissions. The correlation in the emissions results shows that in most cases changes in CO and HC emissions are of about the same order. Thus it can be concluded that RME has a generally uniform effect on tailpipe CO and HC, again possibly implying a global impact on catalyst operation.

Figure 21 Normalized HC vs. normalized CO emissions over the UDC cold start cycle



5. CONCLUSIONS

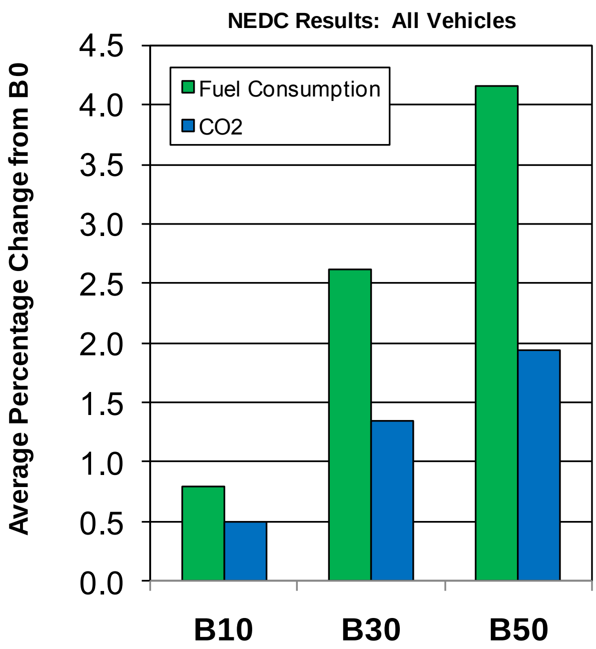
CO_2 Emissions and FC

The primary objective of this study was to determine whether modern vehicles improve their efficiency when running on RME/diesel fuel blends. If this were to occur, the volumetric FC should be lower than predicted from the lower energy content (LHV) of the RME/diesel fuel blend.

This study shows that the volumetric FC is inversely proportional to the volumetric energy content of the RME/diesel fuel blends in all vehicles and over the NEDC and ARTEMIS Urban cycles. Comparable data shown in **Appendix 9** show that the same conclusion applies to the UDC, EUDC, ARTEMIS Road, and the 120 km/h steady-state condition. In other words, the vehicles were not able to compensate for the energy contents of RME/diesel blends through better engine efficiency on the oxygenated fuels.

As anticipated, the CO_2 emissions and volumetric FC increase with increasing RME content. The same trends are observed for all vehicles and cycles, where vehicle and cycle differences are much larger than fuel effects. Focusing on the fuel effects only, however, the CO_2 emissions generally increased linearly with the RME content, the increase for the B50 fuel being between 1-3% in most cases. These conclusions are based on measurements in which DPF regenerations were specifically avoided and the results could be different under ‘real world’ conditions. **Figure 22** shows the average percentage change from baseline in CO_2 emissions and volumetric FC for the RME containing fuels evaluated in this study.

Figure 22 Average percentage change in CO_2 emissions and volumetric FC from baseline (B0) for all three vehicles over the NEDC



Regulated Emissions

RME appears to have a consistent effect on **NOx emissions** over all cycles in all three vehicles with NOx emissions increasing linearly with increasing RME content in the fuel blend. The NOx emissions increase up to 20% with B50 in some cases with most differences being in the 1-10% range depending on the fuel blend and vehicle.

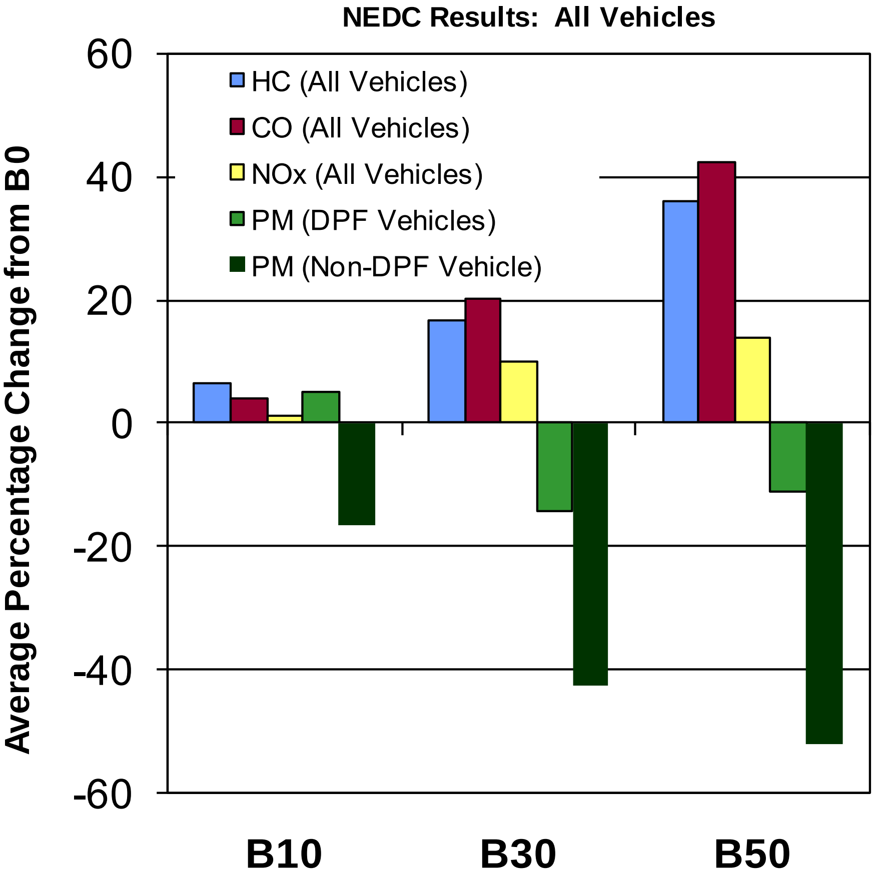
Significant differences in emission levels between legislated and non-legislated cycles indicate the importance of driving conditions on tailpipe emissions. In particular, the more aggressive ARTEMIS driving cycle used here tended to significantly increase NOx emissions (up to 10 times higher) compared to the NEDC. In view of the introduction of the Euro 5 emissions standard and because NOx is probably the most difficult emission to control, a shift of engine calibration towards lower NOx and higher PM emissions could be expected.

With increasing RME, **PM emissions** decreased monotonically. The RME effects were most evident on the non-DPF-equipped Vehicle 2 where PM emissions levels were considerably higher. For this vehicle, RME appears to have a more beneficial effect over the NEDC than over the ARTEMIS Urban cycle. The benefit of RME on PM is essentially negated in the case of the DPF-equipped Vehicles 1 and 3 for which PM emissions stayed at very low levels and were well below the Euro 5 emission standard (recalling that Vehicles 1 and 3 were only homologated to the Euro 4 emissions standard).

With increasing RME content, **CO and HC emissions** increased. This is different from what was observed in the previous EPA study on HD vehicles [9] which generally evaluated results on 2002 Model Year engines and hot driving cycles. The largest fraction of total CO and HC emissions occur over the cold start UDC portion of the NEDC. Over the ARTEMIS Urban cycle, Vehicle 3 showed higher CO emissions than Vehicle 1 and 2 and, unlike them, a significant reduction in CO emissions with increasing RME. In all cases, however, the CO and HC emissions were well below the Euro 5 emission limit. Therefore, the effect of RME on the CO and HC emissions is of minor importance since these emissions are already very low.

The average percentage changes from baseline in regulated emissions over the NEDC are summarized in **Figure 23**.

Figure 23 Average percentage change in regulated emissions for all vehicles over the NEDC



Effect of aftertreatment system on emissions

The NO/NOx ratio depends strongly on the vehicle and driving cycle but there is very little effect of RME concentration. A small trend to lower NO/NOx ratio with increasing biodiesel concentration is most pronounced in Vehicle 3 with the NO/NOx ratio over the EUDC being about 10% lower for the three biodiesel blends compared to the B0 fuel. For this vehicle, a small shift towards more NO_2 is observed when biodiesel is employed which is believed to be due to its DOC performance. Observations made from the bag emissions analyses were confirmed with an on-line analyser that measured instantaneous NOx.

In most cases, CO and HC differences with RME are of about the same order in relative terms. Thus it is concluded that RME has a generally uniform effect on tailpipe CO and HC, again possibly implying a global impact on DOC performance.

6. GLOSSARY

ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems
AUTh	Aristotle University Thessaloniki
BHT	Butylated Hydroxy Toluene
BMEP	Brake Mean Effective Pressure
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
CADC	Common ARTEMIS Driving Cycle
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVS	Constant Volume Sampling system
DF	Dilution Factor
DG TREN	European Commission's Directorate-General for Transport and Energy
DI	Direct Injection
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DPNR	Diesel Particulate and NOx Reduction
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
EEA	European Environment Agency
EN 590	European specification for diesel fuel
EN 14214	European specification for FAME
EPCL	Environmental Pollution Control Laboratory (at AUTh)
EPEFE	European Programme on Emissions, Fuels and Engine Technologies
EUCAR	European Council for Automotive R&D
EUDC	Extra Urban Driving Cycle
FAME	Fatty Acid Methyl Ester
FC	Fuel Consumption

FIE	Fuel Injection Equipment
FPS	Fine Particle Sampler
GRPE	Working Party on Pollution and Energy (UNECE)
HC	Hydrocarbon
HD	Heavy-duty
HEPA	High Efficiency Particulate Air (filter)
HEUI	Hydraulically Actuated Electronically Controlled (unit injectors)
HSDI	High-Speed Direct Injection (engine)
JRC	Joint Research Centre (of the European Commission)
kph	Kilometres per hour
KV40	Kinematic Viscosity at 40°C
LAT	Laboratory of Applied Thermodynamics
LD	Light-duty
LEPA	Low Efficiency Particulate Air
lpm	litres per minute
NEDC	New European Driving Cycle
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxides
OBD	On-Board Diagnostic
PAH	Polycyclic Aromatic Hydrocarbon
PM	Particulate Matter or Mass
PME	Palm Methyl Ester
PMP	Particle Measurement Programme
PN	Particle Number
RME	Rapeseed Methyl Ester
RPM	Revolutions per minute
Significant	Statistically significant at >95% confidence
SUME	Sunflower Methyl Ester

TC	Turbo Charged
T10	Temperature (°C) at which 10% v/v diesel is recovered
T50	Temperature (°C) at which 50% v/v diesel is recovered
T95	Temperature (°C) at which 95% v/v diesel is recovered
UNECE	United Nations Economic Commission for Europe

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While this project was being completed, we were saddened to hear that our collaborator, Professor Stam Stournas at the National Technical University of Athens, had passed away. He was a valued contributor to our project, as well as to European research on fuels and vehicles and his many contributions will be missed.

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APPENDIX 1 IMPACT OF FAME ON FC: PUBLISHED LITERATURE

The effects of FAME on pollutant emissions (see **Appendix 2**), FC, and engine operation have been reported in many studies. As one would expect, however, these studies have been based on different engines, test protocols, and FAME types and concentrations. For this reason, it is difficult to obtain from the already published literature a clear assessment of the impact of biodiesel fuels on vehicle fuel consumption.

In an extensive review, Lapuerta et al [A1-1] concluded with a summary table covering the impacts of biodiesel fuels on gaseous pollutants, power output and fuel consumption (see **Appendix 2**, **Table A2-1**). This table presents the percentage of scientific studies reporting either increases, decreases or no changes in various vehicle emissions and operating characteristics. The results are qualitative because the different test conditions and protocols used in the studies did not permit a quantitative comparison. In contrast to the EPA study results [9] shown in **Figure 4**, this table shows that in some cases, such as for NOx emissions and engine efficiency, no straightforward conclusion can be drawn.

Kousoulidou et al [A1-2] also performed an extensive literature review for the European Environment Agency (EEA) on the impact of biodiesel fuels on pollutant emissions and FC. From this review, FC was reported not to change for low concentration FAME blends and increased with the reduction in the fuel's energy content for higher FAME blends, consistent with the results from our study.

In a study by Fontaras et al [A1-3], five different biodiesel blends were tested in order to examine their impact on emissions and FC of a common-rail passenger car. Limited effects were observed on CO_2 emissions, with only two of the five biodiesel blends (containing PME and SUME) providing statistically significant differences. However, these effects were rather small and in opposite directions, and no global conclusion on the effect of biodiesel on tailpipe CO_2 emissions could be drawn.

In addition, a recent study by Martini et al [A1-4] on two passenger cars did not lead to consistent conclusions. Tests with B30 and B100 in a Euro 3 common-rail passenger car over the NEDC, confirmed that the impact on emissions was greater with higher biodiesel content. In the same study, however, the FC did not seem to be affected by FAME at low concentrations while the increase in volumetric FC was limited to 3% for neat FAME (B100).

In addition to the reviews cited above, Concawe has performed its own review evaluating the potential impact of FAME on fuel consumption. Of the 99 papers examined in this review, 22 papers provided reliable information. When these papers were studied in detail, it was apparent that the experiments were not designed to look specifically at changes in engine efficiency. A best attempt has been made to analyse these papers for engine efficiency trends and, where appropriate, apply calculations to the published data. Unfortunately, the lack of robust experimental design has led to the resulting efficiency data being of questionable quality.

Our assessment of key papers from the published literature is summarised below.

- Most experimental data showed an increase in volumetric FC with increasing FAME content, particularly at higher FAME levels. There was no evidence that the FC debit was recovered with engine efficiency improvements [A1-5,A1-6,A1-7,A1-8,A1-9,A1-10,A1-11,A1-12,A1-13].

- Discriminating differences in FC measurements was not very good, particularly for small changes in FAME content, e.g. between B0 to B10 [A1-14,A1-15,A1-16,A1-17].

- Where studies claimed an engine efficiency benefit with increasing FAME content, the results were generally associated with a lack of statistical discrimination between fuels [A1-18,A1-19].

- Analysing the data “second-hand” from these papers required calculations of energy consumption or engine efficiency, but these relied on the LHVs that were reported in the papers. Some of these LHVs were of questionable accuracy and represent another potential source of error in the analysis [A1-20,A1-21,A1-22,A1-23].

- Some papers reported that lower energy efficiency when using biodiesel could be recovered by optimising the engine operation [A1-24,A1-25].

The overall conclusion from our literature review on FC effects was that no improvement in engine efficiency has been observed from the use of FAME and FAME blends compared to fossil diesel fuel that compensates for the reduction in energy content of the FAME/diesel blend. There is certainly no evidence to suggest an improvement in engine efficiency while there is some evidence to suggest that a reduction in engine efficiency is observed with FAME and with FAME/diesel blends. In this respect, our assessment is consistent with that of Kousoulidou et al [A1-2] where no improvements in engine efficiency were reported and the key controlling factor for the fuel consumption of FAME blends was the change in the fuel’s LHV.

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5. Horn, U. et al (2007) Neat Biodiesel Fuel Engine Tests and Preliminary Modelling. SAE Paper No. 2007-01-0616. Warrendale, PA: Society of Automotive Engineers
Using a single cylinder research engine, rather large error bars (up to 10%) were reported. Fossil diesel fuel was shown to have up to 31% lower FC compared to biodiesel fuels. Both brake thermal efficiency graphs and calculations presented in this paper showed that B100 had 5-14% higher energy consumption compared to fossil diesel.

6. Babu, G. et al (2007) Studies on Performance and Exhaust Emissions of a CI Engine Operating on Diesel and Diesel Biodiesel Blends at Different Injection Timings. SAE Paper No. 2007-01-0613. Warrendale, PA: Society of Automotive Engineers
Using a single cylinder research engine, this paper focused on the effect of ignition timing and pressure and did not directly compare B100 and fossil diesel fuels. Calculations applied to the data suggest that fossil diesel had a lower energy consumption compared to biodiesel blends. The paper tentatively concluded that a lower brake thermal efficiency was observed with biodiesel blends.

7. Tzirakis, E.G. et al (2007) Impact of Biodiesel Blends on Emissions from a Diesel Vehicle Operated in Real Driving Conditions. SAE Paper No. 2007-01-0076. Warrendale, PA: Society of Automotive Engineers
Using a passenger car with a 2-litre engine, this study evaluated increasing energy consumption with increasing FAME concentrations in diesel blends. Calculations based on the paper's original data suggest that these increases were in the range of 1.7%-7.4% with increasing FAME concentration.

