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Gasoline volatility and vehicle performance

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ABSTRACT

A six vehicle study has been completed to investigate the impact of changes in the volatility characteristics of unleaded gasoline containing 10% v/v ethanol on regulated exhaust and evaporative emissions and on hot and cold weather vehicle driveability performance. The vehicles selected for this study were representative of the current EU fleet, met or exceeded Euro 4 emissions certification, spanned the range from upper medium to small vehicle classes, were compatible with 10% v/v ethanol according to the manufacturer's warranty information, and included two modern gasoline Direct Injection Spark Ignition engine types. Results included regulated emissions measured over the New European Driving Cycle (NEDC) at +23°C and -7°C, evaporative emissions according to the European regulatory procedure, cold engine starting and idling at -20°C, and Hot Weather Driveability performance at +40°C.

Unleaded gasolines containing 10% v/v ethanol (E10 gasolines) were specially blended for this study to investigate changes in volatility, specifically in the E70[1] and E100[2] distillation values. The Dry Vapour Pressure Equivalent (DVPE) of all test fuels targeted either summer (60kPa) or winter (100kPa) grade maximum values. The DVPE of the test fuel was selected to be consistent with the type of vehicle test that was completed.

To investigate the impact of volatility changes on vehicle emissions and performance, 'Baseline' E10 gasolines were evaluated having E70 and E100 distillation values at the current maximum limits allowed by the EN 228 gasoline specification. Results on these 'Baseline' gasolines were then compared to fuels having relaxed volatility, that is, where the E70 and E100 values were higher than the maximum limits allowed by the EN 228 specification. These volatility values were selected based on a proposal that CONCAWE has made to the European Committee for Standardisation to relax the volatility specifications for future E10 gasoline blends.

For most vehicle tests, results on the 'Baseline' gasoline were compared to those on a 'Step 2' gasoline in which the $E70_{max}$ and $E100_{max}$ specifications were relaxed by +10% v/v and +4% v/v, respectively. Some tests were also conducted on 'Step 1' gasolines in which the $E70_{max}$ and $E100_{max}$ specifications were relaxed by +4% v/v and +2% v/v, respectively. The 'Step 1' gasolines were consistent with CONCAWE's proposal to CEN for relaxed volatility specifications while tests on the 'Step 2' gasolines represented a more severe test for vehicle emissions and driveability performance.

All six vehicles were able to complete the required driving cycles on all of the test fuels with no false starts, no misfires, no stalls, no failures, and no faults recorded by the On-Board Diagnostics (OBD) systems. Overall, the impacts of gasoline volatility on emissions and driveability performance were small compared to vehicle-to-vehicle differences.

[1] E70 is the percentage of the gasoline sample that evaporates at 70°C
[2] E100 is the percentage of the gasoline sample that evaporates at 100°C

KEYWORDS

Unleaded gasoline, volatility, ethanol, direct injection spark ignition, Euro 4 and 5 emissions limits, New European Driving Cycle

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SUMMARY

Today's European gasoline specification (European Norm EN 228) specifies the volatility requirements for gasoline in order to ensure good performance of vehicles in real world driving conditions. These requirements were put in place following extensive technical studies in the 1990's at a time when vehicles were more sensitive to volatility than they are today and when blending of oxygenates, like ethanol, was not widespread. Different gasoline volatility classes are included in the EN 228 specification that depend on climatic conditions and include minimum and maximum volatility limits for summer and winter gasolines as well as additional limits for seasonal transitions.

Blending ethanol into gasoline at low concentrations alters the volatility characteristics of the resulting blend and the fuel refining and blending process must account for this effect. In addition to increasing the vapour pressure of the ethanol/gasoline blend, ethanol also changes the shape of the blend's distillation curve. This has the potential to impact the vehicle's regulated emissions and driveability performance in cold and hot weather. Furthermore, any change in the blend's distillation characteristics due to ethanol addition must be compensated in the refinery by changing the composition of the hydrocarbon-only gasoline mixture into which the ethanol is ultimately blended.

After completing an extensive literature review on various vehicle performance studies on gasoline/ethanol blends [1], CONCAWE proposed a relaxation in the volatility class maximum limits that are specified in EN 228. To investigate the impact of this proposal on modern European vehicles and validate the conclusions of the literature review, a six vehicle study has been completed to assess the effect of gasoline volatility and ethanol on regulated exhaust and evaporative emissions and on the hot and cold weather driveability performance of modern gasoline vehicles (Euro 4+). These results included regulated emissions measured over the New European Driving Cycle (NEDC) at +23°C and -7°C, evaporative emissions according to the European procedure, cold engine starting and idling at -20°C, and Hot Weather Driveability (HWD) performance at +40°C.

The vehicles selected for this study were representative of the current EU fleet, were certified to Euro 4+ emissions levels, spanned the range from upper medium to small vehicle classes, were compatible with 10% v/v ethanol according to the manufacturer's warranty information, and included two modern gasoline Direct Injection Spark Ignition (DISI) engine types.

Summer and winter grade gasolines containing 10% v/v ethanol were specially blended for this study that had volatility specifications at today's EN 228 maximum limits and at higher limits consistent with CONCAWE's volatility relaxation proposal. The vapour pressures (measured as Dry Vapour Pressure Equivalent (DVPE)) targeted summer grade gasolines with a maximum 60 kPa DVPE and winter grade gasolines with a maximum 100 kPa DVPE. The DVPE of the test fuel was selected to be consistent with the type of vehicle test that was completed.

The results show that all vehicles were able to complete the required driving cycles on all fuels with no false starts, no misfires, no stalls, no failures, and no faults recorded by the On-Board Diagnostics (OBD) system. Overall, the impacts of gasoline volatility on regulated emissions and driveability performance were small compared to vehicle-to-vehicle differences.

1 INTRODUCTION

1.1 BACKGROUND TO GASOLINE VOLATILITY AND VEHICLE PERFORMANCE

The volatility requirements for European gasoline are specified in the European Norm EN 228 [2] and include the DVPE and several parameters that describe the distillation curve as measured in the laboratory by manual or automated equipment [3]. These parameters specify the percentage of the gasoline that evaporates at 70°C (E70), 100°C (E100), and 150°C (E150) as well as Final Boiling Point (FBP) and distillation residue. The Vapour Lock Index (VLI) is also calculated from the DVPE and E70 parameters and limits the allowed variation in these parameters during spring and autumn seasonal transitions.

These parameters define various volatility classes (Table 3 in EN 228) that vary with European climatic and geographical conditions. Each class includes minimum and maximum values for DVPE, E70, and E100 and maximum values for E150, FBP, distillation residue, and calculated VLI. Importantly, the class limits are intended to ensure that the starting and running performance of the customer's vehicle is acceptable over the full range of cold and hot conditions that are typical of each European country throughout the year. For this reason, Member States are responsible for specifying which volatility class or classes apply to their country during winter, summer, and seasonal transitions based on recommendations from an analysis of climatic and geographical conditions by the Member State's National Standardisation Body (NSB).

Today's EN 228 volatility class limits resulted from industry discussions that occurred in the late 1990's based on a detailed analysis of vehicle emissions and performance data collected during that decade. These specifications were later adopted by the European Committee for Standardisation (CEN) in the 2000 time period. The Fuel Quality Directive (FQD, 2009/30/EC) [4] limits the DVPE of market gasoline while allowing Member States to request derogations in DVPE requirements depending upon their particular climatic and air quality conditions.

Since 2000, there have been significant changes in the gasoline vehicle's fuelling system and other engine hardware. For example, carburettors, which were well known to be sensitive to fuel volatility, have largely been replaced by multipoint injection (MPI) fuel systems that are much less sensitive to fuel effects. Today, MPI-equipped engines are seeing increasing competition from gasoline Direct Injection Spark Ignition (DISI) engines in which the fuel is injected directly into the combustion chamber. Although these DISI engines are increasing in the on-road fleet, they are still relatively new and have not been extensively tested on a wide range of fuel types.

Tighter regulated and evaporative emissions requirements have also been mandated in order to improve local air quality. This is resulting in increasing sophistication in engine hardware, engine management systems (EMS), and exhaust aftertreatment. Longer-term performance and the greater use of OBD systems have also been implemented on modern vehicles, especially those complying with Euro 4+ emissions limits.

On the fuel side, the sulphur content of EN 228 gasoline is now less than 10 parts-per-million (ppm) which has enabled exhaust aftertreatment systems to achieve very low regulated emissions over the life of the vehicle. The change in Euro emissions limits over time for gasoline vehicles is shown in **Table 1.1**. Regulated emissions over the New European Driving Cycle (NEDC) include carbon monoxide (CO), total (THC) and non-methane hydrocarbons (NMHC), and nitrogen oxides (NOx). In addition, a particulate matter (PM) limit is now included for DISI engines and a particle number (PN) limit is expected for these engine types with the introduction of Euro 6 emissions limits in 2014.

Table 1.1 European emission standards for gasoline passenger cars over the NEDC with emissions stated in grams/kilometre [5]

Standard	Effective (TA)	CO	THC	NMHC	NOx	HC+NOx	PM	PN#
Euro 1	1992	2.72				0.97		
Euro 2	1996	2.2				0.5		
Euro 3	2000	2.3	0.2		0.15			
Euro 4	2005	1.0	0.1		0.08			
Euro 5a	2009	1.0	0.1	0.068	0.06		0.005[a]	
Euro 5b	2011	1.0	0.1	0.068	0.06		0.0045[a]	
Euro 6	2014	1.0	0.1	0.068	0.06		0.0045[a]	TBC[a]

[a] for vehicles with DISI engines

At the same time, oxygenated blending components are increasingly used to increase the renewable energy content of road transport fuels. The Renewable Energy Directive (RED, 2009/28/EC) [6] mandates that 10% of sustainably-produced renewable energy must be incorporated into transport fuels by 2020. Only fairly common products, such as ethanol from sugar fermentation and fatty acid methyl esters (FAME) esterified from natural oils, are likely to be available in sufficient quantities to meet the 2020 mandate.

For gasoline blending in Europe, ethanol, ethers (such as Ethyl Tertiary-Butyl Ether (ETBE)), and other oxygenates can be used. The current EN 228 specification allows up to a maximum of 2.7 wt% oxygen and specifies maximum contents of 5% v/v ethanol (commonly referred to as ‘E5’) or 15% v/v ether. These oxygenates can be blended separately or together as long as the maximum oxygen content does not exceed 2.7 wt%. CEN’s Technical Committee 19 (TC19) is working to increase the maximum limit to 3.7 wt% oxygen, corresponding to a maximum 10% v/v ethanol (‘E10’), in line with the FQD legislation [4].

Numerous studies have now been conducted in many countries to support the use of E10 and higher ethanol concentrations in gasoline. These include analytical blending studies and vehicle testing to investigate the impact of higher oxygenate concentrations on regulated emissions, evaporative emissions, and vehicle performance under hot and cold temperature conditions. The vehicle studies have been driven by the realisation that higher ethanol concentrations dramatically change the distillation curve for the gasoline/oxygenate blend and, therefore, have the potential to change the performance of current and future vehicles using these blends.

In 2009, CONCAWE completed a literature review [1] summarizing approximately 20 years of published reports on the impact of fuel volatility on vehicle driveability performance under hot and cold weather conditions. These published reports included studies conducted in Europe, the USA, and Australia using a wide range of vehicle types and test conditions. Seven major studies on Hot Weather Driveability (HWD) and eleven major studies on Cold Weather Driveability (CWD) vehicle performance were analysed.

Hot Weather Driveability (HWD) of vehicles was found to be affected most strongly by the "front-end" volatility of gasoline, especially the DVPE and E70 values. According to the published literature, modern vehicles using MPI technology are much less susceptible to HWD problems compared to older carburetted engines. However, two early technology DISI vehicles tested in a 2002 CONCAWE/GFC programme did show more driveability demerits on high volatility ethanol/gasoline blends [7,8].

Extensive testing completed by the Coordinating Research Council (CRC) in the USA has derived alternative volatility properties for gasoline that correlate with HWD performance on ethanol/gasoline blends but these have not yet been incorporated into US gasoline specifications. Current EN 228 specifications appear to be adequate to control HWD performance in European vehicles but some increase in the $E70_{max}$ limits may be justified in order to produce gasolines containing ethanol at 10% v/v and higher.

Cold Weather Driveability (CWD) is affected most strongly by mid-range volatility, defined in Europe by the E100 volatility parameter. CWD performance is an issue for modern vehicles because it is linked to exhaust emissions under cold starting conditions. For splash blends of ethanol in gasoline, CWD performance was found to improve somewhat due to the higher volatility of the ethanol/gasoline blend. CWD performance degraded, however, when the ethanol/gasoline blend was at the same volatility level as a hydrocarbon-only fuel. This was because of ethanol's higher latent heat of vaporisation and a leaning effect on the air-fuel ratio (AFR) due to ethanol under open-loop engine conditions. Open-loop conditions typically apply in the first few hundred seconds after starting a cold engine before the exhaust aftertreatment system has reached a minimum operating temperature.

The current E100 limits in the EN 228 gasoline specification are fixed for all volatility classes. To properly control CWD, however, the minimum E100 volatility limits should vary with ambient temperature and should include an ethanol offset. For example, the CRC in the USA has developed new fuel parameters, called "Driveability Indices" (DIs), that include ethanol offset terms, but these only apply to US vehicles. Ideally, a European DI should be developed on modern European vehicles and applied in future gasoline specifications.

In the USA, the gasoline specification (ASTM D4814 [9]) already recognises the impact of ethanol blending on distillation properties. The specification allows a relaxation in the T50[1] value from 77°C (170°F) to 66°C (150°F) when 1 to 10% v/v ethanol is blended into the gasoline. (A T50 of 66°C is roughly equivalent to an E70 value of 55-60%, that is, about 5-10% higher than the current E70 maximum values in the EN 228 specification.) Ethanol/gasoline blends having T50 values at or near 66°C are widely available in the US market today with no reported vehicle problems. In addition, the gasoline vehicle technology is essentially the same in the USA as it is in Europe so that it is unlikely that a comparable relaxation in the EN 228 E70 specification would result in vehicle problems in Europe.

Based on these studies, CONCAWE's literature review [1] concluded that relaxing the $E70_{max}$ and $E100_{max}$ volatility limits is not likely to significantly impact the hot and

[1] T50 is the temperature at which 50% of the sample has evaporated

cold weather driveability performance of modern vehicles. This literature review was later combined with a detailed assessment of the impact of ethanol in gasoline on regulated and unregulated emissions, including particulate emissions [10]. Because some of the vehicles in these published studies represented older, non-European technology, however, there remained open questions whether a relaxation in gasoline volatility specifications would increase the risk of vehicle performance or customer satisfaction problems in Europe.

1.1.1 BEP525 Study

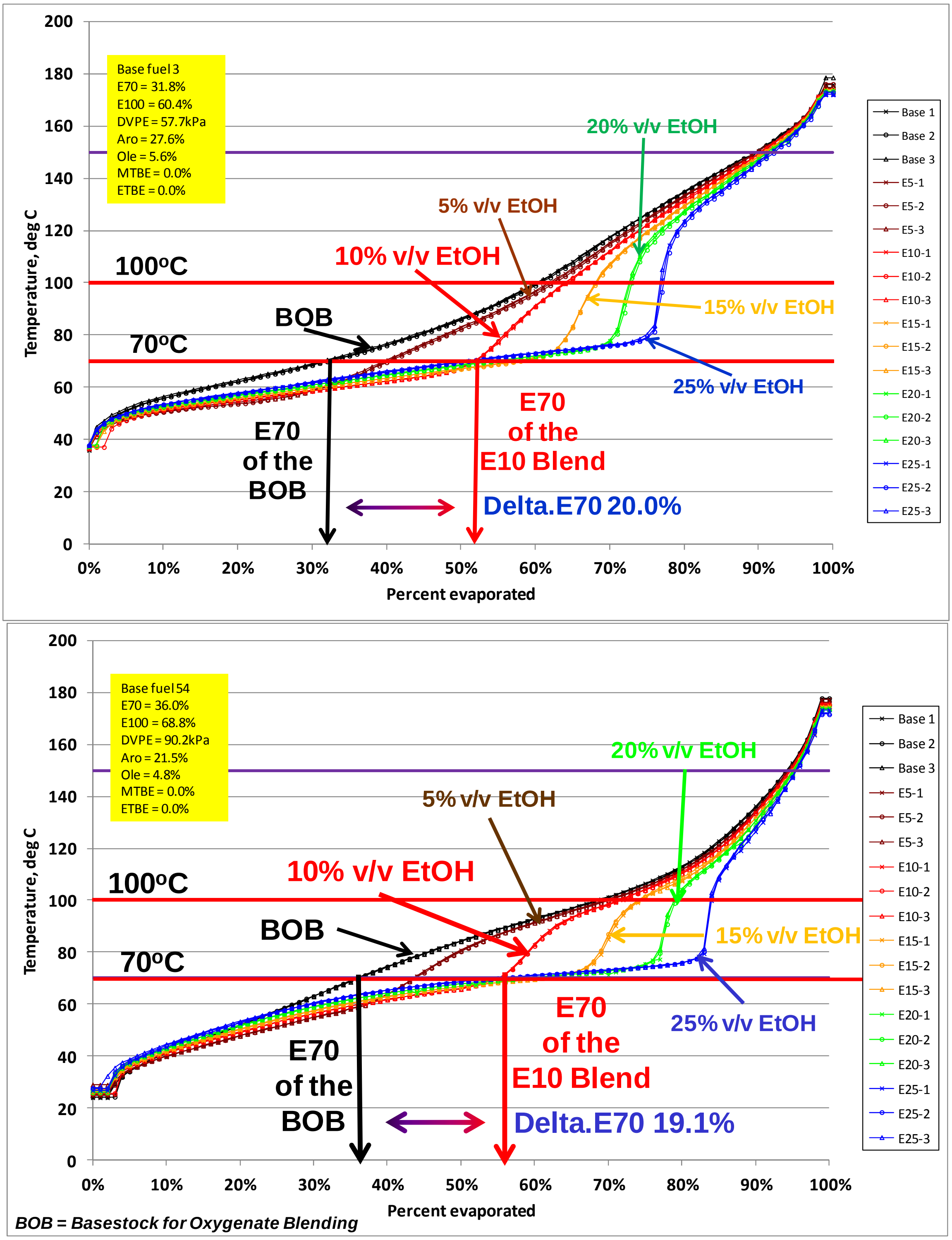
To better understand the impact of ethanol on gasoline blending and volatility, the literature study cited above [1,10] also reviewed published analytical data on ethanol/gasoline blends. A clear conclusion from this review was that there is not a consistent body of publicly available analytical data that adequately describes the impact of ethanol blending on the properties of ethanol/gasoline blends. More data are available at the 5 and 10% v/v ethanol levels than at higher levels but conclusions could only be reached by pooling the data from various unrelated studies.

Although informative, this data pooling approach introduced uncertainties regarding data quality, especially for blending and analytical data that had been obtained from many different studies and laboratories. For example, some studies reported volatility data using parameters different from those used in European specifications while other studies did not report blend composition data at all. In addition, the fuel properties investigated were generally limited to those considered to be ‘realistic’ for the marketplace where the research was being done. These factors limited the ability to quantitatively assess the impact of molecular composition (aromatics, olefins, etc.) on blending and volatility changes.

For this reason, CONCAWE and Shell Global Solutions UK collaborated on an EC-funded project called the BEP525 Study [10]. The objective of this study was to complete an analytical blending study to measure the impact of different ethanol levels on the properties of ethanol/gasoline blends. In this study, 60 base gasolines were designed, blended from refinery blend streams (including two different ethers), and characterized using EN 228 test methods. Ethanol was then splash-blended into these base gasolines at five concentrations from 5 to 25% v/v ethanol. The 60 base gasolines and 300 ethanol/gasoline blends were then fully characterized for changes in DVPE, volatility, and molecular composition.

Two examples from the BEP525 Study are shown in **Figure 1.1**. In these figures, the distillation curve for the hydrocarbon-only base gasoline, called the Basestock for Oxygenate Blending (BOB), is shown in black while those for the ethanol blends are shown in different colours. Three different measurements of the distillation curve for each sample are superimposed in this figure, as indicated by the legend on the right-hand side of each figure. The top curves are for a 57.7 kPa DVPE BOB (summer class) while the bottom curves are for a 90.2 kPa DVPE BOB (winter class). The effect of ethanol on the E70 value and the shape of the distillation curve are especially large at 10% v/v ethanol but the effects are substantial at all ethanol levels.

