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Gasoline Direct Injection Particulate Study

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ABSTRACT

Two modern Gasoline Direct Injection (GDI) light duty vehicles have been tested to investigate the effect of oxygenates (mainly ethanol) on particulates - both mass and number, fuel economy and regulated emissions.

The GDI vehicles used in this study met Euro 4 and Euro 5 emissions limits and were tested over the New European Driving Cycle (NEDC) using ethanol containing gasolines at different oxygen levels and RON values. An ether-containing blend was also tested for comparison. Both matched RON and oxygen content ethanol and ether blends were specially prepared and tested as well as splash blended ethanol containing fuels. Fuels were tested in duplicate using a randomized test order in order to improve statistical certainty. A rigorous test protocol was used to allow the vehicle to adapt to each fuel and reduce carryover effects.

This report gives the results of this testing and makes some conclusions on the effect of matched and splash-blended oxygenates on particulates - both particulate matter (PM) and particulate number (PN). In general fuel effects were small compared to vehicle to vehicle effects and did not affect the vehicles ability to meet the legislated specifications. Some individual observations were made in one vehicle where PN reduced with ethanol levels at >3.7 mass% oxygen compared to lower levels and fuel consumption debits were observed in both vehicles although the low levels of PM produced by these modern vehicles made it difficult to come to any conclusions on fuel effects on this parameter.

KEYWORDS

GDI, particulate number, particulate mass, fuel economy

INTERNET

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

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SUMMARY

Gasoline Direct Injection (GDI) engines typically emit higher particulate number (PN) emissions than conventional port fuel injected (PFI) engines due to the reduced time for fuel atomization in the combustion chamber and the greater possibility of fuel impingement on the cylinder surface. For this reason, particulate mass (PM) emissions limits were added for GDI vehicles in Europe starting with the Euro 5 emissions regulations.

Although Gasoline Particle Filters (GPFs) may ultimately be the preferred approach to reduce PN and PM emissions, the effect of fuel composition on particulate emissions is also of interest. This report investigates the effects of fuel properties, in particular the use of two different fuel oxygenates representative of current and future fuels, on particulate and other regulated emissions from two modern European GDI cars.

The GDI vehicles used in this study met Euro 4 and Euro 5 emissions limits and were tested over the New European Driving Cycle (NEDC) using ethanol and ether-containing gasolines at different oxygen levels characterized by a range of RON values. Both oxygenate containing matched RON and matched oxygen content blends were specially prepared and tested. In addition fuels were also splash blended with ethanol and an ETBE-containing matched blend was also tested for comparison. Fuels were tested in duplicate using a randomized test order in order to improve statistical certainty. A rigorous test protocol was used to allow the vehicle to adapt to each fuel and reduce carryover effects.

All results were well within applicable limits for both vehicles (Vehicle 1: Euro 4, Vehicle 2: Euro 5) except for a single non-methane hydrocarbon (NMHC) data point from Vehicle 2. Although only two GDI vehicles were tested, in both cases the vehicle had a greater impact on particle and gaseous emissions than the fuel and driving cycle.

PM measured gravimetrically was difficult to interpret for fuel effects because the PM emission levels were very low from these modern GDI vehicles. All PN results fell within interim Euro 6 (2014) limit of 6×10^{12}, but exceeded the final target for Euro 6 (2017) PN level of 6×10^{11} which was surprising given that neither of these vehicles were optimized for Euro 6 emissions levels.

Oxygen content had no measurable effects on PM or gaseous emissions over the NEDC cycle. However, a step-change down in PN emissions for Vehicle 1 was observed for fuels containing >3.7% mass oxygen compared to lower oxygen levels. Fuel consumption tends to increase with increasing fuel oxygen content and other fuel related parameters such as oxygenate content, E100 (%age evaporated at 100°C) and reducing calorific value. At the same oxygen content, ETBE had no different effect on volumetric fuel consumption compared to Ethanol.

In fuels of matched octane, there were no statistically significant differences in emissions or fuel consumption consistent across the vehicles between E0 and E10. Between hydrocarbon base fuel and the same splash blended with 10% and 20% volume of ethanol there were no effects on emissions which were statistically significant in both vehicles, but a statistically significant penalty in fuel consumption was observed in both vehicles with the E20 blend. Although not the main focus of the study it was observed that varying RON between 95 and 98 RON without the

presence of oxygenate had no consistent effect on emissions or volumetric fuel consumption in these vehicles.

1. INTRODUCTION

Emissions have been the focus of worldwide legislation for more than twenty-five years. In particular, particulates have been part of European diesel passenger car legislation since 1992 when the first modern standards came into being and have become progressively tighter as time has gone on with Euro 5 and 6 having limits of 0.005 g/km converging with those in the US and other parts of the world.

The accurate measurement of automotive particle emissions continues to be of considerable interest within the regulatory environment. Particles from vehicles and from other sources are now accepted as having an impact on air quality and on human health [1,2]. Despite extensive studies, however, the mechanisms by which ultrafine particles impact human health are still uncertain, although there are several hypotheses that attempt to explain the relationship between particle parameters and health impacts.

The introduction of clean fuels and advanced vehicle and after-treatment technologies has resulted in a substantial reduction in automotive particulate mass (PM) emissions [3,4] with a corresponding improvement in air quality. This reduction in PM emissions, however, has also made the remaining low levels of particle emissions increasingly difficult to practically measure (with vehicle compliance regulations still based on PM). For this reason, considerable work has been undertaken internationally to address improved measurement techniques [5], either by modifying filter procedures for mass measurement (PM) or by introducing a new metric for ultrafine particles (PN). Over the past decade, many studies [6,7,8] have investigated different techniques and measurement protocols for ensuring the repeatable measurement of particle number emissions. It is now generally accepted that automotive particle emissions fall into two broad categories [17]:

- “Nucleation” mode particles, generally less than about 30 nm particle size, comprising predominantly condensed volatile material, mainly sulphates and heavy hydrocarbons, and
- “Accumulation” mode particles, mainly carbonaceous in nature and larger than about 30 nm particle size.

The DG TREN “Particulates” Consortium [14] addressed issues related to the formation and measurement of both nucleation and accumulation mode particles under different conditions and provided a harmonised particulate sampling and measurement methodology. Within this test work, accumulation mode particles were measured using an Electrical Low Pressure Impactor (ELPI) after volatile material had been removed from the particles by passing them through a Thermal Denuder (TD).

This methodology was applied in the DG TREN programme to quantify the effects of fuel properties and vehicle technology changes on both nucleation and accumulation mode particles. This work resulted in an improved understanding and knowledge of particle emissions, as well as a substantial database of validated data, and included measurements over a wide range of test cycles. Concawe’s work within the DG TREN Consortium effort was published separately [28]

In addition to the DG TREN Consortium, an extensive “Particle Measurement Programme” (PMP) was carried out under the sponsorship of the UNECE GRPE [15]. The objective of this programme on light-duty vehicles initially was develop and then validate a methodology to measure carbonaceous particles that could be used within the regulatory framework to certify the emissions performance of new vehicles. The methods tested included both particulate mass and carbonaceous particle number measurements. Accumulation mode carbonaceous particles were selected for the particle number measurements because they can be more repeatedly sampled and measured while nucleation mode particles do not substantially contribute to particulate mass measurements. Phase I of the PMP assessed a variety of measurement approaches and selected two (one particulate mass based and one particle number based) for further investigation in Phase II. The particulate mass method was based on the US 2007 filter procedure. The particle number measurement used a novel approach to eliminate nucleation particles. For this measurement, a Constant Volume Sampling (CVS) system was used (in line with current regulatory requirements) and a subsample extracted from the CVS was subjected to rapid expansion in a hot evaporation tube. This approach rapidly reduces the partial pressure of the exhaust gas stream and ensures that any volatile material remains in the gas phase or, if already condensed on the carbonaceous particles, re-volatilizes into the gas phase before the particles are detected. Instead of the ELPI detector used in the DG TREN programme, a Condensation Particle Counter (CPC) is used to count the resulting “dry” carbonaceous particles.

This PMP procedure led to revisions in both the light duty and heavy duty regulated measurement protocols [16] and the addition of particle number measurements to future light duty vehicle certifications [10,18]. This is the technique that has been used to assess light-duty vehicles and a compliance limit of $6x10^{11}$ particles/km for light-duty diesel vehicles was adopted in the EU’s Euro 5b technical regulation.

Up until recently gasoline legislation has concentrated on carbon monoxide, hydrocarbons and NOx. However, there have been increasing concerns with new technologies and the number of very small particulates being generated which it is thought can penetrate more deeply in the lungs than larger particles. Gasoline Direct Injection (GDI) vehicles have been shown to produce more particulates than Port Fuel Injection vehicles (PFI). GDI vehicles may operate in a stratified charge lean mode or in a homogeneous charge stoichiometric mode. The formation of soot in GDI engines is thought to come from two mechanisms – stratification of the charge leading to rich burning zones in the fuel jet and the fuel spray striking the piston forming polls of liquid which burn to form particulates and hydrocarbons. Stoichiometric GDI engines use early injection to minimize stratification but this propensity for impingement leads to more soot formation than PFI engines [17]. As a result gasoline particulate limits were phased in from Euro 5 onwards for direct injection engines only in 2009 with increased emphasis on particulates with Euro 6 limits in 2014 using the PMP protocol with particulate number limits being phased in for new vehicles for 2014 to 2017 [16]. The upper limit of 6×10^{11} particles/km for diesel vehicles will also apply to gasoline GDI vehicles from 2017 with a first stage interim limit of 6×10^{12} particles/km introduced in 2014. A recent CRC report has highlighted the challenges of measuring PM emissions at very low levels and concluded that there is still work to be done to understand test variability at these levels [32].

A European Joint Research Centre report from 2011 which describes a cost benefit analysis [11] makes the assumption that GDI vehicles at least in the short time frame will not meet stricter limits from engine developments alone and will require the use of GPF although it does state that this is thought to be the worst case scenario and there are other options are likely to be successful in a longer timeframe. A Transport and Environment briefing [9] suggests that that the use of a gasoline particulate filter (GPF) will be necessary to meet the new standards, however this did not involve the vehicle optimization including optimization of the injection system which is likely to be the focus of OEM research for Euro 6 vehicles. In a recent joint programme by Concawe and AECC a commercial GDI vehicle in combination with a GPF was tested using current NEDC and future WLTC and Real Driving Emissions test cycles (RDE) and it was found that the vehicle easily met the standards for Euro 6 [34].

Other recent articles published by SAE [13] and presented at the International Vienna Motor Symposium [12] suggest that a range of solutions are likely to be available including combined port fuelled and direct injection systems and highly controlled direct injection systems. In the latter presentation, Bosch presented data on a 350 bar gasoline direct injection system, demonstrating reduced particle number compared to a 200 bar system and that the 2017 limits were met.

In parallel to the developments on vehicle technology and emissions regulation, the Renewable Energy Directive (RED, 2009/28/EC) [19] requires 10% renewable energy in transport fuels by 2020 within the European Union while the Fuel Quality Directive (FQD, 2009/30/EC) [20] will also require reductions in GHG emissions intensities from transport fuels of 6%. 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 to try to meet these requirements. Oxygenates in the form of ethanol and ETBE are the most commonly used components which are being added to fossil gasoline while fatty acid methyl esters (FAME) from difference sources are commonly used in diesel fuels. EN228 can now contain up to 10% ethanol while the diesel fuel specification can contain up to B7.

Literature searches have suggested that there is only limited data on particulates from direct injection engines and even less on the effect of oxygenates on gasoline particulates. The presence of oxygen in fuel has been shown in previous studies to effect PM and PN in diesel vehicles (see for example [30]), so it may be reasonably expected to affect gasoline direct injection combustion as well. However, the data that exists particularly on oxygenates suggests a complex story. It appears that emissions from direct injection engines are very dependent on test cycle. A most comprehensive study was carried out by JPEC [21] which concluded that particulates from fuels, particularly those including oxygenates was greatly influenced by test cycle and only those which were close to conditions experienced with congested roads (i.e. low speed) showed a decrease in particulates with increasing oxygenate content, although the European test cycle NEDC was not run in that study.

In fact most of the studies that have been carried out have been on US cycles. A CRC study looked at E10, E15 and E20 tested in 15 vehicles using the LA-92 test cycle. They found a decrease in HC and CO, NOx did not change and varying results for particulates [22]. Karavalakis et al. ran two GDI vehicles on the US Federal Test Procedure (FTP) drive cycle with a variety of different alcohol containing fuels and responses increasing up to E20 ranged from no difference in particulate in one vehicle to significant reduction compared to the other ethanol containing fuels. Longer chain alcohols e.g. butanols showed higher amounts of particulates [23,33]. Storey et. al compared E0 with E30 and isobutanol (iso Bu48) and although the E30 showed less mass, E0 had the lowest mean particle size followed by the iso Bu48 and the E30 [24,25].

Vuk and Vander Griend [26] carried out an evaluation on three 2011 model year vehicles on the FTP75 and US06 drive cycles on 0, E10, E30 and E50 and found that although the oxygenated fuels decreased particulate compared to the base fuel, the optimum treat of ethanol was E10. It was hypothesised that the ethanol promotes evaporation and significantly reduces particulates in fuels containing high boiling point aromatics. Catapano et. al [27] also came to similar conclusions in studies using an optical engine although they said that the higher ethanol containing fuels could lead to increased fuel impingement depending on rpm and whether the engine was being run on part or full load.

Previous studies have sometimes involved attempts to match the properties of different fuels and sometimes only used splash blended (i.e. unmatched) fuels. It was decided to generate more data by conducting a test program to improve Concawe's understanding of the PM/PN performance from two modern (Euro 4+) gasoline direct injection vehicles using the European NEDC test cycle and a mixture of matched and splash blended fuels. In a previous study [28], Concawe investigated particulate mass (PM) and particle number (PN) emissions from two gasoline direct injection (GDI) vehicles. These were a 2003 vehicle meeting Euro 3 emissions levels and a 2004 vehicle meeting Euro 4 emissions levels. Two different petrol fuels were used in these tests but neither fuel contained oxygenates.

Oxygenated fuels were used in another study which included a Euro 4 GDI vehicle along with two port fuel injected vehicles [29]. In this study although fuel properties including octane and oxygenates were widely varied, fuel effects were found to be small compared to vehicle to vehicle and drive cycle differences. The study did demonstrate the difference in particulates between PFI and GDI vehicles. In addition, tailpipe emissions were collected, including CO_2, NO_x, HC, CO, PM, and PN as well as information on the composition of the particulates from these tests.

The current study extends the previous work to include two more modern (Euro 4 and Euro 5) GDI vehicles using the European NEDC test cycle. A wider range of fuels has also been investigated including ethanol in fuels both octane matched and splash blended as well as an octane matched ETBE containing fuel in order to better understand the effect of these components, if any, on PM and PN.

2. TEST PROGRAMME

2.1. VEHICLE SELECTION AND PREPARATION

The two vehicles were chosen as it they were thought to be representative of the current road vehicle population. Both were stoichiometric GDI vehicles equipped with three-way catalysts and which were demonstrated to meet either Euro 4 or Euro 5 emissions standards. The larger 6-cylinder vehicle was naturally aspirated while the medium sized 4-cylinder vehicle was turbocharged.

- Vehicle 1 was a 6 cylinder in-line 2.5l gasoline engine with 6-speed manual transmission, direct injection and around 23,000 miles at the start of the trial. This vehicle met Euro 4 emissions standards.

- Vehicle 2 was a 4 cylinder in-line 1.8l gasoline engine with 6-speed Manual transmission, direct injection and around 9,000 miles at the start of the trial. This vehicle met Euro 5 emission standards.

Both vehicles were equipped with after-treatment systems. Detailed descriptions of these two vehicles is provided in **Table 1**.

Table 1 Vehicle descriptions

Vehicle No.	**1**	**2**
Vehicle Class	Upper Medium	Medium
Category	M1	M1
Emission Standard (homologation)	Euro 4	Euro 5
Engine Displacement (litres)	2.5	1.8
Max. Power (kW)	140	118
Inertia Class (kg)	1590	1470
Cylinder	6	4
Valves	24	16
Aspiration	Natural	Turbo
Combustion Type	Homogeneous stoichiometric	Homogeneous stoichiometric
Injection System	DI	DI
After-treatment device	TWC	TWC
Drive	RWD	FWD
Transmission	Manual 6-speed	Manual 6-speed
E10 Compatible?	Yes	Yes
Registration Date	15/06/2007	4/6/2009
Mileage at start of test (miles)	23,354	8,890

Before starting the main test programme, a scoping study was conducted on two GDI vehicles at the Millbrook Proving Ground (UK) in 2010-11. This scoping study tested two modern GDI vehicles on the CEC RF-02-08 E5 European reference fuel. The results of the scoping study are included in **Appendix 1** and demonstrated that the vehicles met the required homologation standards of Euro 4 and Euro 5 respectively.

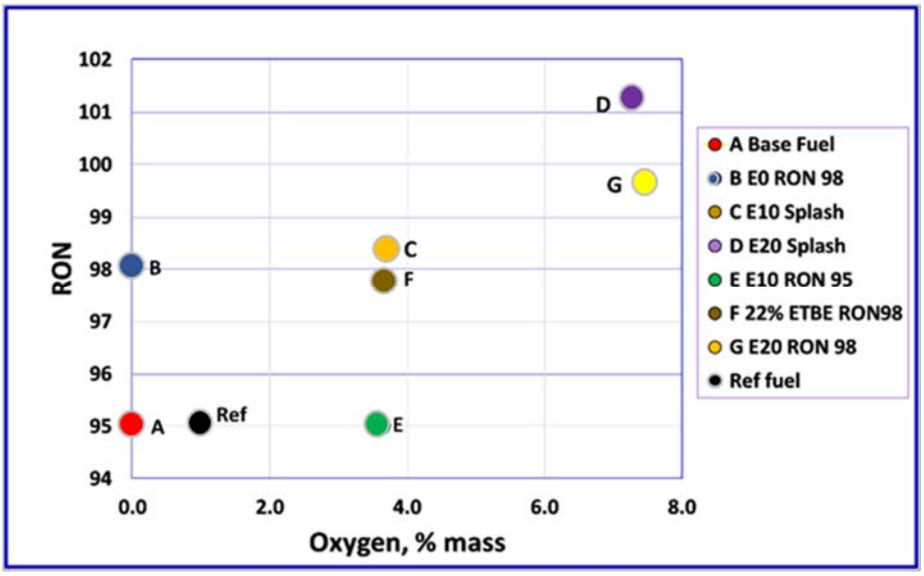
2.2. TEST FUELS, BLENDING AND HANDLING

2.2.1. Test Fuels

The test fuels blended for this study constituted an orthogonal matrix of fuels with three levels of RON (around 95, 98 and over 100) and three levels of Oxygen content (0%, around 3.7% and 7% and above) corresponding to ethanol levels of E0, E10 (or 22% ETBE) and E20. Fuel A was used as the base fuel for all the others. The fuels were blended to achieve a matrix with RON and oxygen content as the primary variables.

Fuel A: Base fuel, hydrocarbon-only at 95RON
Fuel B: Hydrocarbon-only fuel blended to 98RON
Fuel C: E10 splash blended into Fuel A (resulting in RON 98.4)
Fuel D: E20 splash blended into Fuel A (resulting in RON 101.2)
Fuel E: E10 fuel with RON matched to Fuel A (resulting in RON 95.0)
Fuel F: 22% ETBE fuel with RON matched to Fuel B (resulting in RON 97.8)
Fuel G: E20 fuel with RON matched to Fuel B (resulting in RON 99.6)
The matrix is summarized in the following chart (**Figure 1**).

Figure 1 – Fuel matrix including target fuel properties



A CEC Euro 5 reference fuel was also run interspersed with the test fuels in a randomized order. The full analytical analysis of the reference fuel as well as the test fuels is given in **Appendix 6**.

2.2.2. Fuel Blending

Fuels were blended at Coryton Advanced Fuels in the UK from a mixture of European refinery blending components that were supplied by Coryton. Small trial blends were made and tested for the main parameters to ensure that they met the requirements of the matrix before blending larger volumes of each fuel. Full specification testing was carried out on these larger blends and that is what is reported in **Appendix 6**.