8. Pradeep, V. et al (2005) Evaluation of Performance, Emission and Combustion Parameters of a CI Engine Fuelled with Biodiesel from Rubber Seed Oil and its Blends. SAE Paper No. 2005-26-353. Warrendale, PA: Society of Automotive Engineers
Using a single cylinder engine, the paper attributed lower engine efficiency to the higher viscosity of the biodiesel fuel. B100 demonstrated lower thermal efficiency, particularly at high power outputs. It also showed greater energy consumption than fossil diesel, which the paper attributed to the fuel's higher boiling point. There was a general trend of increasing energy consumption with increasing FAME content. The high exhaust gas temperatures for B100 indicated poor combustion quality.

[11] The information shown in italics is Concawe's own assessment of key findings from the cited paper.

9. Adolfo, S. et al (2005) Experimental Characterisation of a Common Rail Engine Fuelled with Different Biodiesel. SAE Paper No. 2005-01-2207. Warrendale, PA: Society of Automotive Engineers
Using a 1.9-litre turbo charged common rail engine, this paper made no reference to engine efficiency. The FC was higher on biodiesel than on fossil diesel due to changes in the fuel's LHV. However, actual LHVs were not reported for the test fuels making it difficult to calculate the change in FC.

10. Tormos, B. et al (2005) Heavy-Duty Diesel Engine Performance and Emission Measurements for Biodiesel (from Cooking Oil) Blends Used in the ECOBUS Project. SAE Paper No. 2005-01-2205. Warrendale, PA: Society of Automotive Engineers
Using an HD engine, this paper did not mention engine efficiency. FC increases were broadly in line with decreasing LHV as the FAME content of the fuel increased. The smallest FC differences were seen on a high load, low RPM cycle. A B30 fuel showed lower energy consumption than fossil diesel. However, the measurement error was not reported so that the small differences in energy consumption with different fuels could be within the measurement error.

11. Xiaoming, L. et al (2005) An Experimental Investigation on Combustion and Emissions Characteristics or Turbocharged DI Engines Fuelled with Blends of Biodiesel. SAE Paper No. 2005-01-2199. Warrendale, PA: Society of Automotive Engineers
A B20 blend showed very similar FC to fossil diesel below engine speeds of 1200rpm. The volumetric FC increased with increasing FAME content. There were no references to efficiency and no energy consumption differences were apparent.

12. Sinha, S. et al (2005) Performance Evaluation of a Biodiesel (Rice Bran Oil Methyl ester) Fuelled Transport Diesel Engine. SAE Paper No. 2005-01-1730. Warrendale, PA: Society of Automotive Engineers
Unexpected trends and the lack of error bars raise some questions about these results. The paper reported small improvements in thermal efficiency (1.5%-3%) at full load. The paper also reported that the BSEC for all biodiesel blends was lower than for fossil diesel and that B20 and B10 showed lower BSEC at all loads.

13. Corgard, D.D. et al (2001) Effects of alternative fuels and intake port geometry on HSDI diesel engine performance and emissions. SAE Paper No. 2001-01-0647. Warrendale, PA: Society of Automotive Engineers
This paper used a small bore DI diesel engine. The main interest of the study was air flow and swirl effects and not biodiesel fuels. There is a mention in the text that no change in BSFC was observed for 0%, 15% and 30% biodiesel blends, but this may reflect the repeatability of the experimental method rather than any actual engine efficiency effects.

14. Haas, M.J. et al (2001) Engine performance of biodiesel fuel prepared from soybean soapstock: A high quality renewable fuel produced from a waste feedstock. *Energy & Fuels, 15, 5, 1207-1212*
Using an HD engine, this paper mentioned that B100 had a worse BSFC than reference certification diesel, but that the BSFC for B20 was the same as the reference diesel. This may reflect the discrimination of the BSFC method, rather than a real effect. There were no specific references to changes in engine efficiency.

15. Chueping, S. et al (2007) A study of the Quantitative Impact on Emissions of High Proportion RME-based Biodiesel Blends. SAE Paper No. 2007-01-0072. Warrendale, PA: Society of Automotive Engineers
Using a single cylinder engine, this study investigated the effect of engine conditions

(e.g. injection timing and EGR) on performance. Plots suggest that the thermal efficiency was worse with increasing FAME content, but by only a very small amount. The magnitude of errors was not reported making definitive statements difficult.

16. Suryawanski, J.G. (2006) Performance and Emission Characteristics of CI Engine Fuelled by Coconut Oil Methyl ester. SAE Paper No. 2006-32-0077/JSAE Paper No. 20066577. Warrendale, PA: Society of Automotive Engineers
Using a single cylinder engine, BSEC and brake thermal efficiency were found to be similar for biodiesel fuels and fossil diesel at part and full load.

17. Suryanarayanah, S. (2006) Determination of the Proportion of Blend of Biodiesel with Diesel for Optimal Engine Performance and Emission Characteristics. SAE Paper No. 2006-01-35344. Warrendale, PA: Society of Automotive Engineers
Using a 0.66-litre engine, artificial neural networks were used to estimate the results rather than actual experimental values, making it difficult to evaluate the accuracy of the method and the interpretation of results. The paper reported that the lowest FC was achieved using a B15 blend. A graph was used to predict the SFC vs. %FAME but there was no explanation provided for the unexpected trends shown in the graph.

18. Tschoeke, H. and Braungarten, G. (2002) Biodiesel und Partikelfilter. Proceedings of the 2nd International Conference, Braunschweig, Sept 16-17 2002, 69-86
This paper investigated the effectiveness of DPFs in the presence of biodiesel. Nevertheless, there is some evidence in Figure 2 that up to 3% lower energy consumption was observed under some test conditions. This improvement disappeared, however, at the nominal performance condition. This paper was not studied in greater detail because there was no clear indication of the number of repeat tests and the likely associated error.

19. Rosc, R. et al (2007) Research Concerning Some Combustion Characteristics of a Biodiesel Type Fuel in a D.I. Agricultural Diesel Engine. SAE Paper No. 2007-01-0075. Warrendale, PA: Society of Automotive Engineers
In this paper, best fit lines to the data had a reasonable spread making definitive statements about the results difficult. A slight increase in engine efficiency was reported with the biodiesel blend. Greater engine efficiency was attributed to a higher oxygen content for the FAME blend.

20. Grimaldi, C.N. et al (2001) Performance and emissions of common rail DI diesel engine using fossil and different bio-derived fuels. SAE Paper No. 2001-01-2017. Warrendale, PA: Society of Automotive Engineers
This paper reported consistent expectations for FAME giving rise to lower smoke emissions and poorer fuel consumption. There was no evidence of better engine efficiency with biodiesel fuels. The paper commented that the FC results and torque were completely in line with the higher density and lower energy contents (LHV) of the biodiesel blends.

21. Li, H. et al (2007) Study of Emission and Combustion Characteristics of RME B100 Biodiesel from a Heavy duty DI Diesel Engine. SAE Paper No. 2007-01-0074. Warrendale, PA: Society of Automotive Engineers
Using an HD engine, this paper focused on emissions. The greater fuel consumption observed for FAME (12%-15%) was attributed to its lower energy content (LHV) No reference was made to engine efficiency and LHV values for the fuels tested were not reported, thus no additional calculations could be applied to this paper's results.

22. Kawano, D. et al (2006) Application of Biodiesel Fuel to Modern Diesel Engine. SAE Paper No. 2006-01-0233. Warrendale, PA: Society of Automotive Engineers

Using a 4L, 4-cylinder engine, this paper did not mention efficiency measurements on biodiesel fuels. Some BSFC data were presented but it was not possible to make any definitive statements on energy efficiency without having LHV data on the test fuels.

23. Vehaeven, E. et al (2005) Results of demonstration and evaluation projects of biodiesel from rapeseed and used frying oil on light and heavy duty vehicles. SAE Paper No. 2005-01-2201. Warrendale, PA: Society of Automotive Engineers
This paper reported on-the-road and chassis dynamometer experiments. Greater engine efficiency was attributed to the oxygen content of the FAME improving combustion. On-the-road experiments showed no efficiency difference between fossil diesel and FAME. Chassis-dyno tests showed that low blends (e.g., B20) achieved lower fuel consumption than diesel in spite of its lower energy content (LHV). However, overlapping error bars meant that definitive statements could not be made on energy efficiency.

24. Last, R.J. et al (1995) Emissions and performance characteristics of a 4-stroke, direct-injected diesel engine fuelled with blends of biodiesel and low sulfur diesel fuel. SAE Paper No. 950054. Warrendale, PA: Society of Automotive Engineers
This paper focused on an HD DI engine equipped with hydraulically actuated electronically controlled (HEUI) unit injectors, a 2-way catalyst, and EGR. The paper reported that the mass fuel consumption with biodiesel was worse than with fossil diesel. When the engine was optimised for a specific fuel, then the mass FC was similar to that found on fossil diesel.

25. Suryawanski, J.G. et al (2005) Effect of Injection Timing Retard on Emissions and performance of a Pongamia Oil Methyl Ester Fuelled CI Engine. SAE Paper No. 2005-01-3677. Warrendale, PA: Society of Automotive Engineers
Using a KIRLOSTAR TV1 4-stroke single cylinder engine, the brake thermal efficiency was found to be similar for all blends of pongamia oil methyl ester compared to fossil diesel at standard injection timing. With retarded injection timing (4°) and at lower BMEP, the biodiesel showed lower energy consumption but this difference disappeared as the BMEP increased.

26. Horn, U. et al (2007) Detailed Heat Release Analyses with Regards to Combustion of RME and Oxygenated Fuels in an HSDI Diesel Engine. SAE Paper No. 2007-01-0627. Warrendale, PA: Society of Automotive Engineers
This paper focused on the effect of EGR on key performance parameters. No fuel consumption data were reported. Results were acquired from detailed heat release analysis on a high-speed DI (HSDI) diesel engine. The energy conversion efficiency for the heat release in the cylinder was calculated from the maximum heat release and the supplied energy. This efficiency was slightly higher for European diesel fuel compared to RME.

27. Bittle, J.A. et al (2010) Biodiesel Effects on Influencing Parameters of Brake Fuel Conversion Efficiency in a Medium-duty Diesel Engine. *J Eng Gas Turbines & Power, 132, 12, 122801-122810*
Changes in fuel consumption were investigated at nine different operating conditions for fossil diesel and B100 derived from palm oil. No changes in brake fuel conversion efficiency were observed except at high loads conditions.

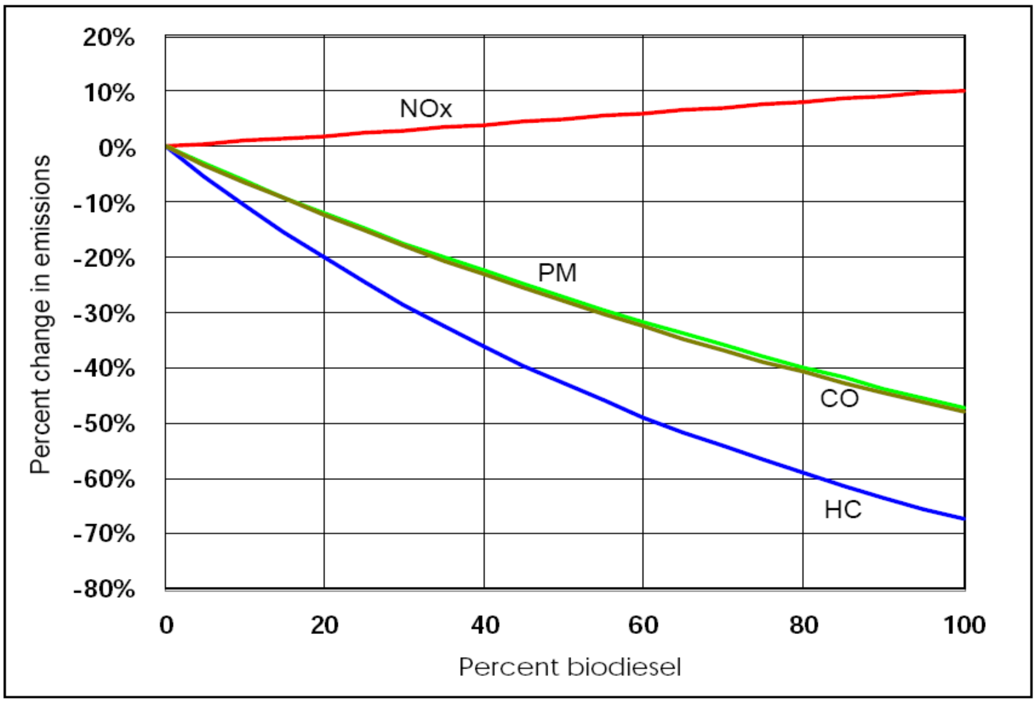
APPENDIX 2 IMPACT OF FAME ON EMISSIONS: PUBLISHED LITERATURE

Compared to FC effects, many more studies have been reported on the impact of FAME on regulated and unregulated emissions. For this reason, this Appendix addresses only a subset of recent publications and does not claim to be a comprehensive literature survey. Some examples are provided in each instance as representative of many more that address essentially the same topic.

The effect of FAME type and concentration on regulated emissions has been widely studied. The majority of publications are related to emissions from HD engines and have covered a wide range of different test procedures and protocols. A range of biodiesel types have been tested, including both animal and vegetable based components, both in their unreacted and also in their esterified state. A range of concentrations have been examined up to and including 100% biodiesel on a variety of engines (both commercial and research) and including a wide range of test conditions. Because of this diversity in tests and results, it is difficult to develop a consensus from reading the literature alone.

In 2002, however, the US EPA [A2-1] completed an analysis involving more than 800 sets of emissions data. These data were collected from a range of studies which included all of the variables mentioned above and a detailed statistical analysis was completed to summarise the effects of biodiesel fuels on regulated emissions. **Figure A2-1** is reproduced from this study and is frequently cited to show the impact of increasing biodiesel content on emissions.

Figure A2-1 Average emission impacts of biodiesel for heavy-duty highway engines [A2-1]



Since this EPA study was reported, this graph has represented the most widely held view on the effects of biodiesel on regulated emissions. It should be emphasized, however, that the study was carried out only on heavy duty engines (primarily US engines) and on a variety of fuels and test procedures (including hot start tests) and did not include engines equipped with after-treatment technologies. Consequently, extending these conclusions to other applications, such as European light-duty diesel vehicles, may not be appropriate.

There are also European publications that relate to heavy duty testing which predate this study. Some gave results in line with those reported by the EPA [A2-1,A2-3,A2-4] while others [A2-5,A2-6] reported differences, normally with respect to NOx emissions, where a reduction in NOx with increasing FAME was reported.

Since 2002, there have been many more publications on heavy duty engine results, again including most of the variables mentioned above. Short of carrying out another EPA-type statistical analysis, it is difficult to compare the magnitude of the results published. However, it is possible to look at the results 'in the round' and establish whether they agree with the directional trends already reported in the EPA study.

From our evaluation, many publications were found that agree completely with the EPA trends [A2-7,A2-8,A2-9,A2-10,A2-11] while others show some variation, again, most commonly with respect to NOx [A2-12,A2-13]. One paper [A2-14] addressed the use of a catalytic converter on a heavy duty engine and reported that its use resulted in a corresponding reduction in NOx as the biodiesel concentration increased.

However, results from heavy duty engines, and especially engines typically used in the US market, cannot necessarily be extrapolated to the European passenger car fleet in which common rail engines dominate, exhaust aftertreatment systems such as oxidation catalysts and DPFs have become standard equipment and the diesel fuel used as basic blendstock has a significantly higher cetane number than in the US. Furthermore, the European certification test emphasises cold engine starting conditions where the presence of biodiesel can have a different impact compared to hot start conditions.

There are considerably fewer publications related to the effect of biodiesel in light duty applications. Again, the available papers cover a wide range of variables with respect to FAME, concentration of blends, engine conditions etc. One early paper [A2-4] presented limited results using neat RME and concluded that all regulated emissions (including NOx) were reduced when FAME was used. Another relatively early paper [A2-15] showed reductions in HC and CO and increases in NOx, but no effect on PM.