Figure 1.1 Examples of gasoline distillation curves as a function of increasing ethanol concentration for BOBs having low (top) and high (bottom) DVPEs



Using the bottom figure as an example, the E70 of the BOB is 36.0%, that is about 36% of the hydrocarbon-only gasoline evaporates in the distillation apparatus when the measurement temperature has reached 70°C. This E70 value is almost in the middle of the allowed EN 228 volatility class range, which is between 22 and 50% for winter class gasoline.

The other distillation curves in these figures show the impact of increasing ethanol content, from 5 to 25% v/v, on the E70 and E100 values. For example, again in the bottom figure, blending 10% v/v ethanol into the BOB increases the E70 of the ethanol/gasoline blend to about 55%. This Delta.E70 is 19.1% higher than that of the BOB and about 5% higher than the maximum E70 allowed in the EN 228 specification for winter class gasolines. Delta.E70 represents the difference between the E70 of the ethanol/gasoline blend at a particular ethanol concentration and the E70 of the corresponding BOB.

The results of the BEP525 Study show how dramatically the addition of ethanol impacts the volatility of ethanol/gasoline blends. Although this effect has been well recognized for DVPE for many years, the effect of increasing ethanol concentration on E70 and E100 was less well understood. **Table 1.2** summarizes the range of values that were measured in the BEP525 Study for differences from the BOB for DVPE, E70, and E100 with increasing ethanol concentration. The range of values for Delta.DVPE, Delta.E70, and Delta.E100 is based on the largest and smallest values observed for all 360 BOBs and ethanol blends.

Table 1.2 Ranges of measured Delta.DVPE, Delta.E70, and Delta.E100 values at each ethanol concentration from the BEP525 Study [10]

Ethanol Concentration	Delta.DVPE	Delta.E70	Delta.E100
5% v/v	+1 to +8kPa	+2 to +10%	0 to +5%
10% v/v	0 to +9kPa	+6 to +20%	+2 to +11%
15% v/v	-2 to +8kPa	+3 to +26%	+3 to +17%
20% v/v	-3 to +7kPa	0 to +24%	+6 to +22%
25% v/v	-10 to +7kPa	-4 to +20%	+9 to +28%

Some modelling work was also reported in the study that highlighted the complex relationships between fuel composition and volatility. More work should be done to better understand these relationships.

For fuel suppliers, these changes in DVPE, E70, and E100 with ethanol blending are important because they must be anticipated in refining, fuel blending, and fuel distribution and supply in order to ensure that the final fuel blends dispensed at the service station are in compliance with all of the prevailing specifications.

1.1.2 Precision of E70 and E100 Measurements

In Section 2 and Appendix 5 of reference [10], the effect of the change in shape of the distillation curve on the precision of the E70 measurement was investigated. The preliminary analysis showed that it is difficult to obtain accurate values for E70 in fuels having high ethanol concentrations. This is because the distillation curves of the ethanol/gasoline blends are unusually flat in the 70-80°C distillation range due to the formation of azeotropes (constant boiling point mixtures) between ethanol and the hydrocarbons comprising the blends. The E70 values are especially affected because of the similarity of the specification temperature (70°C) and the normal boiling point of ethanol (78.4°C). Until all of the ethanol has evaporated from the blend, the distillation curve remains essentially flat, increasing the E70 value. Similar but smaller increases in the E100 distillation values are observed with increasing ethanol content.

In [10], the E70 and E100 values for BOBs and ethanol/gasoline blends were estimated from distillation curves that had been measured in triplicate using a PAC OptiDist™ Analyser. The measurements were completed according to the EN ISO 3405 standard [3] using the automated distillation apparatus method. A new version of this standard was published in 2011 [11] with a revised precision statement based on a 2006 inter-laboratory study. This study showed that the precision of the automated distillation measurement method has improved. For this reason, the analysis of the repeatability 'r'[2] and reproducibility 'R'[3] of E70 and E100 given in Appendix 5 of [10] has been investigated further by reanalysing the data from [10] using the new precision statement from [11].

ISO 3405 [11] and **Appendix 8** explain how the precision of E70 measurements can be estimated from the precision of the corresponding T_{xx} numbers[4], where xx = the E70 value, and the slopes of the distillation curves at 70°C. To assess the impact of ethanol blending on the E70 precision, the slopes at the E70 point were estimated for each of the 1,080 measured distillation curves from the BEP525 Study [10] (omitting any curves that were missing or non-monotonic at 70°C). This allowed the corresponding repeatability and reproducibility figures for E70 to be derived from the formulae in the 2011 ISO 3405 precision statement. The calculated values for E70 are shown below for the various base fuels and their ethanol blends. Similar analyses were completed for the E100 values from the same distillation curves.

The results of these analyses are shown in **Figures 1.2** and **1.3** for the repeatability and reproducibility, respectively, of the E70 measurement. In each figure, the six histograms show the variation in r and R values of E70 measurements for the BOBs (upper left) and the five different ethanol concentrations.

[2] Repeatability 'r': The value equal to or below which the absolute difference between two single test results on identical material obtained by the same operator at the same laboratory using the same equipment in a short interval of time may be expected to lie with a probability of 95%.

[3] Reproducibility 'R': The value equal to or below which the absolute difference between two single test results on identical material obtained by operators in different laboratories using the standardized test method may be expected to lie with a probability of 95%.

[4] T_{xx} is the temperature at which xx% v/v of the sample has evaporated.

Figure 1.2 Reanalysis of the repeatability ('r') of E70 values for BOBs and ethanol blends from the BEP525 Study as a function of increasing ethanol concentration

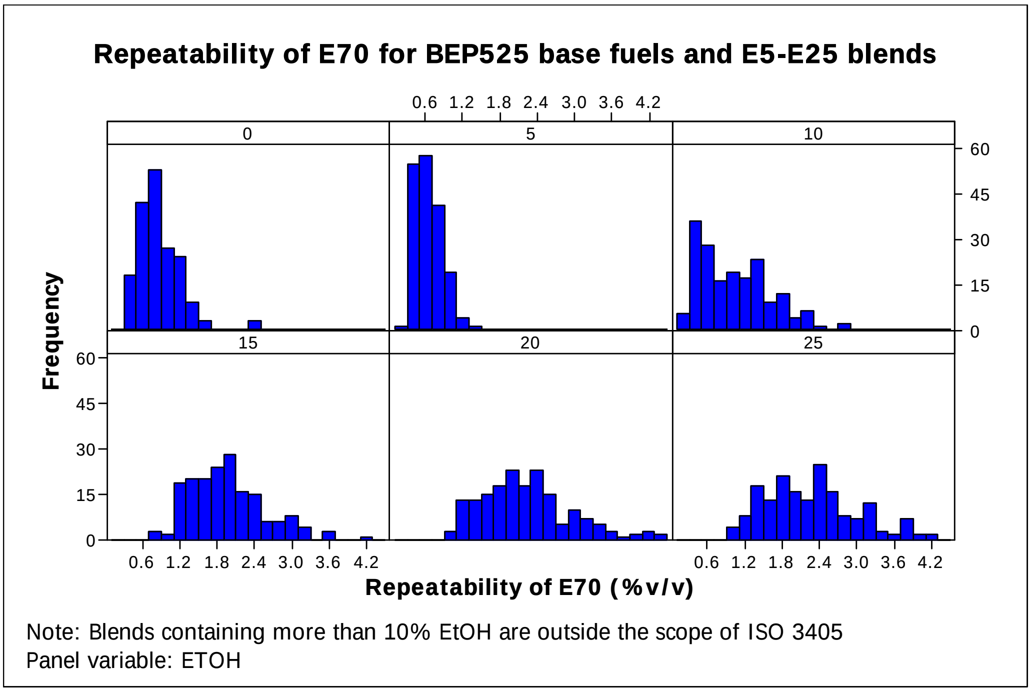
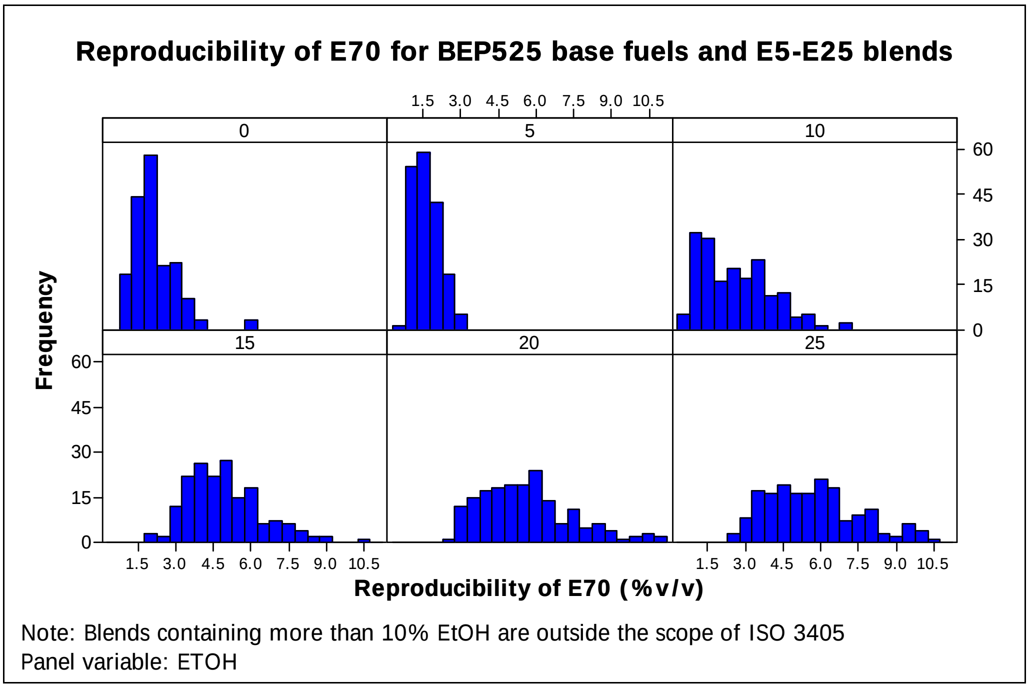


Figure 1.3 Reanalysis of the reproducibility ('R') of E70 values for BOBs and ethanol blends from the BEP525 Study as a function of increasing ethanol concentration. Note the change in x-axis scale compared to **Figure 1.2**.



From **Figure 1.3**, it can be seen that the reproducibility of the E70 measurement generally gets worse as the ethanol concentration increases because the distillation curves are flatter and less precisely defined at the 70°C point. Interestingly, however, the precision of the E70 measurement is slightly better for E5 blends than it is for BOBs and higher ethanol blends. This is because the slopes of the distillation curves at 70°C tend to be slightly steeper at 5% v/v ethanol, as shown in **Figure 1.1**.

The average precision values at each ethanol concentration are summarised in **Table 1.3**.

Table 1.3 Calculated E70 and E100 repeatability and reproducibility values as a function of increasing ethanol concentration

Ethanol Content	Repeatability 'r'		Reproducibility 'R'	
(% v/v)	E70	E100	E70	E100
0	0.87	0.58	2.16	1.48
5	0.64	0.53	1.60	1.35
10	1.02	0.40	2.55	1.03
15	1.96	0.24	4.93	0.60
20	2.24	0.14	5.63	0.36
25	2.27	0.11	5.70	0.28

According to ISO 3405 [11]:

Measurements of E70 and E100 are out of scope at these ethanol contents
Measurements of E70 and E100 are out of scope at these ethanol contents and the estimates of 'r' and 'R' are unreliable[5]

Annex C of ISO 3405 actually quotes a single reproducibility value of 2.7% v/v for E70 and 2.2% v/v for E100. It is clear from the above histograms, however, that a single value is not appropriate for the wide range of BOBs and ethanol/gasoline blends that were studied in the BEP525 Study. It should be noted that many of the 60 BOBs and 300 ethanol/gasoline blends that were evaluated in this study are outside the EN 228 limits for one or more specification parameter.

The values in **Table 1.3** show that the reproducibility of E70 measurements is about 18% worse for the 10% v/v ethanol blends than for the corresponding BOBs because of the flattening of the distillation curve with ethanol addition. The E100 measurements pose less of a problem because the slopes of the distillation curves are generally steeper at 100°C, regardless of the ethanol concentration. In fact, the repeatability and reproducibility of E100 become smaller as the ethanol concentration increases. More details on this analysis can be found in **Appendix 8**.

Because the maximum and minimum volatility limits cannot be exceeded for the gasolines dispensed at service stations, less precision in the volatility measurement must be compensated in the refining and oxygenate blending process. The repeatability and reproducibility values shown in **Table 1.3** will be an important consideration for ethanol blending above 10% v/v.

[5] The scope of the ISO 3405 precision statement limits gasolines to those with oxygenates up to 10% v/v ethanol or MTBE. So, strictly speaking, the 30 base fuels from the BEP525 Study with 11% or 22% MTBE or ETBE and all of their ethanol blends are also outside the scope of this precision statement.

Future work should investigate other measures of volatility that would be more precise and more appropriate for gasoline containing higher ethanol concentrations. Since vehicle driveability performance is related to fuel volatility, more work will also be needed to relate these other measures of volatility to hot and cold weather driveability performance in modern vehicles.

1.1.3 CONCAWE's Proposal for Volatility Relaxation

Because all of the EN 228 specifications must be met for the gasoline dispensed at the service station, any increase in the volatility of the market-ready ethanol/gasoline blend due to ethanol must be compensated by reducing the volatility properties of the BOB. Reducing the DVPE and other volatility properties of the BOB can have a manufacturing and financial impact on those refineries that tend to produce gasolines having above average volatility properties for the BOB.

The impact of ethanol on DVPE was immediately recognized by the European Commission in 2009 and DVPE requirements were maintained in the updated FQD [4] in order to mitigate vehicle-related evaporative emissions. The effect of ethanol on the other volatility parameters, such as E70 and E100, was less well understood, however, and are being addressed by CEN/TC19.

In 2009, CONCAWE initially raised a concern with CEN/TC19 Working Group 21 (WG21), responsible for the EN 228 gasoline specification, regarding the impact of higher ethanol blending levels on the distillation profile of the ethanol/gasoline blend and, therefore, on the volatility limits. At the time, very few fuel suppliers were preparing for broad-market E10 blending except for those who were already manufacturing BOBs for export markets. Market fuel surveys in this same time period suggested that only some refineries and some countries were blending E5 petrol with E70 and E100 distillation values above the mean of the volatility class limit range. CONCAWE recognized, however, that a relaxation in volatility limits could be important to enable E10 and higher oxygenates blending and pointed this out to WG21. The same will apply to any future oxygenate blending level higher than 3.7 wt% oxygen.

Because of these effects and the literature and analytical work that had already been completed, CONCAWE proposed a relaxation of the $E70_{max}$, $E100_{max}$, and Vapour Lock Index (VLI) values for E10 gasolines in November, 2009. CONCAWE's first proposal was to relax, for all volatility classes, the $E70_{max}$ limits by +10%, the $E100_{max}$ limits by +4%, and the VLI limits by calculation based on the new $E70_{max}$ limits. No changes in volatility were proposed for the so-called E5 'protection grade' gasoline in order to ensure the performance of older vehicles.

Based on concerns raised by other CEN stakeholders regarding the performance of the current fleet on such a relaxed volatility gasoline, CONCAWE revised its initial proposal in February, 2010. This revised proposal was a two-step relaxation of the volatility limits for E10 gasolines only consisting of a:

- +4% increase in the $E70_{max}$ limits upon revision of EN 228 and an additional increase of +3% in 2014;
- +2% increase in the $E100_{max}$ limits with the revision of EN 228 and an additional increase of +2% in 2014; and
- VLI limits increased by calculation in line with the change in $E70_{max}$ limits.

Additionally, a footnote to the E10 volatility table was proposed stating that the volatility limits would be reviewed in the future based on any relevant information brought to the attention of CEN/TC19. This footnote was intended to ensure that new technical and market information could be brought to the attention of CEN/TC19 WG21 following the revision of EN 228.

In support of this proposal, CONCAWE stated that the revised proposal was conservative compared to the full range of changes in E70 and E100 when blending up to 10% v/v ethanol, as shown in **Table 1.2**. The proposed two-step relaxation in $E70_{max}$, $E100_{max}$, and VLI values and the footnote to the volatility table were also intended to reduce the risk of marketplace problems while ensuring that new technical data or market problems could be brought to CEN's attention.

An important question then is whether the proposed relaxation in E70 and E100 volatility limits would increase the risk that E10-compatible European vehicles would fail to meet regulated emissions and vehicle driveability requirements. Although new vehicles are type approved using an E5 reference fuel having mid-range EN 228 values for volatility and other properties, the vehicle's regulated emissions, driveability performance, and durability are typically verified by each manufacturer on other gasolines having a broader range of properties. However, the results of these tests, and the properties of the fuels used to obtain the results, are generally not reported publicly.

2 TEST PROGRAMME

In order to learn more about the potential risks to vehicles in the current European fleet, CONCAWE completed a six vehicle study at Millbrook Proving Grounds Ltd., Bedford, UK, and the results of this study are presented in this report.

The objective of this study was to assess the effect of gasoline volatility and oxygenates on regulated exhaust and evaporative emissions and on the cold and hot weather driveability performance of modern gasoline vehicles (Euro 4+). The vehicles selected for this study were representative of the current EU fleet, homologated to Euro 4 or 5 emissions limits, and compatible with 10% v/v ethanol according to manufacturer warranty information [12]. The E10 gasolines that were specially blended for this study included the range of relaxed volatility that CONCAWE had proposed to CEN/TC19 WG21 in 2010. The intent to conduct this vehicle test programme was communicated to WG21 members in September, 2010.

The full results from this vehicle study are being made available to help guide the current and future revisions of the EN 228 gasoline specification.

2.1 TEST VEHICLES

Six low-mileage passenger vehicles were sourced for this study meeting the following criteria:

- Representative of Model Year 2000+ production with a range from upper medium to small vehicle classes;
- Compatible with 10% v/v ethanol/gasoline blends based on ACEA's list of compatible vehicles [12];
- Represent the most popular passenger vehicles in today's European fleet;
- Include at least two modern gasoline Direct Injection Spark Ignition (DISI) vehicles;
- Be type approved for at least Euro 4 regulated emissions level;
- Preferably have a manual transmission;
- Be in good working order; and
- Have no less than 8,000km and no more than 60,000km on the odometer.

The vehicles were sourced from local car dealerships and their characteristics are summarised in **Table 2.1**.

Table 2.1 Characteristics of vehicles evaluated in this study

Vehicle No.	**1**	**2**	**3**	**4**	**5**	**6**
Vehicle Class	Upper Medium	Medium	Small	Lower Medium	Mini	Small
Category	M1	M1	M1	M1	M1	M1
Emissions Homologation	Euro 4	Euro 5	Euro 4	Euro 4	Euro 4	Euro 4
Engine Displacement (litres)	2.5	1.8	1.4	1.6	1.0	1.25
Max. Power (kW)	140	118	57	80.5	50	60
Inertia Class (kg)	1590	1470	1130	1360	910	1020
Cylinder	6	4	4	4	3	4
Valves	24	16	8	16	12	16
Aspiration	Natural	Turbo	Natural	Natural	Natural	Natural
Combustion Type	Homogeneous stoichiometric	Homogeneous stoichiometric	Homogeneous stoichiometric	Homogeneous stoichiometric	Homogeneous stoichiometric	Homogeneous stoichiometric
Injection System	Direct Injection	Direct Injection	Sequential Fuel Injection	Sequential Fuel Injection	Sequential Fuel Injection	Sequential Fuel Injection
After-treatment device	Three-way Catalyst	Three-way Catalyst	Three-way Catalyst	Three-way Catalyst	Three-way Catalyst	Three-way Catalyst
Rear or Front Wheel Drive	Rear	Front	Front	Front	Front	Front
Transmission	Manual 6-speed	Manual 6-speed	Manual 5-speed	Manual 6-speed	Manual 5-speed	Manual 5-speed
Drive by wire?	Yes	Yes	Yes	Yes	No	Yes
Traction control?	Yes	Yes	Yes	Yes	No	No
E10 Compatible?	Yes	Yes	Yes	Yes	Yes	Yes
Registration Date	15/06/2007	04/06/2009	29/09/2007	29/09/2009	23/07/2008	28/01/2010
Mileage at start of test (miles)	23,354	8,890	21,496	14,934	13,704	15,607

Details on how these vehicles were prepared and instrumented for testing can be found in **Appendix 1**.