2.2.3. Fuel Handling

All of the test fuels, except the Euro 5 reference fuel, were provided and delivered to the test laboratory in quantities of one 200L barrel per fuel type. Euro 5 reference fuel (RF02-08) was provided by Millbrook Proving Ground. All the fuels were stored in secure storage compartments compliant with safety data sheets for the fuels and storage requirements provided by Concawe. In order to minimise the risk of contaminating the test fuels and the fuel systems on the test vehicles, separate fuel delivery pumps were used for each fuel type and followed rigorous drain and flush procedure before each test to prevent dilution of the test fuel (see Test Procedure for more detail). Each of the test fuels was tested twice on each vehicle in the following randomized order (**Table 2**) with the reference fuel interspersed at more regular intervals

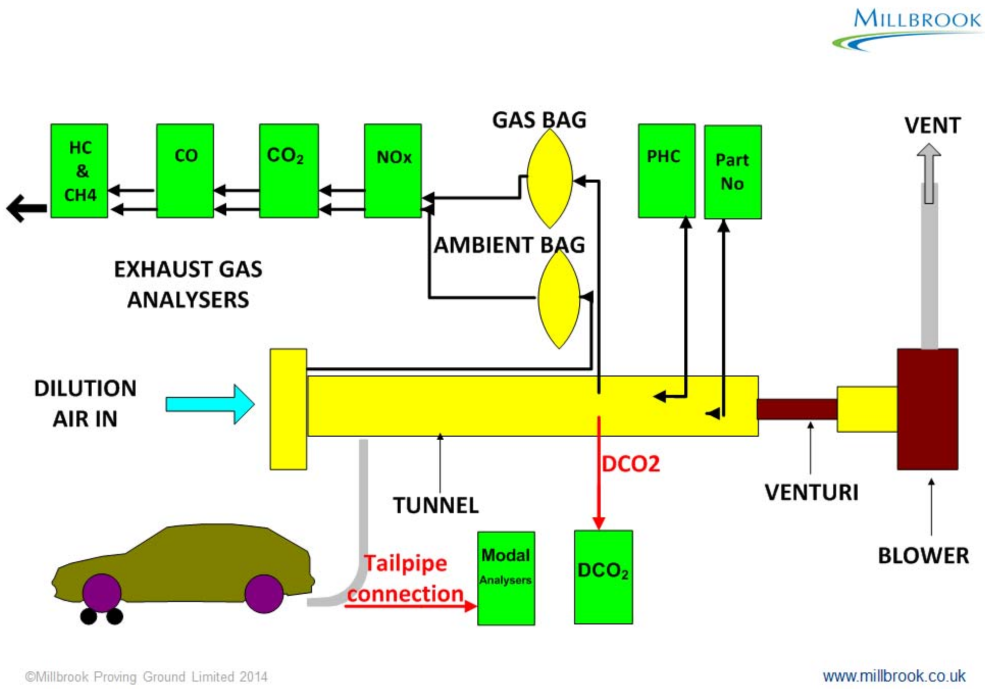
Table 2 Fuel test order

	Vehicle 1	Vehicle 2
Test 1	Reference	Reference
Test 2	Fuel A	Fuel F
Test 3	Fuel D	Fuel B
Test 4	Fuel C	Fuel E
Test 5	Reference	Reference
Test 6	Fuel E	Fuel G
Test 7	Fuel F	Fuel A
Test 8	Fuel B	Fuel C
Test 9	Fuel G	Fuel D
Test 10	Reference	Reference
Test 11	Fuel D	Fuel C
Test 12	Fuel F	Fuel A
Test 13	Fuel B	Fuel G
Test 14	Fuel C	Fuel F
Test 15	Reference	Reference
Test 16	Fuel A	Fuel D
Test 17	Fuel G	Fuel E
Test 18	Fuel E	Fuel B
Test 19	Reference	Reference

3. TEST METHODOLOGY

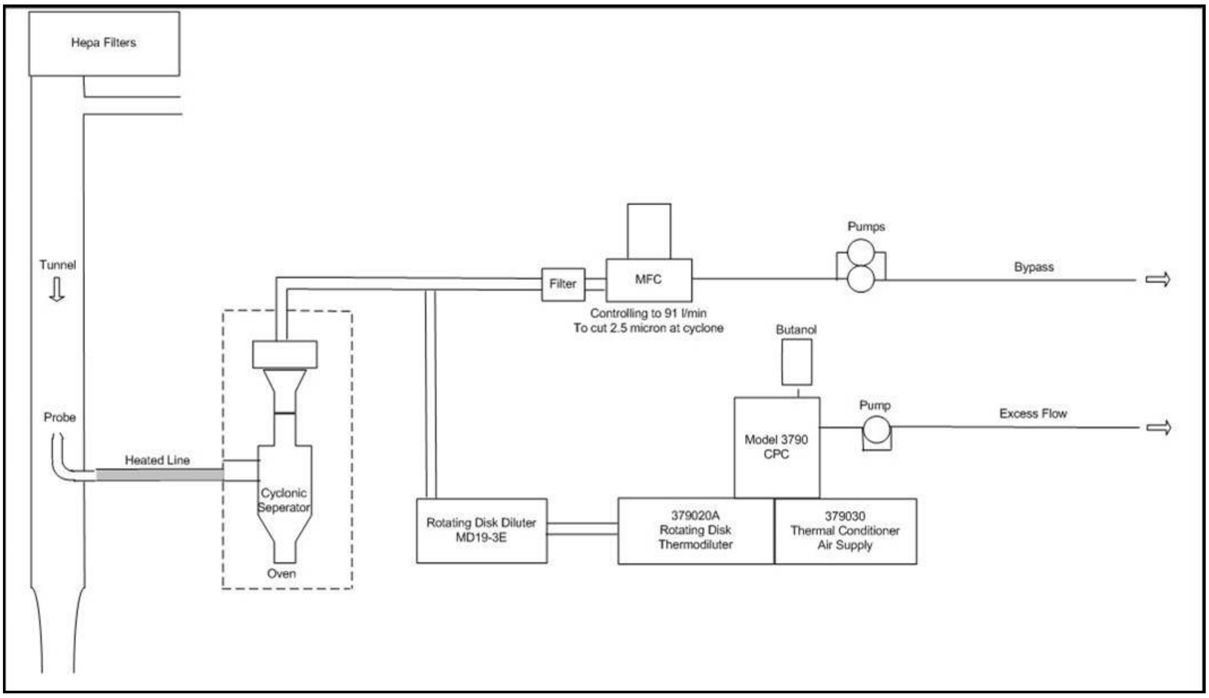
3.1. TEST PROTOCOL

Figure 2 – Experimental set-up including dynamometer and CVS tunnel



A diagram of the experimental set up is shown in **Figure 2**. A constant volume sampling (CVS) system was used where the vehicle exhaust is attached to a dilution tunnel. A line runs to a gas bag which collects the sample for HC, CH_4, CO, CO_2,and NOx. This is compared to a sample of the dilution air collected in the ambient bag which is used to correct the measurements for ambient air levels. In addition the tailpipe was corrected directly to modal analysers. A line from the dilution tunnel runs to a DCO2 analyser as well particulate mass collection by way of a single phase particulate filter and particulate number equipment. The latter is detailed in **Figure 3** and uses the PMP protocol which was developed as a result of the work described in the introduction. The system uses an Electrical Low Pressure Impactor (ELPI) to count the particles. The particulate number system consists of the cyclonic separator along with two thermal diluters in series attached to a Condensation Particle Counter.

Figure 3 – Particle Number Measurement System



In order to achieve comparable results, each vehicle was put through a carefully designed preparation procedure, conducted before the start of each test. The aim of the procedure was to ensure that each fuel was fully flushed from the system and that there was no carryover from one fuel to the next. The protocol was as follows: -

- Conduct fuel tank drain
- Fill with 15 litres of test fuel
- Set tyre pressures
- Conduct 2 NEDC cycles on chassis dynamometer
- Conduct fuel tank drain
- Fill with 15 litres of test fuel
- Conduct 2 NEDC cycles on chassis dynamometer
- Conduct fuel tank drain
- Fill with 15 litres of test fuel
- Full exhaust leak check
- Tyre pressure check
- Preconditioning Cycle – ECE + 2 x EUDC
- Overnight Soak
- NEDC Test

The NEDC cycles were conducted on a chassis dynamometer to allow the engine ‘learn’ map to learn all the speed and load points seen over a transient drive cycle. Conducting the four NEDC cycles with combined time of 80 minutes, ensured that the “learn” had enough time to be fully optimised.

The fuel was drained on three occasions to ensure that there was no contamination in the fuel system from the previous fuel and the carryover effect was eliminated. Upon completion of the third fuel fill, a full exhaust leak check was carried out before the NEDC emissions test.

The tyre pressures were set to the manufacturers recommended specification and then increased by 50% to account for the twin-roll chassis dynamometer. The preconditioning cycle was performed and was then followed by a minimum ‘cold’ soak period of 6 hours at ambient temperature during which, the vehicle was connected to a battery charger to ensure that variations in battery condition did not affect the results. An emissions test was then conducted to the specifications detailed in EC directive 70/220 amended to the latest rule [18].

3.1.1. Test Cycle

The New European Drive Cycle (NEDC), over which the exhaust emissions and fuel consumption of light duty vehicles is evaluated, consists of two phases, Urban (ECE) and Extra-Urban (EUDC) and is performed on a chassis dynamometer. **Figures 4 a)** and **b)** show the drive tests including comparisons for Vehicle 1 (a) and Vehicle 2 (b). This demonstrates the repeatability of the tests as well as the cycles themselves.

3.1.1.1. Urban Cycle

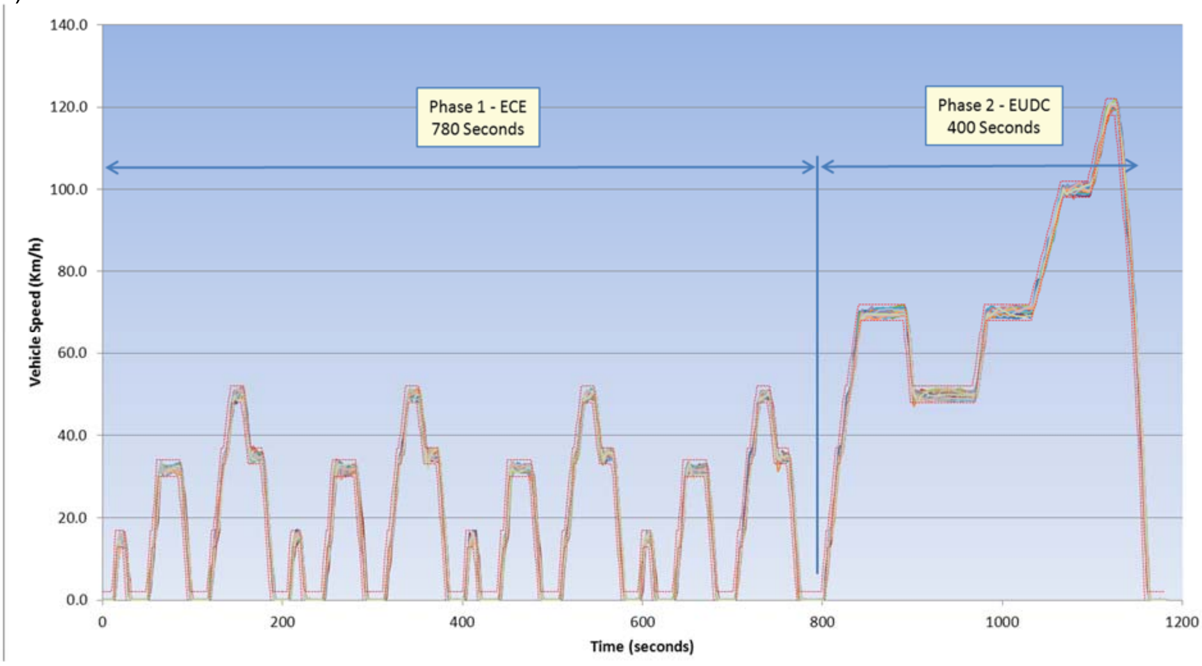
The urban test cycle is carried out in a laboratory at an ambient temperature of 20°C to 30°C on a rolling road from a cold start i.e. the engine has not run for several hours. The cycle consists of a series of accelerations, steady speeds, decelerations and idling. Maximum speed is 31mph (50 km/h), average speed 12 mph (19 km/h) and the distance covered is 2.5 miles (4km). The cycle is shown as Phase 1 in **Figures 4 a)** and **b).**

3.1.1.2. Extra-Urban Cycle

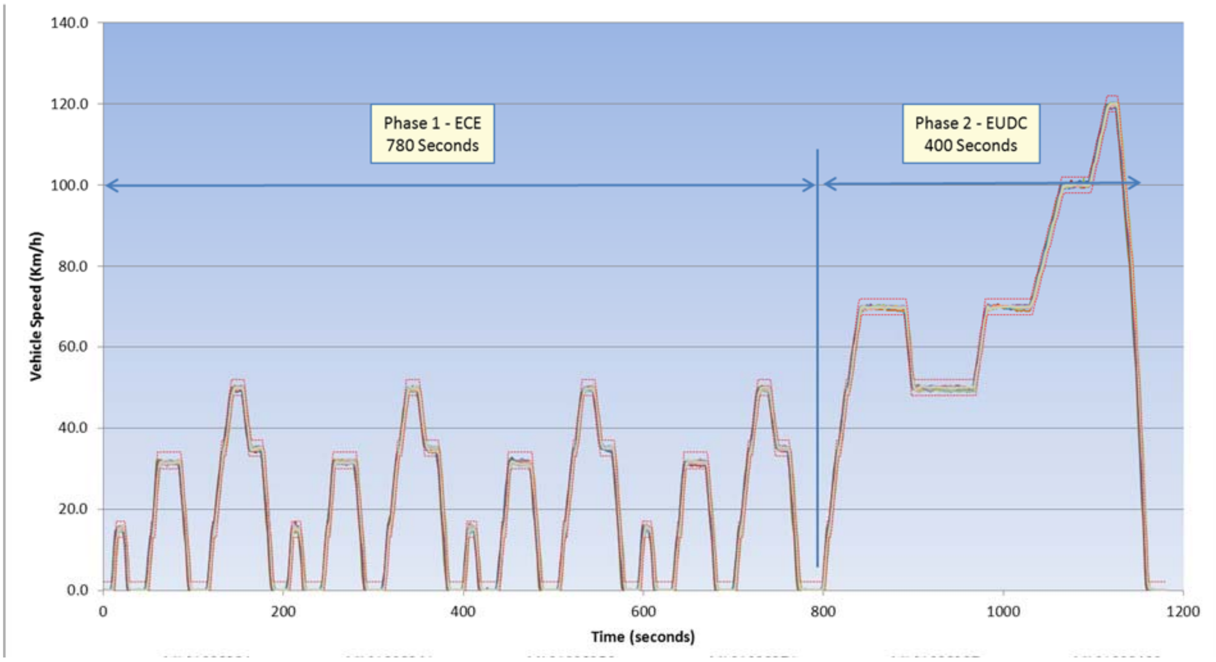
This cycle is conducted immediately following the urban cycle and consists of roughly half-steady speed driving and the remainder accelerations, decelerations and some idling. Maximum speed is 75 mph (120 km/h), average speed is 39 mph (63 km/h) and the distance covered is 4.3 miles (7km). The cycle is shown as Phase 2 in **Figures 4 a)** and **b)**.

Figures 4 a)** and **b) – Drive test comparisons of all tests for a) Vehicle 1 and b) Vehicle 2

a)



b)



3.2. EMISSIONS MEASUREMENTS

3.2.1. Particulate mass and number

Particulate mass measurements were carried out with a single phase particulate filter. Particulate Measuring Programme (PMP) method and Electrical Low Pressure Impactor (ELPI) were used to determine Particulate number and Particulate size distribution respectively

3.2.2. Fuel Consumption

Fuel consumption was calculated using the carbon balance method as outlined in EC directive 70/220 amended to the latest rule. In all tests, second by second measurements were taken to allow analysis of vehicle operation in greater detail at various points in the test. Actual fuel property data was used in the calculation to allow for the effect of differences in fuel properties on fuel consumption [31].

3.2.3. Regulated emissions

Mass emissions were determined by sampling the vehicle tailpipe emissions using industry standard constant volume sampling (CVS) technology. Integrated bag sampled emissions were collected for each phase of the test and corrected for ambient contaminants. Emissions collected and detection methods were as follows:-

- NMHC (Non-methane hydrocarbons) – Flame ionization
- THC (Total hydrocarbons) – Flame ionization
- CO (Carbon monoxide) – Non-dispersive infrared
- NOx (Oxides of nitrogen) - Chemiluminescence
- CO_2 (Carbon dioxide) – Non-dispersive infrared

3.2.4. Expression of emissions results

The exhaust emission results are presented as a combined value for the urban and extra-urban cycle together and are given in grams per kilometre (g/km). The results are therefore an average of the two parts of the test, weighted by the distances covered in each part. Fuel consumption results are presented in the same way but the figures are expressed as litres per 100km (L/100km)

4. TEST RESULTS AND DISCUSSION

4.1. DATA HANDLING AND STATISTICAL ANALYSIS

There are various ways of determining means in statistics - geometric mean is a type of mean or average, which indicates the central tendency or typical value of a set of numbers by using the product of their values (as opposed to the arithmetic mean which uses their sum). Whilst geometric means have been used for particulate number to give consistency with other Concawe reports, arithmetic means have been used for all other emissions.

After the raw emissions & fuel economy data were scrutinized for outliers and a single outlier was rejected, the data were analysed to identify systematic drift and where the trend was significant at the 99% confidence level, trend corrections were applied. The PM data for Vehicle 2 was corrected on the natural scale and the geometric means for the PN data for the Vehicle 1 were corrected on the ln scale. Where applicable, the corrected data is plotted.

In accordance with the recommendation of the statistician and for consistency with previous related studies, error bars shown in plots are based on +/-1.4SE so the error bars when present show mean value +/- 1.4 times the error of the mean. The factor 1.4 was chosen purely for consistency with recent Concawe reports. The original rationale was the 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 in between the limits shown. Error bars based on a factor of 1.4 are too narrow for determining significant differences in the current programme where few tests were carried out. Such an interpretation would require an error factor in the region of 1.5 to 1.6 depending on the number of valid tests and whether a time correction has been applied.

The mean values have been tabulated and plotted and have been calculated with the removal of a single Vehicle 1 NOx result which was deemed to be a statistical outlier with a studentised residual significantly different from zero at P<1% (see **Appendix 5**).

Trend corrections have been applied whenever the trend was significant at P<1%. PM levels were near to the minimum level of detection for the gravimetric method, so some level of variability is expected. In addition there appeared to be a downward trend for Vehicle 2 and trend correction was carried out. The details are given in **Appendix 3**. When the variability of the current testing is compared with the previous work that was carried out to develop the PMP protocol [28] it is found to be consistent with the previous work for Vehicle 1 and an improvement over the previous variability for Vehicle 2.

All PN results fell within the interim Euro 6 limit of 6 x 10^{12}/km, but most results exceeded the final target for Euro 6 PN level of 6 x 10^{11}/km. There was a trend correction applied in the case of Vehicle 1 as there appeared to be a downward trend. After trend corrections PN emissions showed considerable variations between repeat runs but again these variations were consistent with previous data.

Furthermore a blank test was performed each week, without a vehicle, to evaluate the background particulate mass and number of both the tunnel and test cell. Particulate mass and number were sampled in a similar way as for the test fuels during this test. The particulate mass filter is weighed before and after the test and was considered a pass if the weight did not increase by more than 0.01 mg. For the particle number result, the nominal distance for the NEDC cycle is used to obtain a #/km result and the internal pass/fail criteria was 3 x e10 particles/km. The data indicated that all the checks conducted during the programme met the pass/fail criteria. For both the reference fuel and for the whole fuel set, there was a general trend for high PN results to be matched by high PM results, which suggests that much of this variability may be attributable to the vehicle.

4.2. FUEL AND PROPERTY EFFECTS ON PARTICULATES

The fuel set was designed to allow the effects of some fuel properties to be evaluated in isolation from the range of fuel properties affected when oxygenates are blended with hydrocarbon gasoline base fuels. The fuel set also enabled the relative effects of two oxygenate compounds, (Ethanol and ETBE) to be evaluated at iso-oxygen content and enabled the effects of splash blending of Ethanol at two concentrations to be evaluated. Specific fuel comparisons and their aims are summarized in **Table 3**.

Table 3 Specific comparisons and objectives

Fuel comparison	Objective to evaluate
Base fuel vs E10 matched octane	Oxygenate effects at iso-octane
E10 splash vs ETBE 22 (vs E0)	Oxygenate type at iso-oxygen
E0, E10 and E20	Ethanol splash blending
Base fuel (95 octane) vs 98 octane	Octane effects with no oxygenates

Plotting the emissions mean data against fuel properties enables general trends in the dataset to be identified, but has the disadvantage that multiple fuel properties are changing in addition to that plotted. We have, therefore included the mean data but also some specific comparisons where the test design has allowed fuels to be more easily compared. We have concentrated on fuel property effects on PM, PN, fuel consumption and NOx in the main body of the text which are of most interest. Other plots of HC, CO and CO_2 are included in the appendix where there are consistent trends observed between the two vehicles. Where there is no plot there is no apparent correlation between the relevant fuel property and any emission. The strength of the apparent correlations have been statistically tested by calculating the root mean square error and R^2 values and these are commented on in the text and are also listed in **Appendix 5**. Fuel descriptors and colour coding are shown in **Figure 5**.

Figure 5 Fuel descriptors and colour codings

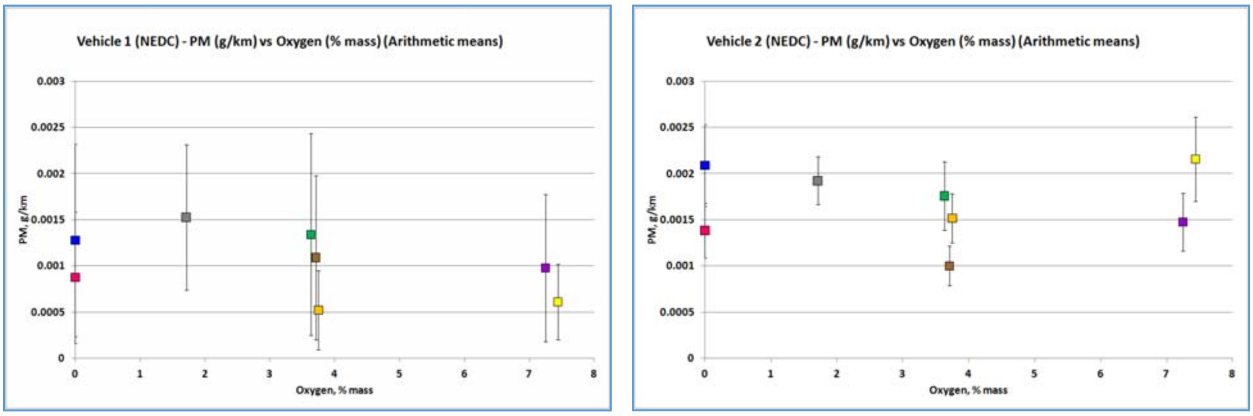
RF 02 08	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E	Fuel F	Fuel G
Ref fuel	Base Fuel	High Octane	E10 Splash	E20 Splash	E10 matched	22% ETBE	E20 matched

4.2.1. Fuel Property Effects on PM

4.2.1.1. Oxygenate Effects

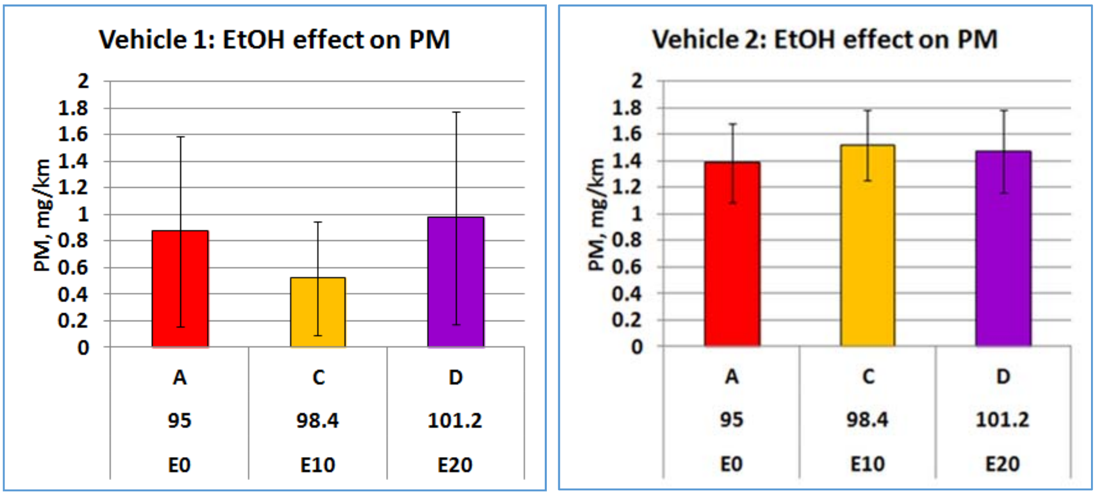
Mean PM was plotted against oxygen content for each vehicle and this can be seen in **Figure 6**. Although the absolute PM values were in the same range for both vehicles, the range of the error bars for Vehicle 1 was much greater than Vehicle 2. This is not thought to be due to any problem with the testing and just due to differences in the vehicles and their control systems.