Other papers on emissions from light-duty vehicles [A2-13,A2-16,A2-17,A2-18,A2-19] showed emissions trends that are similar to the EPA study, while some others [A2-20,A2-21,A2-22] report reductions in NOx and one [A2-23] reported an increase on HC and CO.

In a recent and quite extensive review, Lapuerta et al [A2-24] summarised these results in the following table regarding the impacts of biodiesel on gaseous pollutants, power output, and FC (**Table A2-1**). The table shows the percentage of scientific studies reporting either increases, decreases or no changes in various emissions and operation characteristics. The results are qualitative because the different conditions and protocols used in the studies do not make a direct comparison possible. In contrast to the EPA study, this table indicates that there are general trends but, in certain cases such as for NOx and efficiency, no straightforward conclusion can be drawn.

Table A2-1 Estimated share of literature (in percentage of number of publications) reporting decreases, similarities or increases in engine performance and emissions using biodiesel and diesel fuels [A2-24]

	Increases	Same[a]	Decreases	Synergies
Effective power (full load)	-	2	96	2
Brake-specific fuel consumption	98	2	-	-
Thermal efficiency	8	80	4	8
NOx emissions	85	10	5	-
PM emissions	3	2	95	-
THC emissions	1	3	95	1
CO emissions	2	7	90	1

[a] Many references included in this category have reported both increases and decreases depending on engine load conditions, engine type, engine operation temperature, etc.

LAT/AUTh has also performed an extensive literature review [A2-23] for the EEA on the impact of biodiesel on pollutant emissions and fuel consumption. The results confirmed that the use of biodiesel results in higher NOx and lower PM emissions. The size of these effects is related to the biodiesel concentration, the vehicle operating conditions, and the engine technology. The effect of biodiesel on CO and HC is generally reported to be beneficial. However, only limited studies were conducted on modern vehicles equipped with diesel oxidation catalysts or other exhaust aftertreatment technologies, configurations which might change this picture. Because of this, the picture regarding CO and HC might be significantly different for modern diesel passenger cars.

In a recent LAT study [A2-26], five different biodiesel blends were tested in order to examine their impact on the emissions and consumption of a common-rail passenger car. Small effects were observed on CO_2 emissions, with only two (PME, SUME) of the five blends providing statistically significant differences. However, these differences were rather limited and in opposite directions and there was no global conclusion on the effect of biodiesel on tailpipe CO_2 emissions. The effect of biodiesel on HC and CO emissions was more prominent over the cold-start driving cycles where the absolute HC and CO emission levels were higher. Over these cycles, B10 fuels resulted in ~25% higher HC and CO emissions than B0 diesel fuel. The ratios of HC and CO emissions over cold-start and hot driving cycles were different for the B0 and B10 fuels. These results indicated that DOC performance was different when biodiesel was used. The effect of different biodiesel blends on NOx emissions was variable, ranging from –7% to +11% on average, depending on the type of biodiesel feedstock.

In addition, a recent study from the Joint Research Centre [A2-26] on two passenger cars did not lead to consistent conclusions. NEDC tests on a Euro 3 common-rail equipped car using B30 and B100 fuels confirmed that the regulated emissions were higher with increasing biodiesel content. The largest effect was observed when neat biodiesel (B100) was used, suggesting that the different properties of the fuels resulted in a non-optimized engine operation, leading to significant increases in certain pollutants, such as CO, HC and NOx. However, fuel consumption did not seem to be affected by the presence of biodiesel at low concentrations while the increase in fuel consumption was limited to 3% with neat biodiesel (B100). The same fuels, when used on a unit-injector equipped Euro 3 car, led to completely different observations concerning the impact of biodiesel on modern passenger cars. Therefore, the effect of biodiesel blends on NOx emissions from passenger cars is not straightforward and appears to depend on feedstock, vehicle technology and operating conditions.

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4. Staat et al (1995). The effects of rapeseed oil methyl ester on diesel engine performance, exhaust emissions and long term behavior. SAE Paper No. 950053. Warrendale, PA: Society of Automotive Engineers

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9. Chuepeng et al (2007). A study of quantitative impact on emissions of high proportion RME based blends. SAE Paper No. 2007-01-0072. Warrendale, PA: Society of Automotive Engineers

10. Krahl et al (2005). The influence of fuel design on the exhaust gas emissions and health effects. SAE Paper No. 2005-01-3772. Warrendale, PA: Society of Automotive Engineers

11. Xiaoming et al (2005). An experimental investigation on combustion and emissions characteristics of turbocharged DI engines fuelled with blends of biodiesel. SAE Paper No. 2005-01-2199. Warrendale, PA: Society of Automotive Engineers

12. Sharp et al (2005). Heavy duty diesel engine emission tests using special biodiesel fuel. SAE Paper No. 2005-01-3671. Warrendale, PA: Society of Automotive Engineers

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17. Grimaldi et al (2002). Common rail HSDI diesel engine combustion and emissions with fossil/bio-derived fuel blends. SAE Paper No. 2002-01-0865. Warrendale, PA: Society of Automotive Engineers

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20. Lance et al (2004). Emissions performance of pure vegetable oil in two European light duty vehicles. SAE Paper No. 2004-01-1881. Warrendale, PA: Society of Automotive Engineers

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27. Martini, G. et al (2007) Effect of biodiesel fuels on pollutant emissions from Euro 3 LD diesel vehicles (1). Report EUR 22745 EN. Ispra : DG JRC - IES

APPENDIX 3 ANALYTICAL DATA FOR RME AND DIESEL TEST FUELS

Rapeseed Methyl Ester (RME)			
Property	Units	Test Method	B100
Data from Fuel Blender[12]			
Cetane Number		EN ISO 5165	55.1
Derived Cetane Number		IP 498	61.2
Density at 15°C	kg/m^3	EN ISO 12185	883.1
Flash point	°C	EN ISO 2719	>110
Viscosity at 40°C	mm^2/s	DIN EN ISO 3104	4.4
Sulphur	mg/kg	EN ISO 20846	<3.0
Oxidation Stability	hrs	EN 14112	10.0
Ester content	% m/m	ISO 5508/EN 14103	97.1
Iodine number	g/100g	EN 14111	114.6
Carbon Number : # double bonds			
C12:0	% m/m	ISO 5508/EN14103	0.0
C14:0	% m/m	ISO 5508/EN14103	0.1
C16:0	% m/m	ISO 5508/EN14103	4.4
C16:1	% m/m	ISO 5508/EN14103	0.3
C18:0	% m/m	ISO 5508/EN14103	1.6
C18:1	% m/m	ISO 5508/EN14103	60.8
C18:2	% m/m	ISO 5508/EN14103	18.7
C18:3	% m/m	ISO 5508/EN14103	9.9
C20:0	% m/m	ISO 5508/EN14103	0.6
C20:1	% m/m	ISO 5508/EN14103	1.4
C22:0	% m/m	ISO 5508/EN14103	0.3
C22:1	% m/m	ISO 5508/EN14103	0.0
C24:0	% m/m	ISO 5508/EN14103	NR
C24:1	% m/m	ISO 5508/EN14103	NR
Glycerine, total	% m/m	EN 14105	0.18
Acid number	Mg KOH/g	EN 14104	0.07
Methanol content	% m/m	EN 14110	0.02
Water content	mg/kg	EN ISO 12937	100
Concawe Data[13]			
Carbon content	% wt	ASTM D5291	76.98
Hydrogen content	% wt	ASTM D5291	12.00
Oxygen content	% wt	In-house method	10.3
H/C Molar Ratio		Calculated	1.86
Gross heating value	MJ/kg	ASTM D240/IP 12	39.73
Net heating value	MJ/kg	ASTM D240/IP 12	37.18

[12] Single measurements as reported on the fuel blender's Certificate of Analysis
[13] Average of two or more measurements conducted at Concawe Member Companies

Test Fuels						
Fuel Property	Units	Test Method	B0	B10	B30	B50
Data from Fuel Blender[14]						
Cetane Number		EN ISO 5165	53.2	53.6	53.8	53.9
Cetane Index (4 variable)		ASTM D4737	60.3	59.1	57.6	56.1
Density at 15˚C	kg/m^3	EN ISO 12185	823.1	829.1	841.0	853.0
Initial Boiling Point	°C	EN ISO 3405	202.8	204.9	206.1	214.3
Distillation T50	°C	EN ISO 3405	271.2	277.2	293.6	312.0
Distillation T95	°C	EN ISO 3405	316.5	330.5	339.3	344.3
Final Boiling Point	°C	EN ISO 3405	326.5	337.3	344.2	352.1
Flash point	°C	EN ISO 2719	80	76	91	97
CFPP	°C	EN116	-22	-21	-25	-21
Cloud Point	°C	EN ISO 3015	NM	-18	-14	-11
Viscosity at 40˚C	mm^2/s	EN ISO 3104	2.661	2.785	3.081	3.410
Total Aromatics	% m/m	EN 12916	22.3	18.3	15.0	10.6
Mono-aromatics	% m/m	EN 12916	20.8	17.1	14.1	9.9
Di-aromatics	% m/m	EN 12916	1.4	1.2	0.9	0.7
Tri-aromatics	% m/m	EN 12916	0.1	0.1	<0.1	<0.1
Polycyclic Aromatic Hydrocarbons	% m/m	EN 12916	1.2	1.2	0.9	0.6
FAME Content	% vol	EN 14078	<0.1	10.7	30.6	50.9
Sulphur	mg/kg	EN ISO 20846	<3	<3	<3	<3
Copper Corrosion 3h @ 50°C		EN ISO 2160	1A	1A	1A	1A
Oxidation Stability	g/m^3	EN ISO 12205	4	0.2	0.1	0.1
Oxidation Stability	hrs	EN 15751	NM	64.6	31.3	21.5
Water Content	mg/kg	EN ISO 12937	22	37	138	138
Ash Content	% m/m	EN ISO 6245	0.002	<0.001	<0.001	<0.001
HFRR	Micron	EN ISO 12156	227	156	171	168

[14] Single measurements as reported on the fuel blender's Certificate of Analysis

APPENDIX 4 TEST protocol

Vehicle fuelling

As described below, no back-to-back measurements with the same fuel were conducted. Therefore, in order to facilitate fuel changes between measurements, minimize cross fuel contamination and ensure optimal washing of the vehicle fuelling system, it was decided to use an external fuel tank for these tests. Guidelines were received from the manufacturers in order to ensure proper engine fuelling and operation. When required, an external low pressure pump was employed for vehicle fuelling.

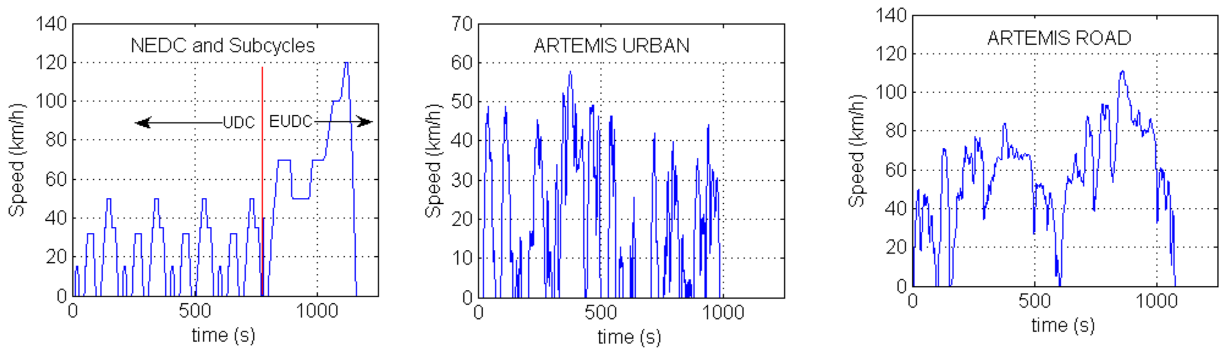
Simulation of Vehicle Resistances

For simulating vehicle resistances on the chassis dynamometer, data regarding coast down times and reference mass were provided by the manufacturers. Particularly for Vehicle C, different reference masses were employed for fuel consumption and for gaseous pollutant tests. Since the scope of the study was primarily to test the effect of biodiesel on fuel consumption, the reference mass corresponding to the fuel consumption test was used for all tests.

Driving cycles – protocol outline

For addressing the needs of the study, a protocol was selected which combined the European NEDC certification cycle and other test cycles that simulate “real world” driving. The objective was to obtain data regarding the effect of RME over the NEDC, which is one of the most referenced cycles, but also understand how RME might impact more “real world” operation, particularly over urban and semi-urban conditions. The “real world” driving cycles were developed in the framework of the ARTEMIS project [12] and are considered representative of city (URBAN) and rural (ROAD) driving conditions in Europe. In addition, two steady state modes were used (at 50 and 120 km/h) for measuring particle size distributions and particle number emissions. The speed versus time profiles for the NEDC and ARTEMIS cycles are presented in **Figure A4-1.** The NEDC profile also shows the UDC and EUDC portions.

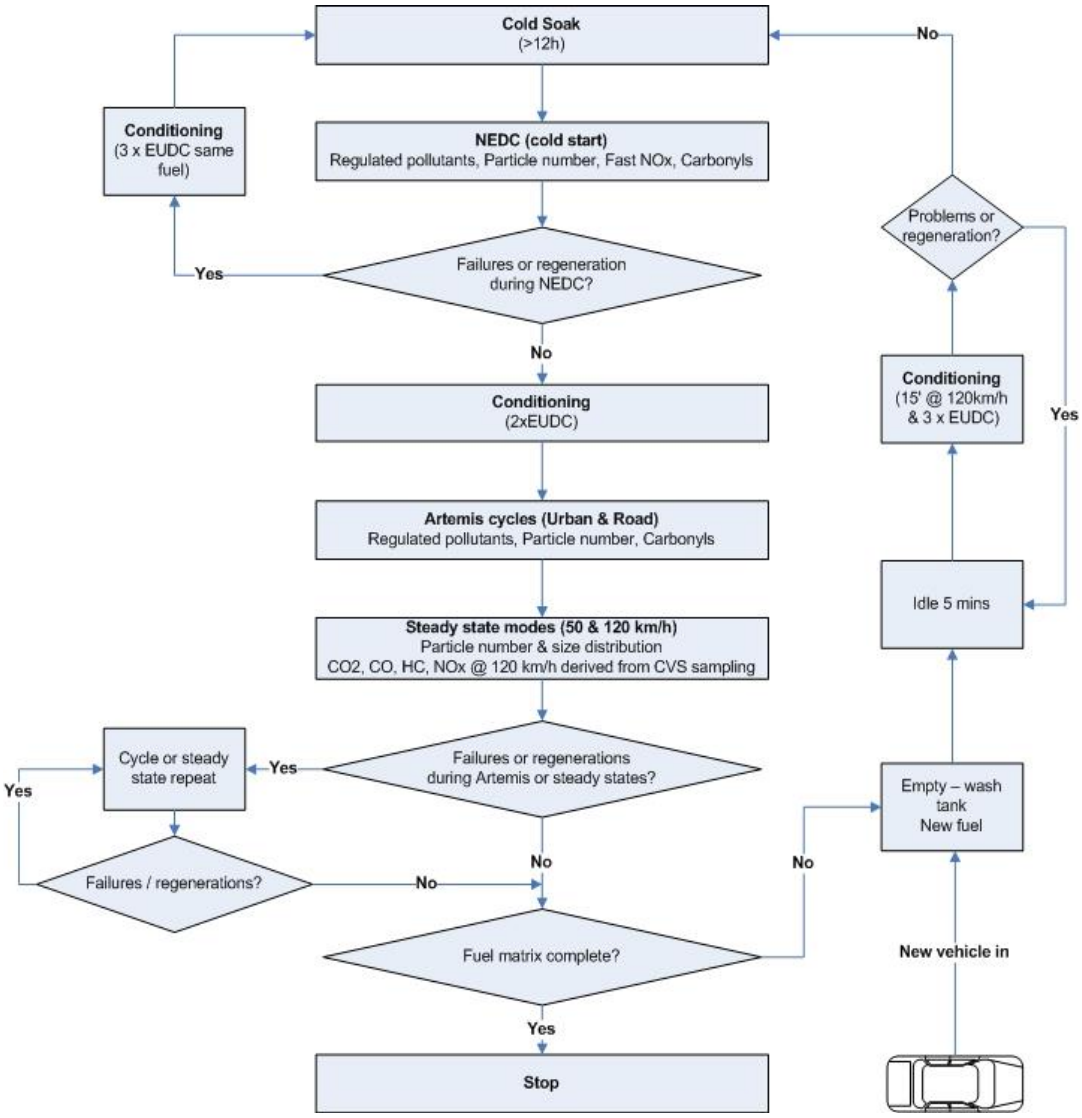
Figure A4-1 Driving cycles used in this study



The daily measurement protocol started with the NEDC, which is a cold-start driving cycle. The NEDC consists of an urban part (UDC) where the engine starts from room temperature and an extra-urban part (EUDC) for testing the car at higher than urban speeds. The NEDC was followed by 2 x EUDC for vehicle conditioning purposes before completing the two measurements associated with the ARTEMIS Urban and Road cycles. Each vehicle testing day ended with tests at constant speed (50 and 120 km/h). Each constant speed test consisted of 5-10 minutes of conditioning and approximately 15 minutes of measurement.