2.2 TEST FUELS

Table 2.2 summarises the blending targets and measured values for summer (Class A) and winter (Class E1) test fuels that were specially blended for this study by Total ACS[6]. As shown in **Table 2.2**, the fuels used in this study have been colour-coded to clarify the results reported in **Section 3** and in the **Appendices**. The analytical data provided by the fuel blender on each fuel were used in the FC data analyses. Fuel samples at the testing facility were crosschecked by a second analytical laboratory in order to ensure that the fuel samples being tested were correctly labelled. More information on these test fuels can be found in **Appendix 7**.

[6] The same blended fuels have been provided to ACEA members and to a 3rd party testing facility for vehicle testing.

Table 2.2 Targets and measured values for test fuels

Baseline Fuels			
Summer (Class A)		**Winter (Class E1)**	
CEC RF-02-08 (BLACK) (CONDITION AND PRETEST FUEL)			
Target values:	Measured values:		
60 kPa $DVPE_{max}$ 5% v/v Ethanol E70 mid-range E100 mid-range	58.7 kPa DVPE 4.7% v/v Ethanol 37.0% E70 53.5% E100		
Baseline E10-A (ORANGE)		**Baseline E10-E (BLUE)**	
Target values:	Measured values:	Target values:	Measured values:
60 kPa $DVPE_{max}$ 10% v/v Ethanol 48% $E70_{max}$ Class A 71% $E100_{max}$ Class A	57.1 kPa DVPE 9.7% v/v Ethanol 49.7% E70 68.4% E100 918.9 VLI	95 kPa DVPE 10% v/v Ethanol 50% $E70_{max}$ Class E 71% $E100_{max}$ Class E	97.0 kPa DVPE 9.5% v/v Ethanol 51.9% E70 67.1% E100 1333.3 VLI
Relaxed Volatility Fuels			
Summer (Class A)		**Winter (Class E1)**	
Step 1 E10-A (BROWN)		**Step 1 E10-E (PURPLE)**	
Target values:	Measured values:	Target values:	Measured values:
60 kPa $DVPE_{max}$ 10% v/v Ethanol 52% E70 (max+4%) 73% E100 (max+2%)	58.7 kPa DVPE 9.5% v/v Ethanol 52.9% v/v E70 73.2% v/v E100 957.3 VLI	95 kPa DVPE 10% v/v Ethanol 54% E70 (max+4%) 73% E100 (max+2%)	93.2 kPa DVPE 9.5% v/v Ethanol 54.9% E70 70.9% E100 1316.3 VLI
Step 2 E10-A (GREEN)		**Step 2 E10-E (RED)**	
Target values:	Measured values:	Target values:	Measured values:
60 kPa $DVPE_{max}$ 10% v/v Ethanol 58% E70 (max+10%) 75% E100 (max+4%)	61.0 kPa DVPE 9.4% v/v Ethanol 59.4% v/v E70 75.7% v/v E100 1025.8 VLI	95 kPa DVPE 10% v/v Ethanol 60% E70 (max+10%) 75% E100 (max+4%)	94.1 kPa DVPE 9.4% v/v Ethanol 60.6% E70 73.9% E100 1365.2 VLI

With the exception of the ethanol content and volatility parameters, the EN 228 specifications were used as targets for the other properties of the blended gasolines. In order to achieve the targeted increases in E70 and E100 while holding the DVPE and ethanol content fixed, it was not possible to keep all of the other parameters constant. For example, some changes in the aromatics and olefins contents were unavoidable with changes in the E70 and E100 properties. These changes were not considered to be large enough, however, to impact the vehicle emissions and performance results.

Except for the CEC RF-02-08 fuel that was used for vehicle conditioning and test preparation, all of the gasolines used in this study contained 10% v/v ethanol. The ‘Baseline’ gasolines were blended so that the E70 and E100 values were at or close to the maximum values allowed for the volatility class. The ‘Step 1’ gasolines had E70 and E100 volatility values that were approximately +4% and +2%, respectively, higher than the ‘Baseline’ gasolines and represented CONCAWE’s revised proposal to WG21 for volatility relaxation. The ‘Step 2’ gasolines had E70 and E100 volatility values that were approximately +10% and +4%, respectively, higher than the 'Baseline' gasolines and represented CONCAWE's original proposal to WG21 for volatility relaxation. The distillation profiles for these fuels are shown in **Figures 2.1** and **2.2**.

In order to evaluate a more severe volatility relaxation scenario, most of the vehicle tests in this study were conducted by comparing results for the 'Baseline' and 'Step 2' fuels. Where necessary, some tests were also completed on the 'Step 1' fuels.

Figure 2.1 Distillation curves for summer grade test fuels (Class A)

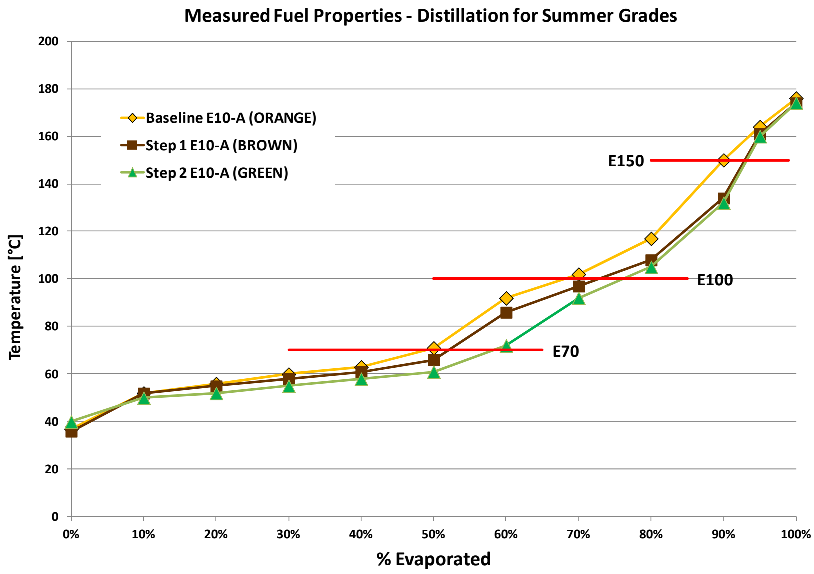
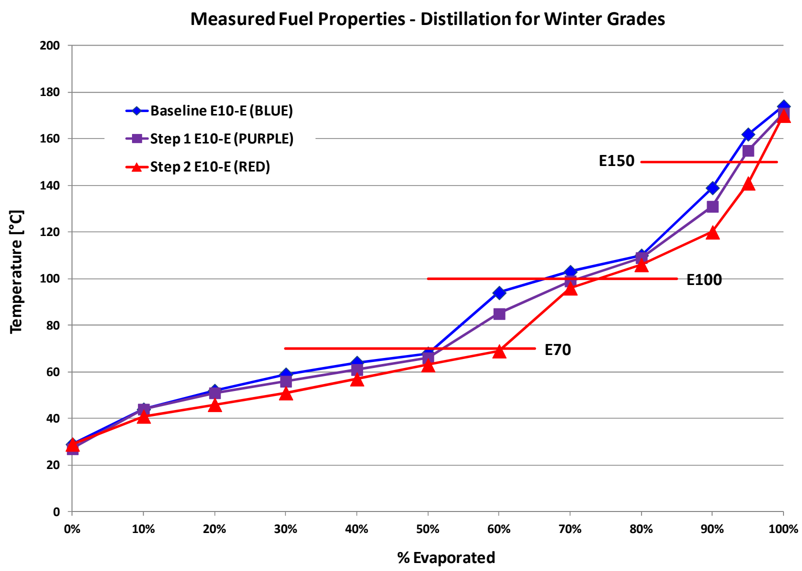


Figure 2.2 Distillation curves for winter grade test fuels (Class E1)



3 RESULTS AND DISCUSSION

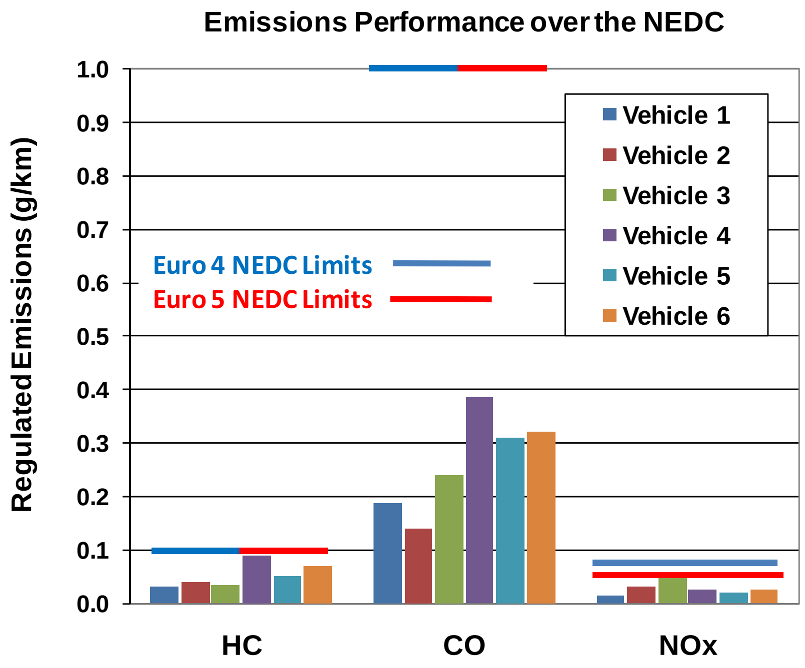
3.1 NEDC REGULATED EMISSIONS AT START OF STUDY

3.1.1 Results

Following the vehicle preparation and coastdown evaluation described in **Appendix 1**, each vehicle was tested over the New European Driving Cycle (NEDC) and compared to the appropriate Euro 4 or 5 limit values for that vehicle. If the measured values were higher than expected, the vehicle was taken to the test track and driven at high speed for about one hour on detergent-containing gasoline in order to ensure fuel system cleanliness. Following this additional driving, the vehicle was then returned to the test facility and the standard conditioning and pre-test procedure was again completed. This process was used for Vehicles 4 and 6 while the results on the other four vehicles were considered acceptable without additional conditioning.

As can be seen in **Figure 3.1.1**, all of the vehicles had regulated emissions that were well below the Euro 4/5 limits over the NEDC at +23°C (see **Table 1.1**). For these tests, the EU certification fuel (CEC RF-02-08) was used. Vehicles 1 and 2 were equipped with modern DISI engines. Vehicle 2 was certified to the Euro 5 emissions standard while the other five vehicles were certified to the Euro 4 emissions standard.

Figure 3.1.1 NEDC regulated emissions at +23°C at the start of study



The CO_2 emissions (in g/km) and fuel consumption (FC) by carbon balance (in l/100km) were also measured and are shown in **Figures 3.1.2** and **3.1.3**, respectively.

Figure 3.1.2 NEDC CO_2 emissions (in g/km) at +23°C at the start of study

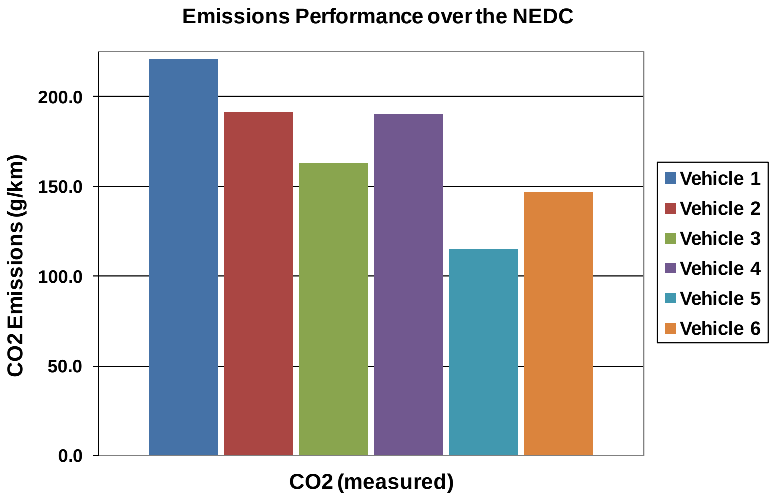
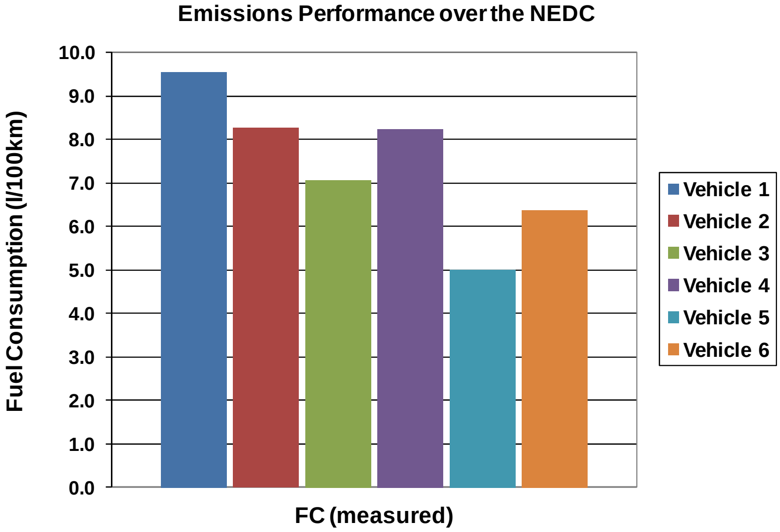


Figure 3.1.3 NEDC FC (in l/100km) at +23°C at the start of study



Although new vehicles must meet conformity of production requirements for CO_2 emissions and FC, there are no compliance requirements for these parameters for in-use vehicles. Nonetheless, these values are of increasing interest to regulators and consumers and were measured following vehicle preparation in order to evaluate the performance of the used vehicles selected for this study.

Table 3.1.1 compares the manufacturer-reported type approval values and the measurements of the same parameters following vehicle preparation described in **Section 2.1** and **Appendix 1**. These results were obtained over the NEDC at +23°C using the CEC RF-02-08 certification fuel and were measured at the same time as the regulated emissions.

Table 3.1.1 Manufacturer-reported type approval values and measurements of the same parameter at the start of the study

Vehicle	Euro Standard	Measurement	Manufacturer reported type approval	Measured at start of study	Measured vs. Type Approval
1	Euro 4	CO_2 (g/km)	174	221	127%
		FC (l/100km)	7.3	9.6	131%
2	Euro 5	CO_2 (g/km)	178	191	107%
		FC (l/100km)	7.6	8.3	109%
3	Euro 4	CO_2 (g/km)	139	163	117%
		FC (l/100km)	5.9	7.1	120%
4	Euro 4	CO_2 (g/km)	163	191	117%
		FC (l/100km)	6.9	8.3	120%
5	Euro 4	CO_2 (g/km)	106	115	109%
		FC (l/100km)	4.5	5.0	111%
6	Euro 4	CO_2 (g/km)	139	147	106%
		FC (l/100km)	5.8	6.4	110%

As can be seen from **Table 3.1.1**, the CO_2 emissions and FC measured at the start of the study over the regulatory procedure exceeded the manufacturers' reported type approval values for the same make and model by 6 to 27% for CO_2 emissions and 9 to 31% for FC. This was the case even though the test lab was skilled in these measurements and rigorously followed the regulatory procedures for vehicle preparation and coastdown measurements. Similar discrepancies in CO_2 and FC results have been reported by others [13,14].

3.2 NEDC REGULATED EMISSIONS AT +23°C

3.2.1 Overview of NEDC regulated emissions at +23°C

Following the vehicle validation tests shown in **Section 3.1**, the same vehicles were evaluated on two summer class test fuels at +23°C over the NEDC. Regulated emissions, including HC, CO, NOx, and CO_2, as well as the fuel consumption (FC) by carbon balance were measured at +23°C over the NEDC. The test procedure and results from these tests are shown in **Appendix 2**.

The NEDC at +23°C is a legislated test for spark ignition (SI) vehicles. The regulated limits from the combined ECE and EUDC phases of the NEDC test are 0.1 g/km for THC emissions and 1.0 g/km for CO emissions. The regulated limits for NOx emissions are 0.08 g/km for the Euro 4 vehicles and 0.06 g/km for the Euro 5 vehicle (Vehicle 2).

3.2.2 Results

All of the data are shown in **Appendix 2** and the fleet-average values are shown in this section. Two summer class gasolines were tested: the Baseline E10-A (ORANGE) and the Step 2 E10-A (GREEN). Both fuels were tested at least twice on each of the six test vehicles using different semi-randomized test orders for each fuel. The charts in this section and in **Appendix 2** show the test results in date order. Because each vehicle was undergoing different tests, the results for each vehicle spanned between 2 and 8 months elapsed time although tests on each vehicle were completed over a shorter time period.

Arithmetic means are shown for the HC and CO_2 emissions results and for the calculated fuel consumption (FC). Because the CO and NOx emissions varied quite markedly among the vehicles, geometric means are shown for these fleet-average results[7].

All of the data are included in the average values and there were no statistical outliers. Some trends over time were observed for some vehicle and emission combinations but these were not considered to be strong enough to warrant trend correction.

Figures 3.2.1 to **3.2.5** show the fleet-average values for HC, CO, NOx, and CO_2 emissions and FC, respectively. The error bars in these figures are plotted at +/-1.4 standard errors (SE) for consistency with the EPEFE programme [15] and other CONCAWE studies [16,17,18,19]. An approximate statistical analysis[8] suggests that there is no significant difference in HC or NOx emissions between these two fuels. However, CO emissions were on average about 36% higher for the Step 2 E10-A (GREEN) fuel, significant at $P<0.1\%$[9]. All CO emissions results were well within the Euro 4/5 limit of 1.0 g/km for all vehicles, however.

The difference in CO_2 emissions was not significant (at $P<5\%$) even though the error bars in **Figure 3.2.4** do not overlap[10]. However, the volumetric FC (in l/100km) was 2.72% higher (significant at $P<1\%$) on the Step 2 E10-A (GREEN) fuel compared to the Baseline E10-A (ORANGE) fuel. The FC results are explained in **Section 3.2.3**.

Overall, there was no vehicle and fuel interaction that was statistically significant. This means that there was no statistical evidence to suggest that the vehicles responded to the two test fuels in different ways.

7 Geometric means are used to damp down the dominance of higher-emitting vehicles when comparing different fuels.

8 On a technical note, it is difficult to perform a rigorous statistical analysis combining emissions measurements from cars of different models. Responses to fuels and test-to-test variability levels can vary and inferences may depend on whether the fleet is considered to be fixed or random. The significant levels and error bars in this report are derived from a simplified (unbalanced) two-way analysis of variance model and must be regarded as approximate.

9 $P<0.1\%$ = the probability that such an event could be observed by chance when no real effect exists is less than 0.1%. In other words, we are 99.9% confident that the effect is real.

10 Because only a limited number of tests were conducted in this study, there must be a small gap between the 1.4 SE error bars for a statistical significance at $P<5\%$.