Figure 6: Mean PM per fuel plotted against oxygen content.



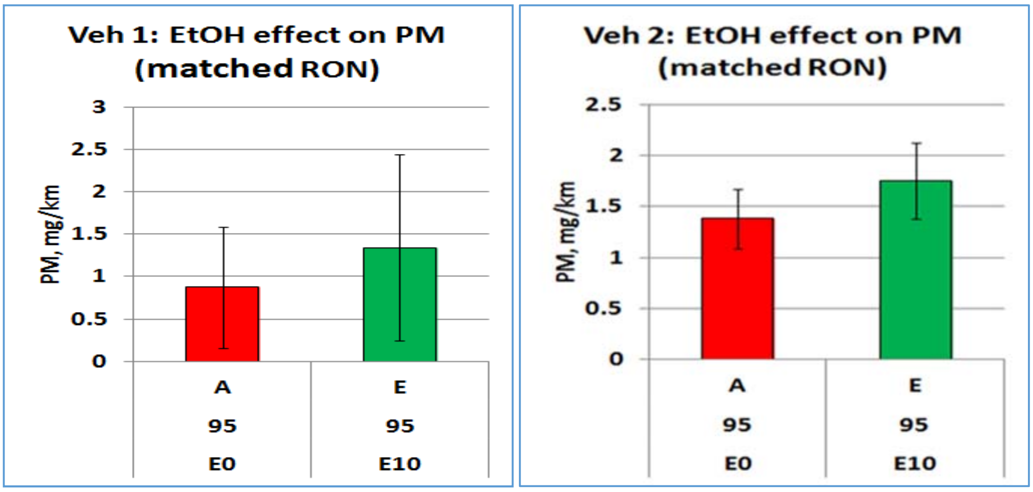
There is substantial overlap between error bars for both vehicles, which is likely to be related to the low absolute PM values, as correlation between increasing oxygen content and decreasing PM would be expected. The strength of the correlation is not statistically significant. It is not possible to compare all the fuels as mentioned previously as multiple properties are changing but fuels A, C and D could be compared as C and D are based on fuel A with the addition of 10% and 20% ethanol respectively and the results are shown in **Figure 7**.

Figure 7: Ethanol splash-blended effects



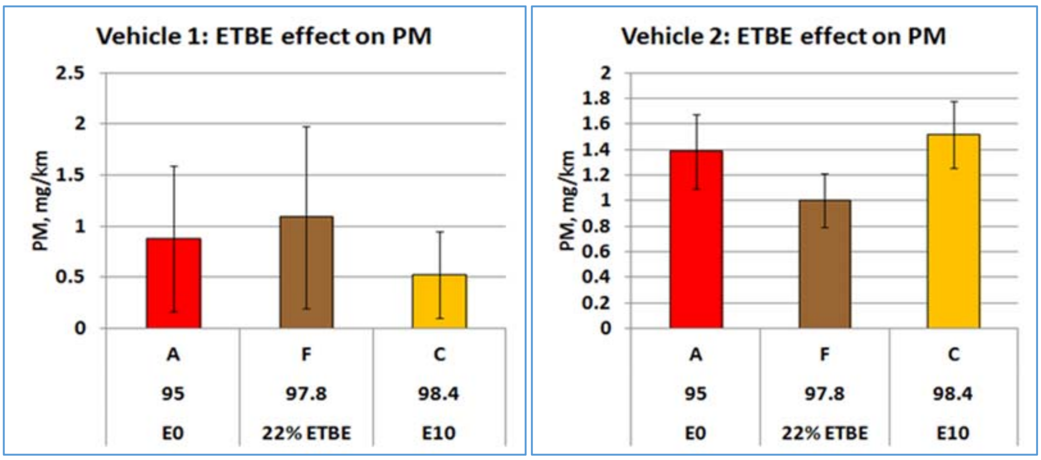
For both vehicles there is no significant difference between the fuels at these low levels. Even with matching RON as shown in **Figure 8** when comparing fuels A and E there was no significant difference. It should be noted that the lack of benefit could be related to insufficient sensitivity of the gravimetric PM measurement method at these low PM levels.

Figure 8: Effect of 10% ethanol with matched RON



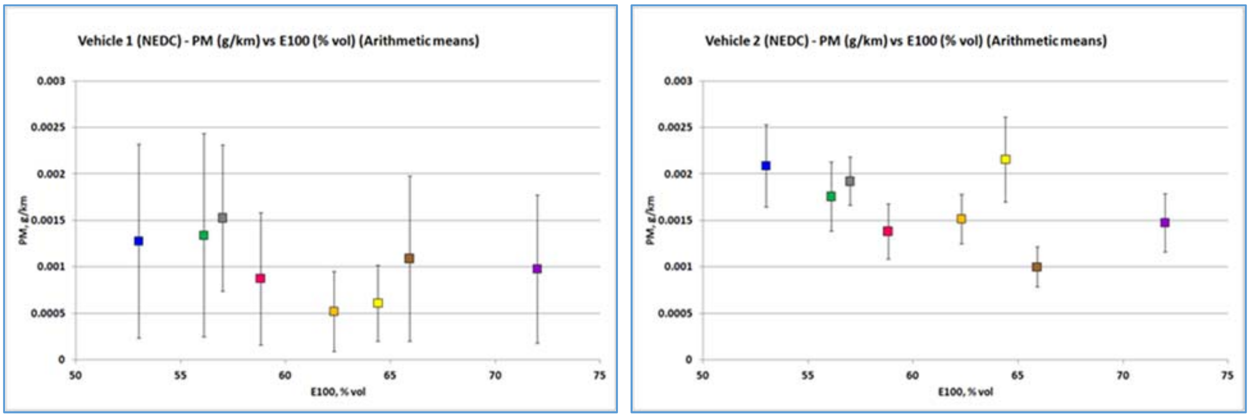
The effect of looking at the effect of different oxygenates was investigated by comparing ETBE and Ethanol at the same oxygen level equivalent to E10. The fuel comparison was Fuel F (ETBE containing) and Fuel C (Ethanol containing) with Fuel A which is shown in **Figure 9**. The increase in octane compared with fuel A was similar at approximately 3 octane numbers. Only for Vehicle 2 was there a significant difference between the two oxygenates with ETBE giving a lower level of PM than ethanol although this was not significantly lower than the non-ethanol containing fuel A. This could be due to dilution effects of the ETBE which gives a fuel containing lower levels of aromatics than the E10.

Figure 9: Different oxygenates at same oxygen level



Finally, when the effect of E100 is plotted for both vehicles (**Figure 10**),although the error bars were wide for Vehicle 1, there are indications of a correlation with Vehicle 2. This is consistent with the correlation which was observed with the oxygen content and increasing oxygenates which have higher volatility than gasoline.

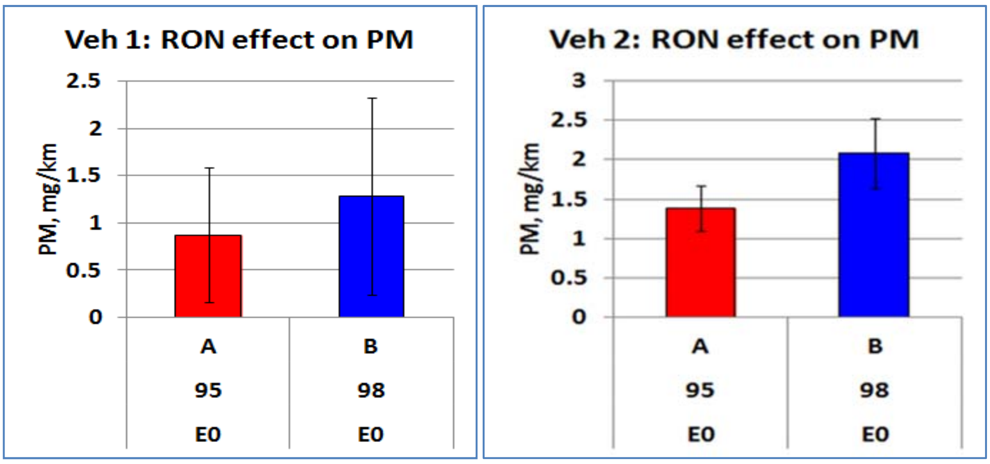
Figure 10: Effect of volatility (E100) on PM



4.2.1.2. Effect of RON on PM

The fuel set also allowed us to attempt to evaluate the effect of RON on PM (**Figure 11**), only on non-oxygenate containing fuels, although this was not the focus of the study. When Fuel B was compared with Fuel A for Vehicle 2 only there was a significant increase in PM observed when moving from 95 to 98 octane. Vehicle 2 is optimised for 95 octane so this may just reflect the optimization for the lower octane level.

Figure 11: Effect of RON on PM for non-oxygenated fuels

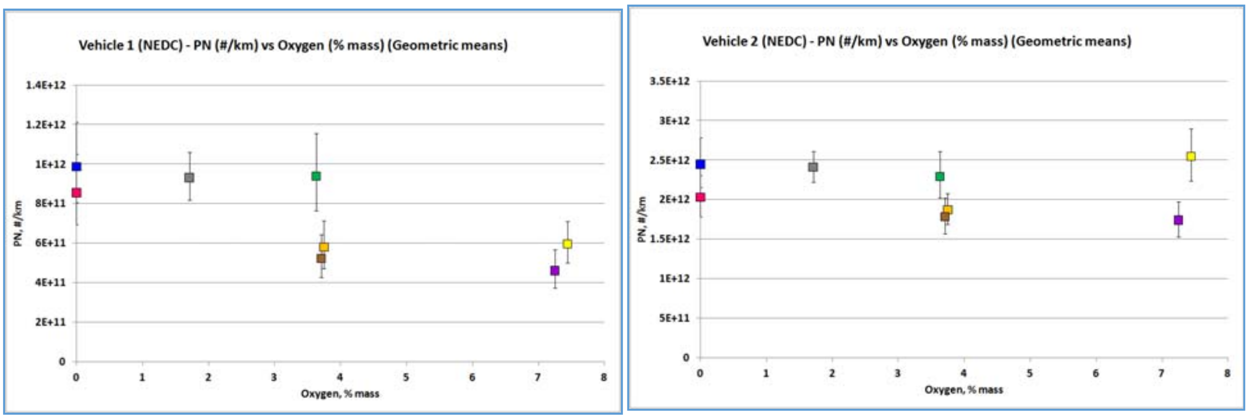


4.2.2. Fuel Property Effects on PN

4.2.2.1. Effect of oxygenates

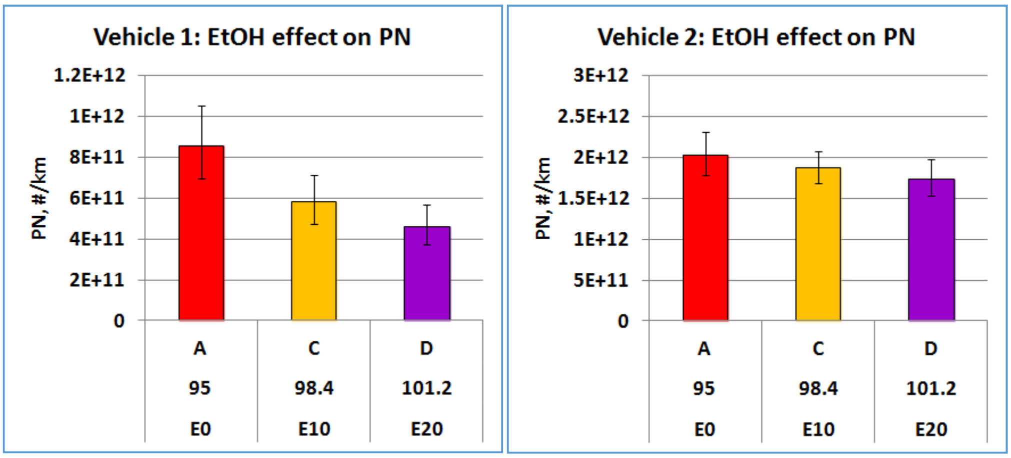
Mean PN and oxygen content was compared in **Figure 12** below. For the PN measurements the absolute values for Vehicle 1 were around half those for Vehicle 2.

Figure 12: Mean particle number per fuel plotted versus oxygen content.



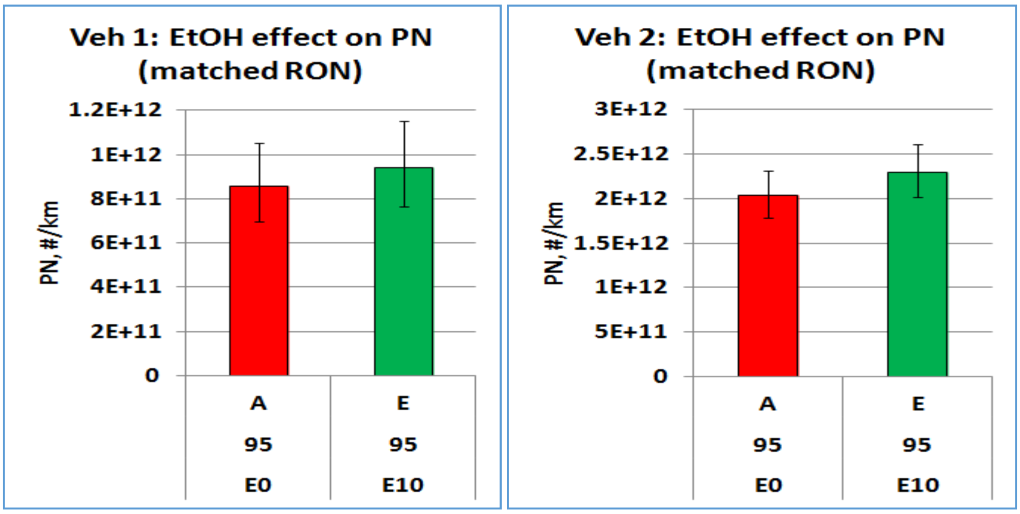
There is a statistically significant correlation between fuel oxygen content and PN at the P <5% (95%) confidence level in the Vehicle 1 data for oxygenate levels above 3.5%. This is not observed in the Vehicle 2 data. This effect is also shown below in Vehicle 1 comparing splash blended ethanol fuels at 10% and 20% ethanol (Fuels C and D respectively) with E0 (Fuel A) with no attempt to correct for RON (**Figure 13**).

Figure 13: Ethanol splash blend effects on PN



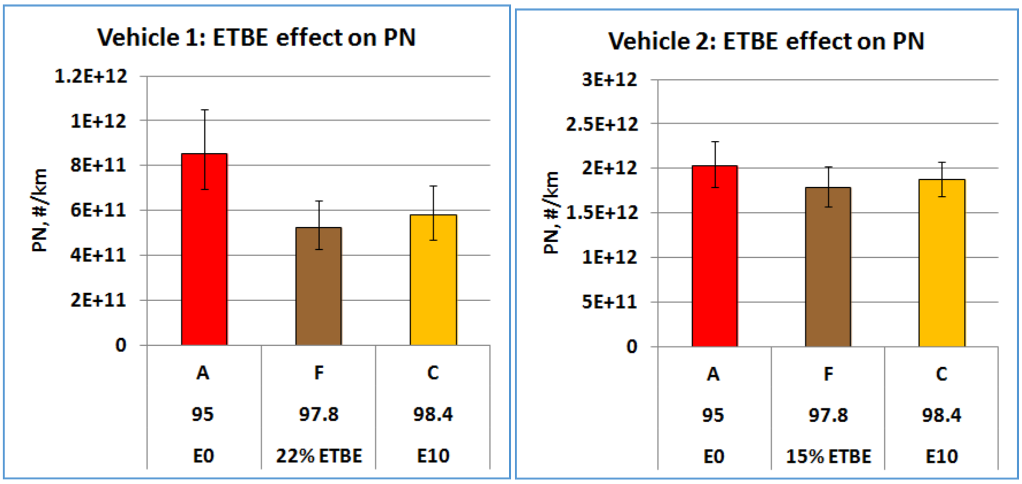
When RON is matched however there is no significant difference between non-ethanol and 10% ethanol containing fuels observed for either vehicle as shown in **Figure 14**. The error bars are overlapping in both cases.

Figure 14: No significant ethanol effects on PN with matched RON



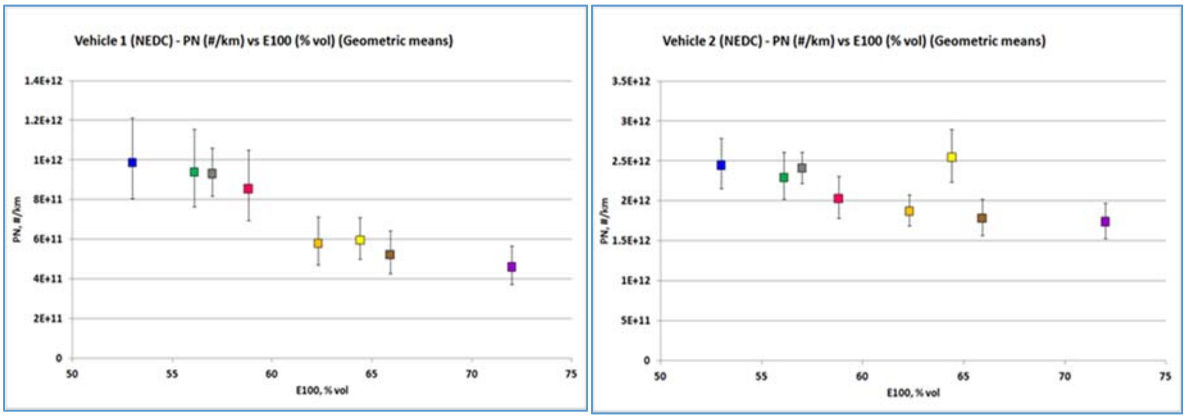
Comparing Ethanol and ETBE with matched oxygen content (**Figure 15**) there is also no significant difference in PN results between the two oxygenates although Vehicle 1 did see a benefit in the oxygenate containing fuels. There was no significant benefit observed in the second vehicle.

Figure 15: Comparison of ETBE and Ethanol effects on PN at matched oxygen content



There was a strong correlation between PN and E100 as shown in **Figure 16** with a significant reduction in PN for higher oxygenate levels similar to that noted for the oxygen content for Vehicle 1.

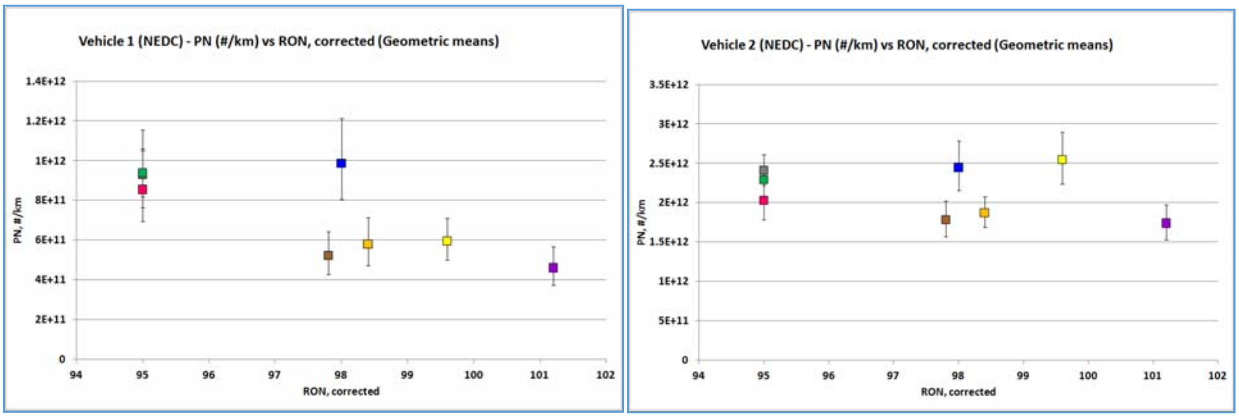
Figure 16*: Comparison between PN and E100*



4.2.2.2. Effect of octane

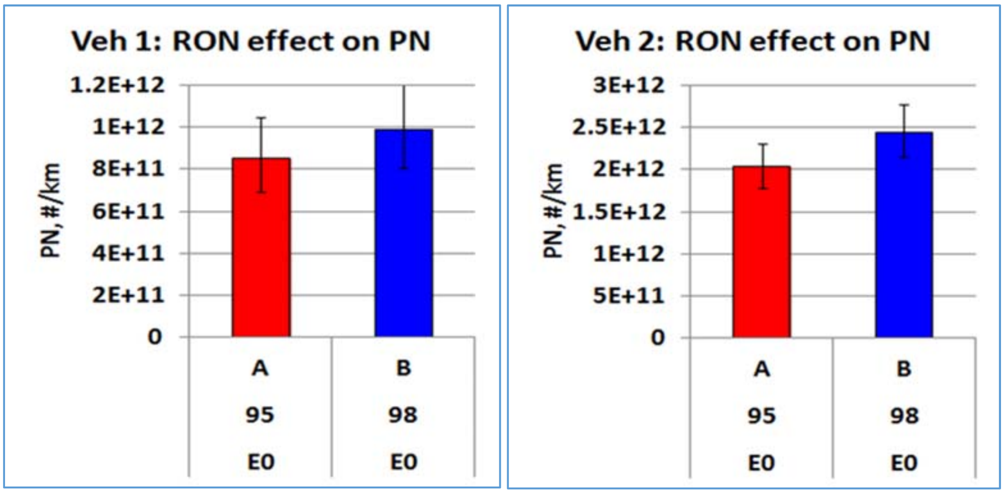
Again, although it was not the focus of the study, the effect of octane was also observed. The mean PN is plotted against RON and is shown in **Figure 17**. There was no strong correlation in this case although for Vehicle 1 the higher RON fuels did appear to give lower PN. This may be due to the fact that the higher RON fuels tend to be those which contain higher levels of oxygenates.