After the measurements were completed, fuel change followed by vehicle conditioning took place. The tank was emptied and washed with the new fuel and the vehicle was then operated for a short time on the new fuel. During the first 15 seconds of operation with the new fuel, the returning fuel was collected and discarded in order to avoid contamination caused by any of the previous fuel remaining in the fuel lines. The vehicle was left to idle for 5 minutes and then the conditioning process was initiated. A detailed flowchart of the measurement and conditioning processes is provided in **Figure A4-2**.

Figure A4-2 Flowchart of the vehicle test protocol



Testing sequence

No back-to-back measurements were performed with the same fuel. Each fuel was tested once and then another fuel was used. The fuel testing order was different for each vehicle. The test sequences performed are presented in **Table A4-1**.

Table A4-1 Testing sequence for the three vehicles (with dates and vehicle mileage)

Vehicle 1			Vehicle 2			Vehicle 3		
Fuel	Date tested	Mileage (km)	Fuel	Date tested	Mileage (km)	Fuel	Date tested	Mileage (km)
B0	3/3/09	3487	B0	7/4/09	62118	B0	25/5/2009	27603
B10	4/3/09	3637	B10	8/4/09	62269	B30	26/5/2009	27751
B50	6/3/09	3819	B50	9/4/09	62420	B10	27/5/2009	27899
B30	9/3/09	3968	B30	10/4/09	62571	B50	29/5/2009	28046
B0	10/3/09	4117	B0	24/4/09	63116	B0	1/6/2009	28194
B10	11/3/09	4270	B30	27/4/09	63267	B50	2/6/2009	28342
B30	12/3/09	4448	B50	28/4/09	63418	B30	3/6/2009	28489
B50	13/3/09	4598	B10	29/4/09	63659	B10	4/6/2009	28638
B0	16/3/09	4748	B0	30/4/09	63720	B0	5/6/2009	28785
B50	17/3/09	4897	B10	4/5/09	63870	B10	9/6/2009	28933
B30	18/3/09	5046	B30	5/5/09	64021	B30	11/6/2009	29081
B10	19/3/09	5195	B50	7/5/09	64172	B50	26/6/2009	29542
B0	20/3/09	5411	B0	8/5/09	64323	B0	30/6/2009	29690
B10	23/3/09	5559	B30	11/5/09	64476	B50	1/7/2009	29542
B50	27/3/09	5762	B10	13/5/09	64629	B30	2/7/2009	29986
B30	30/3/09	5911	B50	14/5/09	64780	B10	3/7/2009	30134
B0	31/3/09	6060	B0	15/5/09	64913	B0	6/7/2009	30282

As shown in this table, the testing sequences were divided into sub-blocks of four fuels. Each block constituted of all four fuels examined and always began with a B0 fuel. The rest of the fuels were tested in random order. This scheme was decided after analyzing the repeatability of previous measurements which defined the total number of repetitions necessary. As mentioned, each RME/diesel blend was tested 4 times on each vehicle and the reference B0 fuel five times.

ECU data recording

During the measurement and the conditioning periods, data were retrieved from the engine ECU on various important operating parameters. The data were recorded using a standard OBD-II tool. Among the parameters monitored and recorded were: engine RPM, engine load, acceleration pedal position (if available), EGR rate (if available), air flow, exhaust gas temperature (if available) and possible engine fault codes.

Monitoring and recording these data helped evaluate the repeatability of each vehicle's engine operation and additionally helped to identify possible DPF regenerations. In the first case, the engine RPM and load were used to compare how the vehicle was driven over each driving cycle and in addition for identifying possible changes in EMS caused by the lower energy content of the test fuel. In the second case, exhaust gas temperature data upstream of the DPF were used to identify possible regenerations that might occur during the measurements of Vehicle 1. Such regenerations would distort the fuel consumption and emissions results of the particular test.

Emissions sampling

During the study, different emissions were measured and various sampling techniques were followed. A brief summary of the pollutants/parameters sampled is provided in **Table 3** and in **Section 2**.

With respect to the table, the following should be noted:

- The distinction between NEDC and its sub-cycles is made for emissions that are calculated both over NEDC as a whole and for the individual sub-cycles.
- Over the 120 km/h mode indicative regulated pollutant emissions will be presented based on calculations made using modal data. However this was not a standardized sampling/emissions calculation activity.
- Fast NOx and high volume PM sampling was conducted only for B0 and B50 fuels. One sample of PM was collected for all 3 cycles in this case.

More detailed information is given in the following paragraphs.

Test facility – regulated pollutant sampling

Emission measurements over NEDC and ARTEMIS 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 metal-to-metal connection to avoid exposing the hot exhaust gas to any synthetic material connectors. A flow rate of approximately 500 Nm^3/h was maintained in the CVS tunnel by a positive displacement pump. The dilution air was filtered through a HEPA class H13/EN1822 filter at the inlet of the dilution tunnel. Proportional diluted exhaust samples were collected in bags for gaseous pollutants measurements.

Gaseous pollutants were measured with laboratory analyzers as foreseen by European legislation (chemiluminescence for NOx, flame ionization detector for HC and non dispersive infrared for CO and CO2). Fuel consumption was derived by means of the exhaust-to-fuel carbon balance, taking into account the oxygen content of fuels (see **Appendix 8**). PM samples were collected on 47mm PTFE-coated glass fibre filters (Pallflex TX40HI20-WW) following the PMP specifications as presented below.

In order to obtain an indication of the test fuels' effect over motorway driving conditions, modal data from the 120 km/h steady state mode were employed for calculating CO_2, CO, HC and NOx emissions and fuel consumption. For these calculations the instantaneous signals of the aforementioned analyzers were used.

Test order

The programme was conducted using the statistically designed test order specified in **Table A4-2** below.

Fuels B10, B30 and B50 will be tested four times in each vehicle, while the base fuel B0 will be tested five times in order to obtain improved estimates of baseline performance and engine drift. The three FAME blends B10, B30 and B50 are tested in four randomized blocks, and the base fuel tests are positioned between adjacent blocks and at the start and end of testing. Different randomized orders are used for each vehicle.

Table A4-2 Vehicle and fuel test order

Test	Vehicle A	Vehicle B	Vehicle C
1	B0	B0	B0
2	B10	B10	B30
3	B50	B50	B10
4	B30	B30	B50
5	B0	B0	B0
6	B10	B30	B50
7	B30	B50	B30
8	B50	B10	B10
9	B0	B0	B0
10	B50	B10	B10
11	B30	B30	B30
12	B10	B50	B50

PM sampling

Particulate Matter (PM) sampling was performed following the specifications of the PMP protocol. A separate filter was used for each of the three driving cycles (NEDC, ARTEMIS Urban and Road) for measuring PM emissions.

In addition to the vehicle tests, six additional blank tests were performed for determining background levels for both PM and carbonyl compounds (see below). During these 6 tests, the sampling procedure for PM and carbonyl compounds was repeated identically as for vehicle measurements but the CVS was disconnected from the vehicle tailpipe.

After weighing and calculating PM emissions, the filters were packed in order to be used for determining the soluble organic fraction (SOF) of PM, anions and elemental carbon (EC) by difference. Both PM filters and cartridges were stored according to Concawe's recommendations and were sent for analysis periodically as the measurements progressed. It is noted here that all PM filters (including the ones from ARTEMIS Road which are not scheduled for analysis) were stored in case some of them need to be used in the future.

The SOF analysis and measurements of aldehyde and ketone emissions were completed by the Environmental Pollution Control Laboratory (EPCL) of the Department of Chemistry at AUTh.

Filter Preparation

Pallflex TX40 Fluorocarbon coated glass fibre filters were used. The filter batch was always recorded. The filter diameter was 47 mm.

The particle sample filters (both blank and loaded) were conditioned (as regards temperature and humidity) 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 aluminium plate during their conditioning period. Moreover, they were placed under a perforated aluminium cover in order to be protected from dust and be in contact with the environment at the same time.

Three reference filters were kept in the clean room and were weighed at the same time as the blank and loaded filters, in-line with the PMP regulation. Each sample filter (blank and loaded) was weighed more than once during its conditioning period. The conditioning period is set to 2- 80 h by the PMP procedure. However, because of the subsequent non-regulated pollutant analyses the loaded filters were normally kept 24-48 h in the clean room and then immediately stored, in order to ensure no change of the PM composition.

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 aluminium mat to avoid development of static charge. A reference weight 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.

Filter storage

After their final weighing, the filters were packed in order to be first stored and then sent for PM speciation analyses. The filter paper was folded in half with the side containing the particulate deposit on the inside. The folded 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 area of a refrigerator.

Each bag was separately labelled. The bag labelling included the filter code number which identifies a unique test and the loaded filter conditioning time. The date of the final weighing, the weight of the filter, the batch number of the filter, and the initials of the person preparing the filter sample bag were also recorded.

APPENDIX 5 STATISTICAL DATA ANALYSIS

This Appendix provides additional information on the statistical analysis methods discussed in **Section 3.2**.

Outlier detection using studentized residuals

The data were examined for possible outliers and trends by examining studentized residuals (residuals divided by their standard errors) in analysis of (co)variance models fitted to the measured emissions, or fuel consumption, for a particular vehicle and cycle on both the natural and log-transformed scale. In this study, we fitted a one-way ANOVA model to each vehicle × cycle × emission combination with emission or ln(emission) as the response variable and fuel as the classifying factor. Trends were sought by treating test order as a covariate.

The studentized residuals were compared against the upper 5% and 1% points tabulated in [26]. Suspicious results were queried with the originating laboratory and were not rejected unless there were sound engineering reasons to believe that something untoward had happened in that particular test. In the event, only a few results were rejected, as follows:

Vehicle 1:

CO results in NEDC/UDC/EUDC on 6 March 2009 on B50 (abnormally high)
CO result at 120 km/h on 19 March 2009 on B10 (abnormally high)
HC results in Artemis Road & Urban cycles on 27 March 2009 on B50 (abnormally high)

Vehicle 2:

NOx and NO results in NEDC/UDC/EUDC on 9 April 2009 on B50 (abnormally high); the corresponding NO/NOx results were also rejected
PM result in NEDC on 28 April 2009 on B50 (abnormally low)

In addition, the following results became outliers after the trend correction had been applied and so were removed before calculating trend corrected means:

Vehicle 1:

CO_2 and FC results in Artemis Urban cycle on 31 March 2009 on B0 (abnormally high)

Arithmetic and geometric means and error bars

In **Appendix 6** and the bar charts in **Section 4**, arithmetic means are used for fuel consumption, gaseous emissions, the NO/NOx ratio, and PM despite the lognormality assumed in the data. Geometric (i.e. logarithmic) means give excellent comparisons between fuels on a percentage basis but have the disadvantage of underestimating total emissions to the atmosphere. Arithmetic means give better estimates of total emissions to the atmosphere but can be inflated unduly by isolated high results.

Each vehicle × cycle × emission measurement data set was analysed separately. The arithmetic mean emissions and fuel consumption, and their standard errors, were estimated for the various fuels from a weighted analysis of variance or covariance in which each measurement was assigned a weight equal to

$$\text{weight} = 1 / (\text{mean emission for that fuel and vehicle})^2$$

to take account of the lognormality in the data (see [23], Annex 05).

In the bar charts presented in **Section 4**, the error bars show the

mean value ±1.4 x standard error of mean

The 1.4 factor was chosen for consistency with both the EPEFE [23] and recent Concawe reports [13,14,15,16]. The original rationale was that when two fuels were significantly different from one another at $P<5\%$, their error bars would not overlap; this factor also gave 84% confidence that the true mean lay within the limits shown.

Error bars based on a 1.4 factor err on the side of being slightly too narrow for determining significant differences in the present programme as fewer tests were carried out. Such an interpretation would require error bars based on a factor between 1.52 and 1.56, depending on the exact number of valid tests and whether or not a trend correction has been applied. Therefore there needs to be a sizeable gap between the error bars for two fuels for their means to be considered significantly different from one another at $P<5\%$.

APPENDIX 6 EMISSIONS FROM DIESEL VEHICLES

The arithmetic mean emissions and fuel consumption from each vehicle, fuel, and driving cycle are summarized in this Appendix. Both the uncorrected and corrected means are shown wherever a trend correction has been applied. See **Section 3.2** of the report for more details.

CO_2 (g/km) - Arithmetic means

Vehicle	Fuel	NEDC	UDC	EUDC	ARTEMIS Road	ARTEMIS Urban		Steady State 120 km/h	
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Corr	Uncorr	Corr
1	B0	190.2	277.2	139.6	132.9	300.2	297.3	142.4	
1	B10	191.4	282.0	138.7	134.4	304.4	304.4	140.1	
1	B30	194.9	286.4	141.6	133.8	304.8	305.8	143.6	
1	B50	194.7	286.3	141.4	135.4	304.6	305.1	145.2	
2	B0	158.4	215.0	125.6	135.6	242.6		142.1	142.1
2	B10	160.3	217.3	127.1	136.7	244.7		140.2	140.3
2	B30	160.2	217.2	127.4	136.8	247.2		143.5	143.6
2	B50	162.2	219.9	128.9	138.2	247.4		142.1	142.0
3	B0	169.2	217.5	141.2	153.2	266.3		160.1	
3	B10	168.5	214.9	141.6	152.7	263.4		159.9	
3	B30	169.8	216.6	142.8	153.7	264.6		161.2	
3	B50	170.9	219.0	143.0	155.0	266.4		161.8	

Fuel Consumption (l/100km) - Arithmetic means

Vehicle	Fuel	NEDC	UDC	EUDC	ARTEMIS Road	ARTEMIS Urban		Steady State 120 km/h	
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Corr	Uncorr	Corr
1	B0	7.353	10.724	5.395	5.135	11.603	11.490	5.502	
1	B10	7.423	10.945	5.377	5.209	11.801	11.801	5.430	
1	B30	7.630	11.221	5.538	5.234	11.925	11.964	5.618	
1	B50	7.693	11.328	5.582	5.344	12.024	12.043	5.730	
2	B0	6.129	8.335	4.853	5.243	9.378		5.493	5.493
2	B10	6.223	8.449	4.927	5.300	9.485		5.438	5.440
2	B30	6.277	8.527	4.986	5.355	9.672		5.617	5.619
2	B50	6.414	8.711	5.087	5.456	9.767		5.611	5.607
3	B0	6.544	8.424	5.459	5.923	10.308		6.187	
3	B10	6.536	8.344	5.490	5.920	10.222		6.197	
3	B30	6.652	8.495	5.587	6.015	10.359		6.309	
3	B50	6.753	8.669	5.643	6.117	10.520		6.386	