Figure 3.2.1 Fleet-average HC emissions at +23°C over the NEDC

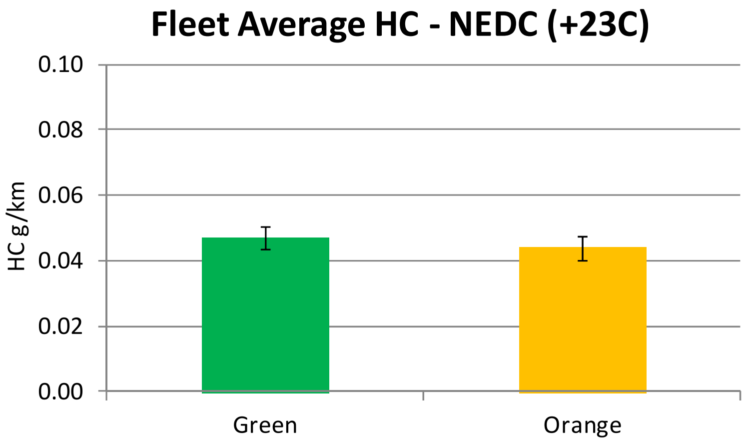


Figure 3.2.2 Fleet-average CO emissions at +23°C over the NEDC (geometric means)

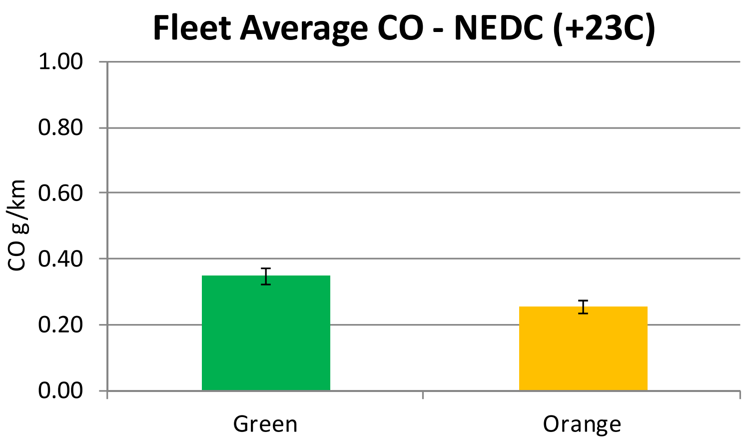


Figure 3.2.3 Fleet-average NOx emissions at +23°C over the NEDC (geometric means)

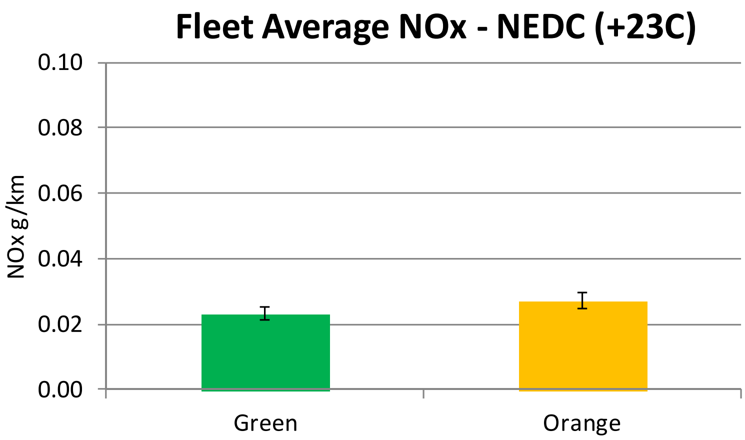


Figure 3.2.4 Fleet-average CO_2 emissions at +23°C over the NEDC

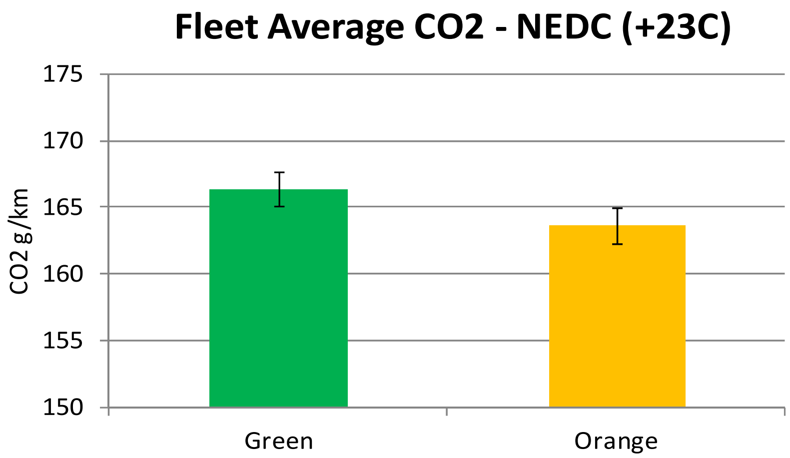
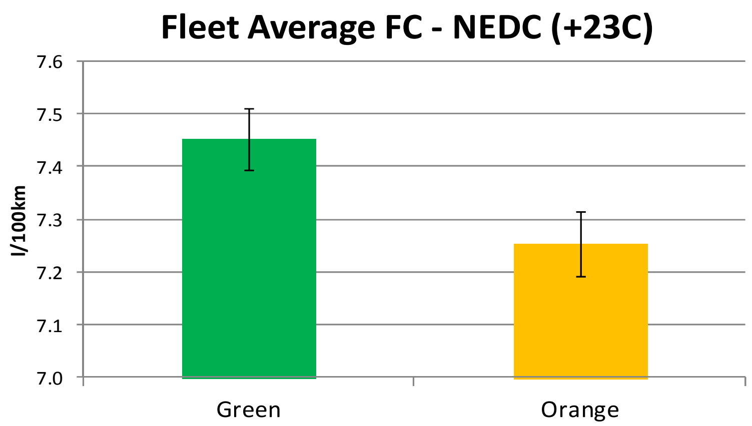


Figure 3.2.5 Fleet-average fuel consumption at +23°C over the NEDC



3.2.3 Conclusions from NEDC regulated emissions testing at +23°C

As was seen in the previous section, the difference in CO_2 emissions between the two fuels was just less than significant at P<5%. On the other hand, the fleet-average volumetric FC was statistically higher for the Step 2 E10-A (GREEN) fuel at P<1%.

By comparing results from the Step 2 E10-A (GREEN) fuel and the Baseline E10-A (ORANGE) fuel, the following observations can be made:

- The fleet-average results showed a 1.68% difference in CO_2 emissions with the Step 2 E10-A (GREEN) fuel giving the higher results.
- To calculate the carbon balance FC, the CO and HC emissions must be included in the calculation. When this is done, the difference in carbon emissions increases slightly to 1.78% (mainly due to the CO emissions).

- The Carbon Weight Fraction (CWF) is then used to convert the emitted grams of carbon to grams of fuel by dividing by the CWF. This computation gives the mass FC and the difference between the fuels is reduced slightly to 1.66%.
- The mass FC is then divided by the fuel density in order to convert the result to volumetric FC. Because there was a 1.03% difference in density between the two test fuels, this results in a 2.72% difference in volumetric FC.

In summary, the 1.03% difference in fuel density is primarily responsible for the apparent inconsistency between the CO_2 emissions results (a 1.68% fleet-average difference that was not statistically significant at P<5%) and the volumetric FC results (a 2.72% fleet-average difference that was statistically significant at P<1%).

- The impacts of fuel volatility on regulated emissions over the NEDC at +23^{o}C were small relative to vehicle-to-vehicle effects.
- No major differences were observed in the fleet-average HC and NOx emissions between the Baseline E10-A (ORANGE) and Step 2 E10-A (GREEN) fuels for NEDC regulated emissions at +23°C. The fleet-average CO emissions were 36% higher on the more volatile (GREEN) fuel but well below the Euro 4/5 limit for this test.

3.3 COLD STARTING PERFORMANCE AT -20°C

3.3.1 Overview of cold engine starting and idling testing

In preliminary test results presented to CEN/TC19 WG21 by other experts, cold starting and idling tests were highlighted as a particular concern. In these reported tests, engine and exhaust performance was monitored as the cold engine was started at -20°C and warmed up at idle to a cooling water temperature of at least 90°C. When using fuels with higher E70 values, about 10% richer lambda values were observed during the warm-up phase compared to results using EN 228 gasoline. Higher CO emissions were also reported.

The results presented covered the first 6000 engine revolutions after cold engine starting, or equivalent to 6 minutes idling at 1000rpm. The richer lambda values observed in these tests were speculated to increase the risk of longer starting times, engine stalling, higher smoke levels, fouling of spark plugs, lubricant dilution, and deterioration of cold temperature vehicle driveability even though these problems were not actually observed.

Because of these reported results, cold engine starting and idling at -20°C was also a focus of CONCAWE's vehicle study. The test procedure and complete results are included in **Appendix 3**.

3.3.2 Results

3.3.2.1 Engine Speed and Temperature

Results are presented here comparing the winter grade Baseline E10-E (BLUE) fuel with the Step 2 E10-E (RED) fuel. These two E10 gasolines had E70 values of 51.9% (BLUE) and 60.6% (RED), with other parameters held constant as much as possible. The E100 values for these fuels were 67.1% and 73.9%, respectively.

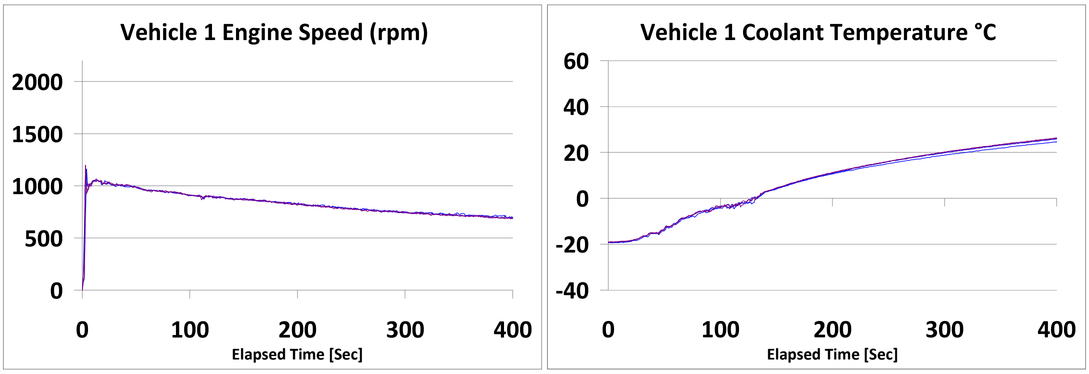
Some tests were also carried out on two vehicles by comparing the Baseline E10-E (BLUE) fuel with the Step 1 E10-E (PURPLE) fuel and the results from these tests are presented in **Appendix 3**. The PURPLE fuel had a measured E70 value of 54.9%. Consistent with the smaller change in E70 between the BLUE and PURPLE fuels, smaller effects were observed compared to results on the Step 2 E10-E (RED) fuel.

All vehicles started easily and completed the 1180s test. On all three test fuels, starting times were less than 1.6s and idle speeds were stable and consistent throughout the test. Where there was some evidence of test-to-test variation (Vehicles 3 and 6), this appeared randomly and there was no evidence of a fuel-specific effect.

Coolant temperatures were measured using thermocouples located in the top hose of the test vehicles (i.e. the 'cold' side of the thermostat). In spite of this, recorded temperatures started to rise very quickly after engine start and reached 25-50°C after only 400s. Temperatures generally followed consistent profiles for each test. Vehicles 3 and 6 again showed a small degree of test-to-test variability but this was not related to the fuel type.

Examples are shown in **Figure 3.3.1** for Vehicle 1, with full results in **Appendix 3**. Results for both the Baseline E10-E (BLUE) fuel and the Step 2 E10-E (RED) fuel are shown in these figures.

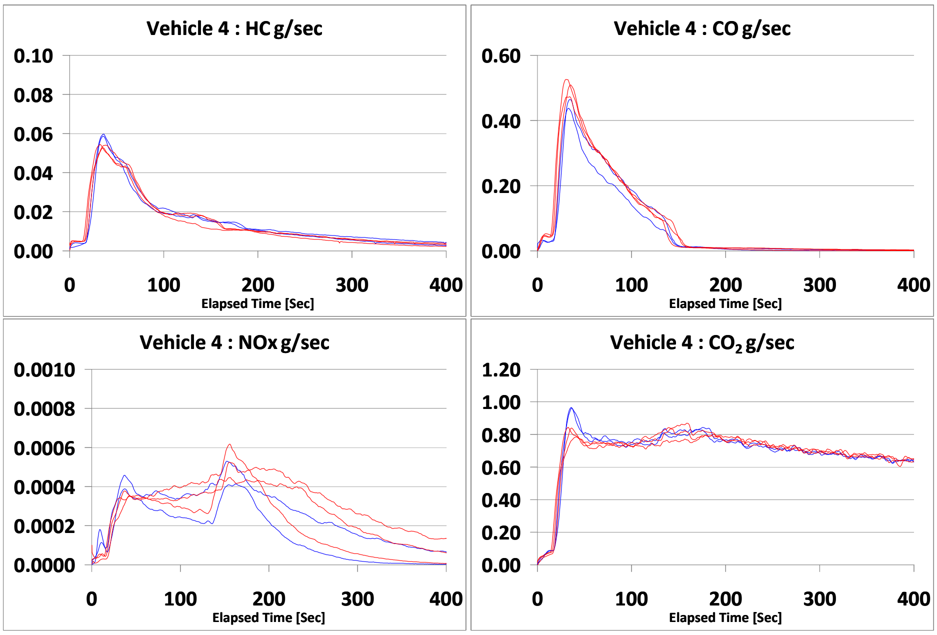
Figure 3.3.1 Engine speed and coolant temperature at idle following cold engine starting at -20°C for Vehicle 1



3.3.2.2 Exhaust Emissions and Lambda

Exhaust emissions results are shown here for Vehicle 4. Plots for all vehicles can be found in **Appendix 3**.

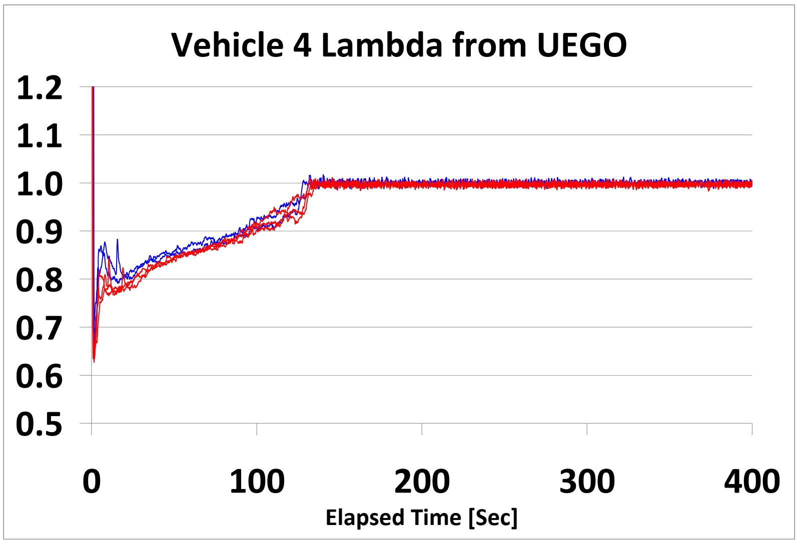
Figure 3.3.2 Exhaust emissions at idle following cold engine starting at -20°C for Vehicle 4



Emissions of HC and CO were higher on both fuels in the early seconds after starting but dropped quickly to low levels after about 400s. For HC emissions, differences between fuels were variable and small: compared to the BLUE fuel, the more volatile RED fuel gave lower exhaust emissions on Vehicles 1 and 4, higher emissions on Vehicles 2 and 3, and no clear difference on Vehicles 5 and 6. For CO emissions, peak values ranging from 7% to 11% were usually observed less than 100s after cold engine starting. In this initial period, the Step 2 E10-E (RED) fuel produced higher CO emissions on all six vehicles, although the difference was very small for Vehicle 5. NOx emissions were very low throughout this cold starting test and are not discussed further.

Exhaust air-fuel ratio (AFR) was measured using a heated Universal Exhaust Gas Oxygen (UEGO) sensor that had been specially fitted to each vehicle. The locations of the test sensors on the vehicles are shown in **Appendix 1**. Because the UEGO sensor was independently heated, it could be used to monitor the AFR (lambda value) from the beginning of the test, while the vehicle's own sensor would take some time to warm up and establish lambda control. The manufacturer's installed oxygen sensor was also monitored, but it was not disturbed and was allowed to control the vehicle as designed.

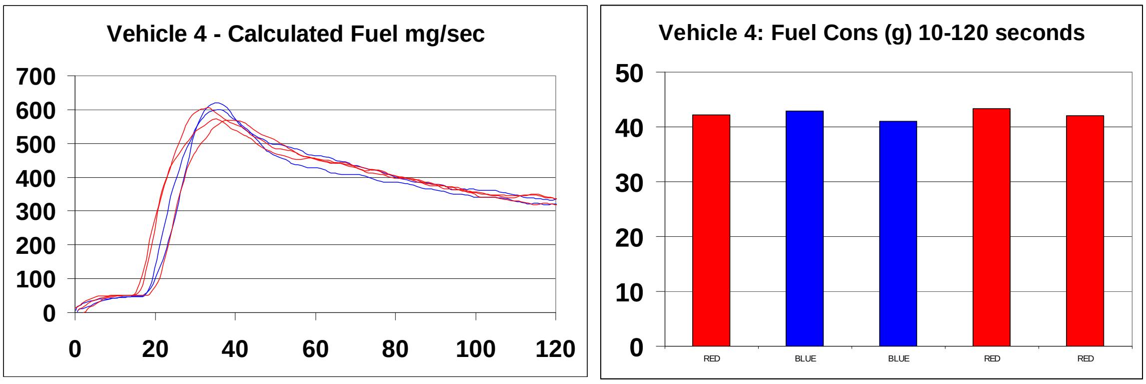
Figure 3.3.3 Lambda measured by the exhaust UEGO sensor



As shown in **Figure 3.3.3**, a clear transition from open-loop operation to lambda control (where lambda=1) was seen for Vehicles 3, 4 and 5, while the other three vehicles approached lambda=1 in a more casual way. Vehicle 2 appeared to reach lambda control at about 50s, but remained slightly rich of lambda=1 throughout the 1180s test. Vehicle 6 appeared to trend lean after a period of lambda=1 operation. The fuel did not affect the time required for any vehicle to reach lambda control.

During the open-loop period, which varied between vehicles from about 50 to 300s, measured exhaust lambda values were lower (richer) on the higher volatility (RED) fuel. There are, however, indications that the UEGO lambda reading should not necessarily be taken at face value. Fuel flows for the two fuels were calculated and found to be essentially identical, as illustrated for Vehicle 4 in **Figure 3.3.4**. The fuel flow is calculated from the exhaust emission measurements, taking full account of unburned hydrocarbons and CO emissions.

Figure 3.3.4 Calculated fuel flow and fuel consumption for Vehicle 4



Throttle positions and spark advance were measured for all vehicles except for Vehicle 5 and showed no measureable differences between tests. Under these conditions, the amount of air drawn through the engine should be identical for the two test fuels. Direct measurements of mass air flow on Vehicles 1 and 2 (the only two vehicles where it was possible to do this) confirmed that this was the case. From these results, the AFR and lambda values should be the same for both fuels.

This leaves the question of how to interpret the exhaust lambda differences between the two fuels. The UEGO sensor contains a zirconia measuring cell and the AFR is calculated by measuring the amount of oxygen that has to be electrochemically pumped in or out to achieve a stoichiometric balance. Under rich conditions, the AFR is proportional to the amount of oxygen required to complete the oxidation of the unburned species (HC, CO and H_2).

In our tests, since the Step 2 E10-E (RED) fuel was found to be less completely burned than the Baseline E10-E (BLUE) fuel, the RED fuel should require more oxygen input to reach stoichiometry and hence should be recorded by the UEGO sensor as giving a richer AFR compared to the BLUE fuel. However, the diffusion rates of HC, CO and H_2 are different and these can subtly affect the UEGO results. CO and HC tend to bias the sensor lean, while H_2 (which we did not directly measure) tends to bias the sensor rich. The sensor calibration includes an empirical correction for these factors, but this is presumably related to the actual AFR and is unlikely to adjust for compositional variations at the same AFR. While the UEGO gives a good estimate of the general lambda trends as the engine warms up, we should treat the relatively small differences indicated between the fuels with some caution.

The ultimate objective of these tests was to assess how conditions in the combustion chamber change as the fuel volatility increases. For practical reasons, we have approached this question indirectly by looking at conditions in the vehicle exhaust. From the above evaluation of fuel and air flows, we can say that there is no clear evidence that the more volatile fuel produces an overall richer mixture.

However, the change in fuel volatility will affect the distribution of fuel in the combustion chamber and hence the local AFR as well as the distribution of liquid and gaseous fuel within the combustion chamber. From the available data, we can only form a qualitative picture of what is happening but the compositional differences in the exhaust gases provide evidence that there are some fuel-related effects. The more volatile Step 2 E10-E (RED) fuel will evaporate more quickly and hence mix more thoroughly than the Baseline E10-E (BLUE) fuel. We cannot clearly predict conditions around the spark plug or at the cylinder wall but better evaporation and mixing with a more volatile fuel might be expected to reduce, and not increase, the risk of coking and deposit formation.

Small amounts of unburned fuel can also enter the engine crankcase and over time dilute the lubricating oil. Apart from this, because gasoline is a light and volatile fuel, we do not expect any unburned fuel to remain in the combustion chamber or exhaust system, so it should all reach the exhaust analysers. As shown above, no differences could be detected in the amount of fuel combustion products in the exhaust, which suggests that the amount of fuel lost to the lube oil is similar for the two BLUE and RED test fuels. There is, however, a small difference in the amount of energy released from the two fuels in the peak emission period. Because the RED fuel produces somewhat more CO, it must release less energy than the BLUE fuel. No difference is seen in the idle speed but less lube oil dilution might explain this observation.