Figure 17: Mean PN plotted against RON



When comparing the 95 and 98 RON fuels without oxygenate there was no significant change in PN as shown in **Figure 18**.

Figure 18: Comparison of PN from different octane levels



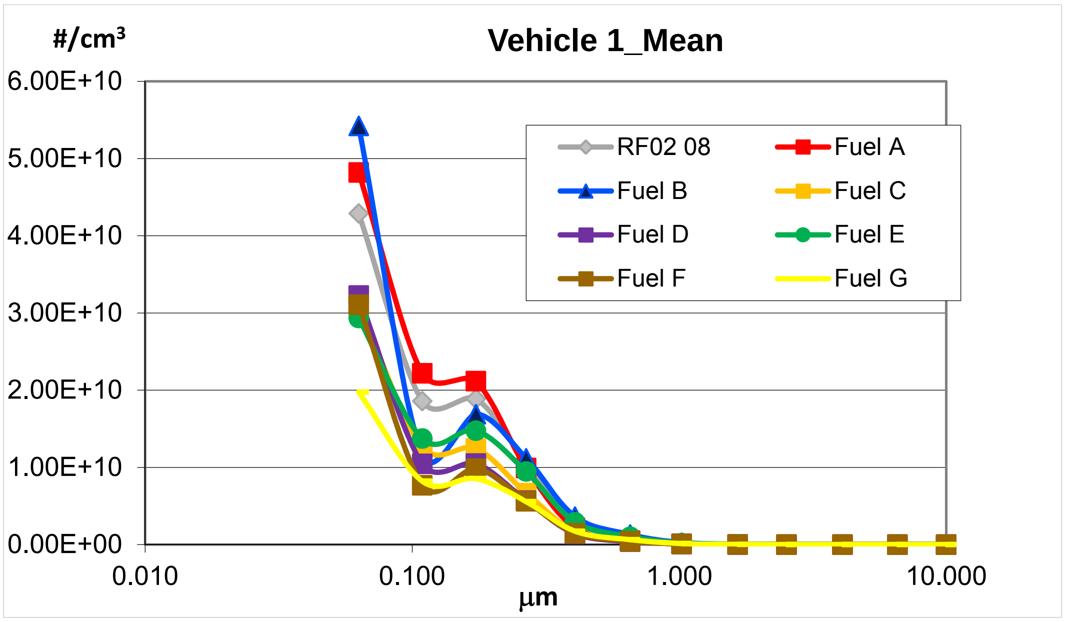
4.2.3. Effects on Particle Size Distribution

The particle size distribution NEDC data have been plotted for both vehicles and all fuels. For each vehicle eight single test graphs were created, one for each fuel type. From these a summary plot shows the comparison of the single fuel test repetitions arithmetic mean value.

A basic evaluation was carried out of the individual data set as plotted. The comparison of a single fuel is done on thirteen different diameter dimensional sizes, following the instrument's (ELPI) functioning principles.

From the Vehicle 1 summary line plot analysis, **Figure 19**, the existence of a mode of particles before the 0.063 µm, is suggested by the decreasing slope of the curves while the presence of a specific mode at 0.173 µm with one inflection point at 0.109 µm is clear. There seems to be a decreasing trend passing from lower diameter particles size to the larger ones and seems to be a specific fuel emission rate, starting from fuel B to A, RF02 08, D, C, F, E until fuel G. Nevertheless the crossover of the single fuels lines do not allow us to state anything about the overall PN emission behaviour of the single fuels with respect to the others.

Figure 19: Vehicle 1 summary line plot – Arithmetic Mean



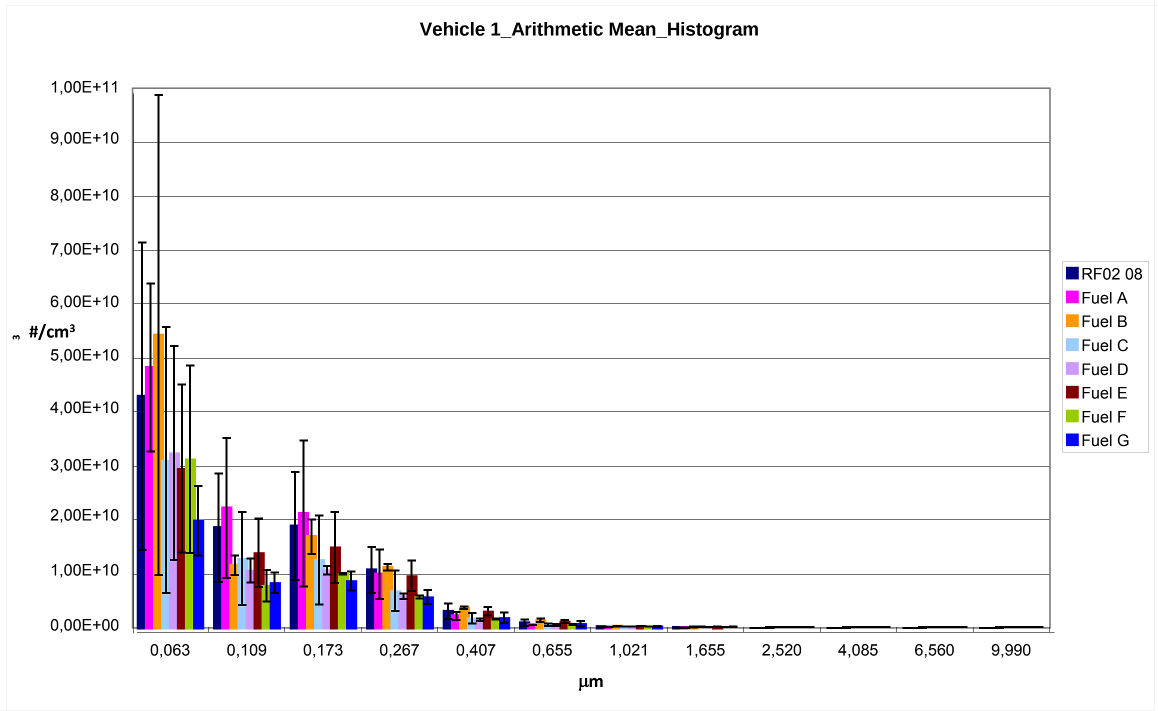
Analysis of the summary histogram plot, **Figure 20** shows the number of particulates is higher with particulates of low diameter, 0.063 µm, 0.109 µm, 0.173 µm, 0.267 µm, decreasing as the diameters increase until the particulate disappears at a size of over 1 µm. As reported above, the single bars represent the arithmetic mean of NEDC test repetitions run for each fuel and the error bars included are the standard deviations calculated for the same set of values.

0.063 µm: the PN value is around 4.00E +10 #/cm^3, for reference fuel RF02 08, and increases to over 5.00E +10 #/cm^3 for fuel B; gradually it reduces to 3.00E +10 #/cm^3 for fuels C, D, E, F and and 2.00E +10 #/cm^3 for fuel G. It seems that the first three fuels generate more small particles than the others and that fuel G reaches the lowest emission level in terms of PN, however the high amount of error suggests that the differences between fuels are not significant. The maximum PN value was recorded for fuel B, 5.43E +10 #/cm^3.

0.109 µm: The PN values decrease with respect to previous diameter size and the maximum value of 2.22E +10 #/cm^3 is reached by Fuel A. Fuels B, C, D, and E are more or less at the same emission level, while fuels F and G are the lowest emitters. The size of the error bars is reduced but they still overlap making the differences not significant.

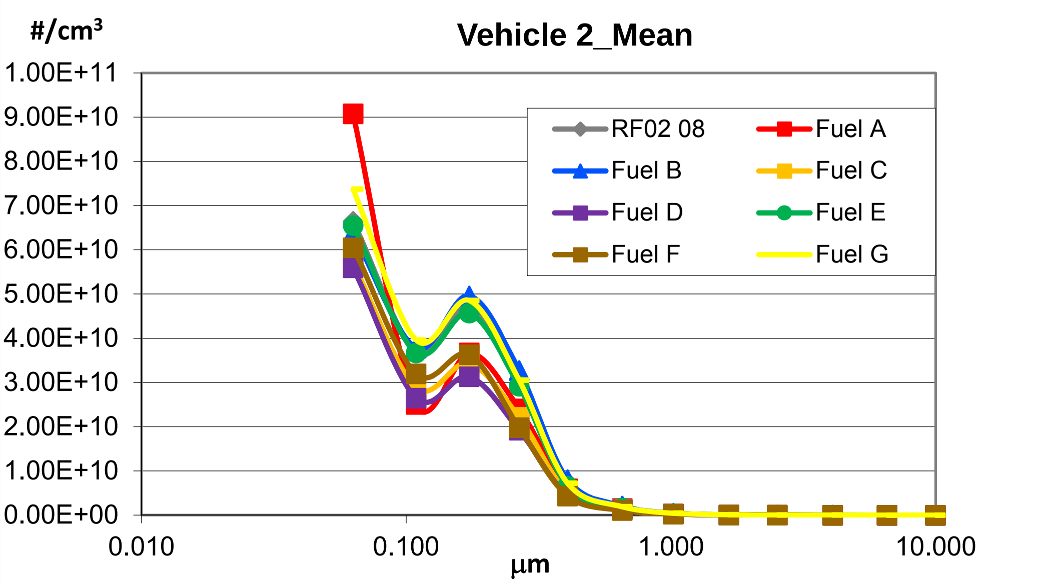
0.173 µm: for this diameter the behaviour is similar to the previous one; reference fuel RF02 08, fuel A, C, D and fuel G have kept the same emission level, whereas fuels B and E PN values have increased. The error bars still overlap and therefore, the differences are not significant.

Figure 20: Vehicle 1 summary histogram plot – Arithmetic Mean



The Vehicle summary line plot analysis, **Figure 21**, shows again the presence of a specific mode at 0.173 µm, one inflection point at 0.109 µm and the existence of a mode before the 0.063 µm is still suggested. There seems to be a trend of decreasing PN moving from lower diameter particle sizes to the larger ones and seems to be decreasing numbers of particulate starting from fuel A followed by G, RF02 08, E, B, F, C, until fuel D. The fuel line A, crossing over all the other fuels lines, is the only exception which does not follow the decreasing fuel emission trend.

Figure 21: Vehicle 2 summary line plot – Arithmetic Mean



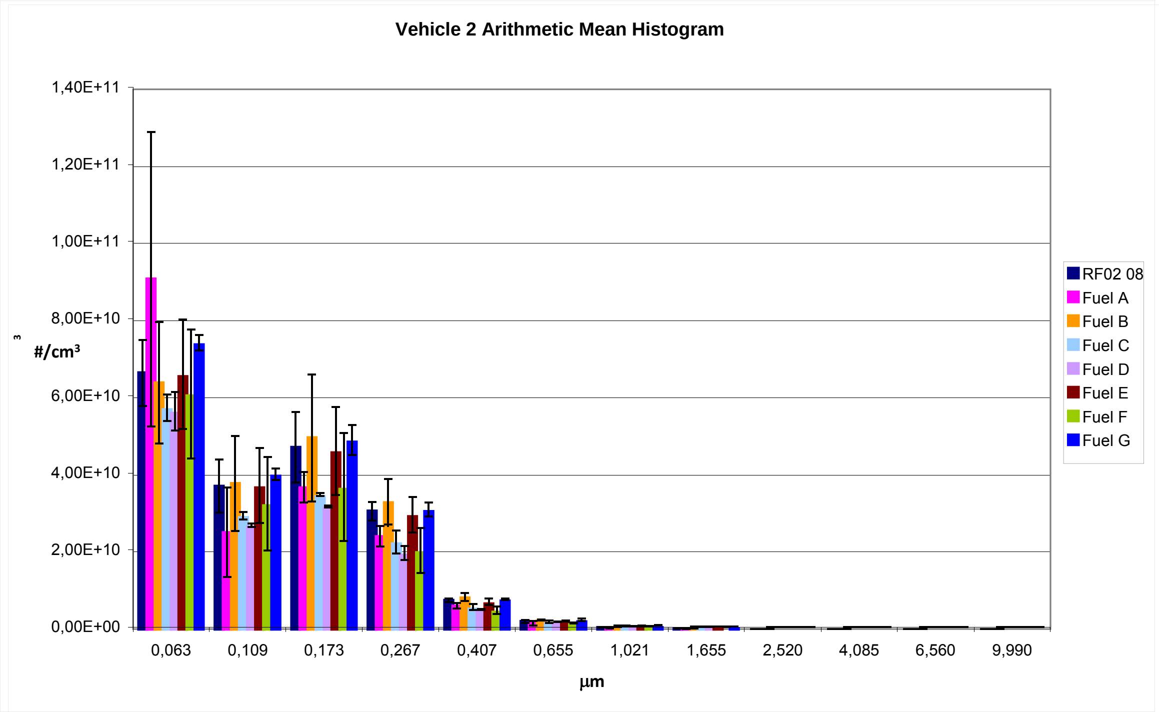
The summary histogram plot analysis of Vehicle 2 shows, **Figure 22,** the PN reduces moving from the lowest diameter, 0.063 µm to successively, 0.109 µm, 0.173 µm, and 0.267 µm. It decreases as diameter increases until the particulates disappear at over 1 µm. As reported above, the single bars represent the arithmetic mean of NEDC test repetitions run for each fuel and the error bars shown are the standard deviation calculated for the same set of values.

0.063 µm: the PN value is around 6.50E +10 #/cm^3, for reference fuel RF02 08, and increases to 10.00E +10 #/cm^3 for fuel A; gradually it reduces to around 6.00E +10 #/cm^3 for fuels B, C, D, E, F and 7.00E +10 #/cm^3 for Fuel G. It seems that fuels A, RF02 08 and G generate more small particles than the others and the fuel D reaches the lowest emission level, however the size of the error bars suggests that the differences between fuels are not significant. The maximum PN value was recorded for fuel A, 9.08E +10 #/cm^3.

0.109 µm: The PN values decrease with respect to previous diameter size and the maxim value is reached by fuel G, 3.96E +10 #/cm^3. Fuels C and D are more or less at the same emission level as well as FR02 08, B and E, while fuel A has become the lowest emitter. The variability shown by the error bars is reduced, but they overlap so the differences are still not significant.

0.173 µm: for this diameter the behaviour is similar to the previous one, where all fuel PN values have increased. The error bars still overlap, making the differences not significant.

Figure 22: Vehicle 2 summary histogram plot – Arithmetic Means



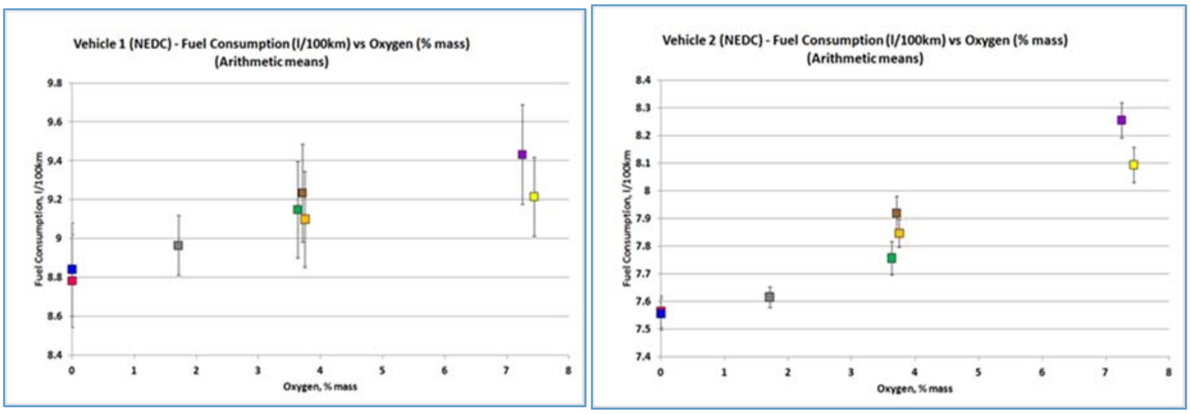
4.2.4. Fuel Property Effects on Fuel Consumption

4.2.4.1. Oxygenates

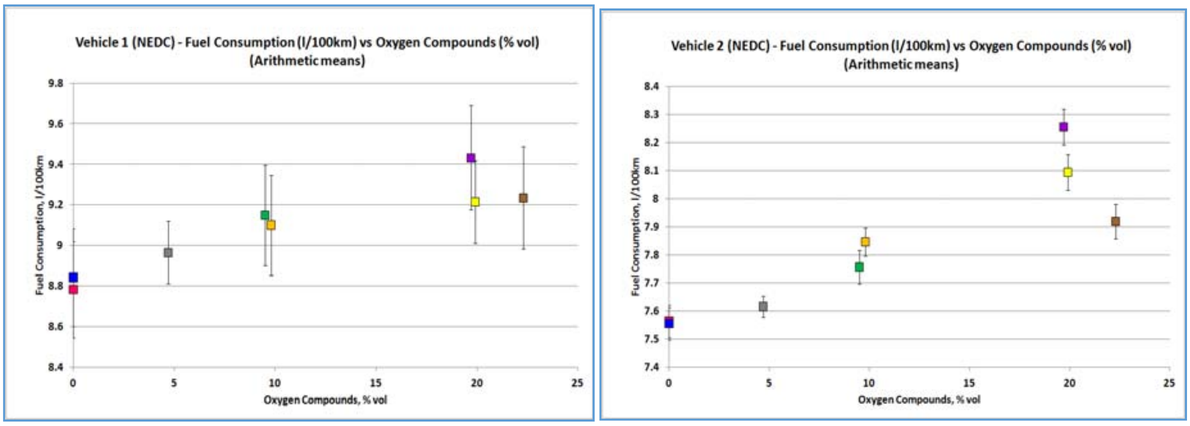
For Vehicle 2 Fuel consumption was plotted against oxygen content, %age of oxygen compounds and E100 (**Figure 23**) and there was a strong correlation particularly with oxygen content with slightly weaker correlation for oxygen compounds. The correlation is statistically significant at the P <1% and P <0.1% (99% and 99.9%) confidence levels for vehicles 1 and 2 respectively. Vehicle 1 had larger error bars as before although there were still indications of the same kind of correlation which has been observed in previous studies.