NOx (g/km) - Arithmetic means

Vehicle	Fuel	NEDC		UDC	EUDC		ARTEMIS Road		ARTEMIS Urban		Steady State 120 km/h	
		Uncorr	Corr	Uncorr	Uncorr	Corr	Uncorr	Corr	Uncorr	Corr	Uncorr	Corr
1	**B0**	0.231		0.297	0.192		0.633		1.665		0.278	0.278
1	**B10**	0.231		0.303	0.189		0.691		1.688		0.274	0.276
1	**B30**	0.255		0.338	0.207		0.685		1.728		0.283	0.281
1	**B50**	0.268		0.342	0.224		0.788		1.845		0.290	0.290
2	**B0**	0.227		0.301	0.184		0.540	0.540	0.924	0.924	0.279	0.279
2	**B10**	0.232		0.299	0.192		0.556	0.557	0.913	0.917	0.271	0.272
2	**B30**	0.246		0.298	0.216		0.590	0.591	0.987	0.990	0.290	0.291
2	**B50**	0.256		0.305	0.228		0.627	0.624	1.033	1.027	0.308	0.306
3	**B0**	0.263	0.263	0.224	0.286	0.286	0.607	0.593	0.889	0.889	0.584	0.584
3	**B10**	0.268	0.267	0.217	0.298	0.297	0.600	0.603	0.858	0.855	0.581	0.579
3	**B30**	0.293	0.294	0.239	0.324	0.325	0.643	0.650	0.953	0.956	0.628	0.630
3	**B50**	0.298	0.298	0.240	0.332	0.332	0.650	0.655	0.934	0.934	0.635	0.635

CO (g/km) - Arithmetic means

Vehicle	Fuel	NEDC		UDC		EUDC	ARTEMIS Road	ARTEMIS Urban		Steady State 120 km/h
		Uncorr	Corr	Uncorr	Corr	Uncorr	Uncorr	Uncorr	Corr	Uncorr
1	**B0**	0.0633		0.1609		0.0066	0.0064	0.0222		0.0038
1	**B10**	0.0731		0.1874		0.0067	0.0067	0.0219		0.0039
1	**B30**	0.0877		0.2269		0.0066	0.0062	0.0245		0.0032
1	**B50**	0.1047		0.2738		0.0065	0.0064	0.0239		0.0043
2	**B0**	0.1265	0.1265	0.3326	0.3326	0.0072	0.0064	0.0172		0.0067
2	**B10**	0.1293	0.1284	0.3416	0.3392	0.0056	0.0062	0.0172		0.0061
2	**B30**	0.1382	0.1374	0.3694	0.3670	0.0055	0.0066	0.0196		0.0061
2	**B50**	0.1507	0.1524	0.4001	0.4048	0.0065	0.0065	0.0162		0.0060
3	**B0**	0.0879		0.2223		0.0102	0.0573	0.2597	0.2596	0.0222
3	**B10**	0.0833		0.2085		0.0108	0.0420	0.2192	0.2174	0.0227
3	**B30**	0.0996		0.2525		0.0114	0.0316	0.1011	0.1028	0.0231
3	**B50**	0.1241		0.3205		0.0103	0.0116	0.0515	0.0514	0.0218

HC (g/km) - Arithmetic means

Vehicle	Fuel	NEDC		UDC		EUDC	ARTEMIS Road	ARTEMIS Urban	Steady State 120 km/h
		Uncorr	Corr	Uncorr	Corr	Uncorr	Uncorr	Uncorr	Uncorr
1	**B0**	0.0131		0.0304		0.0031	0.0014	0.0060	0.0022
1	**B10**	0.0162		0.0367		0.0043	0.0011	0.0047	0.0020
1	**B30**	0.0171		0.0398		0.0039	0.0005	0.0028	0.0016
1	**B50**	0.0219		0.0520		0.0044	0.0009	0.0033	0.0031
2	**B0**	0.0182	0.0182	0.0390	0.0390	0.0061	0.0163	0.0078	0.0194
2	**B10**	0.0192	0.0191	0.0411	0.0407	0.0065	0.0111	0.0004	0.0216
2	**B30**	0.0202	0.0200	0.0455	0.0452	0.0056	0.0162	0.0115	0.0250
2	**B50**	0.0222	0.0225	0.0495	0.0501	0.0065	0.0108	0.0051	0.0241
3	**B0**	0.0169		0.0346		0.0067	0.0073	0.0106	0.0015
3	**B10**	0.0154		0.0314		0.0062	0.0035	0.0081	0.0013
3	**B30**	0.0185		0.0406		0.0058	0.0019	0.0101	0.0009
3	**B50**	0.0199		0.0446		0.0056	0.0028	0.0081	0.0021

PM (g/km) - Arithmetic means

Vehicle	Fuel	NEDC	ARTEMIS Road	ARTEMIS Urban
		Uncorr	Uncorr	Uncorr
1	B0	0.00066	0.00094	0.00337
1	B10	0.00071	0.00103	0.00330
1	B30	0.00055	0.00080	0.00222
1	B50	0.00060	0.00086	0.00274
2	B0	0.03338	0.02693	0.05113
2	B10	0.02780	0.02509	0.04461
2	B30	0.01910	0.02155	0.03201
2	B50	0.01593	0.01800	0.03404
3	B0	0.00078	0.00170	0.00220
3	B10	0.00080	0.00188	0.00282
3	B30	0.00069	0.00126	0.00202
3	B50	0.00068	0.00276	0.00229

NO (g/km) - Arithmetic means

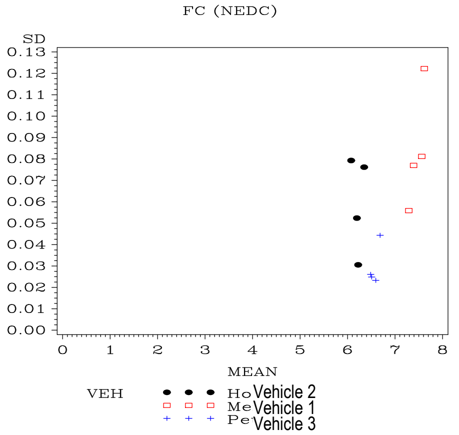
Vehicle	Fuel	NEDC		UDC	EUDC		ARTEMIS Road		ARTEMIS Urban	
		Uncorr	Corr	Uncorr	Uncorr	Corr	Uncorr	Corr	Uncorr	Corr
1	B0	0.070		0.101	0.052		0.165		0.364	
1	B10	0.068		0.101	0.050		0.184		0.372	
1	B30	0.076		0.115	0.053		0.180		0.382	
1	B50	0.078		0.113	0.058		0.205		0.418	
2	B0	0.086	0.086	0.138	0.056	0.056	0.162	0.162	0.305	0.305
2	B10	0.089	0.089	0.139	0.059	0.059	0.170	0.170	0.304	0.305
2	B30	0.091	0.092	0.137	0.065	0.065	0.181	0.182	0.334	0.335
2	B50	0.097	0.093	0.141	0.071	0.065	0.195	0.194	0.355	0.353
3	B0	0.111		0.109	0.112		0.186		0.285	
3	B10	0.105		0.102	0.106		0.178		0.249	
3	B30	0.116		0.114	0.117		0.196		0.306	
3	B50	0.115		0.118	0.113		0.202		0.289	

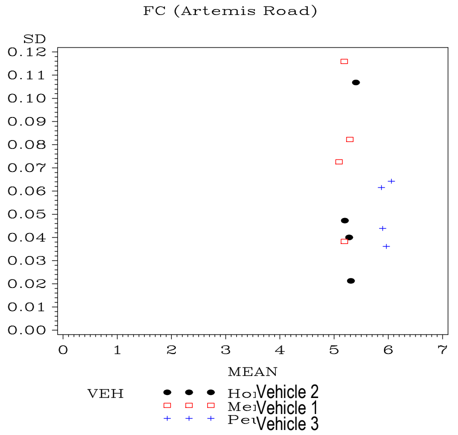
NO/NOx Ratio - Arithmetic means

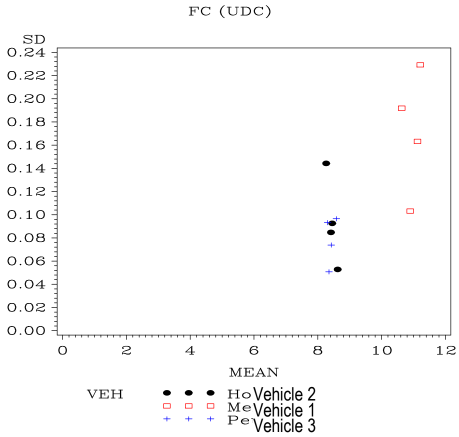
Vehicle	Fuel	NEDC	UDC	EUDC	ARTEMIS Road	ARTEMIS Urban
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr
1	B0	0.304	0.340	0.270	0.262	0.219
1	B10	0.298	0.333	0.265	0.265	0.220
1	B30	0.297	0.338	0.259	0.262	0.221
1	B50	0.293	0.330	0.260	0.261	0.227
2	B0	0.379	0.460	0.303	0.301	0.331
2	B10	0.382	0.465	0.307	0.305	0.332
2	B30	0.371	0.461	0.300	0.307	0.338
2	B50	0.362	0.468	0.288	0.311	0.343
3	B0	0.420	0.488	0.389	0.305	0.322
3	B10	0.389	0.472	0.354	0.296	0.289
3	B30	0.396	0.476	0.362	0.305	0.322
3	B50	0.386	0.493	0.341	0.312	0.309

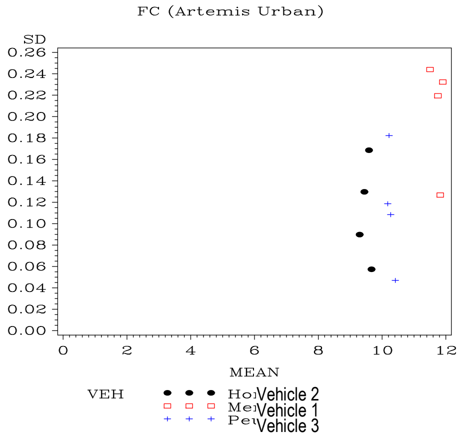
APPENDIX 7 MEANS AND STANDARD DEVIATIONS

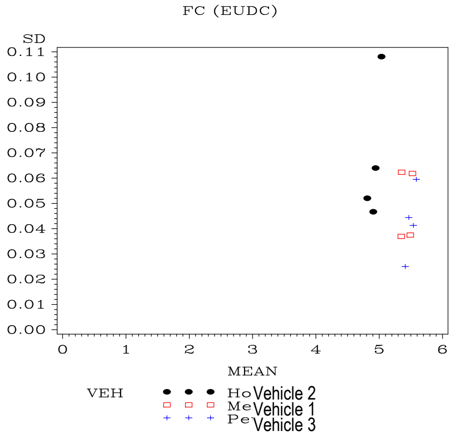
Note: These plots show all data before trend correction or the deletion of outliers.

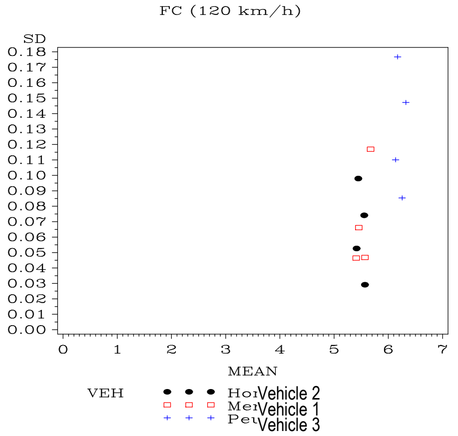




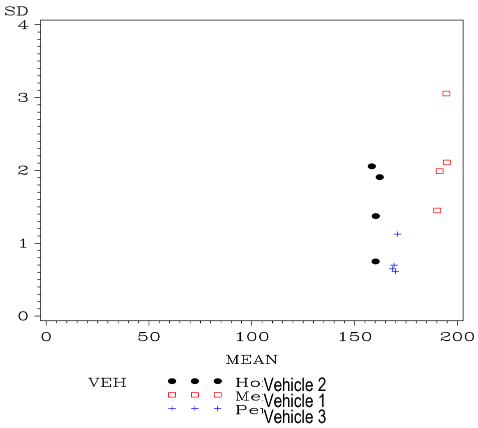




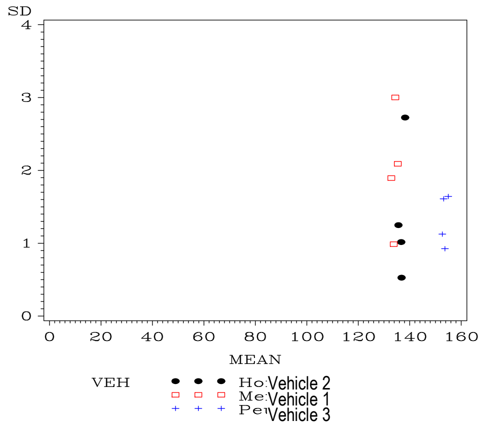




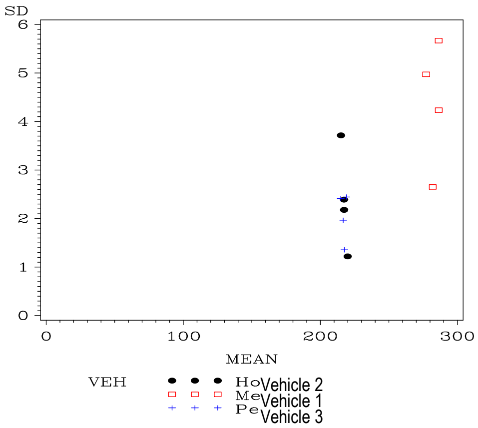
CO2 (NEDC)



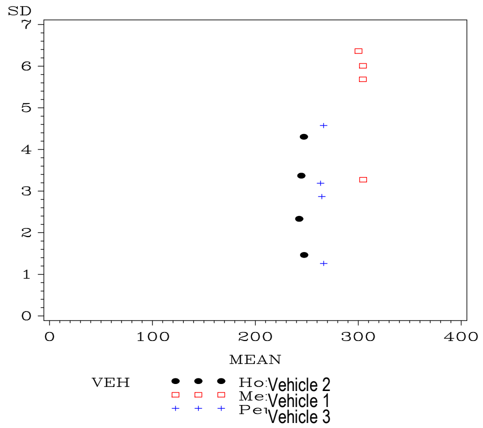
CO2 (Artemis Road)



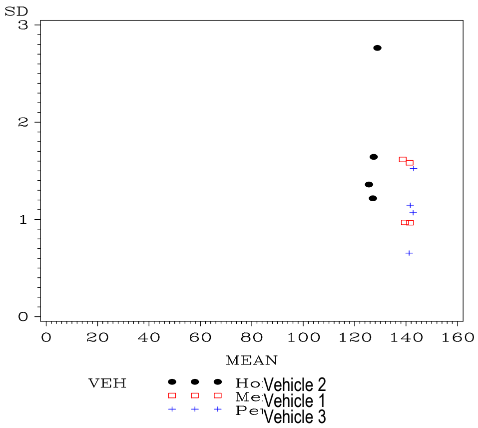
CO2 (UDC)



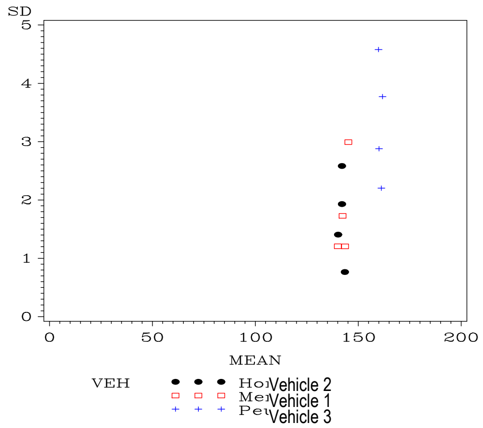
CO2 (Artemis Urban)

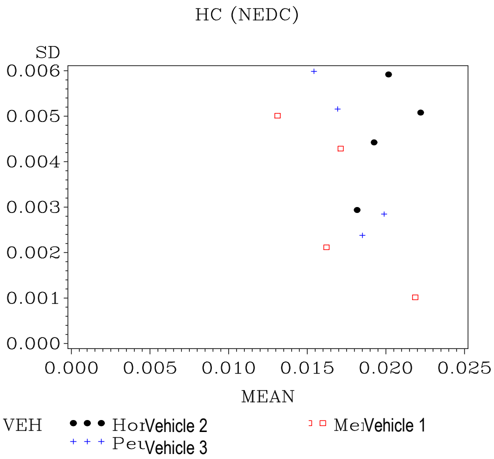


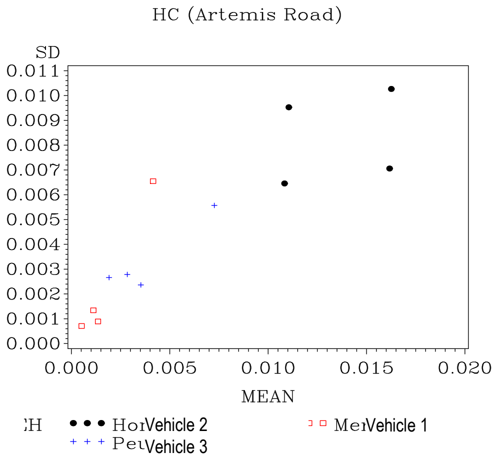
CO2 (EUDC)