These comments are necessarily qualitative, because we are relying on exhaust measurements to evaluate combustion chamber conditions. The issues raised should, however, be considered if further test work in this area is planned. A more detailed evaluation of the data is presented in **Appendix 3**.

3.3.3 Conclusions from cold engine starting performance at -20°C

The tests comparing the Baseline E10-E (BLUE) fuel with the Step 2 E10-E (RED) fuel, having a difference of 8.7% in E70, showed that:

- All vehicles started easily (<1.6 sec) and satisfactorily completed the 1180s test. Idle speeds were stable and consistent throughout and showed no differences between the two test fuels.

- Differences were observed between vehicles in terms of FC, emissions, and time to reach lambda control.

- The more volatile Step 2 E10-E (RED) fuel produced more CO and less CO_2 in the exhaust than the Baseline E10-E (BLUE) fuel, while unburned hydrocarbon levels were slightly lower on the RED fuel.

- Less complete combustion on the Step 2 E10-E (RED) fuel should require a higher fuel flow in order to sustain idle speed. However, in a detailed evaluation on one vehicle (Vehicle 4), FC as calculated from exhaust emissions was found to be the same for both fuels. Air mass flow was also the same for those vehicles where it could be measured, so the overall AFR should be the same for the two test fuels.

- However, based on the exhaust UEGO sensor data, the more volatile Step 2 E10-E (RED) fuel gave slightly richer lambda values during the initial warm-up period.

- The reason for these apparently conflicting results is not clear. It is possible, however, that the UEGO signal is responding to differences in exhaust composition between the two fuels rather than to a change in overall AFR. Alternatively, the lower volatility of the Baseline E10-E (BLUE) fuel may result in some fuel being retained on the cylinder wall during the initial cold engine conditions. If this were the case, then this fraction of fuel would not participate in the combustion process and would not appear in the exhaust gas.

- Although we cannot directly measure conditions in the combustion chamber, we can deduce that the more volatile fuel should give better evaporation and mixing. It is not clear whether the overall effects of this are beneficial or detrimental.

- Some limited results comparing the Step 1 E10-E (PURPLE) fuel with the Baseline E10-E (BLUE) fuel, which differed in E70 by 3%, showed very similar performance for the two fuels.

3.4 NEDC REGULATED EMISSIONS AT -7°C

3.4.1 Overview of NEDC regulated emissions testing at -7°C

The test procedure and additional results from this test are presented in **Appendix 4**.

The -7°C emissions test procedure is a legislated test for spark ignition vehicles. The HC and CO results from the ECE phase of the test are limited to 1.8 g/km and 15.0 g/km, respectively. Individual emission traces (modal tailpipe emission rates in g/s) for the ECE phase of the test (from 0 to 780s) are shown in **Appendix 4**, **Figures A4-7** to **A4-9** for HC, CO and NOx.

Two winter grade fuels were tested, the Baseline E10-E (BLUE) fuel and the Step 2 E10-E (RED) fuel. Both of these fuels were tested at least twice on each of the six test vehicles. For Vehicle 1, there was a partial instrument failure during one of the tests on the BLUE fuel and this test was repeated at the end of the sequence. Results from all tests in date-order are included where the measured data are valid. Tests were run as either RED-BLUE-BLUE-RED or BLUE-RED-RED-BLUE.

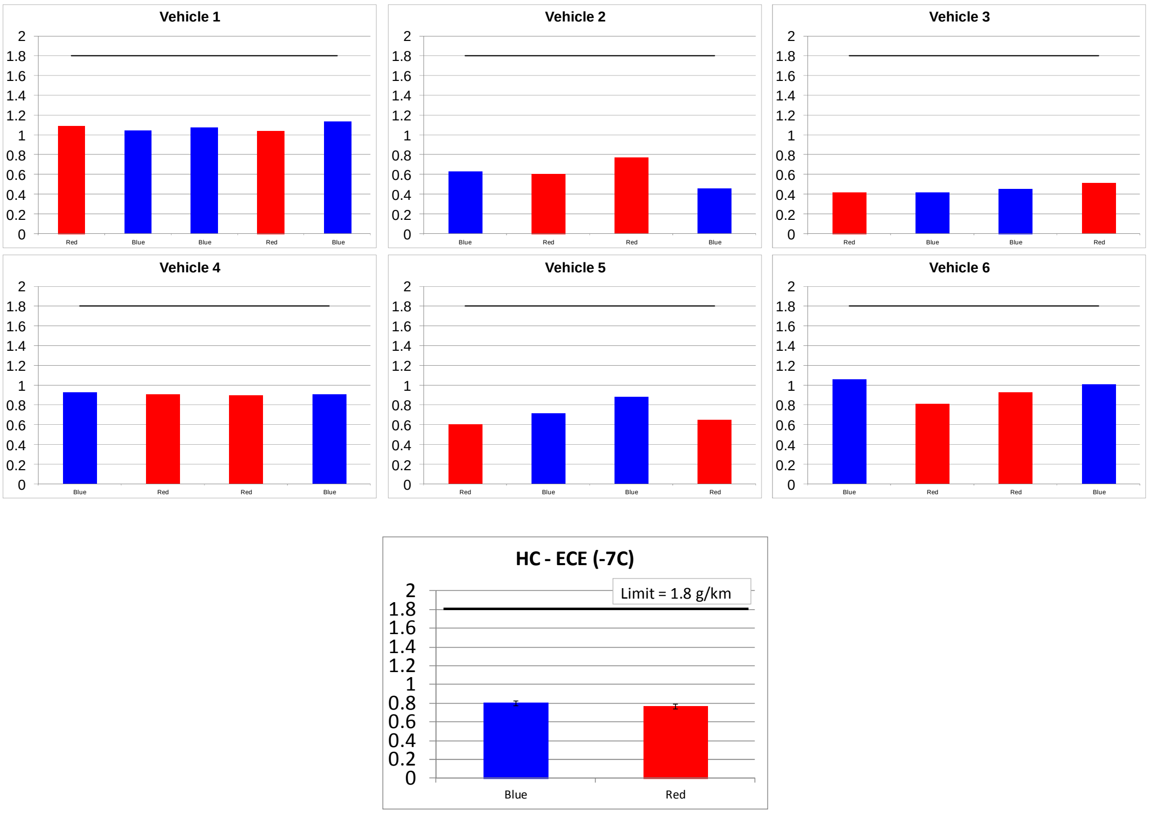
3.4.2 Results

3.4.2.1 ECE Bag Emissions and FC

Results for the legislated HC Bag emissions from the ECE phase of the legislated test are shown in **Figure 3.4.1**. In all vehicles, the HC emissions were well below the legislated limit of 1.8 g/km and varied considerably from one vehicle to another. There was a small amount of test-to-test variability, as shown by the repeat measurements. Different HC emission levels can be seen between the different vehicles but an approximate statistical analysis showed no significant differences between the two fuels[11]. The lower graph shows the fleet-average results for all vehicles and the error bars are again plotted at +/- 1.4 SE (see **Section 3.2.2**). This chart confirms that there is no significant fuel effect on fleet-average HC emissions.

[11] As previously described in Footnote 8 in **Section 3.2.2**. The same caveats apply here.

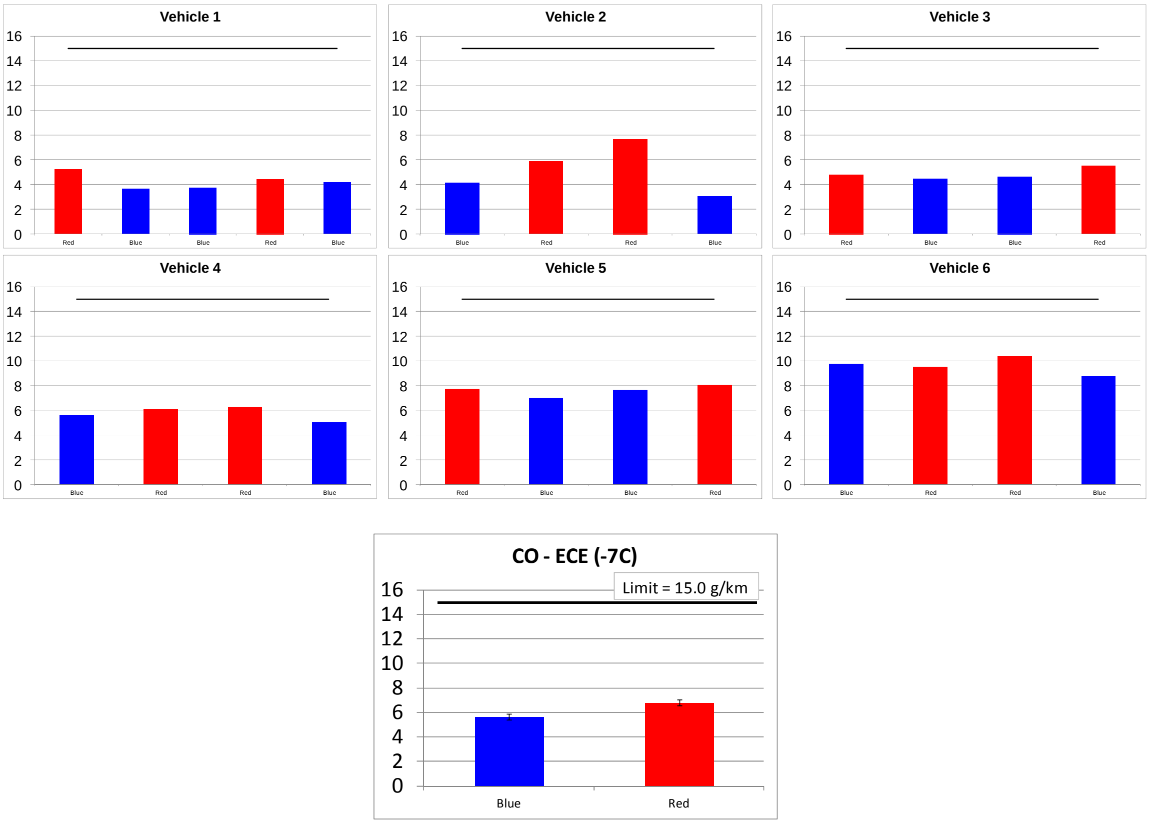
Figure 3.4.1 HC Bag Emissions [g/km] over the ECE phase of the NEDC following cold engine starting at -7°C. The fleet-average results for all vehicles are also shown below.



Results for the CO Bag emissions from the ECE phase of the test are shown in **Figure 3.4.2**. In all vehicles, the CO emissions were well below the legislated limit of 15.0 g/km. Directionally, all six vehicles showed higher CO emissions with the Step 2 E10-E (RED) fuel, with the difference being most evident in Vehicle 2. CO emission levels from Vehicle 6 are more than twice those from Vehicle 1.

The lower graph shows the fleet-average results for all vehicles, together with the +/- 1.4 SE error bars. The fleet-average difference between the two fuels comes predominantly from Vehicle 2 and is significant at P<0.1%. On average, the CO emissions are 20% higher with the Step 2 E10-E (RED) fuel in this -7°C ECE test. The fleet-average CO emissions on both fuels are much less than the legislated limit, however.

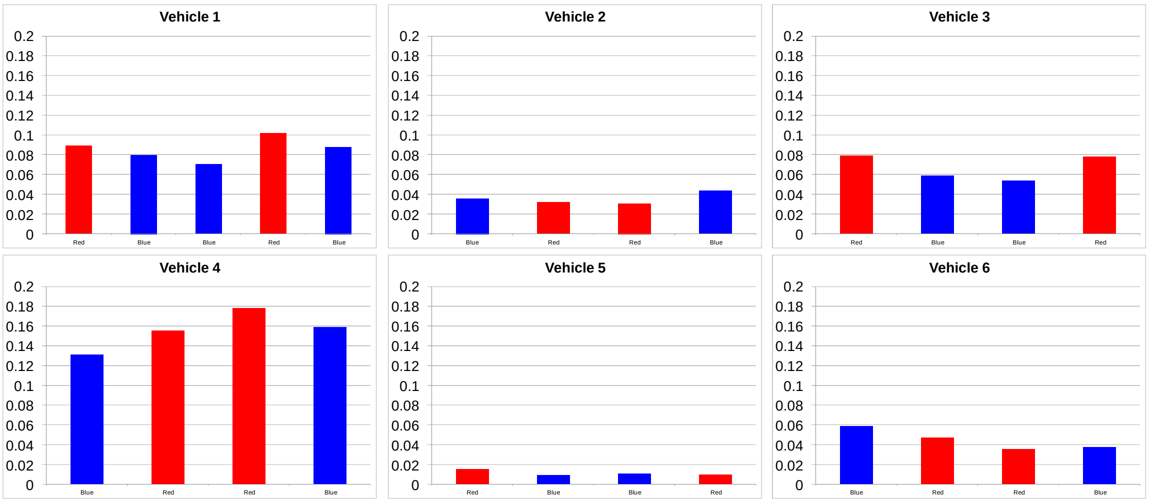
Figure 3.4.2 CO Bag Emissions [g/km] over the ECE phase of the NEDC following cold engine starting at -7°C. The fleet-average results for all vehicles are also shown below.

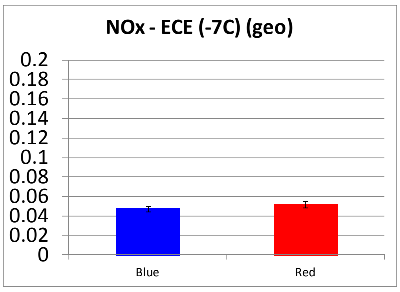


Results for the NOx Bag emissions from the ECE phase of the test are shown in **Figure 3.4.3**. NOx emissions are not legislated in this low ambient temperature test. For comparison, the Euro 5 NOx limit over the legislated NEDC test at +23°C is 0.06 g/km.

There is a small amount of variability, as shown by the repeat measurements, but no significant fuel effects were evident. However, significantly different emission levels can be seen between the different vehicles – about an order of magnitude difference when comparing Vehicle 5 and Vehicle 4, for example. Due to this large difference in the NOx emission levels, a geometric rather than arithmetic mean was calculated when averaging the emissions across vehicles in the lower graph.

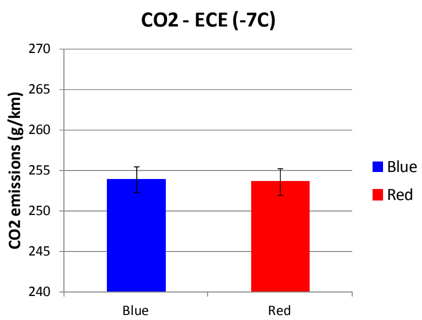
Figure 3.4.3 NOx Bag Emissions [g/km] over the ECE phase of the NEDC following cold engine start at -7°C. The fleet-average (geometric mean) of results for all vehicles is also shown below.





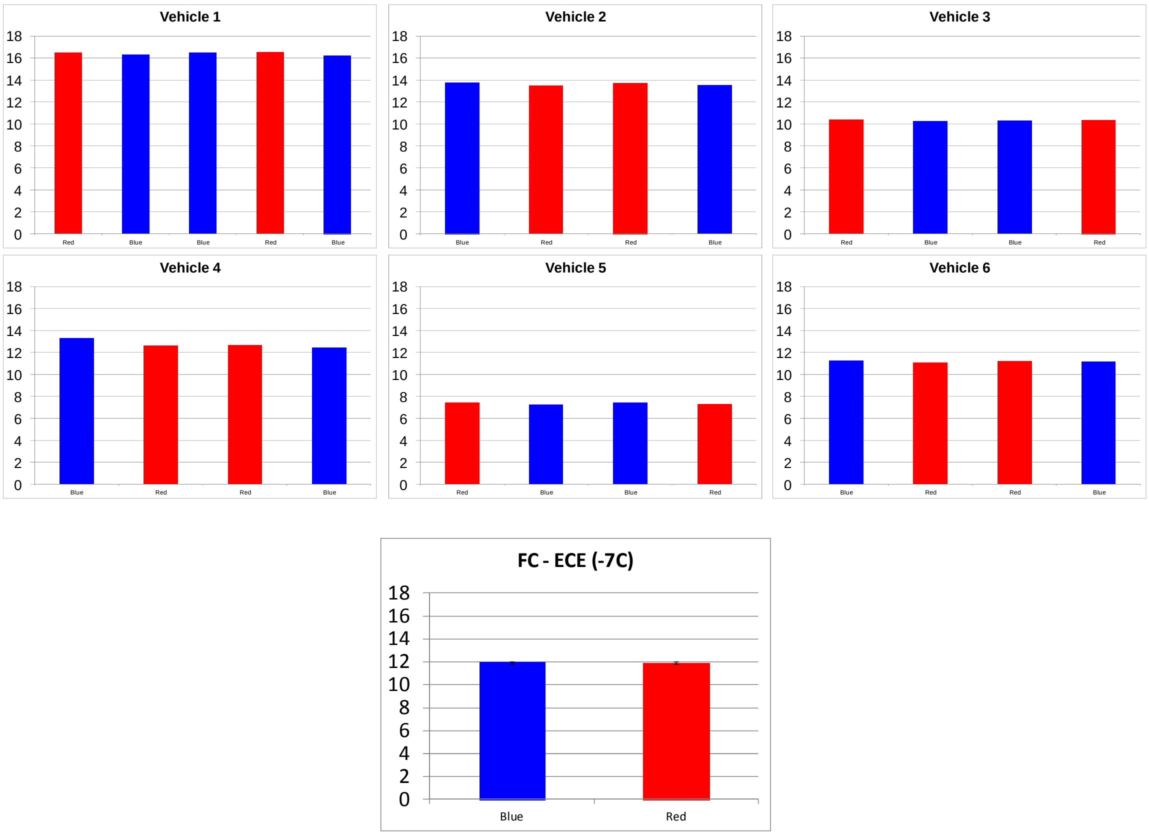
Results for fleet-average CO_2 emissions (in g/km) derived from the Bag emissions over the ECE phase of the NEDC test at -7°C are shown in **Figure 3.4.4**. The graph shows the average results across all vehicles. There is no significant fuel effect on the fleet-average CO_2 emissions.

Figure 3.4.4 Fleet-average CO_2 emissions (in g/km) from Bag emissions over the ECE phase of the NEDC following cold engine start at -7°C.



Results for fuel consumption (FC) (in l/100km) derived from the Bag emissions over the ECE phase of the NEDC test at -7°C are shown in **Figure 3.4.5**. The lower graph shows the fleet-average results across all vehicles. No significant fuel effects were observed.

Figure 3.4.5 FC [in l/100km] derived from Bag emissions over the ECE phase of the NEDC following cold engine start at -7°C. The fleet-average of results for all vehicles is also shown below.

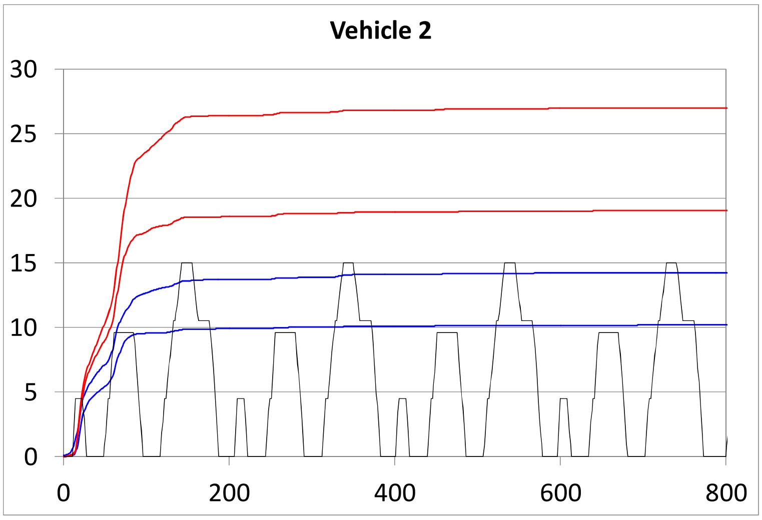


3.4.2.2 Impact of fuel on Vehicle 2 in the first 200 seconds

The CO Bag emissions results indicated that there was an effect of fuel volatility on the CO emissions (**Figure 3.4.2**), particularly in one vehicle (Vehicle 2). For this reason, the rest of this section focuses only on the results from Vehicle 2, which had a DISI engine and was certified to Euro 5 emissions levels.