Figure 23: Fuel consumption plotted versus a) oxygen content b) oxygen compounds and c) E100

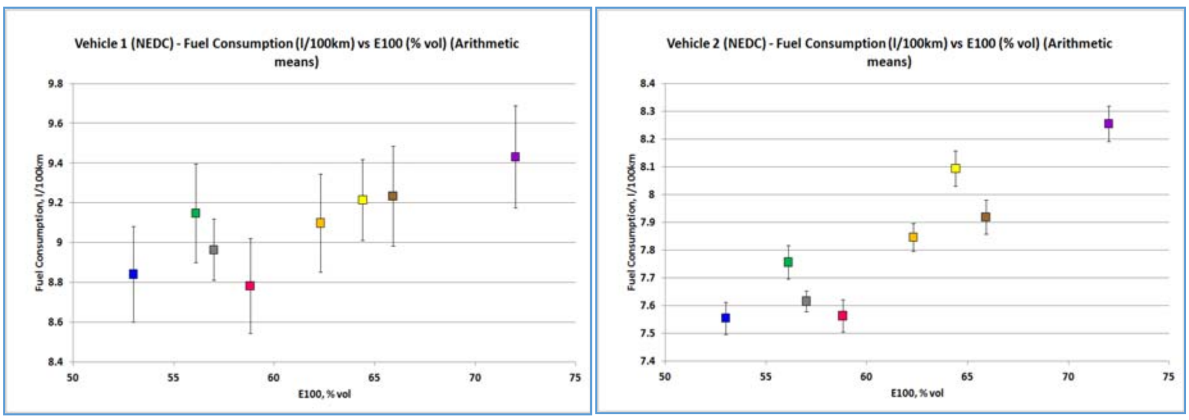
a)



b)

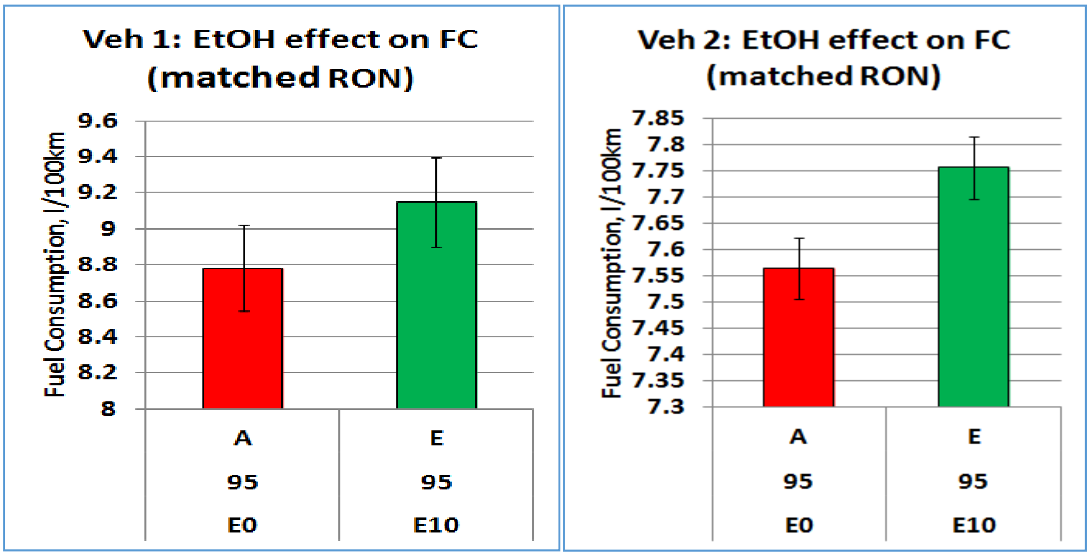


c)



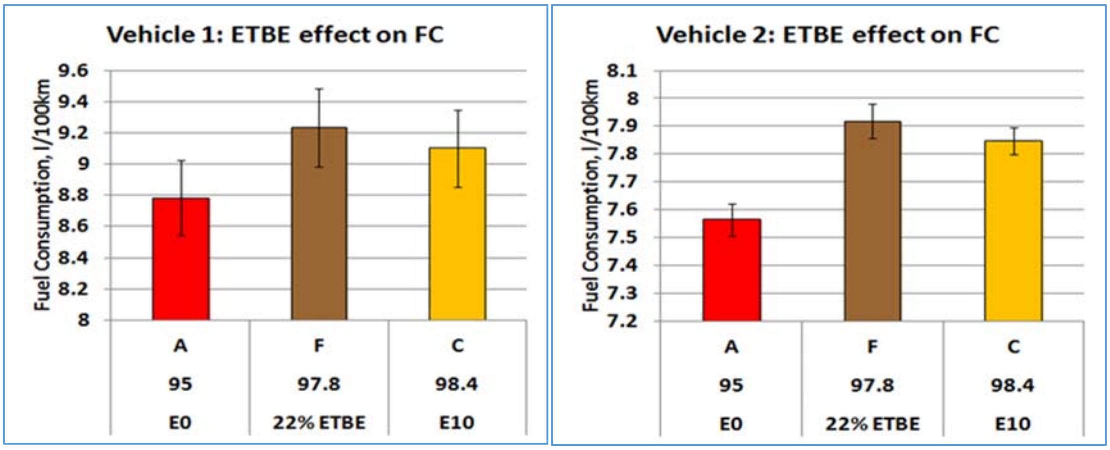
The increase in fuel consumption for two fuels with and without ethanol at 10% and with matched RON is shown in **Figure 24**. There was a significant increase in fuel consumption for Vehicle 2 but not Vehicle 1.

Figure 24: Comparison of fuel consumption for fuels with and without ethanol with matched RON.



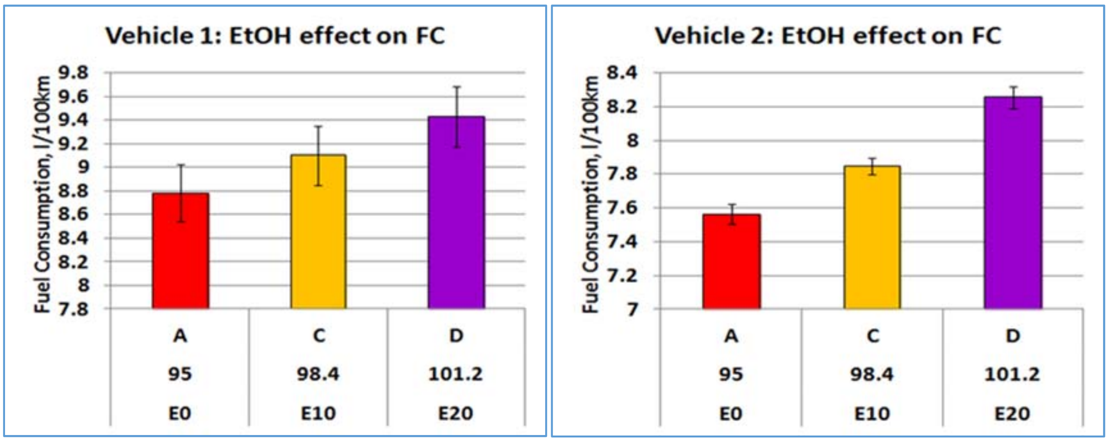
Comparison of ETBE and Ethanol containing fuels with equivalent oxygen content to 10% ethanol (**Figure 25**) gave similar increases in fuel consumption in Vehicle 2 and no significant difference in Vehicle 1.

Figure 25: Effect of different oxygenates with matched oxygen content on fuel consumption



Fuel A when splash blended with ethanol at 10 and 20% (so no attempt to match RON) showed significant increases for E20 in the case of Vehicle 1 and for both E10 and E20 for Vehicle 2 which had lower error as was reported earlier. This is shown in **Figure 26**.

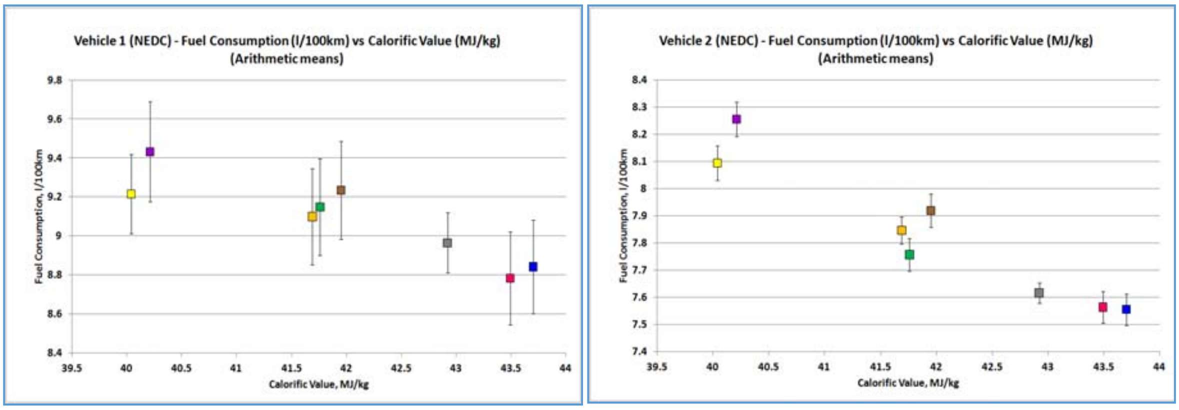
Figure 26: Effect of splash-blended ethanol on fuel consumption



4.2.4.2. Calorific Value

Calorific value by mass versus fuel consumption showing a correlation between increasing fuel consumption with reducing calorific value is shown in **Figure 27**. This is primarily an artifact of the oxygen content of the oxygenate blends.

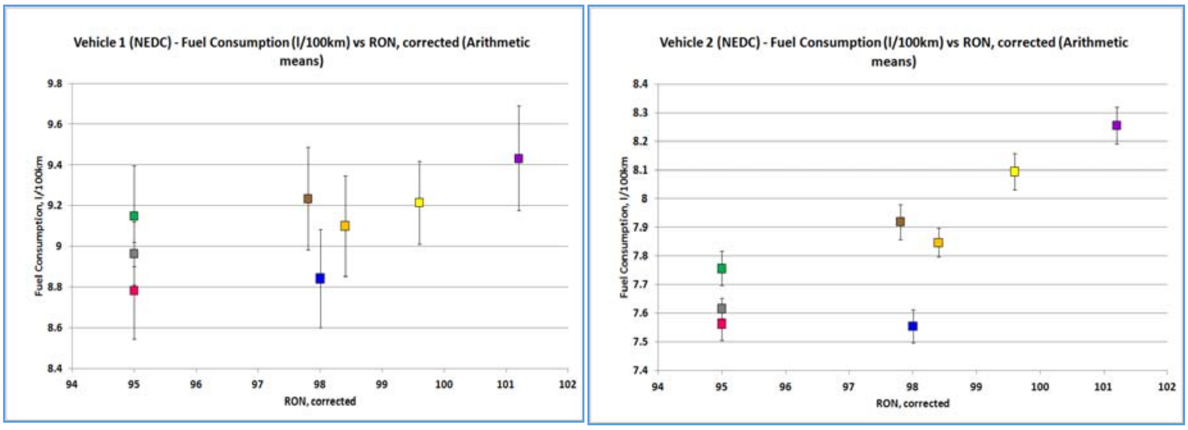
Figure 27: Calorific value is plotted with fuel consumption



4.2.4.3. RON

When RON versus fuel consumption is plotted (**Figure 28**) this shows some evidence of a correlation between increasing RON and increasing fuel consumption. This is likely to be dominated by and coincident with the oxygen content, given that oxygenates tend to be of high RON. This is demonstrated by the high octane E0 fuel (blue) which has lower fuel consumption than the oxygenate blends of similar RON.

Figure 28: RON versus fuel consumption



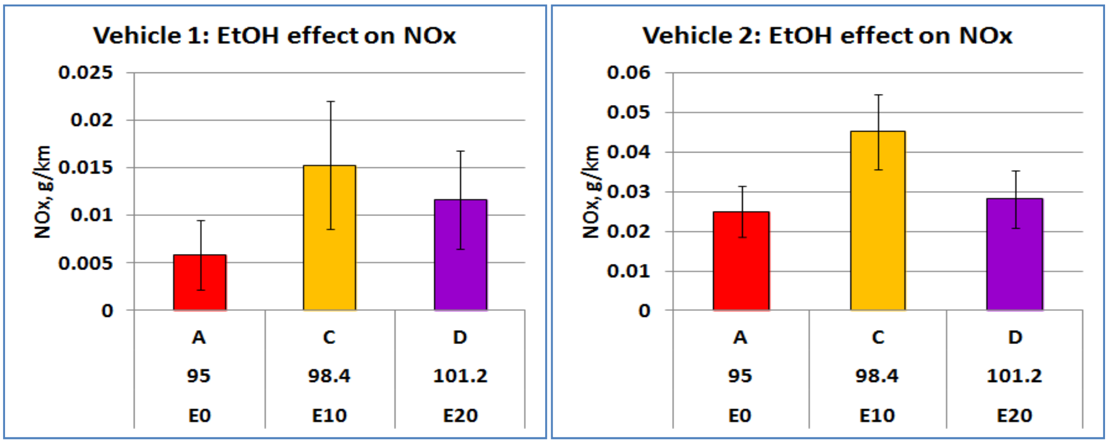
4.3. OTHER FUEL AND PROPERTY EFFECTS OF INTEREST

Although data was collected on the full range of emissions we have chosen to show the effect of the properties being studied on NOx emissions.

4.3.1. Effect of fuel properties on NOx

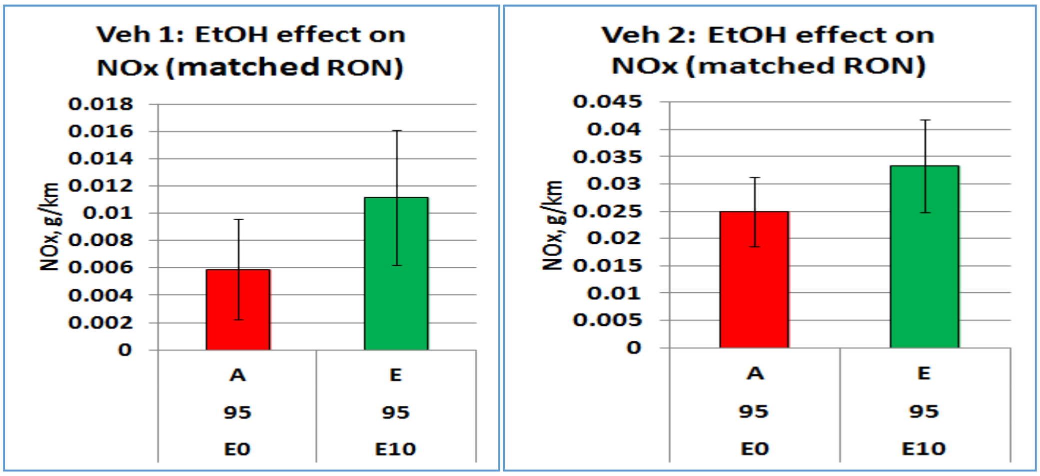
The effect of ethanol on NOx is shown in **Figure 29**. In both vehicles the trend for NOx emissions is the same with E10 appearing to give the highest NOx emissions. However the error bars indicate that the difference going from E10 to E20 was only significant in Vehicle 2. Some workers have seen optimum levels of ethanol around E10 for particulates but we are not aware of any effects for NOx.

Figure 29: Ethanol effect on NOx



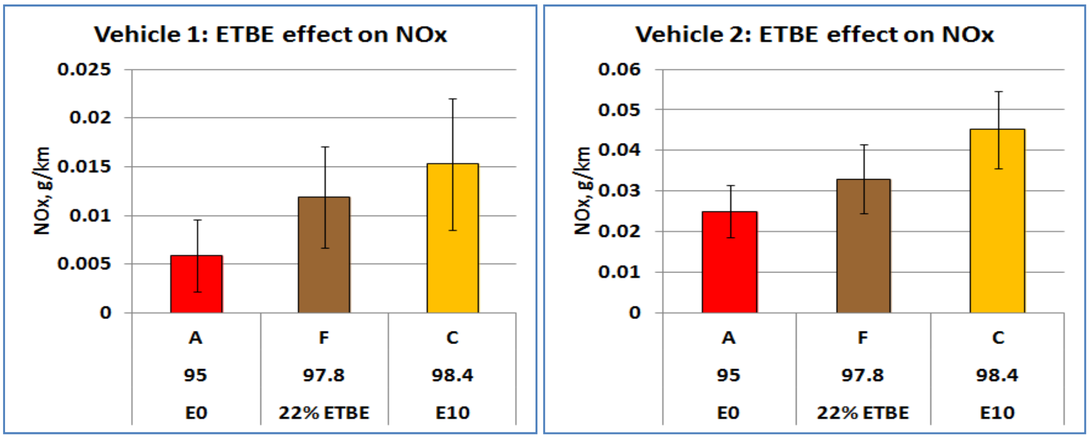
When RON was matched there was no significant difference between E0 and E10 for either vehicle (**Figure 30**).

Figure 30: Effect of E10 on NOx with matched RON



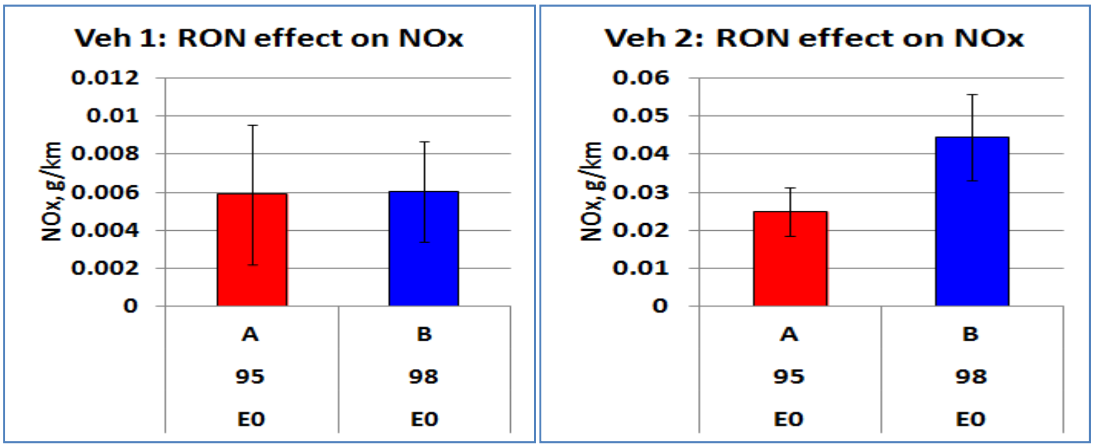
When the NOx emissions of the ETBE-containing fuel were compared with E10 with equivalent oxygen and similar RON there was no significant difference between the two in either vehicle, although in Vehicle 2, the ethanol-containing fuel showed a significant increase in NOx compared to a base without oxygenate (**Figure 31**).

Figure 31: Comparison of ETBE and Ethanol with equivalent oxygen content



When 98 RON fuel was compared with a 95 RON without oxygenates for Vehicle 2 there was a significant increase in NOx (**Figure 32**).

Figure 32: Effect of increasing RON on NOx with no oxygenates



4.3.2. Other Fuel Properties Examined for Correlations with Emissions and Fuel Consumption

In **Appendix 7** other charts are shown where there are trends observed for both vehicles but in most cases the differences were not significant. These cover effects on CO2, HC and CO. In addition to those included in the sections above and the appendix, the fuel properties listed in **Table 4**, below were also examined and no correlations with fuel properties were apparent.

Table 4 Other properties examined

Fuel property	Comment
Density, ASVP, DVPE, IBP, T10, MON (corrected).	No correlations evident which are consistent across vehicles
T50, T90, E150 & FBP	Correlations evident between these volatility related parameters and PN. These parameters are related to the aforementioned E100 and considered an artefact of the oxygen content.

5. CONCLUSIONS

A study of the effects of octane, oxygenates, oxygen content and splash blending of ethanol on exhaust emissions and fuel consumption has been carried out on two direct injection spark ignition passenger cars. From the data it is observed that: -

In general:

- All results were well within applicable limits for both vehicles (Vehicle 1: Euro 4, Vehicle 2: Euro 5) except for a single NMHC data point from Vehicle 2.
- Although only two GDI vehicles were tested, in each case the vehicle had a greater impact on particle and gaseous emissions than the fuel and driving cycle.

On particulates:

- PM measured gravimetrically was difficult to interpret for fuel effects because the PM emission levels were very low from these modern GDI vehicles.
- All PN results fell within the first stage interim Euro 6 (2014) limit of 6×10^{12}, but most results exceeded the final target for Euro 6 (2017) PN level of 6×10^{11}. This was surprising as neither of these vehicles were optimized for Euro 6 emissions levels.
- Oxygen content had no measurable effects on PM or gaseous emissions over the NEDC cycle. However, a step-change down in PN emissions for Vehicle 1 was observed for fuels containing >3.7% mass oxygen over fuels with lower amounts of oxygen.

On fuel consumption:

- Fuel consumption tends to increase with increasing fuel oxygen content and other fuel related parameters such as oxygenate content, E100 and reducing calorific value.
- At the same oxygen content, ETBE had no different effect on volumetric fuel consumption compared to Ethanol.

On octane match versus splash blended fuels:

- In fuels of matched octane, there were no statistically significant differences in emissions across the vehicles between E0 and E10 although in one vehicle (Vehicle 2) there was a significant increase observed in fuel consumption.
- Between hydrocarbon base fuel and the same splash blended with 10% and 20% volume of ethanol there were no effects on emissions which were statistically significant in both vehicles, but a statistically significant penalty in fuel consumption was observed in both vehicles with the E20 blend.
- Although not the main focus of the study it was observed that varying RON between 95 and 98 RON without the presence of oxygenate had no consistent effect on emissions or volumetric fuel consumption in these vehicles.