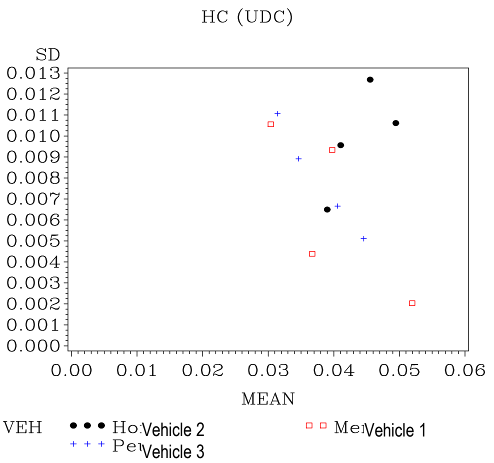


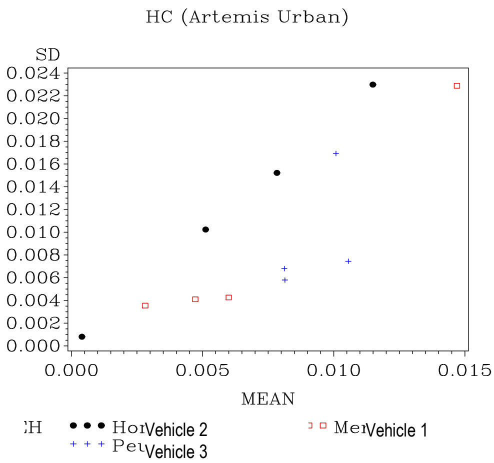
CO2 (120 km/h)

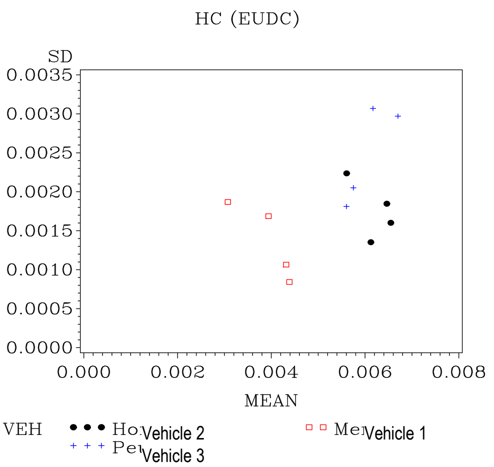


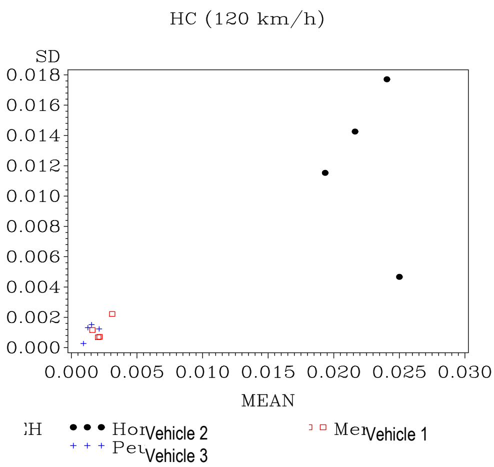

HC (NEDC)
SD
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0.000 0.005 0.010 0.015 0.020 0.025
MEAN
VEH
Vehicle 2
Vehicle 1
Vehicle 3

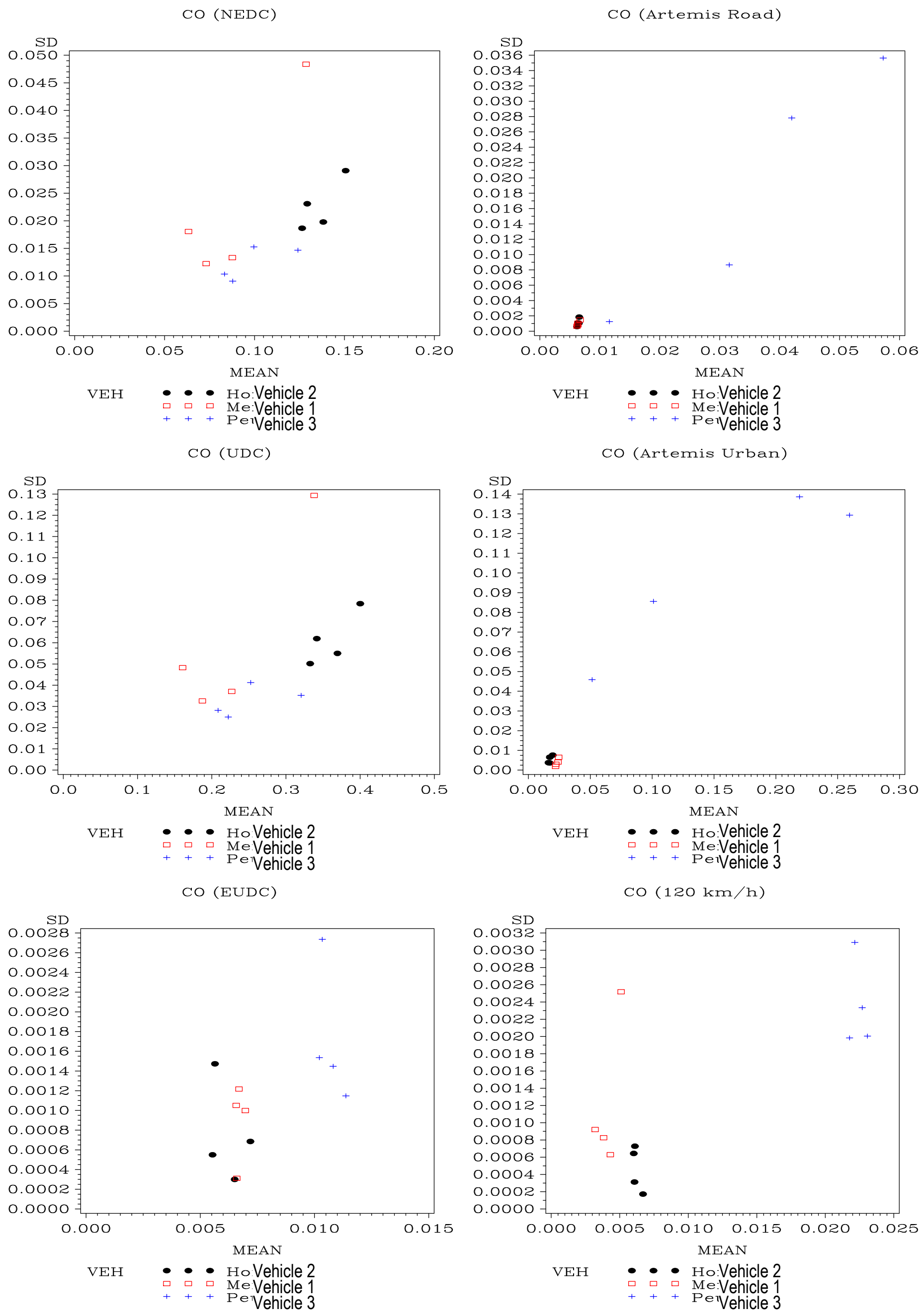

HC (Artemis Road)
SD
0.011
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0.000 0.005 0.010 0.015 0.020
MEAN
Vehicle 2
Vehicle 1
Vehicle 3

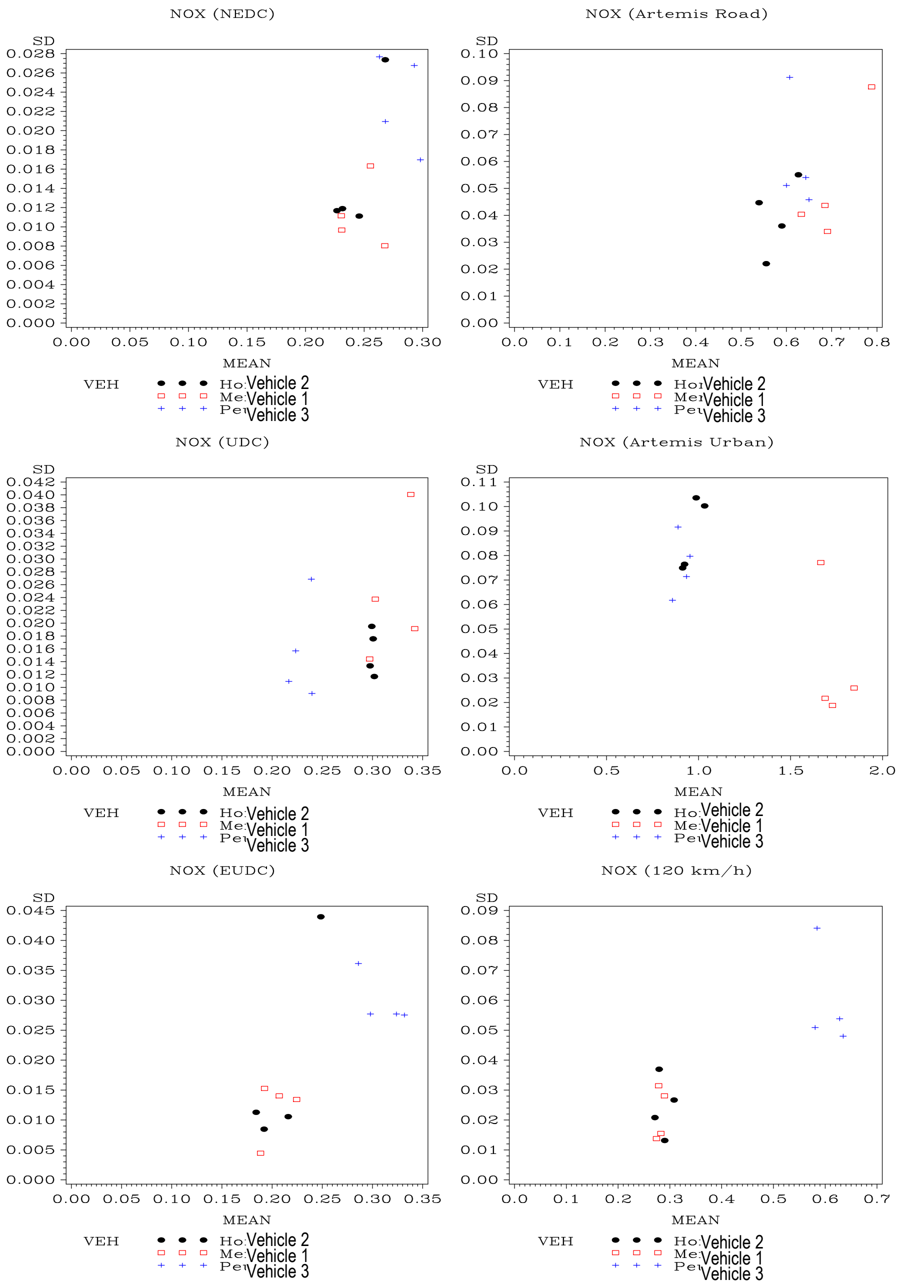

HC (UDC)
SD
0.013
0.012
0.011
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0.00 0.01 0.02 0.03 0.04 0.05 0.06
MEAN
VEH
Vehicle 2
Vehicle 1
Vehicle 3


HC (Artemis Urban)
SD
0.024
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0.000 0.005 0.010 0.015
MEAN
Vehicle 2
Vehicle 1
Vehicle 3

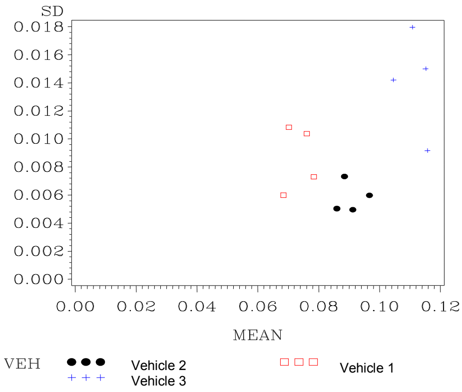

HC (EUDC)
SD
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
0.000 0.002 0.004 0.006 0.008
MEAN
VEH
Vehicle 2
Vehicle 1
Vehicle 3


HC (120 km/h)
SD
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0.000 0.005 0.010 0.015 0.020 0.025 0.030
MEAN
Vehicle 2
Vehicle 1
Vehicle 3

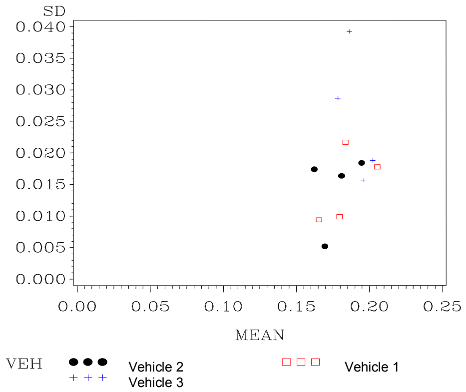

CO (NEDC)
CO (Artemis Road)
CO (UDC)
CO (Artemis Urban)
CO (EUDC)
CO (120 km/h)
SD
MEAN
VEH
Vehicle 2
Vehicle 1
Vehicle 3


NOX (NEDC)
SD
MEAN
VEH
Vehicle 2
Vehicle 1
Vehicle 3
NOX (Artemis Road)
NOX (UDC)
NOX (Artemis Urban)
NOX (EUDC)
NOX (120 km/h)

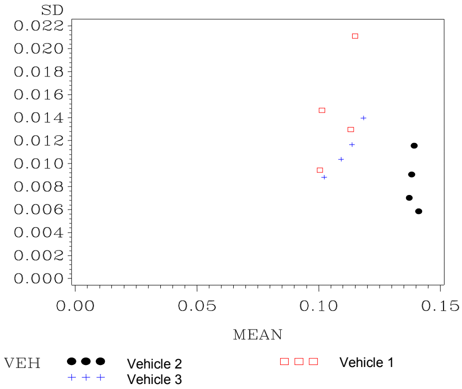
NO (NEDC)



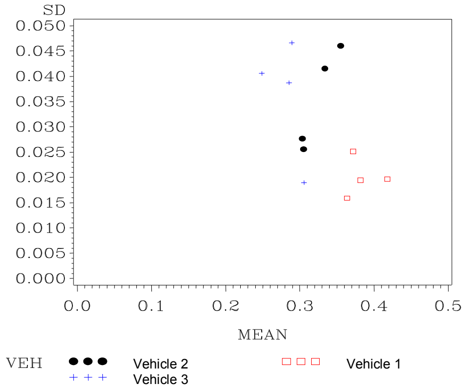
NO (Artemis Road)



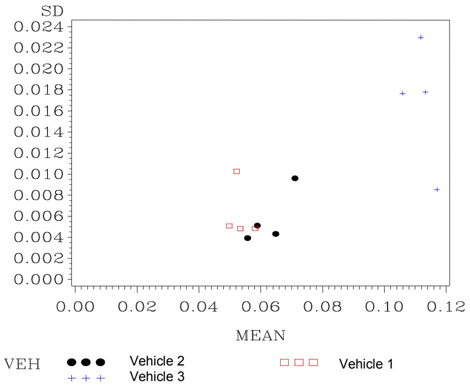
NO (UDC)