The instantaneous CO emissions (**Appendix 4**, **Figure A4-8**) show that the CO emissions are essentially zero as soon as the oxidation catalyst has fully activated, somewhere before 200s. This is confirmed by the cumulative CO emissions plot (derived from the instantaneous CO in g/s), which is shown in **Figure 3.4.6** for Vehicle 2.

Figure 3.4.6 Cumulative CO emissions [in g] over the ECE phase following cold engine starting at -7°C, for Vehicle 2. The x-axis is the time in seconds after cold engine starting.



It is also clear that the difference between fuels occurs within the first 150s of the ECE cycle. The Bag derived CO emissions can be compared to these cumulative CO emission results by dividing the values in **Figure 3.4.6** at the 780s point by the total ECE distance (just over 4 km). For this vehicle, the CO Bag results (**Figure 3.4.2**) are consistently about 20% higher than the cumulative CO emissions summed from the instantaneous values. This difference may result from the short period of apparent zero emissions at the start of the emissions sampling (**Figure 3.4.7**) which may result from a discrepancy between the tail-pipe and dilute emissions sampling at the very start of the cycle. This is confirmed by the CO_2 emissions and hence the carbon-balance FC (**Figure 3.4.8**) which shows that almost no fuel is consumed during the first 11s idle period while the FC rate is relatively high during the next idle period. Therefore, the modal emission rates (g/s) during the first ~11s of the test are incorrect. However, the Bag emissions results, which capture all of the emissions, show that this does not alter the relative emissions from the two fuels.

Figure 3.4.7 Instantaneous CO emissions [in g/s] over ECE-1 following cold engine starting at -7°C, for Vehicle 2. The x-axis is the time in seconds after cold engine starting.

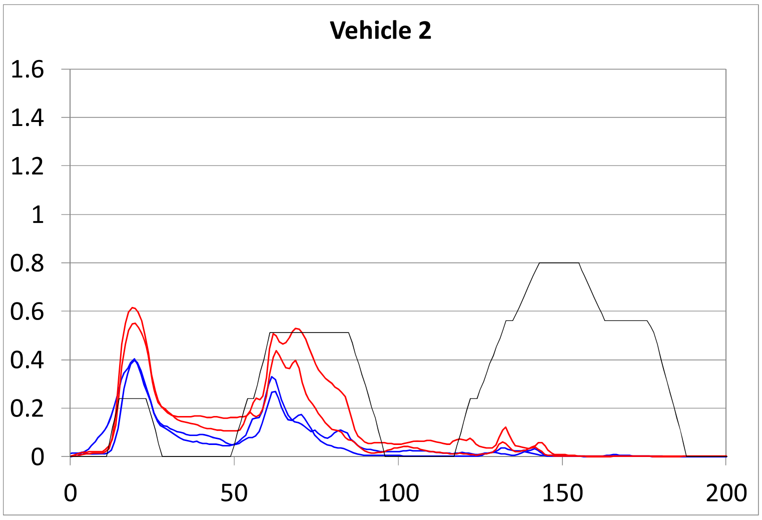
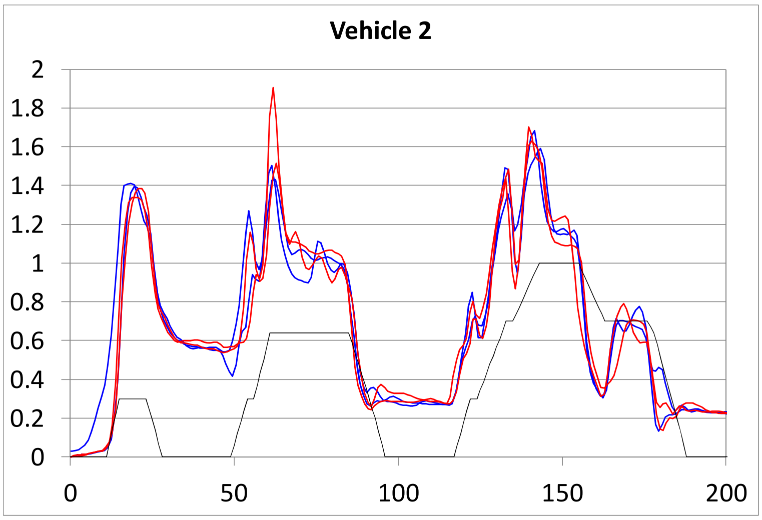


Figure 3.4.8 Instantaneous FC [in g/s] over ECE-1 following cold engine starting at -7°C, for Vehicle 2. The x-axis is the time in seconds after cold engine starting.



The UEGO sensor data for Vehicle 2 suggest that the engine is running richer with the Step 2 E10-E (RED) fuel during the uncontrolled period at the start of the test (**Figure 3.4.9**). Lambda control starts at about 100s, which is also confirmed by the manufacturer's installed lambda sensor activity (**Figure 3.4.10**). The UEGO shows the greatest difference between the two fuels (~5% richer on the RED fuel) during the initial idle period, and the difference is then much smaller, up to the point where the lambda is approximately the same after ~80s of the test cycle.

These small differences in lambda are not evident from the derived fuel flow (**Figure 3.4.8**), the vehicle's EMS mass air flow signal (**Figure 3.4.11**), and the EMS throttle position signal (**Figure 3.4.12**). However, the fuel flow data are unreliable during the first idle period when the greatest lambda difference is seen. After this, there is only about a 2% lambda difference which would be difficult to detect in these fluctuating signals.

Figure 3.4.9 UEGO lambda over ECE-1 following cold engine starting at -7°C, for Vehicle 2. The x-axis is the time in seconds after cold engine starting.

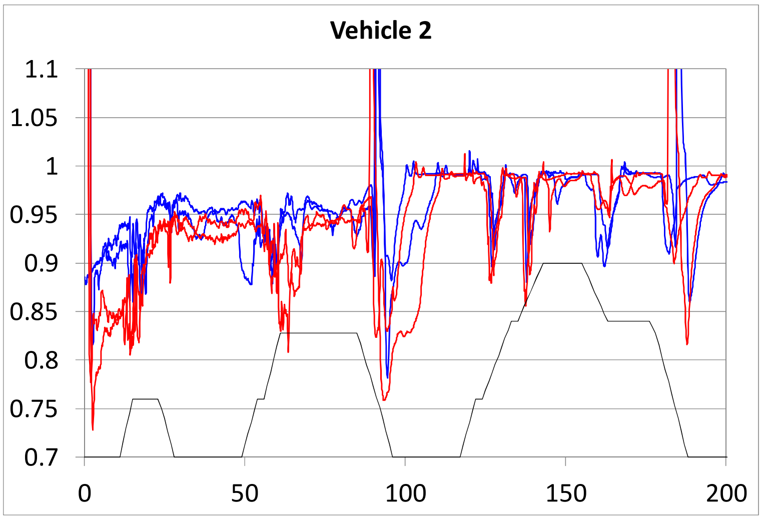


Figure 3.4.10 Manufacturer-installed lambda sensor signal over ECE-1 following cold engine starting at -7°C, for Vehicle 2. The x-axis is the time in seconds after cold engine starting.

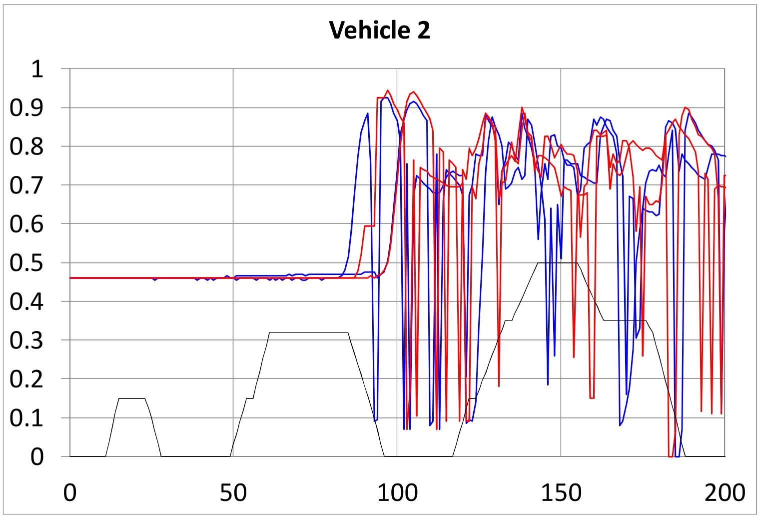


Figure 3.4.11 Mass air flow signal from the EMS over ECE-1 following cold engine starting at -7°C, for Vehicle 2. The x-axis is the time in seconds after cold engine starting.

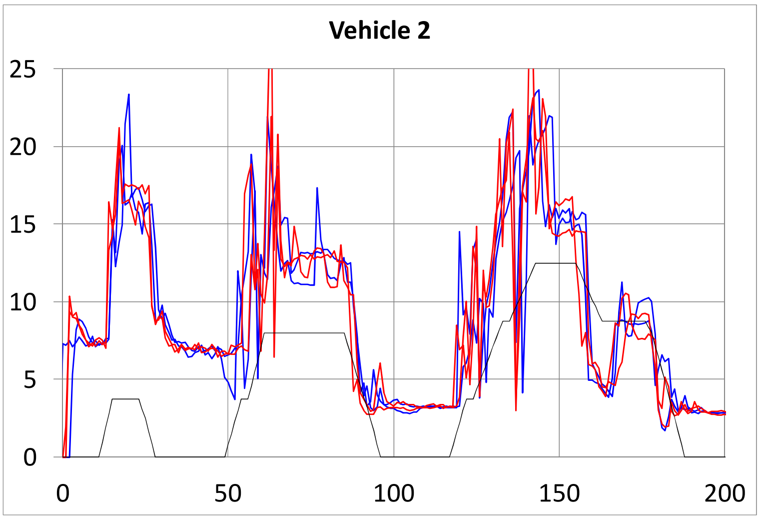
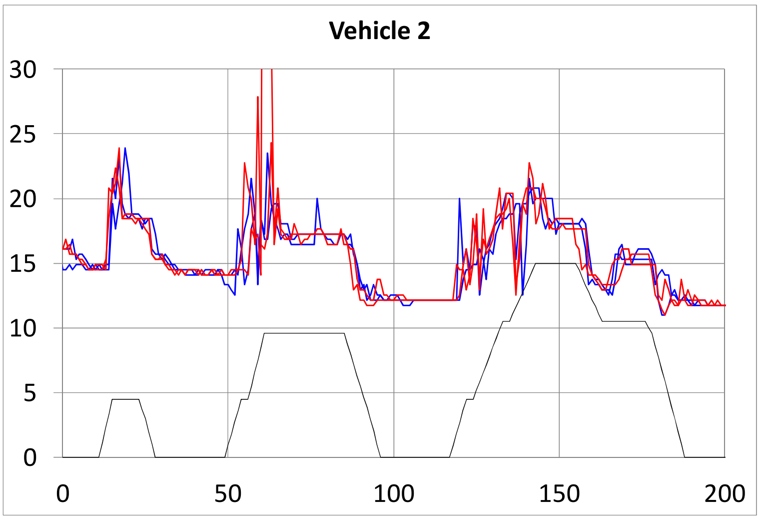
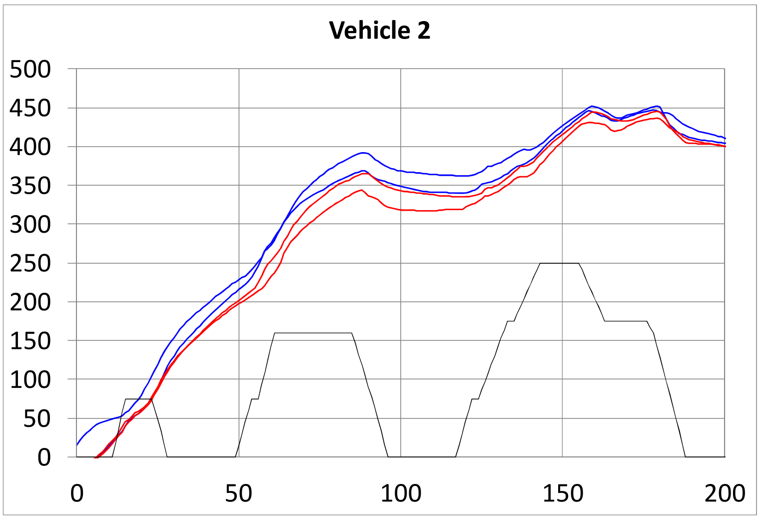


Figure 3.4.12 Throttle position signal from the EMS over ECE-1 following cold engine starting at -7°C, for Vehicle 2. The x-axis is the time in seconds after cold engine starting.



The only other measured difference between the fuels was shown by the exhaust gas temperature measurements. The pre-catalyst exhaust gas temperature (**Figure 3.4.13**) was consistently higher during the first 150s of the cycle on the Baseline E10-E (BLUE) fuel that was apparently running slightly leaner during the majority of this period. The post-catalyst temperature (**Appendix 4**, **Figure A4-5**) was also slightly higher on the BLUE fuel, but the difference between the fuels was delayed until almost 100s after the start of the test.

Figure 3.4.13 Pre-catalyst exhaust gas temperature over ECE-1 following cold engine starting at -7°C, for Vehicle 2. The x-axis is the time in seconds after cold engine starting.



The CO emissions measured in this legislated test were on average 20% higher with the Step 2 E10-E (RED) fuel. This increase in CO was mainly influenced by just one of the six vehicles tested: Vehicle 2 showed almost a 90% increase in CO emissions with the more volatile RED fuel. The impact of volatility on CO emissions in this -7°C test is therefore highly vehicle dependent. From the data collected, however, it is difficult to interpret why this particular vehicle responded in this way. A slightly higher than average (25%) fuel effect on CO was also seen in Vehicle 1, which was the other vehicle equipped with a DISI engine.

The UEGO sensor data for Vehicle 2 suggested that the engine was operating slightly richer on the more volatile (RED) fuel during the first 100s of the test: In the first idle period, the lambda difference is about 5%, but this quickly diminishes to about 2%. The available fuel flow, air mass flow and throttle position data are not sufficiently accurate to confirm or refute this difference in lambda.

There appear to be two possible explanations for the measured effects: (i) there is a slightly higher fuel flow in the case of the Step 2 E10-E (RED) fuel, before lambda control starts, that results in partial combustion but does not produce any extra power or (ii) there is no difference in the fuel flow into the cylinder, but the fuel volatility effect alters the mixture during combustion and the amount of combusted fuel seen in the exhaust system.

Except for the differences in the volatility of the fuel, the other physical properties of the two test fuels were quite similar and thus unlikely to have affected the fuel flow through the injector. It is also unlikely that fuel vapour could impact the fuel delivery at these low temperatures (-7°C) and high pressures of a DISI fuel system. Finally, the molecular composition and C, H, and O contents of the two fuels were also very close so that any differences in stoichiometric AFR were <0.5%. So, it appears unlikely that there was any intrinsic increase in the fuel flow or decrease in the lambda due to the fuel properties except for volatility.

The second explanation could be related to the change in fuel volatility. Since this is a DISI engine, the lower volatility (BLUE) fuel is likely to result in a greater proportion of un-evaporated fuel droplets in the cylinder, particularly under these low temperature starting conditions. Some of this liquid fuel may contact the cold cylinder wall where it can be absorbed in the lubricant film, and thus take no further part in the combustion and exhaust process. As a result, the exhaust gas would be expected to be marginally leaner with the lower volatility (BLUE) fuel. By contrast, a slightly greater proportion of the higher volatility fuel (RED) will evaporate giving richer overall combustion and thus a higher concentration of CO in the exhaust gas.

As the engine starts to warm up, the amount of the lower volatility (BLUE) fuel remaining in a liquid form will be reduced and the two fuels will begin to behave in a similar manner, both in terms of lambda and CO emissions. Although lower volatility may look beneficial in terms of the leaner cold-start combustion and the reduced CO emissions, this may be at the expense of fuel addition to the crankcase and possibly poorer driveability performance.

3.4.3 Conclusions from NEDC regulated emissions testing at -7°C

The tests comparing the Baseline E10-E (BLUE) fuel with the Step 2 E10-E (RED) fuel, having a difference of 8.7% in E70, showed that:

- All vehicles started easily and satisfactorily completed the legislated test. No driveability issues were reported in any tests.
- All vehicles were well within the legislated limits for HC (1.8 g/km) and CO (15 g/km) over the ECE phase of the test.
- Differences that were not fuel related were observed between vehicles in terms of FC, emissions, time to reach lambda control and the variability of the lambda control.
- The Step 2 E10-E (RED) fuel produced more CO in the exhaust than the Baseline E10-E (BLUE) fuel during the first 150s of the test. Although this trend was shown by all vehicles, with a fleet-average increase in CO of 20% on the RED fuel, the effect came predominantly from just one vehicle (90% increase).
- Vehicle 2 which showed the greatest effect was one of the two DISI vehicles and the only vehicle in the fleet homologated to the Euro 5 emissions level. The other DISI vehicle (Vehicle 1) showed a 25% increase in CO with the Step 2 E10-E (RED) fuel which was comparable to the fleet-average. All of the non-DI vehicles showed much smaller CO increases, and well below the fleet-average value.
- For Vehicle 2, the UEGO sensor data showed a richer mixture for the Step 2 E10-E (RED) fuel during the critical period associated with the higher CO emissions, at the start of the test. There was, however, no detectable change in the fuel flow, air flow or throttle setting with this fuel.
- UEGO sensors can show different lambda values due to changes in exhaust gas composition (as explained in **Section 3.3**).
- An alternative explanation is that the lower volatility of the Baseline E10-E (BLUE) fuel allows some fraction of the fuel to remain in a liquid state on the cylinder wall during the initial cold conditions, removing it from the combustion

process and the exhaust gas. This would result in leaner combustion and lower CO exhaust emissions. However, the lower volatility fuel may not be beneficial to the engine as a whole.

3.5 EVAPORATIVE EMISSIONS

3.5.1 Overview of evaporative emissions testing

Evaporative emissions are known to depend on fuel volatility, especially the Vapour Pressure (DVPE). Higher vapour pressure fuels will increase the amount of vapour generated by the fuel system that has to be controlled by the Carbon Canister and Evaporative control system. Ethanol blends, of course, increase volatility and can increase fugitive evaporative emissions, which was investigated in a previous joint JRC/EUCAR/CONCAWE programme [20].

However ethanol in the gasoline can increase evaporative emissions in two other ways. First, it can build up in the canister “heel” reducing the canister’s working capacity. Second, it can increase vapour permeation through some plastic and elastomer components which has been investigated in USA studies [21,22].

DVPE levels of ethanol blends are controlled by EN 228, but to see whether the proposed increases in E70 and higher ethanol level would affect evaporative emissions, testing was carried out on all six vehicles in the Millbrook SHED, using the current EU test procedure as described in **Appendix 5**. Duplicate tests were carried out on two fuels, the Baseline E10-A (ORANGE) and Step 2 E10-A (GREEN). Hot Soak Loss (HSL) and Diurnal emissions were determined separately. Test order was randomised as far as possible within the constraint of only four tests per vehicle, i.e. GREEN-ORANGE-ORANGE-GREEN or ORANGE-GREEN-ORANGE-GREEN, etc.

During the testing, high emissions were seen from several vehicles, well above the regulatory limit of 2g/test. To establish whether this was due to canister breakthrough or to leakage or permeation from the fuel system, extra diurnal tests were carried out with a second canister connected to the outlet of the main vehicle canister.

Separate, new canisters were used for each test fuel, two for each fuel for logistical reasons. Before testing, these were conditioned by loading to breakthrough with butane, and then purging to constant weight. This process was repeated three times. Between tests, canisters were purged to constant weight and then loaded to 2g breakthrough with butane.

Where possible, the carbon canisters were fitted with quick-release connectors, so that they could be removed and weighed at several points during the testing:

- Canister loaded to breakthrough before testing
- After the pre-conditioning drive (ECE + 2*EUDC)
- After overnight soak, before ECE Type 1 cycle
- After ECE Type 1 cycle, before going into SHED
- After Hot Soak and Diurnal tests in SHED

However, this weighing was not always carried out and some weighings were carried out with or without connecting pipework, so not all canister weight data are available.

3.5.2 Results

Canister working capacity was measured during the initial conditioning tests and for some later tests, and full results are given in **Appendix 5**. For most canisters, the purged and breakthrough weights continued to increase with time, as they built up "heels" of heavier hydrocarbons and ethanol. This is consistent with the earlier JRC/EUCAR/CONCAWE study [20]. Working capacity varied from around 50g for the two smaller Vehicles 5 and 6 to over 100g for the larger Vehicles 1 and 2, as would be expected. Working capacity varied surprisingly little over time, though there are few data from the later tests on ethanol fuels. This is because the breakthrough loaded weight as well as the purged weight increases with time as the canister "heel" builds up.