6. GLOSSARY

A/F	Air / Fuel
AFR	Air / Fuel Ratio
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPC	Condensation Particle Counter (sometimes called Condensation Nucleus Counter, CNC)
CR	Compression Ratio
CVS	Constant Volume Sampling
DPF	Diesel Particulate Filter
Exx	Gasoline blend containing xx% ethanol
Exx°C	% fuel evaporated at xx°C
ELPI	Electrical Low Pressure Impactor
ETBE	Ethyl Tertiary Butyl Ether
FTP	Federal Test Procedure
GDI	Gasoline Direct Injection
GPF	Gasoline Particulate Filter
HC	Hydrocarbon
LCV	Lower Calorific Value (same as LHV)
LHV	Lower Heating Value (same as LCV)
MJ	Megajoule
NEDC	New European Driving Cycle
NMHC	Non-Methane Hydrocarbon
MON	Motor Octane Number

NOx	Nitrogen Oxides
PFI	Port Fuel Injection
PM	Particulate Mass
PMP	Particulate Measurement Programme
PN	Particulate Number
RON	Research Octane Number

7. ACKNOWLEDGEMENTS

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APPENDIX 1: SCOPING STUDY

Data from the scoping study is shown in **figures A1.1 a)** and **b)**

Figures A1.1 a) and **b)** Emissions performance over NEDC (2 repetitions on each vehicle)

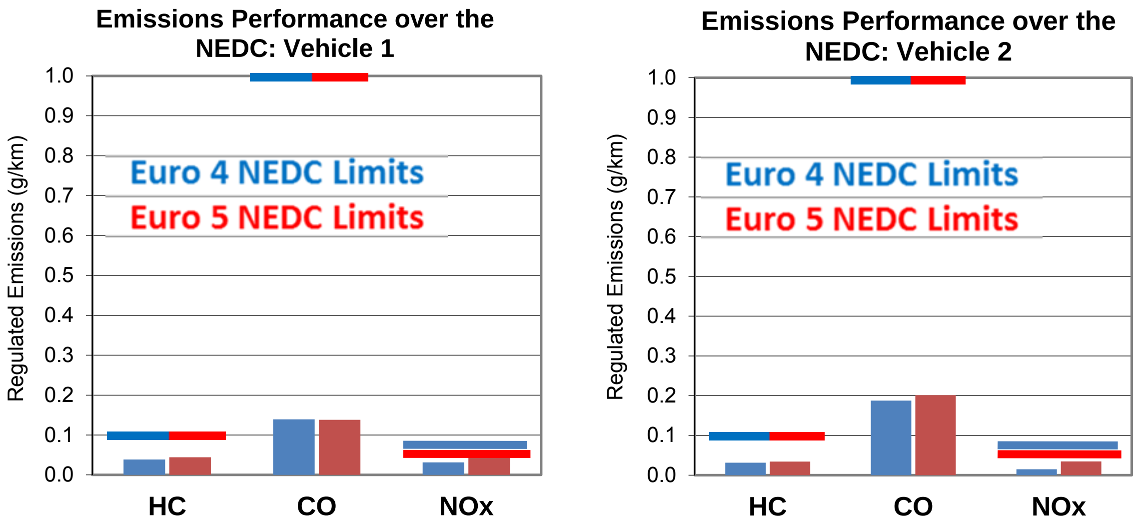
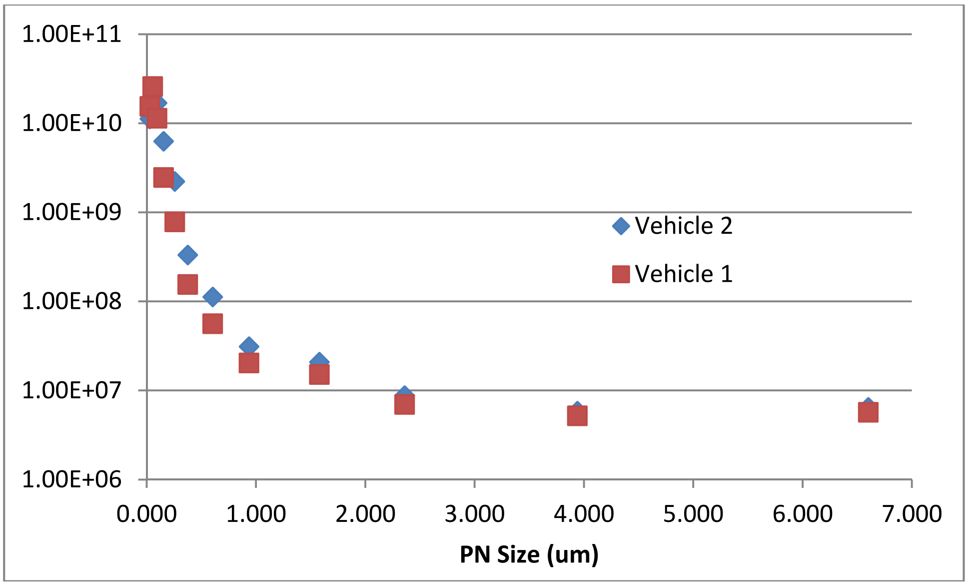


Figure A1.2 Particle Number and size distribution



The scoping study demonstrated that:

- the two vehicles were in compliance with their Euro 4/5 emissions limits;
- the PM emissions were comparable to the Euro 5 limit for GDI vehicles;

- the PN emissions from both vehicles were lower than the Euro 6 PN interim limit for GDI vehicles;
- the PN size distribution was similar for both vehicles.

It was decided that the same two vehicles will be tested on the broader range of fuels shown.
Since the end of the previous trial, these vehicles had been run for 30 minutes each, every other week, to keep the cars operational. Vehicle checks and refueling with pump grade fuel was conducted when required. Ahead of testing both vehicles were subjected to a vehicle service, which included an engine oil change to required specification, engine oil filter change, air filter change and full vehicle safety checks. The fuel filter for each vehicle was located inside the tank and was not changed, as agreed with Concawe. Following the service each car was driven for 1000 miles to break in the engine oil and stabilise the vehicle. During this time the vehicles were driven on pump grade EN228 gasoline.

Before the start of each NEDC test both vehicles were subjected to a thorough fuel flush procedure in order to eliminate carryover effects from one fuel to the next. Throughout the course of the programme each car was tested five times on reference gasoline fuel in order to verify the correct operation and repeatability of the vehicle.

APPENDIX 2: RAW DATA EVALUATION

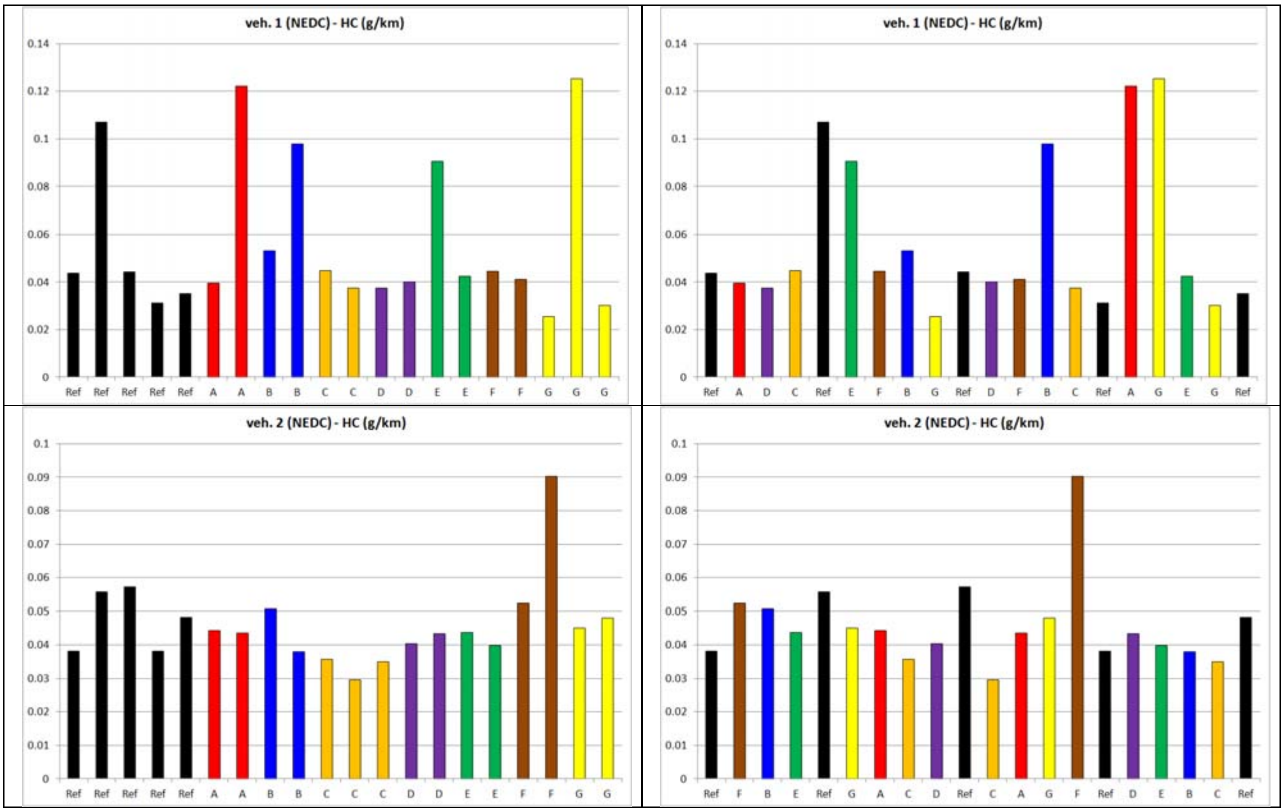
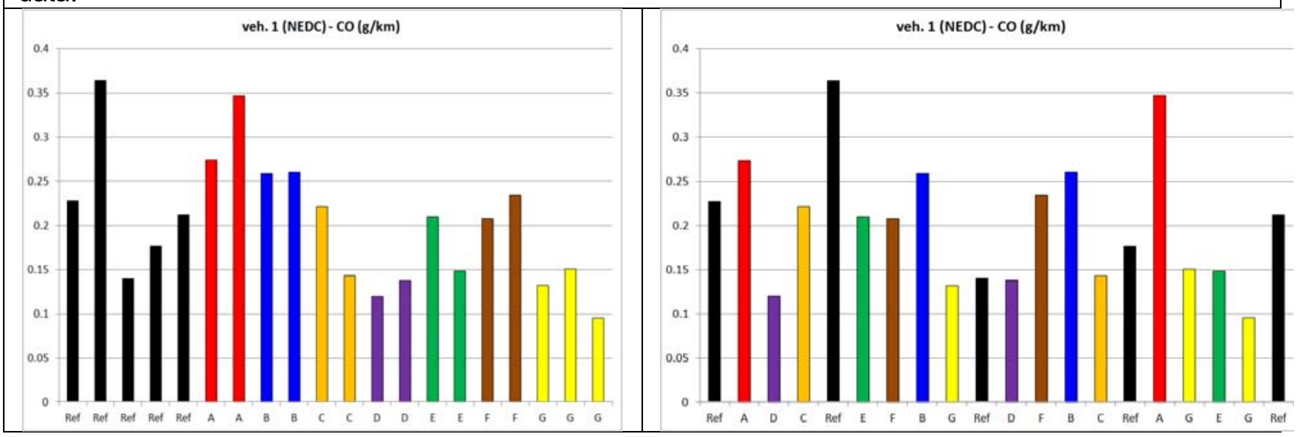


Figure A2.1: Compared to the mean, there is substantial variability in Vehicle 1's HC data, though rather than the variability being around a normal distribution, there appears to be two discrete populations – one above 0.08g/km and one below 0.05g/km. This could be the result of a systemic external effect, which would be readily explained, for example, by LNT regeneration events, or the analyser switching ranges.
Vehicle 2 has much more tightly grouped data with one apparent outlier which has been retained as it cannot be rejected on technical grounds.
Unsurprisingly the NMHC data exhibits very similar trends to those seen in the total HC data, therefore the same comments about distribution and variability apply. There are no fuel related trends apparent in the data.



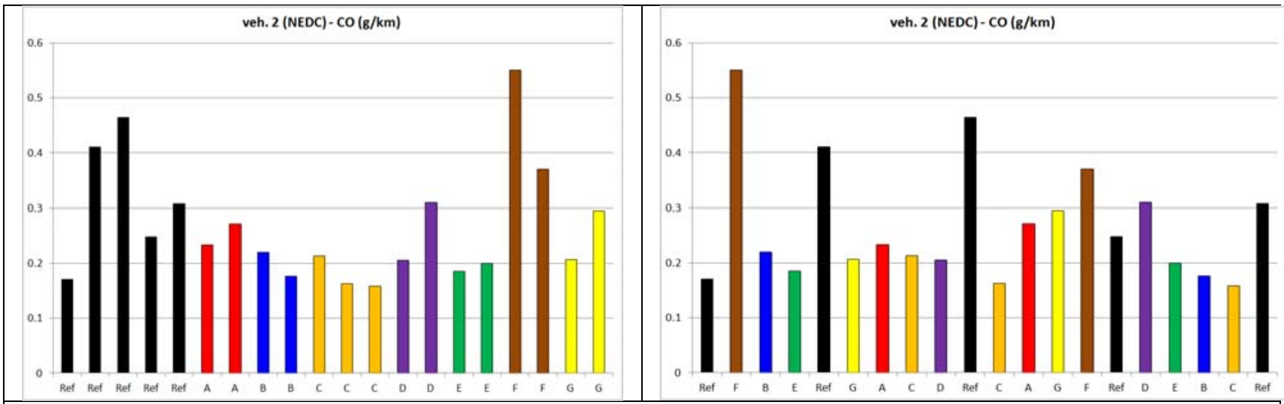


Figure A2.2: Some, but not all of the high results for NMHC in the Vehicle 1 data are reflected in the CO data, suggesting that the apparent two populations in the NMHC data could be a real vehicle effect rather than a HC measurement artefact. There are some potential fuel related trends in the data, however, the trends are not consistent between the vehicles and with only two repeats on most fuels and generally high variability within fuel, the apparent fuel related signals may only be measurement 'bounce'.

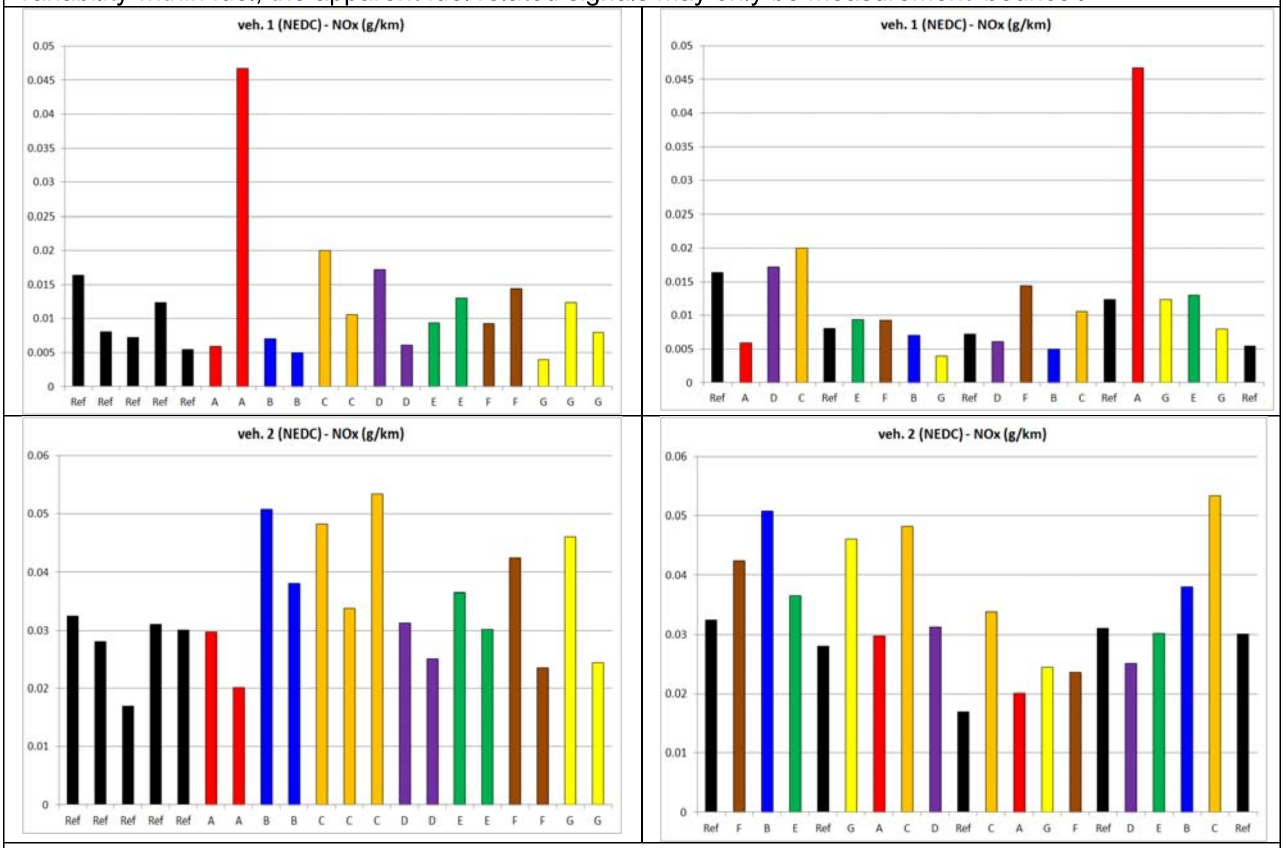


Figure A2.3: There is a clear high outlier in the Vehicle 1 data for the E0 base fuel which has been rejected from the main analysis as a statistical outlier. There are some potential fuel related trends in the data, though the trends are not consistent between the vehicles and therefore are questionable. There is evidence of a baseline fluctuation in the data from both vehicles over time, which would be difficult to adjust for.

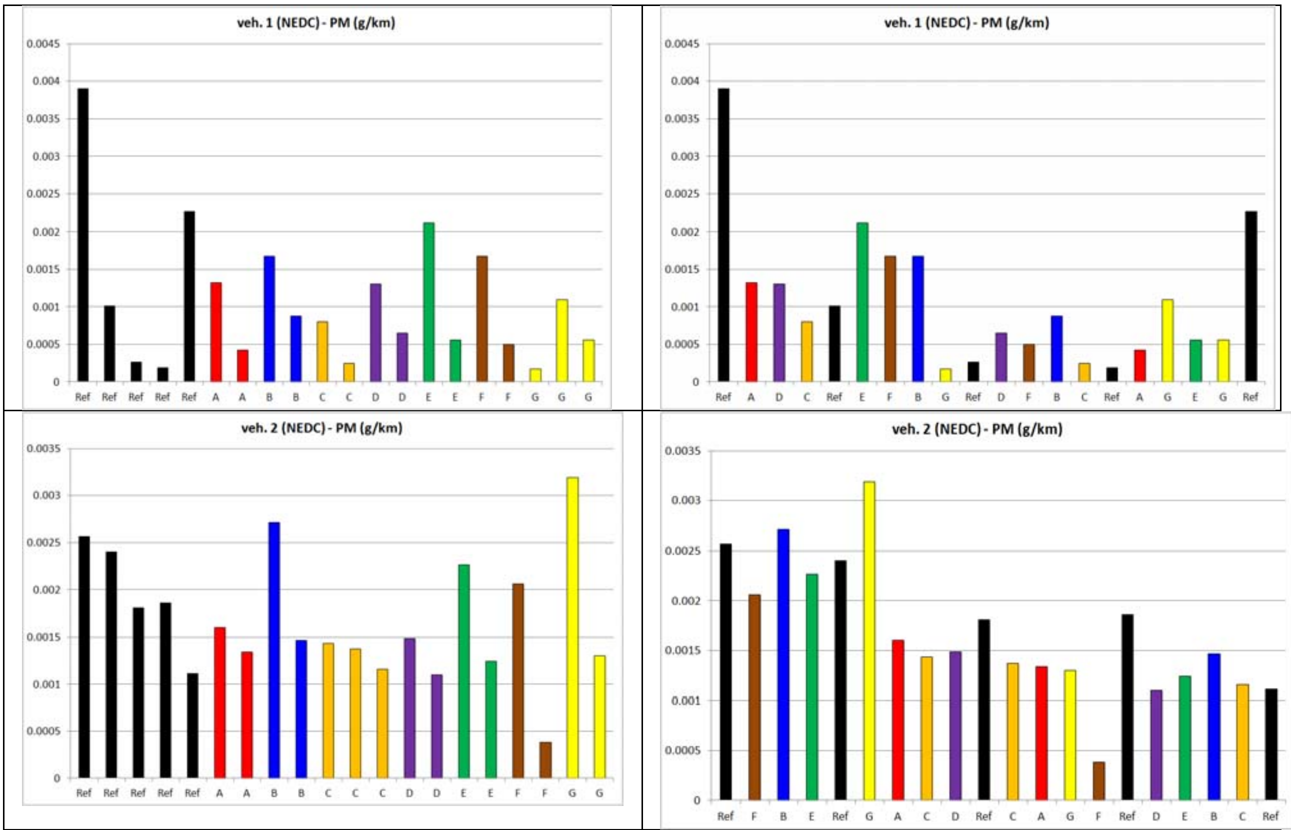
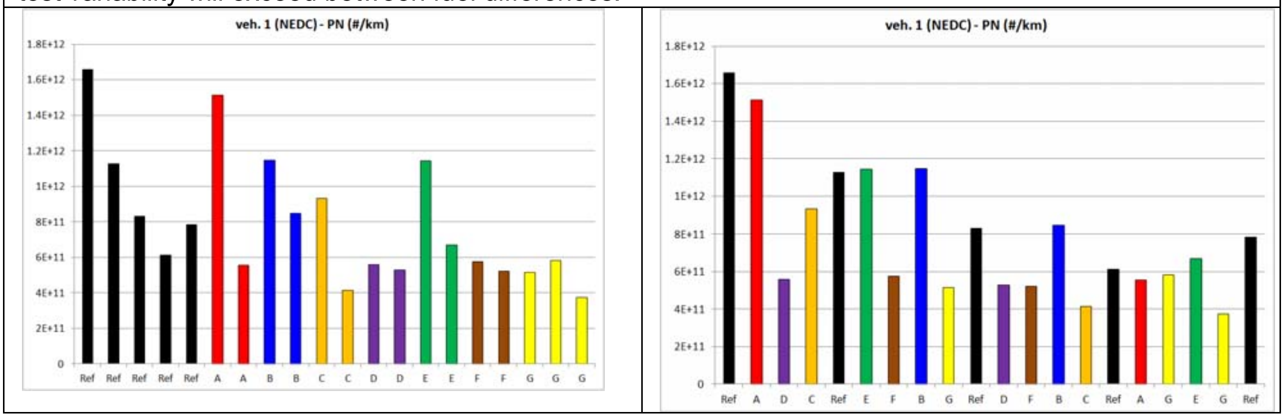


Figure A2.4: The first reference fuel result from Vehicle 1 appears to be a high outlier and within the dataset there appears to be fluctuations over time that exceed any fuel related signals. In the Vehicle 2 data there appears to be a trend towards reducing PM over time but no obvious fuel related differences. PM levels are near to the minimum level of detection for the gravimetric method and therefore it is likely that between test variability will exceed between fuel differences.



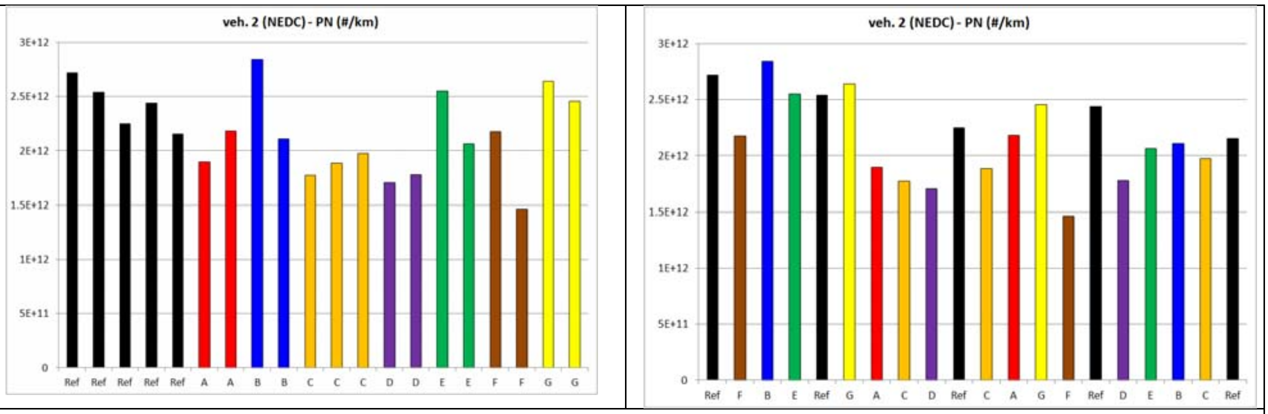


Figure A2.5: There is some evidence of systematic downward drift in the Vehicle 1 data over time which obscures any fuel related trends, however there are still some potential differences. There are also potential fuel related differences in the Vehicle 2 data, but with partially different groups of fuels.