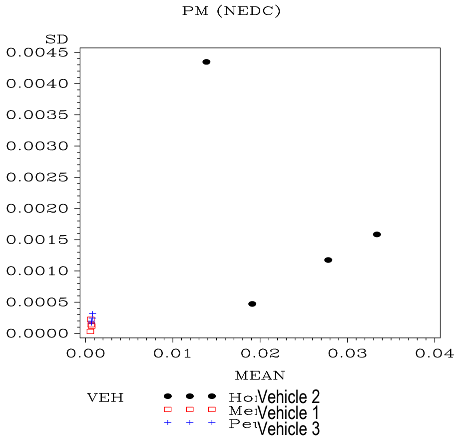


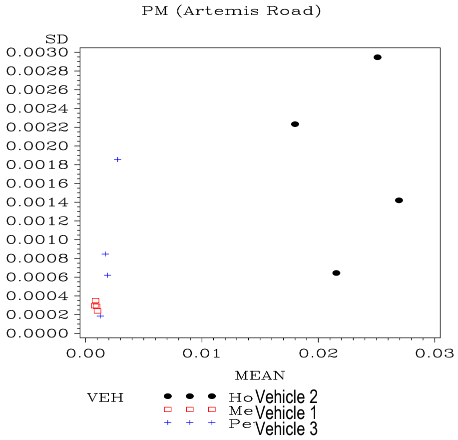
NO (Artemis Urban)

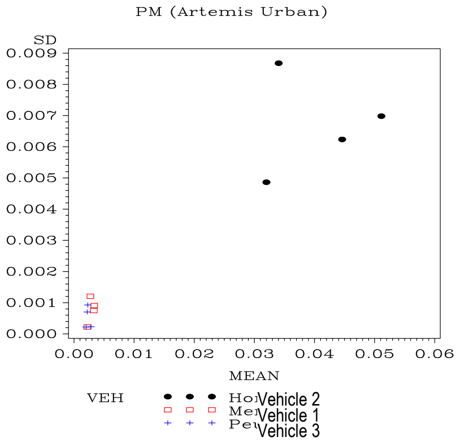


NO (EUDC)




PM (NEDC)
SD
0.0045
0.0040
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
0.00
0.01
0.02
0.03
0.04
MEAN
VEH
Vehicle 2
Vehicle 1
Vehicle 3


PM (Artemis Road)
SD
0.0030
0.0028
0.0026
0.0024
0.0022
0.0020
0.0018
0.0016
0.0014
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
0.00
0.01
0.02
0.03
MEAN
VEH
Vehicle 2
Vehicle 1
Vehicle 3


PM (Artemis Urban)
SD
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0.00
0.01
0.02
0.03
0.04
0.05
0.06
MEAN
VEH
Vehicle 2
Vehicle 1
Vehicle 3

APPENDIX 8 FUEL CONSUMPTION CALCULATIONS

According to the regulated procedure fuel consumption is calculated based on the carbon balance between the exhaust gas and the fuel consumed. The procedure assumes a constant hydrogen/carbon ratio in the fuel for which a fixed value is provided for diesel ($CH_{1.86}$ or C/H = 0.155). The procedure does not foresee yet values for biodiesel and its blends with diesel. In order to accurately calculate fuel consumption and correct for the biodiesel hydrogen-carbon ratios and oxygen content the fundamental equation (below) for carbon balance fuel consumption has been applied.

The fundamental equation for the carbon balance fuel consumption is

$$FC_{l/100km} = \frac{(CWF_{Exh} * HC + 0.429 * CO + 0.273 * CO_2)}{CWF_{Fuel} * SG * 10}$$

Where:

$FC_{l/100km}$	= calculated fuel consumption in l/100 km
CWF_{Fuel}	= carbon weight (mass) fraction of the fuel
CWF_{Exh}	= carbon weight (mass) fraction of the exhaust hydrocarbons
0.429	= carbon weight (mass) fraction of CO
0.273	= carbon weight (mass) fraction of CO_2
HC	= HC emissions for the test (g/km)
CO	= CO emissions for the test (g/km)
CO_2	= CO_2 emissions for the test (g/km)
SG	= density of the fuel (kg/l)

Table A8-1 Fuel properties for fuel consumption calculation

		B0	B10	B30	B50
Carbon Content	% wt	**85.84**	**84.97**	**82.99**	**81.11**
Hydrogen Content	% wt	**13.73**	**13.50**	**13.20**	**12.84**
Oxygen Content	% wt	**<0.04**	**1.1**	**3.3**	**5.4**
H/C Molar Ratio		**1.91**	**1.89**	**1.90**	**1.89**
Density	kg/l	**0.8231**	**0.8291**	**0.8410**	**0.8530**
Dilution factor		**13.32**	**13.42**	**13.56**	**13.74**

The Dilution Factors (DF) used for deriving pollutant emissions in the case of the four test fuels and were calculated from the C/H/O ratios. Although these corrections led to minor changes in fuel consumption (≤1%), they were considered important because the primary scope of the study was to investigate the effect of biodiesel on vehicle energy efficiency. In addition the differentiations expected between the test fuels were of similar order (0.5-5%) and therefore the correction was important. Diesel fuel consumption and emissions were calculated solely on the legislated basis using only the actual fuel density of B0 and not the predefined value.

Calculation of Dilution Factor:

With regard to Euro 5+ emissions legislation for diesel passenger cars and corresponding development trends in exhaust gas measurement technology, such as advanced particulate counter devices, the DF plays an important role for the measurement of regulated emissions over the NEDC. Because the biofuel-containing diesel fuels (e.g., B10) have a carbon-weight fraction that is different from B0, the DF must be calculated based on the biodiesel's actual C/H/O ratio in order to ensure constant dilution with fresh air in the CVS system while measuring tailpipe regulated emissions. The DF is calculated in the automatisation system (e.g. GEM device) of the chassis dynamometer from individual emissions bag concentrations and C/H/O lab fuel analysis parameters by using the formulae from Regulation No. 83 Revision 3 - Amendment 3 (22 July 2009) as shown below:

DF = X / [C(CO2) + (C(HC) + C(CO))*10exp-4]

where:

$C(CO_2)$: bag concentration of CO_2 in vol.-%

C(HC): bag concentration of HC in ppm

C(CO): bag concentration if CO in ppm

And

X = 100 * Cx / [Cx+(Hy/2)+(3,76*(Cx+(Hy/4)-Oz/2))]

where

Cx: evaluated from fuel C content in %[m/m]

Hy: evaluated from fuel H content in %[m/m]

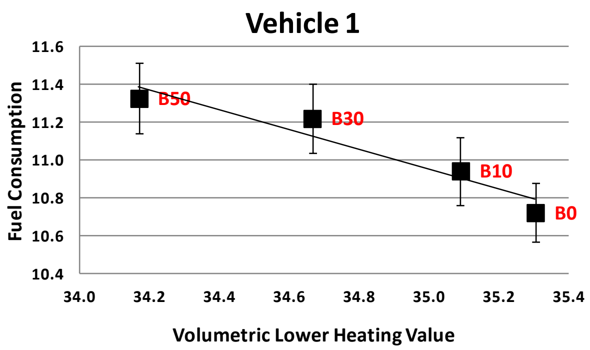
Oz: evaluated from fuel O content in %[m/m]

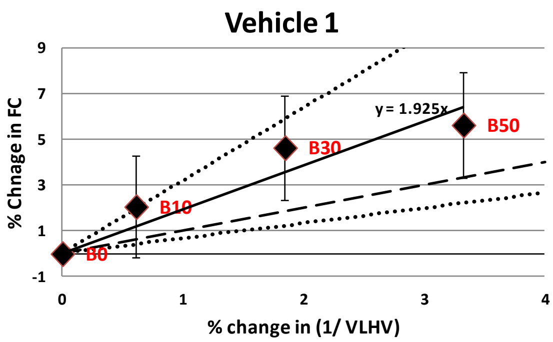
APPENDIX 9 FC RESULTS OVER OTHER TEST CONDITIONS

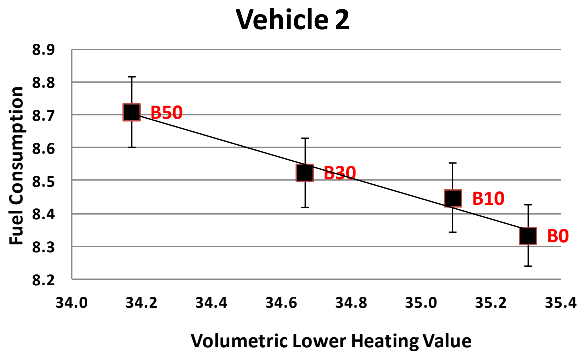
In the following figures, the left-hand charts show the measured FC (in l/100km) versus the VLHV (in MJ/l) of the four test fuels for each of the three vehicles over one particular cycle. The error bars represent 95% confidence limits, calculated as ± 2 SE based on the repeatability of multiple FC measurements. The solid line is a best fit through the data points and the dotted lines show 95% confidence limits for the true regression line. The dashed line is the one-to-one correlation line.

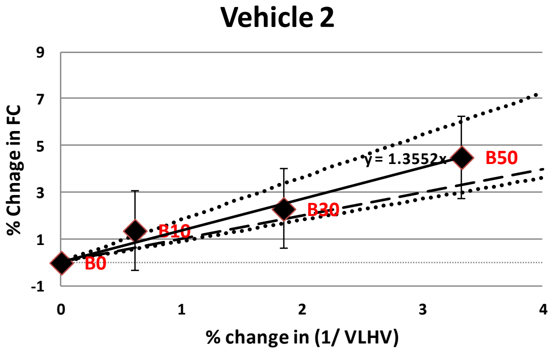
In the right-hand figures, the percent change in FC is plotted versus the percent change in [1/VLHV] using the B0 results for each vehicle as the basis. The error bars again represent 95% confidence limits and the solid line is a best fit through the data points. The slope of this line is also shown. The dotted lines are the 95% confidence limits around the best fit line and the dashed line is a one-to-one correlation line.

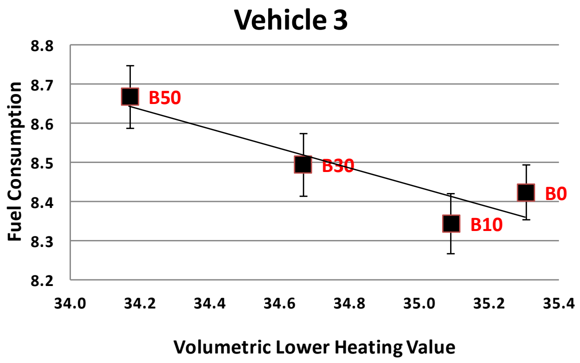
Over the UDC portion of the NEDC:

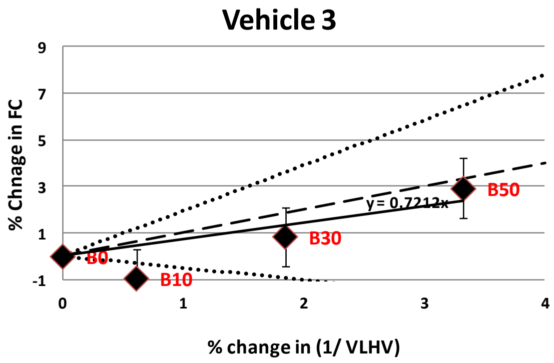




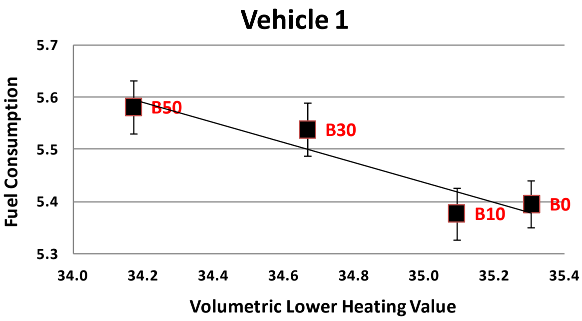


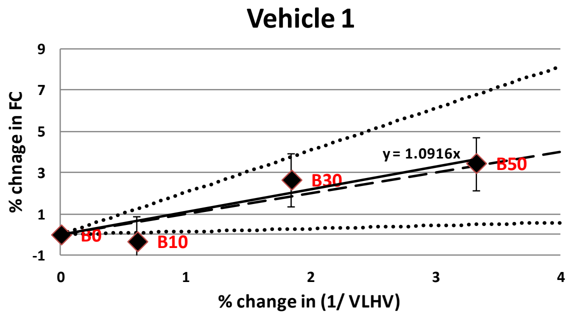


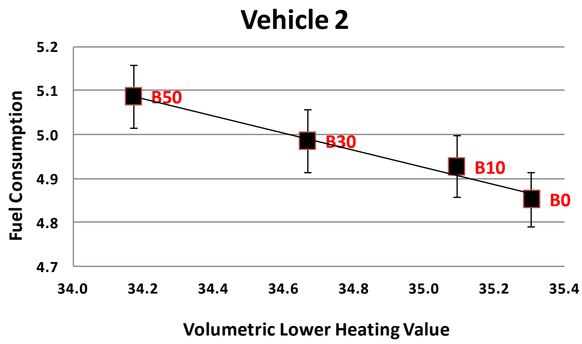


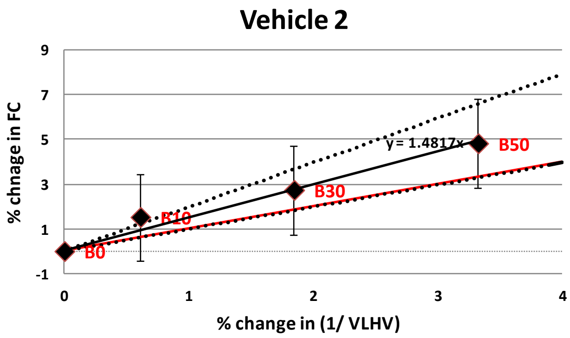


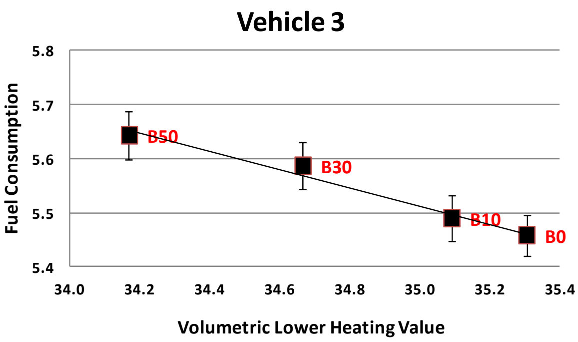
Over the EUDC portion of the NEDC:

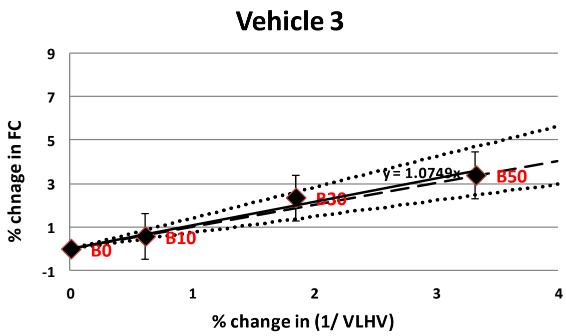




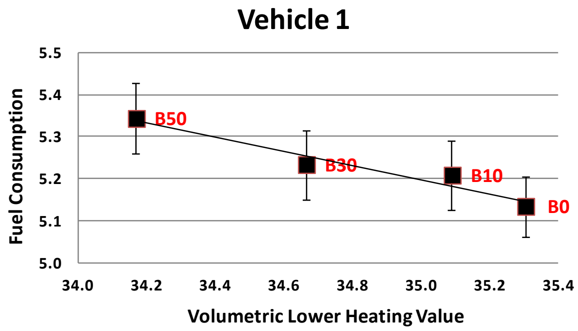


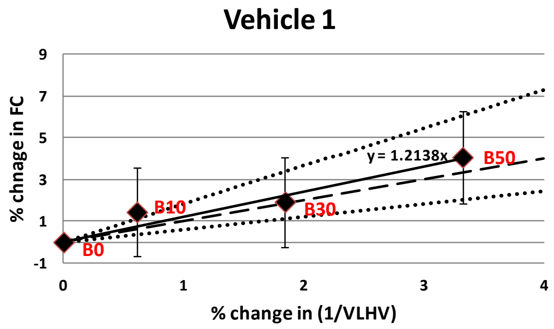


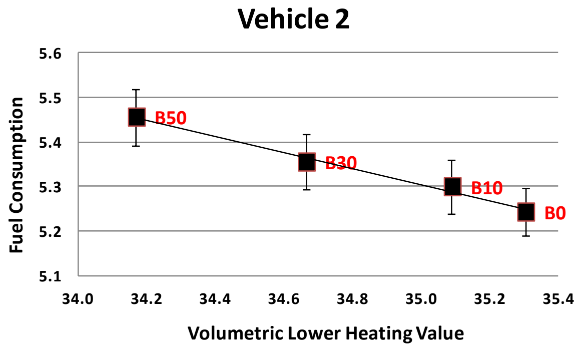


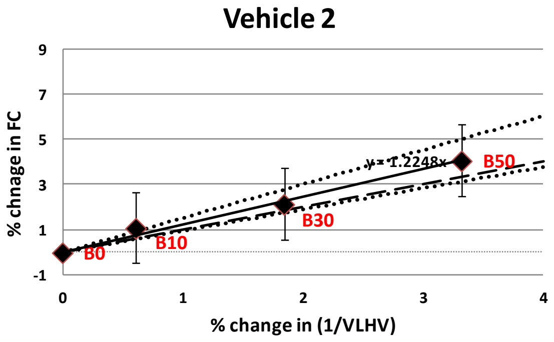


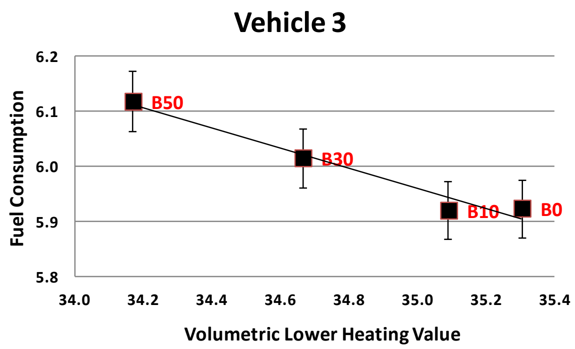
Over the Road portion of the ARTEMIS cycle:

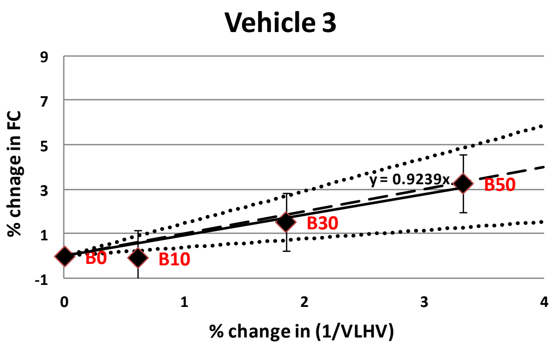




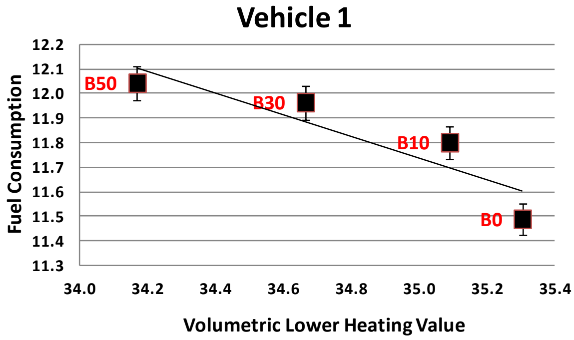


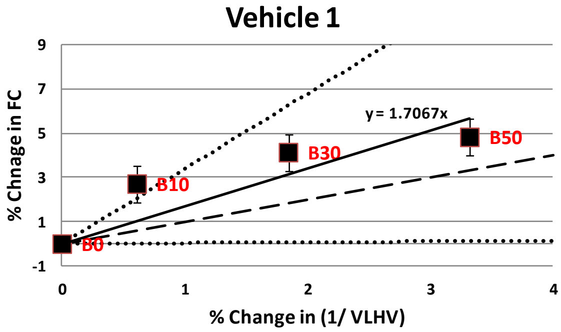


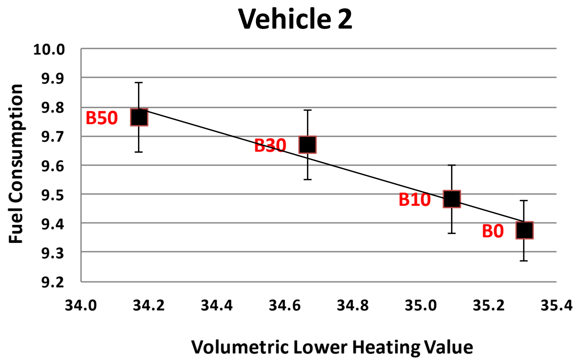


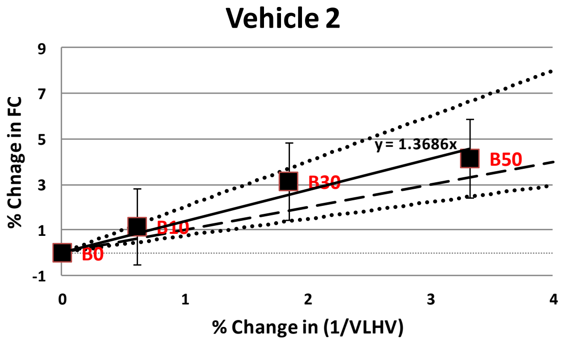


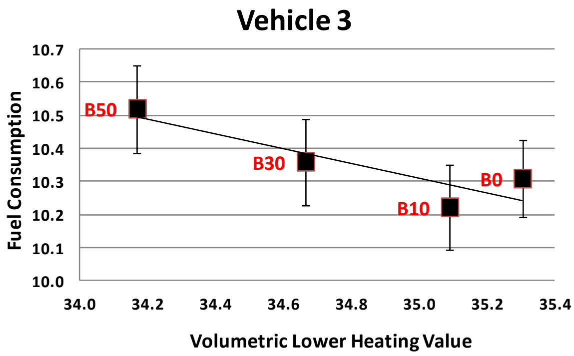
Over the Urban portion of the ARTEMIS cycle:

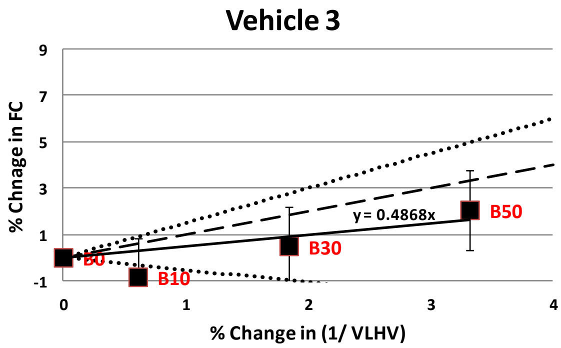




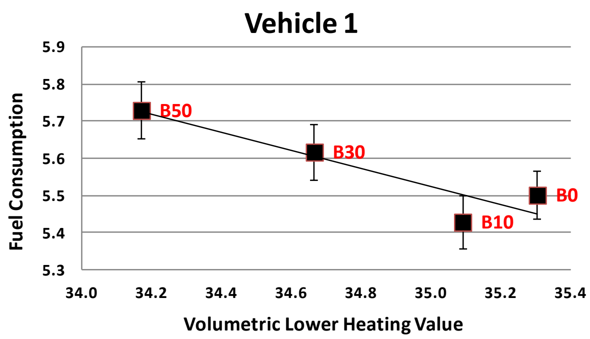


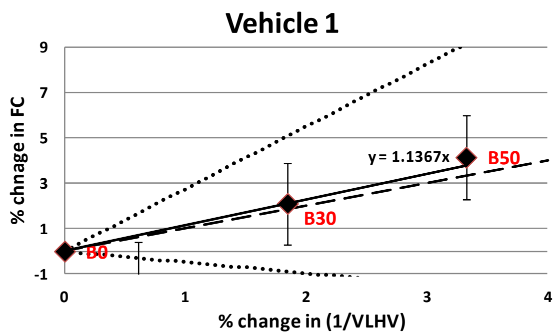


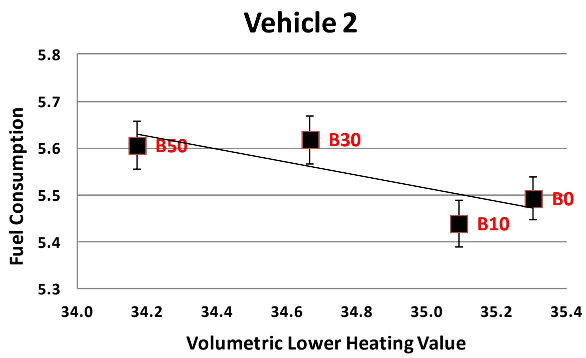


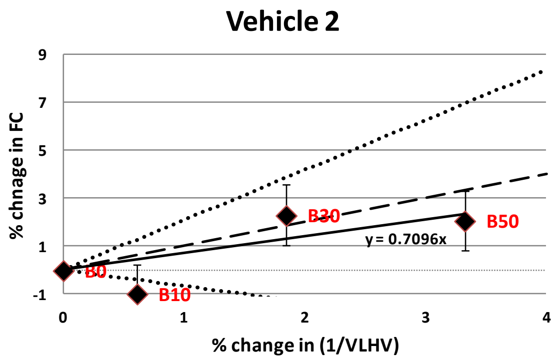


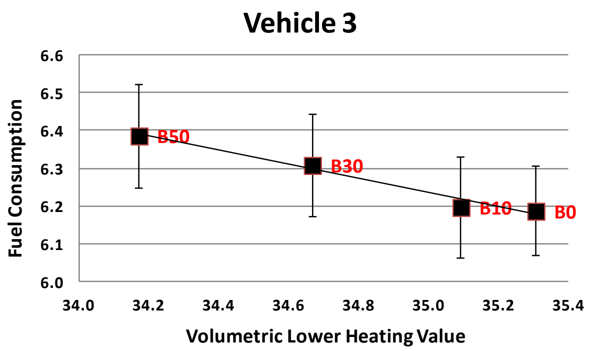
At the 120 km/h steady-state condition:

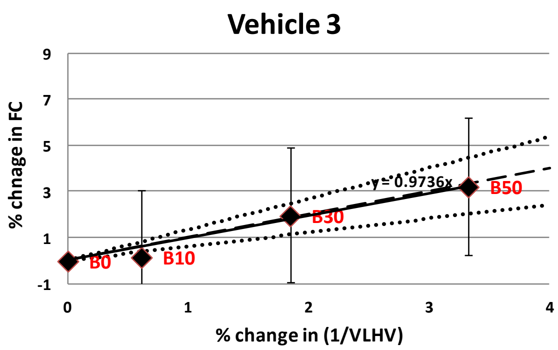




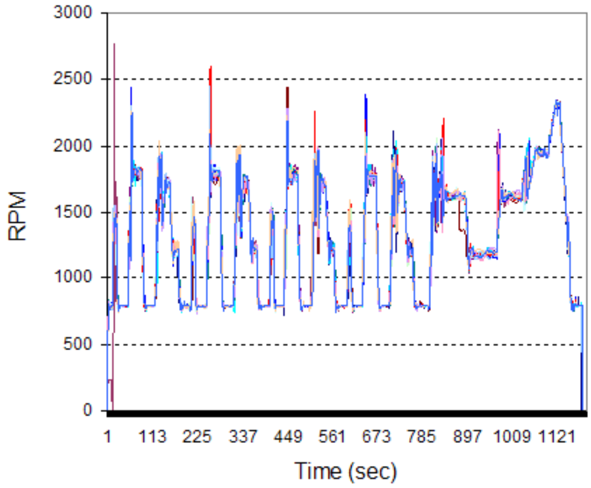




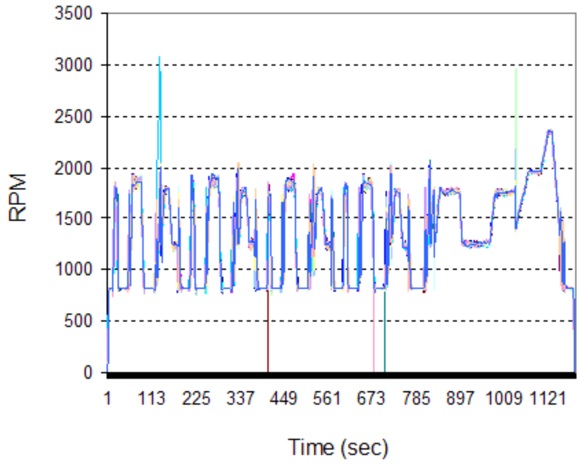




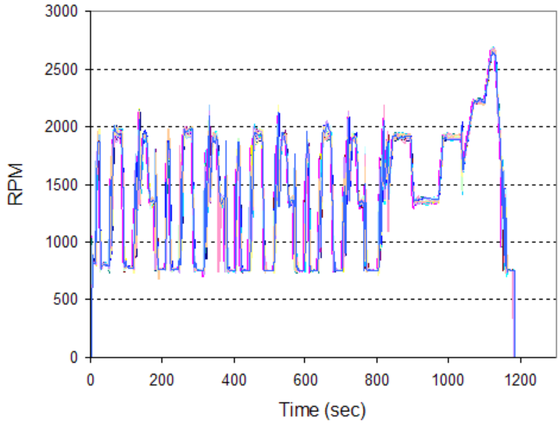
APPENDIX 10 RPM DATA OVER NEDC FOR ALL VEHICLES



Vehicle 1



Vehicle 2



Vehicle 3

APPENDIX 11 ADDITIONAL MEASUREMENTS

Other sampling activities were also performed in parallel as described below.

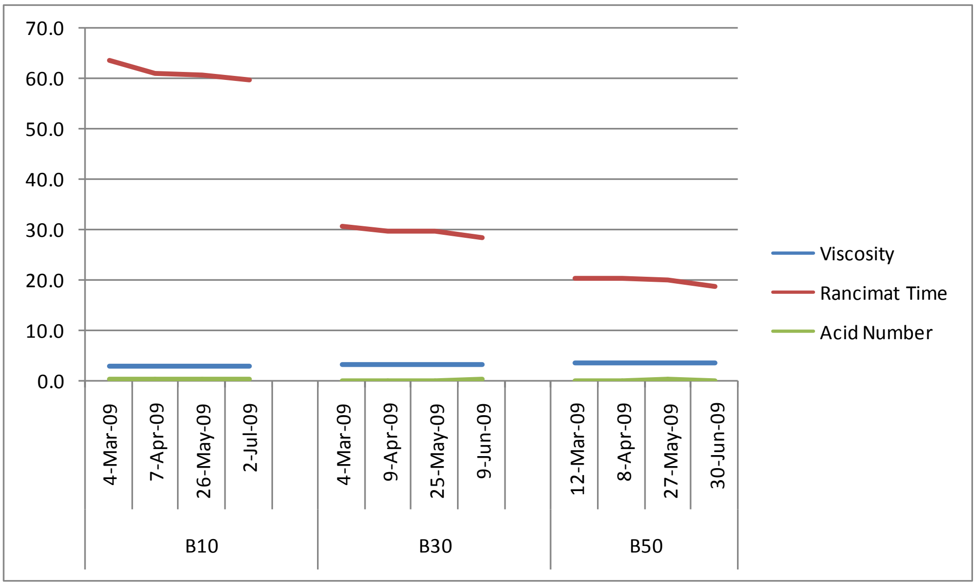
Modified Rancimat tests

At the beginning and the end of each vehicle's test sequence samples of the test blends were collected. These samples were tested for oxidation stability in order to monitor possible oxidation of the fuels while the testing progressed. Samples for the modified Rancimat tests were taken from the barrels opened the following days:

Table A11-1 Rancimat stability of biodiesel fuels

Rancimat stability of biodiesel fuels (LAT test programme)				
Data collected at the National Technical University of Athens				
			EN15751	
Sample	Sampling date	Viscosity	Rancimat Time	Acid Number
		cSt @ 40C	hours	mg KOH/g
B0	28-Feb-09	2.665		
B10	4-Mar-09	2.789	63.6	0.12
	7-Apr-09	2.792	61.2	0.13
	26-May-09	2.791	60.8	0.14
	2-Jul-09	2.787	59.8	0.14
B30	4-Mar-09	3.081	30.6	0.08
	9-Apr-09	3.084	29.7	0.09
	25-May-09	3.083	29.7	0.09
	9-Jun-09	3.085	28.5	0.10
B50	12-Mar-09	3.416	20.2	0.08
	8-Apr-09	3.415	20.2	0.08
	27-May-09	3.421	19.8	0.10
	30-Jun-09	3.419	18.8	0.07

Figure A11-2 Rancimat stability of biodiesel fuels



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