Full test results for all tests carried out including canister weight data are given in **Appendix 5 Table A5.1**. Evaporative emissions are shown below in **Figures 3.5.1** to **3.5.3** with the results arranged in date order.

Vehicles 1, 2 and 6 all met the 2g/test evaporative emissions limit for all tests but the other three vehicles substantially exceeded this limit on all tests. HSL emissions were low for all vehicles, generally less than 0.3g/test and diurnal emissions dominated the total evaporative emissions.

Vehicle 1 showed a trend of increasing diurnal emissions over the first four tests, but emissions were stable after that. None of the other vehicles showed a clear increase with time, except perhaps Vehicle 5 in the later tests. It should be noted that Vehicles 1 and 2 were tested first, in February–March, and would not have seen gasoline containing 10% ethanol before this time. The other vehicles, on the other hand, were tested later (Vehicles 3 and 4 in April–May and Vehicles 5 and 6 in August–September) so they were exposed to gasoline containing 10% v/v ethanol for much longer while undergoing other tests.

There were substantial differences in emissions between repeat tests on the same fuel. Consequently, no statistical analysis has been carried out on the results, as it was felt that the standard deviations would be too great to allow meaningful comparisons. However, by looking at the results, it is clear that there are no significant differences between the two fuels.

Evaporative emissions from vehicles can arise from a number of sources. All fuel system vapours are routed to the carbon canister, so any fuel system emissions should come from vapour breakthrough of the canister. Other sources include fuel system leaks, solvent emissions from plastic and rubber components including tyres, and permeation of fuel vapour through plastic fuel tanks and fuel system hoses/seals. This latter source has been identified as a major problem with ethanol containing fuels and has been studied in the USA [21,22]. Ethanol acts as a solvent opening "pores" in polyethylene fuel tanks and other elastomers, allowing hydrocarbon vapours to pass through. However, this is a slow process and it takes several weeks or months to reach equilibrium.

Figure 3.5.1 HSL and diurnal emissions for Vehicles 1 and 2, with results in date order

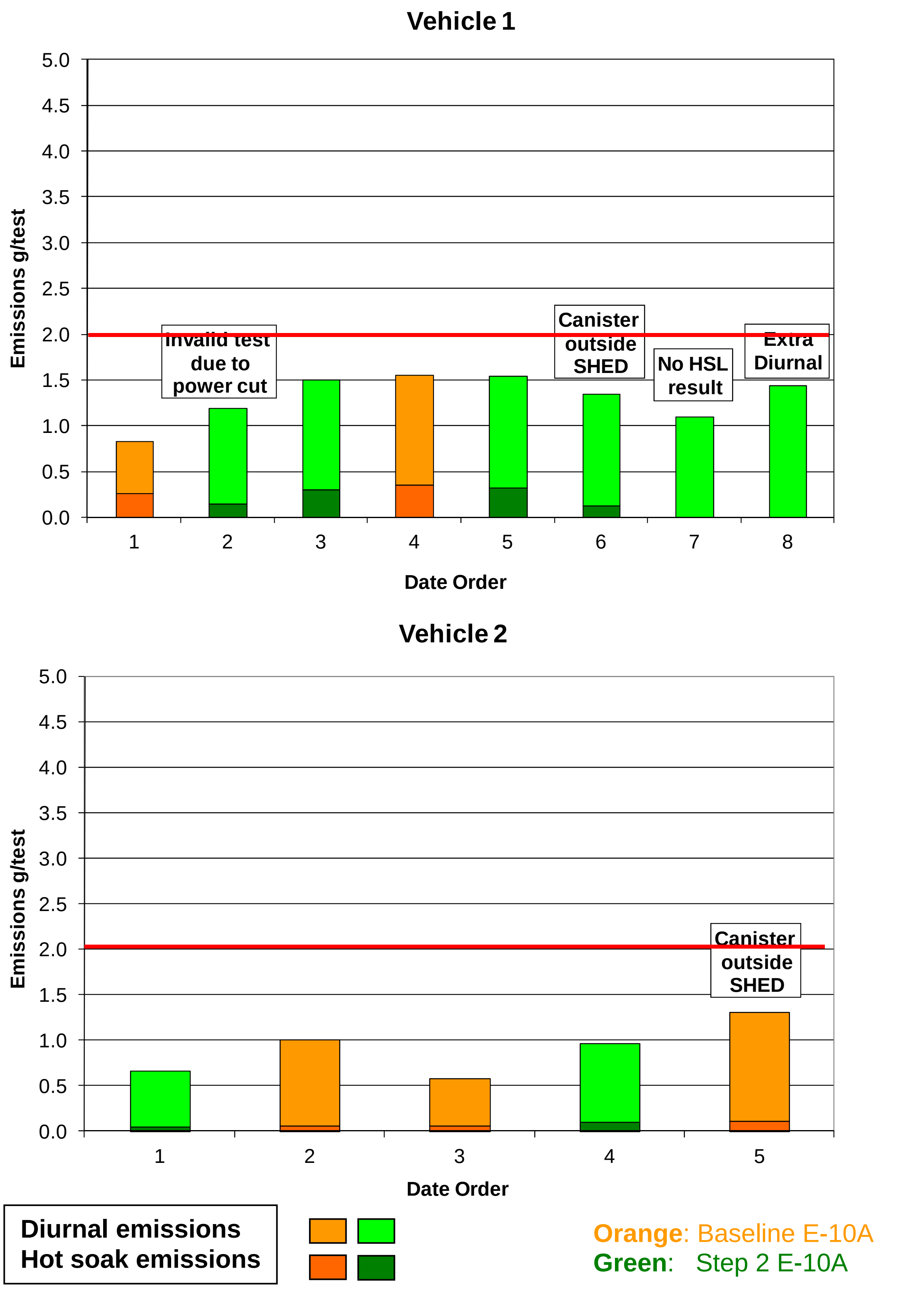


Figure 3.5.2 HSL and diurnal emissions for Vehicles 3 and 4, with results in date order

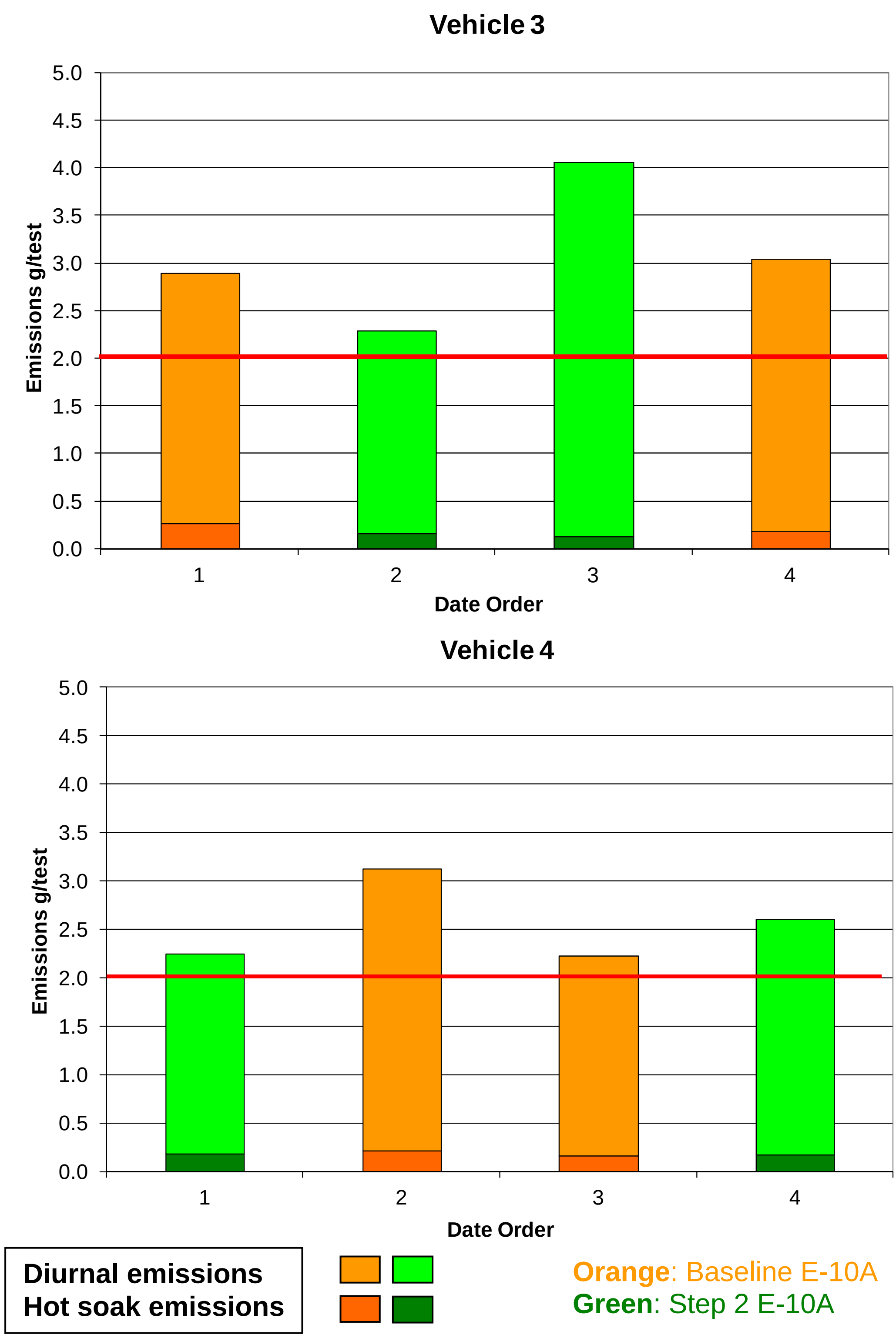
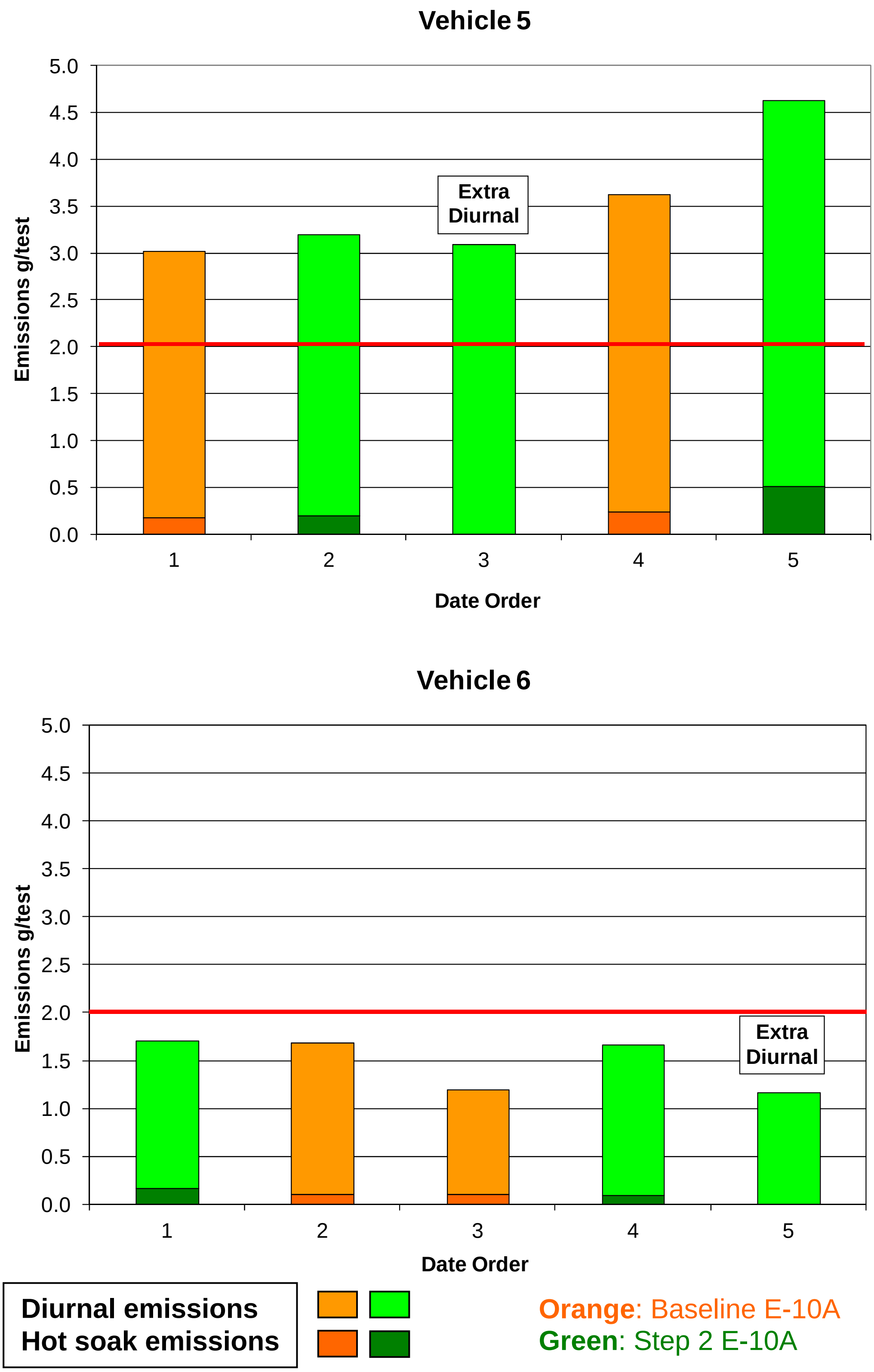


Figure 3.5.3 HSL and diurnal emissions for Vehicles 5 and 6, with results in date order



The high diurnal emissions seen for three of the vehicles suggested that emissions could be coming from sources other than canister breakthrough. To check this possibility, additional tests were run on two vehicles with the carbon canisters outside the SHED and connected to the vehicle via hoses. For logistical reasons Vehicles 1 and 2 were chosen for this exercise, even though they had relatively low emissions. As can be seen from the charts, for Vehicle 1 diurnal emissions on the Step 2 E10-A (GREEN) fuel were similar to previous tests, while for Vehicle 2 on the Baseline E10-A (ORANGE) fuel, emissions were significantly higher.

This confirmed that the diurnal emissions were not coming from the canister but from other sources. By the time these extra tests were completed, all vehicles had the E10 fuels in their fuel tanks for over three months so fuel system elastomers should have reached equilibrium. As a further check, it was decided to run some extra emission tests, and conduct a second diurnal test after the main test, with a second canister connected to the vent of the first (main) canister to adsorb any breakthrough vapours. Results of this exercise are shown in **Table 3.5.1**.

Table 3.5.1 Extra Diurnal tests with second canister in SHED, Vehicles 1, 5, and 6

Vehicle	Hot Soak g/test	Diurnal 1 g/test	Main Canister wt gain in g	Diurnal 2 g/test	Second Canister wt gain in g
1	-	1.10	17.2	1.44	-1.0
2					
3					
4					
5	0.21	3.00	-	3.10	0.2
6	0.09	1.57	7.2	1.17	1.6

In all cases, it is clear that the diurnal emissions from both tests are very similar. For Vehicles 1 and 5, the second canister adsorbs a negligible amount of vapour. Only Vehicle 6 shows some indication of possible canister breakthrough, though this is small. Thus the diurnal emissions do not appear to arise from the canister, but from other sources, possibly including permeation.

An estimate of total evaporative emissions from the vehicle fuel system can be made by adding the HSL, Diurnal emissions and the canister weight gain in the SHED. As can be seen from the penultimate column in **Table A5.1** in **Appendix 5**, where canister weight data are available, the total evaporative emissions are relatively constant for Vehicles 1, 5, and 6.

3.5.3 Conclusions from evaporative emissions testing

- Substantial differences were found between repeat tests on the same fuel, so the data available were not adequate to carry out statistical analysis.
- HSL emissions were low for all tests and evaporative emissions results were dominated by the diurnal emissions.
- Three of the vehicles met the 2 g/test evaporative emissions limit in all tests but the other three vehicles all consistently exceeded the limit, by up to 100%.
- There were no clear differences in emissions for any of the vehicles between the Baseline E10-A (ORANGE) and Step 2 E10-A (GREEN) fuels.

- Additional diurnal tests with extra carbon canisters connected to vehicle canister vents showed that the diurnal emissions were not coming from canister breakthrough, but from other sources, possibly including permeation.
- Canisters were purged to constant weight before each test, then loaded to breakthrough with butane. Both purged weight and, surprisingly, breakthrough loaded weight increased with test number. Working capacity varied surprisingly little with time, but there are little data available from later tests.

3.6 HOT WEATHER DRIVEABILITY AT +40°C

3.6.1 Overview of Hot Weather Driveability testing

Hot Weather Driveability (HWD) or Hot Fuel Handling (HFH) of gasoline vehicles is a function of the fuel's "front-end" volatility (especially DVPE) and ambient temperature and has long been studied. In the USA, HWD is controlled by the volatility term $T_{V/L20}$, i.e. the temperature at which a fuel forms a vapour/liquid ratio of 20.

In Europe, HWD has traditionally been controlled by a Flexible Volatility Index (FVI) which is equal to DVPE + 7*E70. Ethanol, of course, increases both DVPE and E70 (as well as $T_{V/L20}$) so it was essential to study the effect of increasing E70 on HWD in this study.

CONCAWE completed a similar study of the effect of ethanol on both cold and hot weather driveability in 2002 [7,8]. This study showed few volatility-related problems except on two DISI vehicles that showed substantial increases in driveability demerits on high volatility "splash blended" fuels at high ambient temperatures.

A review of the literature on ethanol effects on HWD and CWD was also completed and reported in 2009 [1]. This review showed that modern vehicles are much less susceptible to HWD problems than older carburetted vehicles. In addition, the effects of ethanol on HWD appear to be due solely to its impact on DVPE and E70. The effect of DVPE was also more important than the effect of E70.

All six vehicles were tested at 40ºC on the summer grade (Class A) fuels, Baseline E10-A (ORANGE) and Step 2 E10-A (GREEN). Tests were run using the GFC test procedure, the same as was used for a previous CONCAWE HWD Study [7,8]. The GFC procedure has three "sequences" that represent motorway, mountain climbing and heavy city traffic driving. Full details of the test procedure and a table of results are given in **Appendix 6**. Duplicate tests were run on each fuel with the test order randomised as far as is possible with only four tests per vehicle. Some GFC test requirements for full throttle accelerations were adjusted to keep vehicles stable on the dynamometer.

All vehicles were equipped with Engine Management Systems (EMS) and all except Vehicle 5 had electronic "drive-by-wire" throttle control. This led to some problems during the two wide open throttle (WOT) accelerations in the test cycle. For example, even though the driver would fully depress the accelerator as required by the test protocol, the EMS would not fully open the throttle until about half way through the acceleration (see **Appendix 6** for details). This was probably to limit maximum torque through the transmission and/or to prevent wheelspin on the dynamometer rolls, even though the vehicle's traction control systems had been turned off for all tests. This EMS effect led to longer acceleration times during the tests than when the reference acceleration times were set, and hence substantial “acceleration time” demerits.

This behaviour had not been seen in the previous study [7,8] and is considered to be an artefact of the test procedure with these vehicles while operating on a chassis dynamometer. In addition, substantial idle instability demerits were recorded, especially during the city traffic sequence. This was often found to be due to the time taken for the engine to return to idle after a deceleration, which again was controlled by the EMS. Based on these observations, the GFC test procedure should be updated, or a new procedure developed, to account for the performance of newer, more powerful vehicles equipped with active EMS and ‘drive by wire’ technology.

Comprehensive data logging from the vehicle’s EMS at both 1 and 10Hz was used to study both these issues. More details of this analysis are given in **Appendix 6**.

The original plan was to run tests at 30ºC on any vehicle that showed substantial demerits at 40ºC. However, due to the problems caused by interactions of the EMS with the test procedure and the low overall demerits at +40°C, it was decided not to proceed with additional measurements at +30°C.

3.6.2 Results

Even though the GFC procedure is a severe test of vehicle performance under hot temperature conditions, there were no stalls or failures to comply with the test procedure observed for any vehicle or fuel during this test programme.

In view of the problems experienced during testing with longer acceleration times and idle instability, the demerit ratings for each test were split into three categories: (1) hesitations, stumbles and surges, (2) idle instability, and (3) acceleration times. As already discussed, the results for (3) are believed to be confounded by the vehicles’ EMS.