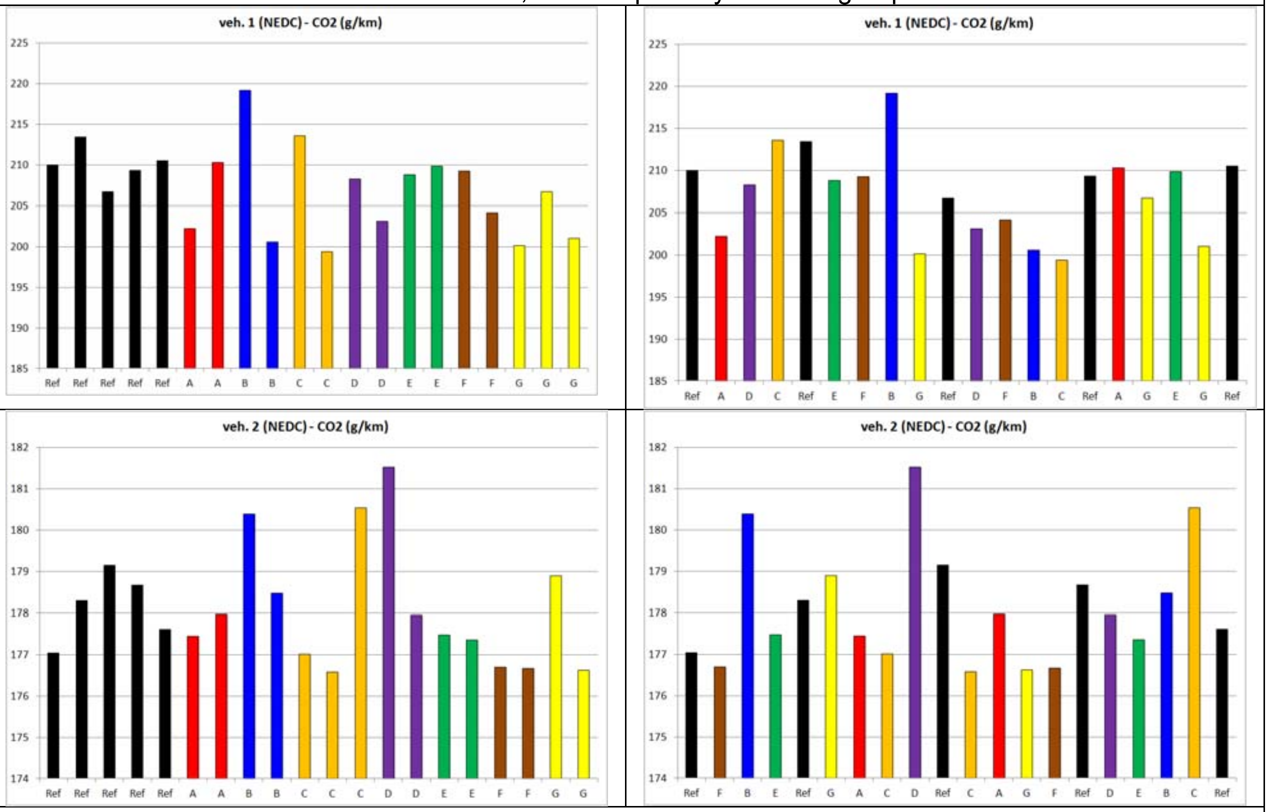


Figure A2.6: CO2 is somewhat variable in Vehicle 1 in particular and no fuel related trends are apparent in the data which are consistent across the vehicles.

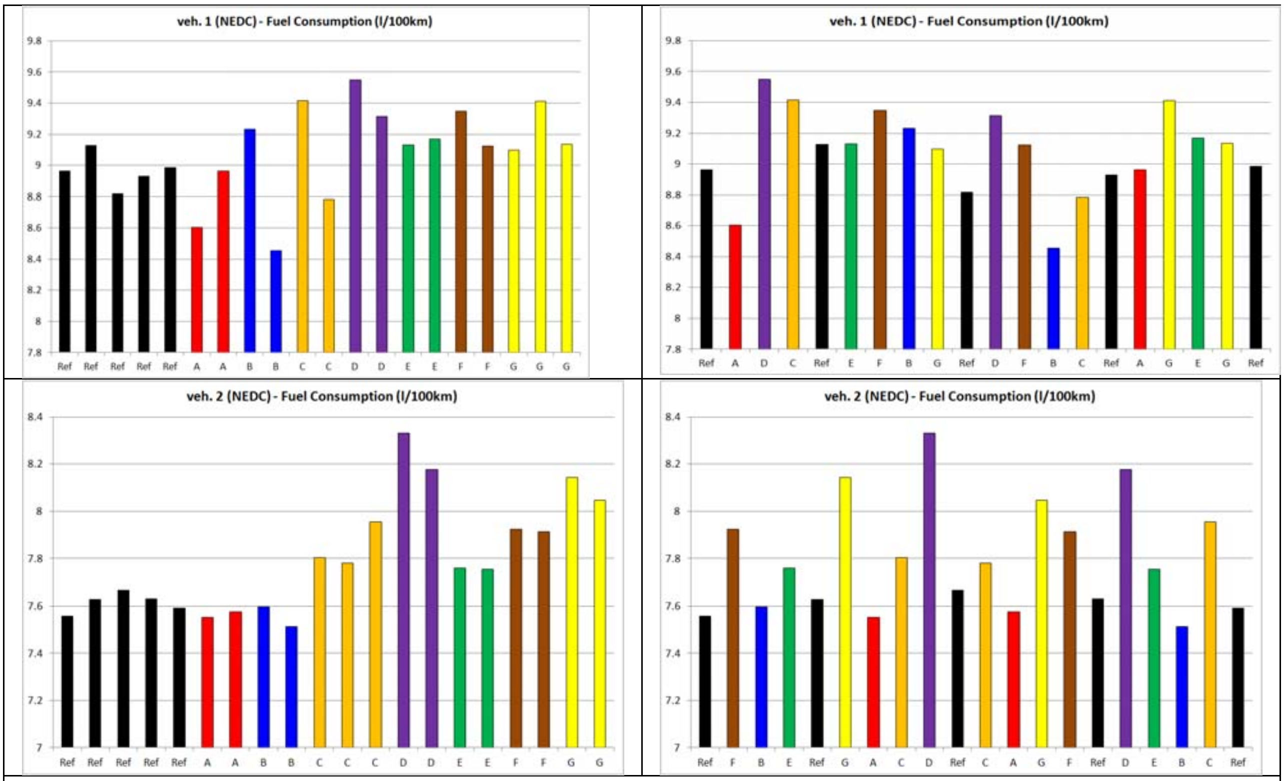
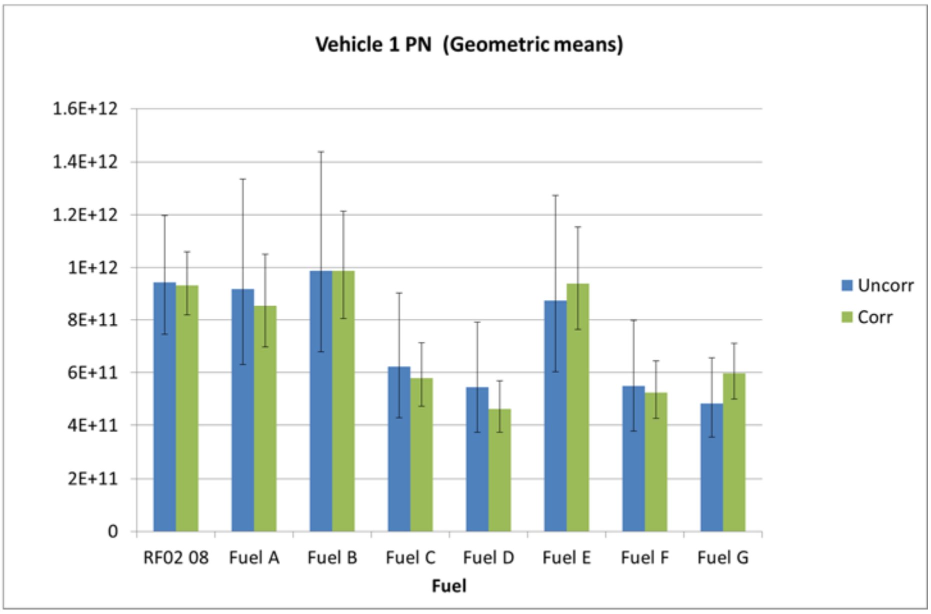


Figure A2.7: Fuel consumption data is noisy from Vehicle 1, but there is some evidence of higher values for higher oxygen fuels. In the Vehicle 2 data, fuel consumption is clearly higher with the higher oxygen content fuels.

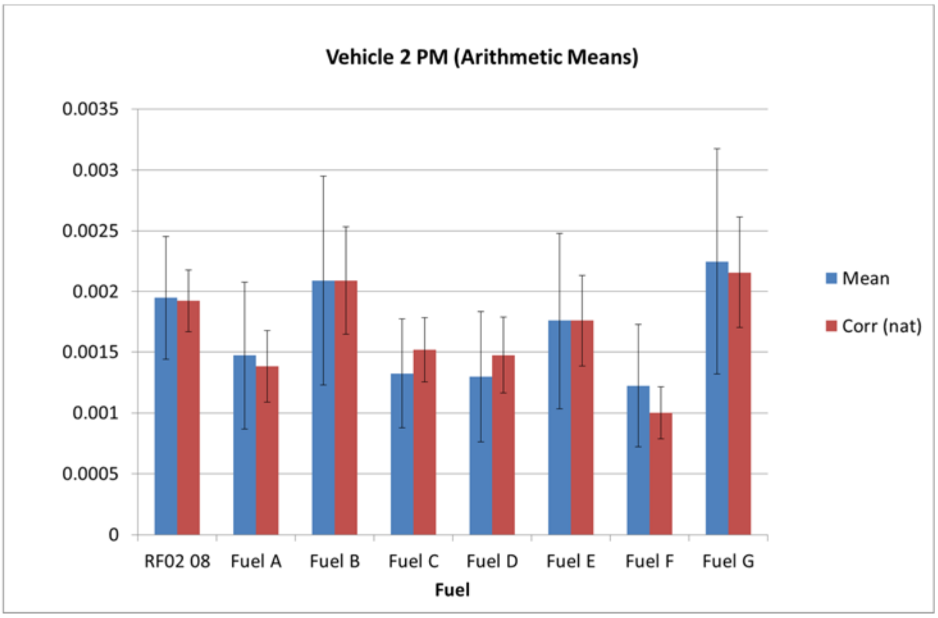
APPENDIX 3: STATISTICAL ANALYSIS – DATA CORRECTIONS

Figure A3.1: Time trend corrections applied to PN data (Vehicle 1) (a) and PM (Vehicle 2) (b) only

a)



b)



APPENDIX 4: TEST DATA

Table A4.1: Vehicle 1 emissions data. Note that the NOx value in the grey box is the rejected statistical outlier and does not figure in the data means.

Test Order	Test Number	Fuel	NMHC (g/km)	HC (g/km)	CO (g/km)	NOx (g/km)	CO_2 (g/km)	PM (g/km)	PN (#)	Fuel Cons (l/100km)
2	ML01008308	Fuel A	0.035	0.040	0.273	0.006	202.2	0.0013	1.51E+12	8.61
16	ML01008775	Fuel A	0.117	0.122	0.347	0.047	210.2	0.0004	5.56E+11	8.96
8	ML01008497	Fuel B	0.048	0.053	0.259	0.007	219.2	0.0017	1.15E+12	9.23
13	ML01008728	Fuel B	0.090	0.098	0.260	0.005	200.6	0.0009	8.50E+11	8.45
4	ML01008363	Fuel C	N/A	0.045	0.221	0.020	213.6	0.0008	9.34E+11	9.42
14	ML01008741	Fuel C	0.034	0.038	0.143	0.011	199.4	0.0002	4.14E+11	8.78
3	ML01008351	Fuel D	N/A	0.037	0.120	0.017	208.3	0.0013	5.60E+11	9.55
11	ML01008628	Fuel D	0.035	0.040	0.138	0.006	203.1	0.0006	5.28E+11	9.31
6	ML01008418	Fuel E	0.082	0.091	0.209	0.009	208.8	0.0021	1.14E+12	9.13
18	ML01008789	Fuel E	0.039	0.042	0.148	0.013	209.8	0.0006	6.70E+11	9.17
7	ML01008479	Fuel F	0.040	0.045	0.208	0.009	209.2	0.0017	5.76E+11	9.35
12	ML01008645	Fuel F	0.036	0.041	0.234	0.014	204.1	0.0005	5.23E+11	9.12
9	ML01008523	Fuel G	0.022	0.026	0.132	0.004	200.1	0.0002	5.15E+11	9.10
17	ML01008780	Fuel G	0.116	0.125	0.151	0.012	206.7	0.0011	5.84E+11	9.41
19	ML01008804	Fuel G	0.025	0.030	0.095	0.008	201.0	0.0006	3.75E+11	9.14
1	ML01008219	RF02 08	0.039	0.044	0.228	0.016	210.0	0.0039	1.66E+12	8.96
5	ML01008377	RF02 08	0.096	0.107	0.364	0.008	213.4	0.0010	1.13E+12	9.13
10	ML01008600	RF02 08	0.041	0.044	0.140	0.007	206.7	0.0003	8.32E+11	8.82
15	ML01008754	RF02 08	0.028	0.031	0.176	0.012	209.3	0.0002	6.13E+11	8.93
20	ML01008820	RF02 08	0.031	0.035	0.212	0.005	210.5	0.0023	7.86E+11	8.98

Table A4.2: Vehicle 2 emissions data

Test Order	Test Number	Fuel	NMHC (g/km)	HC (g/km)	CO (g/km)	NOx (g/km)	CO_2 (g/km)	PM (g/km)	PN (#)	Fuel Cons (l/100km)
7	ML01008507	Fuel A	0.039	0.044	0.233	0.030	177.4	0.0016	1.89E+12	7.55
12	ML01008685	Fuel A	0.037	0.044	0.272	0.020	178.0	0.0013	2.18E+12	7.58
3	ML01008358	Fuel B	0.044	0.051	0.220	0.051	180.4	0.0027	2.84E+12	7.60
18	ML01008768	Fuel B	0.032	0.038	0.177	0.038	178.5	0.0015	2.11E+12	7.51
8	ML01008584	Fuel C	0.030	0.036	0.214	0.048	177.0	0.0014	1.77E+12	7.80
11	ML01008677	Fuel C	0.024	0.030	0.163	0.034	176.6	0.0014	1.88E+12	7.78
19	ML01008785	Fuel C	0.031	0.035	0.159	0.053	180.5	0.0012	1.98E+12	7.96
9	ML01008608	Fuel D	0.033	0.040	0.205	0.031	181.5	0.0015	1.70E+12	8.33
16	ML01008733	Fuel D	0.035	0.043	0.310	0.025	177.9	0.0011	1.78E+12	8.18
4	ML01008371	Fuel E	0.038	0.044	0.185	0.036	177.5	0.0023	2.55E+12	7.76
17	ML01008746	Fuel E	0.034	0.040	0.200	0.030	177.3	0.0012	2.07E+12	7.75
2	ML01008341	Fuel F	0.044	0.052	0.550	0.042	176.7	0.0021	2.18E+12	7.92
14	ML01008712	Fuel F	0.082	0.090	0.370	0.024	176.7	0.0004	1.46E+12	7.91
6	ML01008409	Fuel G	0.039	0.045	0.206	0.046	178.9	0.0032	2.64E+12	8.14
13	ML01008701	Fuel G	0.040	0.048	0.295	0.025	176.6	0.0013	2.45E+12	8.05
1	ML01008321	RF02 08	0.033	0.038	0.171	0.032	177.0	0.0026	2.72E+12	7.56
5	ML01008387	RF02 08	0.049	0.056	0.411	0.028	178.3	0.0024	2.54E+12	7.63
10	ML01008633	RF02 08	0.050	0.057	0.464	0.017	179.1	0.0018	2.25E+12	7.67
15	ML01008718	RF02 08	0.032	0.038	0.248	0.031	178.7	0.0019	2.44E+12	7.63
20	ML01008802	RF02 08	0.042	0.048	0.307	0.030	177.6	0.0011	2.15E+12	7.59

Table A4.3: Vehicle 1 particle size distribution data

	Test Order	1	2	3	4	5	6	7	8	9	10	11	12
	Test Number	ML01008219	ML01008308	ML01008351	ML01008363	ML01008377	ML01008418	ML01008479	ML01008497	ML01008523	ML01008600	ML01008628	ML01008645
	Size µm (D50%)	RF02 08	Fuel A	Fuel D	Fuel C	RF02 08	Fuel E	Fuel F	Fuel B	Fuel G	RF02 08	Fuel D	Fuel F
Stage 1	0.063	9.18E+10	5.92E+10	4.63E+10	4.84E+10	3.40E+10	4.04E+10	4.34E+10	8.57E+10	1.99E+10	2.68E+10	1.83E+10	1.88E+10
Stage 2	0.109	3.54E+10	3.14E+10	1.20E+10	1.88E+10	2.01E+10	1.82E+10	5.65E+09	1.03E+10	9.62E+09	1.43E+10	8.91E+09	9.76E+09
Stage 3	0.173	3.51E+10	3.08E+10	1.11E+10	1.83E+10	2.13E+10	1.94E+10	9.95E+09	1.92E+10	1.00E+10	1.49E+10	9.98E+09	9.77E+09
Stage 4	0.267	1.70E+10	1.32E+10	5.37E+09	9.33E+09	1.29E+10	1.15E+10	5.84E+09	1.17E+10	5.46E+09	9.22E+09	6.06E+09	5.41E+09
Stage 5	0.407	4.38E+09	2.75E+09	1.21E+09	2.33E+09	4.66E+09	3.49E+09	1.55E+09	3.41E+09	1.37E+09	2.79E+09	1.59E+09	1.42E+09
Stage 6	0.655	8.97E+08	5.55E+08	2.62E+08	5.76E+08	1.95E+09	1.20E+09	3.60E+08	1.05E+09	3.50E+08	8.48E+08	5.39E+08	5.24E+08
Stage 7	1.021	1.85E+08	1.34E+08	6.65E+07	1.26E+08	3.21E+08	2.10E+08	7.68E+07	1.97E+08	7.11E+07	1.55E+08	1.02E+08	1.11E+08
Stage 8	1.655	5.94E+07	4.33E+07	2.65E+07	4.01E+07	7.23E+07	6.04E+07	2.44E+07	5.51E+07	2.25E+07	4.05E+07	2.32E+07	2.61E+07
Stage 9	2.520	2.14E+07	1.61E+07	1.03E+07	1.48E+07	2.12E+07	2.28E+07	9.27E+06	1.96E+07	8.53E+06	1.54E+07	8.61E+06	9.52E+06
Stage 10	4.085	1.31E+07	1.01E+07	6.51E+06	8.94E+06	1.23E+07	1.46E+07	5.99E+06	1.23E+07	5.52E+06	1.01E+07	5.56E+06	6.23E+06
Stage 11	6.560	6.96E+06	5.39E+06	3.08E+06	4.30E+06	6.03E+06	7.49E+06	3.14E+06	6.35E+06	2.75E+06	5.30E+06	2.93E+06	3.13E+06
Stage 12	9.990	2.81E+06	2.27E+06	1.26E+06	1.66E+06	2.22E+06	2.99E+06	1.24E+06	2.33E+06	1.09E+06	2.13E+06	1.30E+06	1.26E+06

Table A4.4: Vehicle 2 particle size distribution data

	Test Order	1	2	3	4	5	6	7	8	9	10	11	12
	Test Number	ML01008321	ML01008341	ML01008358	ML01008371	ML01008387	ML01008409	ML01008507	ML01008584	ML01008608	ML01008633	ML01008677	ML01008685
	Size µm (D50%)	RF02 08	Fuel F	Fuel B	Fuel E	RF02 08	Fuel G	Fuel A	Fuel C	Fuel D	RF02 08	Fuel C	Fuel A
Stage 1	0.063	7.80E+10	7.23E+10	7.50E+10	7.55E+10	7.15E+10	7.23E+10	1.18E+11	5.87E+10	5.95E+10	6.27E+10	5.90E+10	6.38E+10
Stage 2	0.109	4.68E+10	4.06E+10	4.65E+10	4.36E+10	4.11E+10	4.07E+10	1.68E+10	2.94E+10	2.68E+10	3.35E+10	2.95E+10	3.33E+10
Stage 3	0.173	6.05E+10	4.62E+10	6.13E+10	5.38E+10	5.16E+10	5.13E+10	3.39E+10	3.46E+10	3.12E+10	4.22E+10	3.39E+10	3.95E+10
Stage 4	0.267	3.34E+10	2.39E+10	3.71E+10	3.24E+10	3.22E+10	3.18E+10	2.22E+10	2.02E+10	1.80E+10	2.78E+10	2.06E+10	2.59E+10
Stage 5	0.407	7.95E+09	5.02E+09	8.96E+09	7.12E+09	7.37E+09	7.36E+09	5.49E+09	4.57E+09	4.48E+09	7.20E+09	4.85E+09	6.54E+09
Stage 6	0.655	1.58E+09	1.01E+09	2.01E+09	1.55E+09	1.63E+09	1.68E+09	1.12E+09	1.03E+09	1.34E+09	2.31E+09	1.45E+09	1.95E+09
Stage 7	1.021	3.44E+08	2.21E+08	4.20E+08	3.29E+08	3.51E+08	4.21E+08	1.89E+08	2.13E+08	2.54E+08	4.64E+08	3.11E+08	4.16E+08
Stage 8	1.655	7.94E+07	5.26E+07	9.28E+07	7.47E+07	8.35E+07	1.08E+08	3.82E+07	4.87E+07	4.36E+07	8.19E+07	5.57E+07	7.64E+07
Stage 9	2.520	2.19E+07	1.55E+07	2.26E+07	2.01E+07	2.14E+07	2.80E+07	1.09E+07	1.35E+07	1.23E+07	2.21E+07	1.53E+07	2.01E+07
Stage 10	4.085	1.09E+07	8.07E+06	1.08E+07	9.63E+06	9.50E+06	1.24E+07	5.53E+06	6.64E+06	6.24E+06	1.17E+07	7.39E+06	1.01E+07
Stage 11	6.560	5.19E+06	3.91E+06	4.94E+06	4.39E+06	3.82E+06	4.93E+06	2.59E+06	2.71E+06	2.65E+06	5.16E+06	2.89E+06	4.11E+06
Stage 12	9.990	1.99E+06	1.54E+06	2.00E+06	1.74E+06	1.44E+06	1.79E+06	1.03E+06	1.10E+06	1.07E+06	1.84E+06	1.15E+06	1.52E+06

APPENDIX 5: P VALUES FOR CORRELATIONS

NS	P<5%	P<1%	P<0.1%

VEH	Model	Dependent	Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
1	MODEL1	PM_C	Intercept	1	0.00122	0.00019607	6.2	0.0008
	MODEL1	PM_C	OXYGEN	1	-0.00005455	0.000045	-1.21	0.271
1	MODEL2	PM_C	Intercept	1	0.00275	0.00125	2.21	0.0694
	MODEL2	PM_C	E100	1	-0.00002811	0.00002026	-1.39	0.2146
1	MODEL3	FC_C	Intercept	1	8.8519	0.05361	165.12	<.0001
	MODEL3	FC_C	OXYGEN	1	0.06943	0.0123	5.64	0.0013
1	MODEL4	FC_C	Intercept	1	7.30609	0.49013	14.91	<.0001
	MODEL4	FC_C	E100	1	0.02916	0.00797	3.66	0.0106
1	MODEL5	FC_C	Intercept	1	8.85353	0.05354	165.35	<.0001
	MODEL5	FC_C	OXYGEN_COMPOUN	1	0.02207	0.00392	5.62	0.0014
1	MODEL6	FC_C	Intercept	1	15.07954	1.16702	12.92	<.0001
	MODEL6	FC_C	CALORIFIC_VALUE	1	-0.1427	0.02779	-5.13	0.0021
2	MODEL1	PM_C	Intercept	1	0.00166	0.00024345	6.81	0.0005
	MODEL1	PM_C	OXYGEN	1	0.00000161	0.00005588	0.03	0.9779
2	MODEL2	PM_C	Intercept	1	0.00353	0.0014	2.52	0.045
	MODEL2	PM_C	E100	1	-0.00003048	0.00002273	-1.34	0.2285
2	MODEL3	FC_C	Intercept	1	7.53112	0.04304	174.98	<.0001
	MODEL3	FC_C	OXYGEN	1	0.08571	0.00988	8.68	0.0001
2	MODEL4	FC_C	Intercept	1	5.52652	0.43017	12.85	<.0001
	MODEL4	FC_C	E100	1	0.03758	0.007	5.37	0.0017
2	MODEL5	FC_C	Intercept	1	7.55285	0.06973	108.31	<.0001
	MODEL5	FC_C	OXYGEN_COMPOUN	1	0.02541	0.00511	4.97	0.0025
2	MODEL6	FC_C	Intercept	1	15.26325	0.97064	15.72	<.0001
	MODEL6	FC_C	CALORIFIC_VALUE	1	-0.17721	0.02312	-7.67	0.0003

APPENDIX 6:

	Model	Dependent	Variable	DF	Parameter	Standard Error	t	Pr > |t|
1	MODEL1	PN_C_E10	Intercept	1	92.17992	10.12325	9.11	<.0001
	MODEL1	PN_C_E10	OXYGEN	1	-5.47313	1.89941	-2.88	0.028
1	MODEL1	PN_C_E10	Intercept	1	250.88013	27.74635	9.04	0.0001
	MODEL1	PN_C_E10	E100	1	-2.90492	0.42823	-6.78	0.0005
2	MODEL1	PN_C_E10	Intercept	1	220.83376	20.35846	10.85	<.0001
	MODEL1	PN_C_E10	OXYGEN	1	-1.95738	4.55496	-0.43	0.6824
2	MODEL1	PN_C_E10	Intercept	1	426.22313	99.40444	4.29	0.0052
	MODEL1	PN_C_E10	E100	1	-3.46644	1.58712	-2.18	0.0717

APPENDIX 6: FUEL PROPERTIES

		COQ	FROM 2012 GDI VEHICLE STUDY						
		Ref fuel	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E	Fuel F	Fuel G
Gasoline Properties	Units	RF 02 08	PR4938	PR4946	PR4943	PR4944	PR4947	PR4948	PR4949
Name		Ref fuel	Base Fuel	High Octane	E10 Splash	E20 Splash	E10 matched	22% ETBE	E20 matched
Density @ 15°C	kg/m³	748.6	743.7	749.6	747.5	752.1	752.3	741.1	758.3
ASVP	kPa	#N/A	63.0	65.8	71.3	70.3	64.0	63.1	58.3
DVPE	kPa	59.7	57.0	59.7	65.0	64.1	58.0	57.1	52.5
Distillation Temperature [°C]									
IBP	°C	34.7	33.6	31.1	34.6	35.9	36.1	30.9	36.7
T5	°C	#N/A	50.6	47.7	48.8	50.0	50.5	48.6	53.7
T10	°C	51.5	55.8	54.0	52.0	53.2	53.8	54.5	57.8
T20	°C	56.0	63.8	64.3	56.6	58.0	58.6	63.7	63.3
T30	°C	62.9	72.0	74.3	60.8	62.4	62.8	71.5	67.5
T40	°C	78.3	81.5	85.4	64.6	66.3	67.0	78.6	70.5
T50	°C	91.9	92.4	99.1	75.2	69.7	90.2	86.2	72.7
T60	°C	103.4	103.8	113.4	99.3	72.6	108.7	95.6	84.5
T70	°C	114.1	115.7	127.0	112.5	96.6	122.4	109.6	117.9
T80	°C	126.3	130.1	144.5	127.3	123.0	140.0	128.7	134.2
T90	°C	151.4	154.5	165.5	152.1	148.6	162.5	149.7	154.8
T95	°C	#N/A	172.0	177.2	171.3	167.1	174.4	165.3	171.8
FBP	°C	195.3	187.2	188.6	185.6	183.6	188.3	177.2	186.4
Recovery	% vol	#N/A	97.2	96.6	97.3	97.4	97.3	96.9	97.1
Residue	% vol	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Loss	% vol	#N/A	1.8	2.4	1.7	1.6	1.7	2.1	1.9
E50	% vol	#N/A	6.4	9.2	8.4	6.6	6.1	8.1	4.5
E70	% vol	34.6	29.4	28.3	49.6	52.5	45.1	30.1	40.0
E100	% vol	57	58.8	53.0	62.3	72.0	56.1	65.9	64.4
E125	% vol	#N/A	78.8	70.9	80.6	82.8	73.4	80.3	76.9
E150	% vol	89.6	90.2	85.4	91.1	92.0	86.0	92.2	89.6
E180	% vol	#N/A	97.7	97.9	97.9	97.8	97.8	#N/A	98.0
VLI		#N/A	776	765	997	1008	896	782	805.0
Sulphur	mg/kg	#N/A	10	6	8	7	#N/A	9	7
MON, corrected	-	85.3	85.3	87.6	86.9	87.9	85.6	88.2	87.6
RON, corrected	-	95	95.0	98.0	98.4	101.2	95.0	97.8	99.6
PIONA									
Paraffins	% vol	#N/A	49.6	36.8	37.4	40.7	39.6	36.2	41.7
Olefins	% vol	6.5	6.4	6.4	5.5	4.8	8.0	6.6	3.1
Naphthenes	% vol	#N/A	12.7	17.1	16.4	10.7	10.5	11.9	6.4
Naphthenes - unsaturated	% vol	#N/A	0.4	0.1	0.1	0.1	0.1	<0.1	0.1
Polynaphthenes	% vol	#N/A	<0.1	<0.1	#N/A	0.0	#N/A	<0.1	<0.1
Aromatics	% vol	31.7	30.4	29.5	28.7	23.2	28.3	19.7	26.6
C11+ HC	% vol	#N/A	0.5	10.1	2.1	0.8	4.0	3.3	2.2
Oxygen Compounds	% vol	4.7	0.0	0.0	9.8	19.7	9.5	22.3	19.9
Saturated HC	% vol	61.8	62.3	53.9	53.8	51.4	50.1	48.1	48.1
Unsaturated HC	% vol	#N/A	6.8	6.5	5.6	4.9	8.1	6.7	3.2

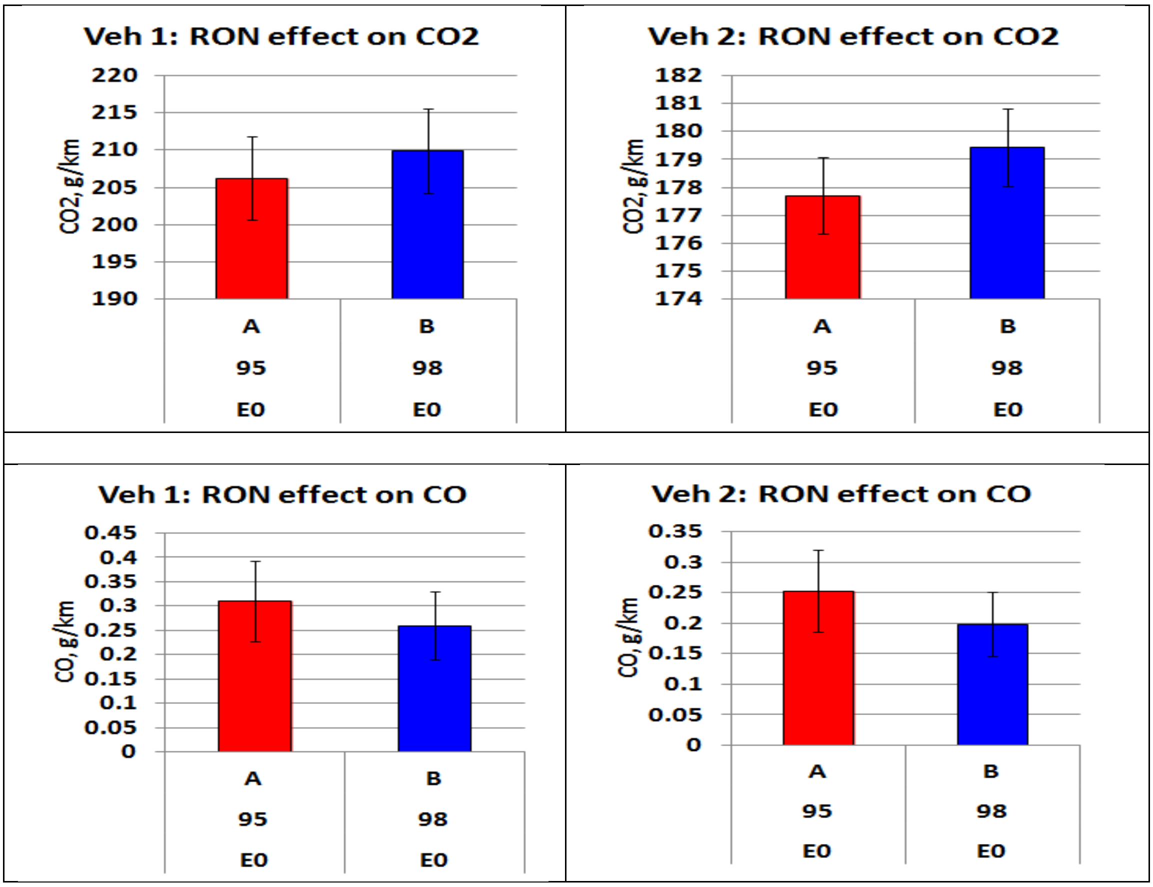
		COQ	FROM 2012 GDI VEHICLE STUDY						
		Ref fuel	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E	Fuel F	Fuel G
Gasoline Properties	Units	RF 02 08	PR4938	PR4946	PR4943	PR4944	PR4947	PR4948	PR4949
Name		Ref fuel	Base Fuel	High Octane	E10 Splash	E20 Splash	E10 matched	22% ETBE	E20 matched
Carbon	% mass	85.62	86.50	86.71	83.04	79.27	83.20	82.63	79.30
Hydrogen	% mass	12.67	13.50	13.29	13.21	13.48	13.17	13.66	13.26
Oxygen	% mass	1.71	0.00	0.00	3.75	7.25	3.63	3.71	7.44
H/C	-	2.687	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Calorific Value	MJ/kg	42.92	43.49	43.70	41.69	40.21	41.76	41.95	40.04
Calorific Value, Gross	MJ/kg	45.22	46.32	46.54	44.40	42.82	44.47	44.68	42.64
GC Alcohols									
Ethanol	%mass	#N/A	#N/A	#N/A	10.5	20.8	10.1	0.0	20.7
Ethanol	%vol	#N/A	#N/A	#N/A	9.8	19.7	9.6	0.0	19.8
ETBE	%mass	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	22.1	#N/A
ETBE	%vol	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	21.9	#N/A

APPENDIX 7: ADDITIONAL PROPERTY EFFECTS

A7.1 Octane Effects at Zero Oxygen

No effects on emissions or fuel consumption which were statistically significant in both vehicles that could be isolated to octane quality were apparent. Parameters where there was either a similar directional signal in both cars or a significant difference in one car are plotted below..1

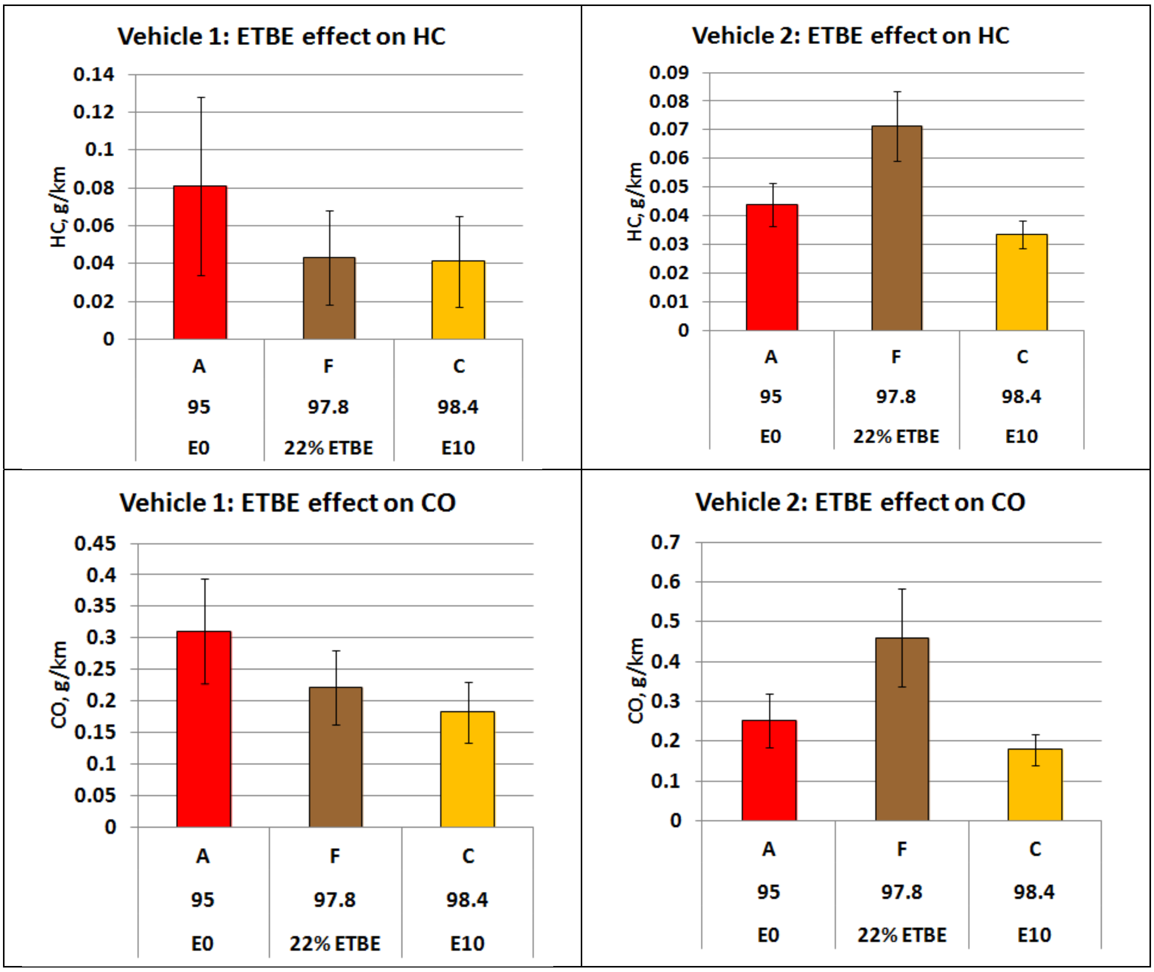
Figure A7.1 RON effects on CO2 and CO



A7.2 Oxygenate Type Effects at Iso-Oxygen

No effects were apparent on emissions or fuel consumption which were statistically significant in both vehicles that could be isolated to oxygenate type (ETBE vs Ethanol). Parameters where there was either a similar directional signal in both cars or a significant difference in one car are plotted below. Although the E0 base fuel is included in the plots below to allow reference between the oxygenates and the hydrocarbon fuel, the key comparison is between the two oxygenate types at iso-oxygen and this is the focus of the comments in this section.

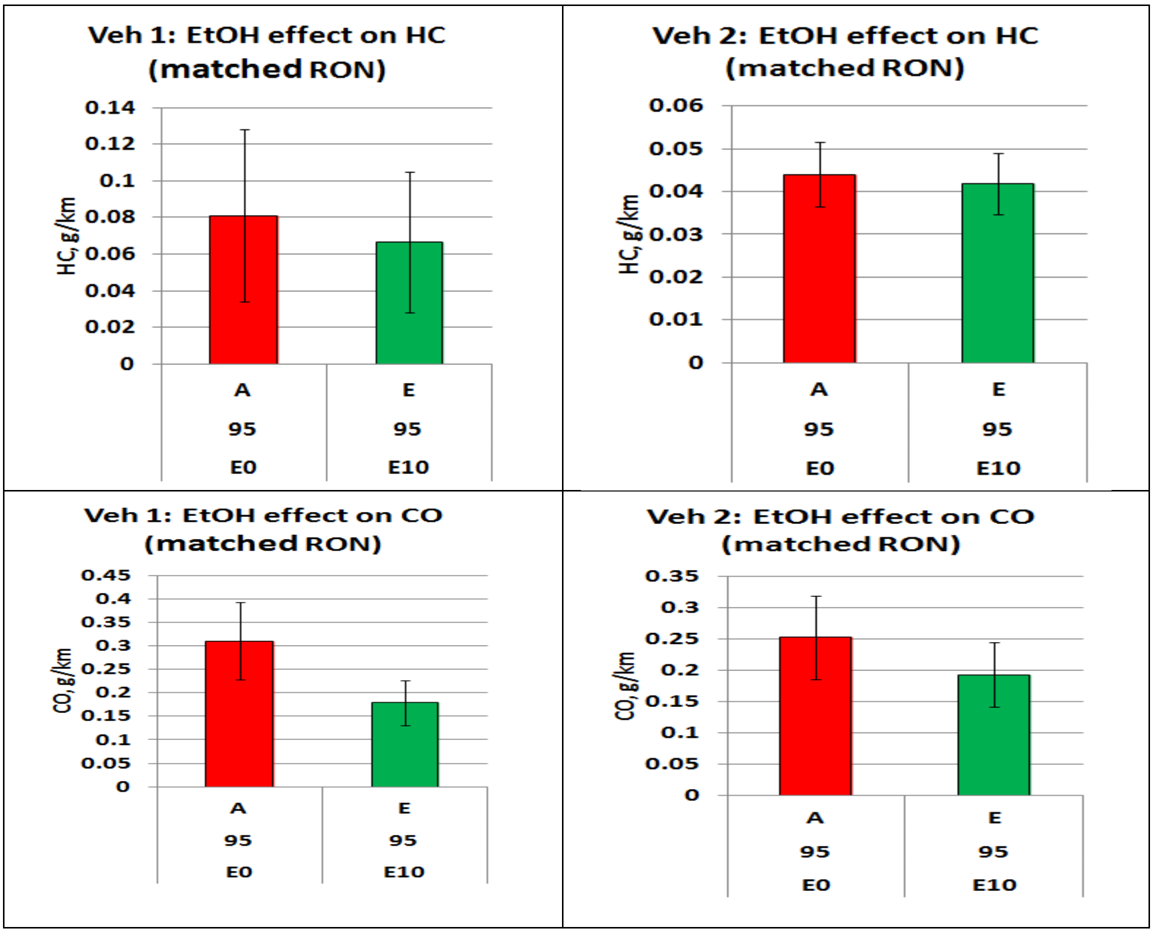
Figure A7.2 ETBE effects on HC and CO



A7.3 Ethanol Effects at Iso-Octane

It was planned to compare E0 vs E10 vs E20 oxygenate effects at iso-octane, however the E20 'matched' fuel was not close enough to E0 in terms of octane to include this as a viable comparison. No effects were apparent on emissions or fuel consumption which were statistically significant in both vehicles that could be isolated to oxygenate at iso-octane. Parameters where there was either a similar directional signal in both cars or a significant difference in one car are plotted below.

Figure A7.3 Ethanol effects on HC and CO



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