Table A6-5 in **Appendix 6** shows results for all individual tests and also for the by-vehicle mean values. These data have been used to generate the figures below. In some cases, a single comparative test was also completed on the CEC RF-02-08 reference fuel and this result is shown on the right of the charts.

Figure 3.6.1 shows results for the first demerit category: hesitations, stumbles and surges. None of the vehicles showed demerits greater than 24 on either of the test fuels, indeed two vehicles showed no demerits at all. For the other four vehicles, two showed a small increase in demerits on the Step 2 E10-A (GREEN) fuel, and two showed a small decrease on this fuel. Overall, there was no clear fuel effect for hesitations, stumbles, and surges.

To put these results in context, 24 demerits was used in the previous CONCAWE study [7,8] to define ‘substantial absolute demerits’ and is equivalent, based on the rating scheme, to two moderate or one severe driveability malfunction. A moderate driveability malfunction would typically be evident to a trained driver-rater while a severe driveability malfunction would typically be evident to an untrained driver.

Figure 3.6.1 HWD demerit ratings at +40°C for hesitations, stumbles and surges. The CEC Reference fuel was not tested on Vehicles 2 and 3.

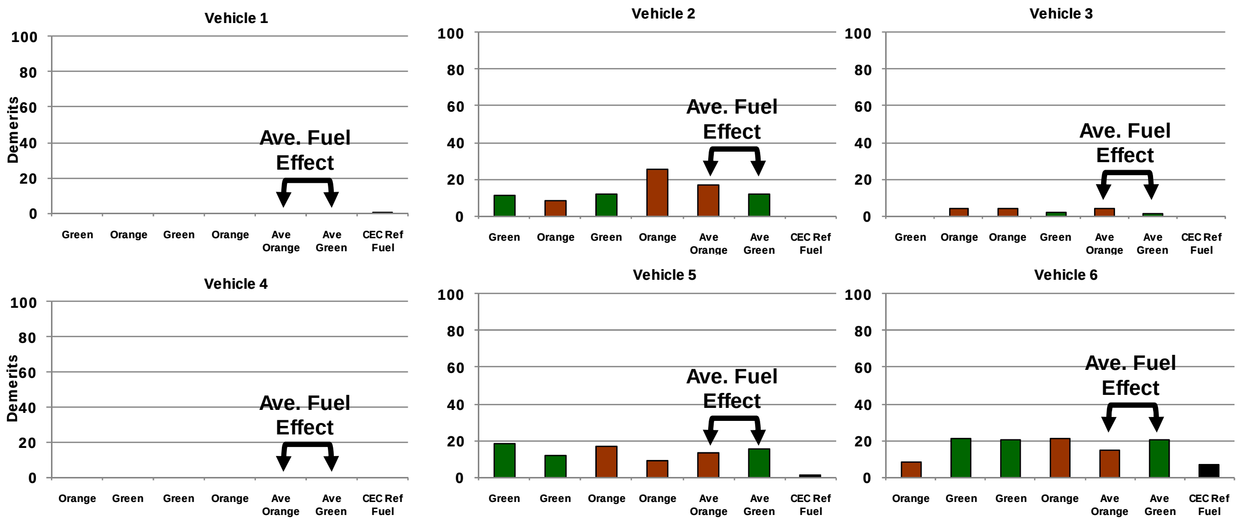


Figure 3.6.2 adds idle instability demerits. Still, three of the vehicles showed low demerits, below 24, while Vehicle 2 had one test on the Baseline E10-A (ORANGE) fuel with 33 demerits. Vehicle 5 showed very high levels of idle instability demerits, due primarily to "flaring" of the engine speed when returning to idle. Five of the vehicles had substantially lower average demerits on the Step 2 E10-E (GREEN) fuel while one (Vehicle 3) had very low and similar demerits on both fuels.

Figure 3.6.2 HWD demerit ratings at +40°C for (1) hesitations, stumbles and surges and (2) idle instability. The CEC Reference fuel was not tested on Vehicles 2 and 3.

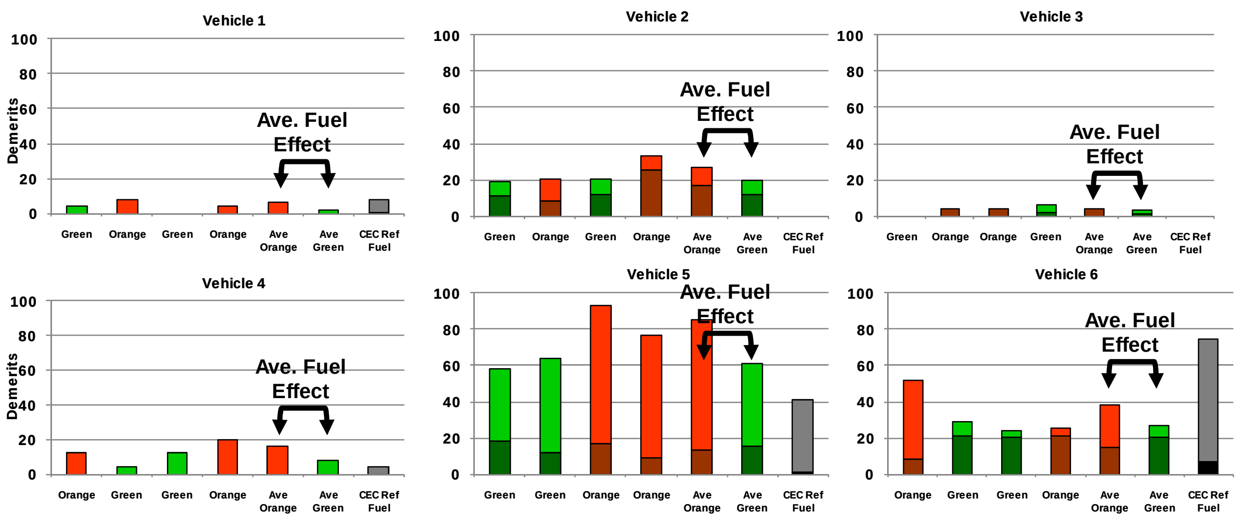
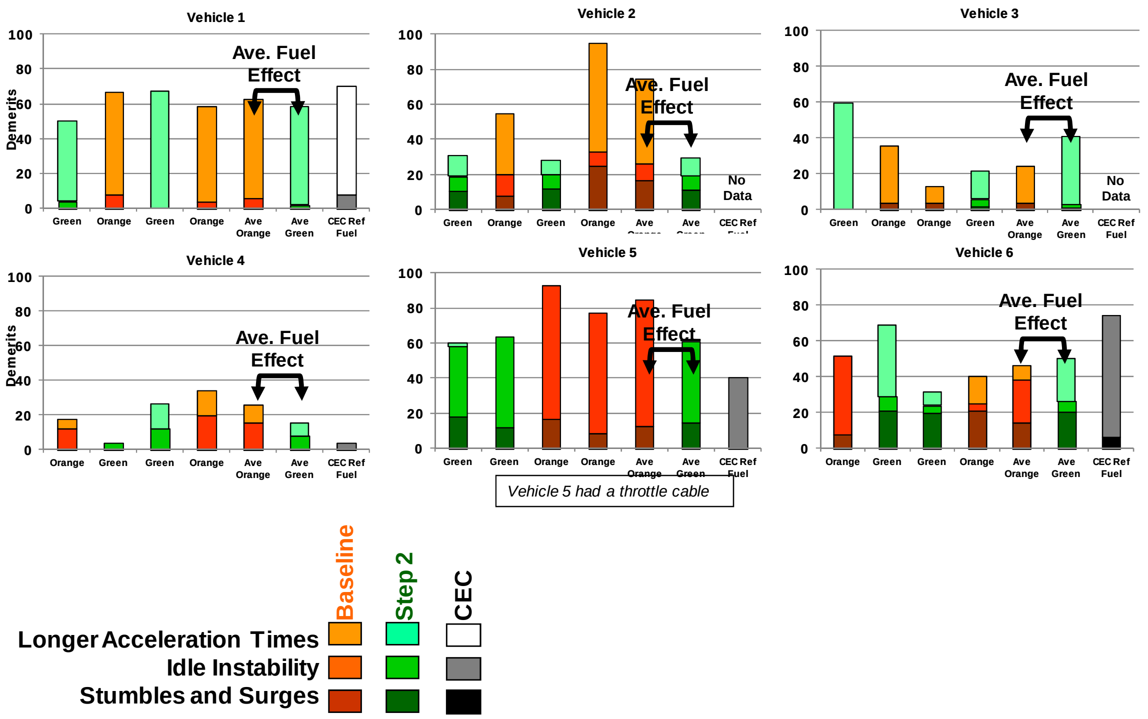


Figure 3.6.3 HWD Demerit ratings at +40°C for (1) stumbles and surges, (2) idle instability, and (3) longer acceleration times. The CEC Reference fuel was not tested on Vehicles 2 and 3.



The higher acceleration time demerits are added in **Figure 3.6.3** which substantially increases the total demerits for all vehicles except for Vehicle 5, which of course has high idle stability demerits. The effect of acceleration time is especially noticeable for Vehicles 1 and 2 on the Baseline E10-A (ORANGE) fuel. When total demerits are considered, Vehicles 2, 4, and 5 show lower average total demerits on the Step 2 E10-A (GREEN) fuel, Vehicle 3 has higher demerits and Vehicles 1 and 6 show very similar levels.

No driveability testing using the GFC procedure has been reported since the previous CONCAWE programme [7,8] in 2004. Thus this is the first time that these issues have been experienced with vehicles having modern EMS and drive-by-wire technology.

No attempt has been made to carry out statistical analysis as there are too few results, but in view of the test-to-test variability, it is unlikely that any of these differences would be statistically significant.

3.6.3 Conclusions from HWD testing at +40°C

- No stalls, fails, hesitations, or misfires were observed for any fuel or vehicle as defined by the demerit rating scheme.
- No overall increase in demerits was observed with the Step 2 E10-A (GREEN) fuel compared to the Baseline E10-A (ORANGE) fuel for hesitations, stumbles and surges and for idle instability.

- For these two demerit rating types:
  - 5 of 6 cars showed lower total average demerits on the Step 2 E10-A (GREEN) fuel compared to the Baseline E10-A (ORANGE) fuel.
  - 1 of 6 cars (Vehicle 3) showed similar total average demerits.
- The two smaller vehicles showed higher demerits due to idle instability during Sequence 6 (heavy city traffic driving).
- Idle speed varied more than expected and was often slow to stabilise when coming back to idle after a cruise or acceleration, introducing some demerits.
- The four larger vehicles, including both DISIs, showed less than 27 demerits, for stumbles and surges and for idle instability.
- Total demerits were higher than expected for all fuels when acceleration demerits were included, but these are believed to be due to the EMS not allowing full throttle when demanded by the driver.
- Most vehicles were outside the limits of gear/speed combinations as specified by the GFC test procedure for Sequence 5 warm-up, so some compromises were made.
- Some minor faults were observed that could not be rated because they were not included in the GFC rating scheme, for example a minor stumble during cruise.
- The GFC procedure should be updated, or a new procedure developed, to account for the performance of more powerful vehicles equipped with modern EMS and ‘drive by wire’ technology.

4 OVERALL CONCLUSIONS

This report describes results from a six vehicle study that was completed to investigate the impact of changes in the volatility characteristics of unleaded gasoline containing 10% v/v ethanol on regulated exhaust and evaporative emissions and on hot and cold weather vehicle driveability performance. The vehicles selected for this study were representative of the current EU fleet, met or exceeded Euro 4 emissions limits, spanned the range from upper medium to small vehicle classes, were compatible with 10% v/v ethanol according to the manufacturer's warranty information, and included two modern gasoline DISI engine types.

Vehicle testing included regulated emissions measured over the New European Driving Cycle (NEDC) at +23°C and -7°C, evaporative emissions according to the European regulatory procedure, cold engine starting and idling at -20°C, and Hot Weather Driveability performance at +40°C.

The conclusions from this study are:

- All vehicles satisfactorily completed all required driving cycles on all fuels with no false starts, no misfires, no stalls, no failures, and no OBD faults.
- Impacts of fuel volatility on emissions and performance were small relative to vehicle-to-vehicle effects.
- No major differences were observed in the fleet-average HC and NOx emissions between the Baseline E10-A (ORANGE) and Step 2 E10-A (GREEN) fuels for NEDC regulated emissions at +23°C. The fleet-average CO emissions were 36% higher on the more volatile (GREEN) fuel but were still well below the Euro 4/5 limits for this test.
- No major differences were observed between the Baseline E10 and Step 2 E10 fuels for fleet-average NEDC regulated emissions at -7°C and for HWD performance at +40°C.
- Cold operation at -20°C and -7°C:
  - Overall conclusions:
    - The measurement of lambda at these cold conditions was critical to understanding the in-cylinder conditions and the resulting impacts on emissions. The following conclusions apply particularly to the -20°C results and to a limited extent the -7°C results.
      - The exhaust UEGO sensor data indicated that the Step 2 E10-E (RED) fuel gave slightly richer lambda during the initial warm-up period. These results were not supported, however, by direct measurements of fuel and air flow, which suggested that there was no difference in AFR between the fuels.
      - The reason for these apparently conflicting results is not clear, but it is possible that the UEGO sensor responded to differences in exhaust composition between the two fuels rather than to a change in overall AFR. Alternatively, the lower volatility of the Baseline E10-E (BLUE) fuel may result in some fuel being retained on the cylinder wall during the initial cold engine conditions. If this were the case,

then this fraction of fuel would not participate in the combustion process and would not appear in the exhaust gas.

- Although conditions in the combustion chamber could not be directly measured, it can be expected that the more volatile Step 2 E10-E (RED) fuel should give better evaporation and mixing even in a cold combustion chamber. It is not clear whether the overall effects of this are beneficial or detrimental.

– Cold starting and Idling at -20°C:

  - The tests comparing the Baseline E10-E (BLUE) fuel with the Step 2 E10-E (RED) fuel, having a difference in E70 of 8.7%, showed:
    - All vehicles started easily (<1.6s) and satisfactorily completed the 1180s test. Idle speeds were stable and consistent throughout and showed no differences between the fuels, although there were differences between vehicles in terms of fuel consumption, emissions, and time to reach lambda control.
    - Compared to the Baseline E10-E (BLUE) fuel, the more volatile Step 2 E10-E (RED) fuel produced more CO, less CO_2, and slightly lower levels of unburned HCs in the exhaust.
    - Limited tests comparing the Step 1 E10-E (PURPLE) fuel with the Baseline E10-E (BLUE) fuel, which differed in E70 by 3%, showed very similar emissions and starting performance.

- ECE regulated emissions at -7°C:
  - The tests comparing the Baseline E10-E (BLUE) fuel with the Step 2 E10-E (RED) fuel, having a difference in E70 of 8.7%, showed:
    - CO and HC emissions on all fuels were well below the ECE regulated limits.
    - Higher fleet-average CO emissions were measured on the Step 2 E10-E (RED) fuel although the effect was dominated by one DISI vehicle (Vehicle 2).
- Evaporative Emissions
  - Hot Soak Loss (HSL) emissions were low for all tests and fuels and the evaporative emissions results were dominated by diurnal emissions.
  - Three of the vehicles met the 2 g/test emission limit in all tests, but the other three vehicles consistently exceeded this limit, by up to 100%.
  - Substantial differences were found between repeat tests on the same fuel, so the data were not adequate to carry out statistical analysis. However, there were no clear differences in emissions for any of the vehicles between the Baseline E10-A (ORANGE) and Step 2 E10-A (GREEN) fuels.
  - Additional diurnal tests with extra carbon canisters connected to the vehicle canister vents showed that the diurnal emissions were not due to canister breakthrough, but from other sources, possibly including permeation through fuel system materials.

- Hot Weather Driveability (HWD) at +40°C:
  - No overall increase in demerits was observed with the Step 2 E10-A (GREEN) fuel compared to the Baseline E10-A (ORANGE) fuel for hesitations, stumbles and surges and for idle instability. For these demerit types 5 of 6 vehicles showed lower demerits on the Step 2 E10-A (GREEN) fuel, and one vehicle showed similar demerits on both fuels.
  - The two smaller vehicles showed higher demerits due to idle instability during Sequence 6 (heavy city traffic driving). This was due to greater idle speed variation than expected after throttle opening and closing.
  - Total demerits were higher than expected for all fuels when acceleration demerits were included, but these are believed to be due to the Engine Management System not allowing full throttle when demanded by the driver.

Overall, the results of this six-vehicle testing support the conclusion from previously published studies that a small relaxation in the $E70_{max}$ and $E100_{max}$ volatility parameters in the EN 228 gasoline specification is not expected to increase the risk of regulated emissions or vehicle driveability performance problems. The majority of the tests completed in this study compared results between ‘Baseline’ and ‘Step 2’ gasolines, in order to provide greater confidence that the performance of ‘Step 1’ gasolines would also be acceptable in real-world use. This conclusion applies to the current fleet of European gasoline vehicles as represented by the six E10-compatible vehicles selected for this study.

5 GLOSSARY

ACEA	European Automobile Manufacturers' Association
AFR	Air-Fuel Ratio
BOB	Basestock for Oxygenate Blending
CAN	Controlled Area Network
CEC	Coordinating European Council
CEN	European Committee for Standardisation
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRC	Coordinating Research Council (USA)
CWD	Cold Weather Driveability
CWF	Carbon Weight Fraction
DI	Driveability Index or Indices
DI	Direct Injection
DISI	Direct Injection Spark Ignition
DVPE	Dry Vapour Pressure Equivalent
E10	10% ethanol (by volume)
E70	Percentage of sample that evaporates at 70°C
E100	Percentage of sample that evaporates at 100°C
E150	Percentage of sample that evaporates at 150°C
ECE	Urban Driving Cycle
EMS	Engine Management System
EN	European Norm
ETBE	Ethyl Tertiary Butyl Ether
EtOH	Ethanol
EUCAR	European Council for Automotive R&D

EUDC	Extra Urban Driving Cycle
FAME	Fatty Acid Methyl Ester
FBP	Final Boiling Point
FC	Fuel Consumption
FQD	Fuel Quality Directive (2009/30/EC)
FVI	Flexible Volatility Index
GC	Gas Chromatograph or Chromatography
GFC	Groupement Français de Coordination
HC	Hydrocarbon
HSL	Hot Soak Loss
HFH	Hot Fuel Handling
HWD	Hot Weather Driveability
IBP	Initial Boiling Point
JRC	Joint Research Centre (of the European Commission)
MPI	Multi-Point Injection
MTBE	Methyl Tertiary Butyl Ether
NEDC	New European Driving Cycle
NMHC	Non-methane Hydrocarbon
NOx	Nitrogen Oxides
NSB	National Standardisation Body
PM	Particulate Matter
RED	Renewable Energy Directive (2009/28/EC)
rpm	Revolutions per minute
SE	Standard Error
SFI	Sequential Fuel Injection
SHED	Sealed Housing for Evaporative Determinations
THC	Total Hydrocarbon

$T_{V/L20}$	Temperature at which a fuel forms a vapour/liquid ratio of 20
T_{xx}	Temperature at which xx% v/v of the sample has evaporated
UEGO	Universal Exhaust Gas Oxygen (sensor)
v/v	volume/volume (volume fraction)
VLI	Vapour Lock Index
VTEC	Variable Temperature Emissions Chamber
WOT	Wide Open Throttle

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APPENDIX 1 VEHICLE PREPARATION

A1.1 VEHICLE SELECTION

In order to ensure the validity of the test work, efforts were made to ensure that the vehicles used were appropriate. Following discussions, it was decided that the vehicles selected must cover a range of model sizes and technologies while fairly representing the share of the current European fleet. The test fleet contained four vehicles with Sequential Fuel Injection (SFI) systems and two with gasoline Direct Injection Spark Ignition (DISI) systems. With regard to engine layout, four vehicles had a four-cylinder engine (Vehicles 2, 3, 4, and 6), one had a three-cylinder engine (Vehicle 5), and one had a six-cylinder engine (Vehicle 1). The 2009 EU vehicle registration records were used to ensure that the vehicle and engine combinations chosen were representative of the current European fleet.

A1.2 COASTDOWN TESTING

After the vehicle had been purchased, each of the test vehicles was weighed and underwent a maintenance and geometry check before being driven on a test track to establish a set of coastdown times. These times were used to simulate the vehicle dynamics when carrying out chassis dynamometer testing. The process followed for the coastdown testing can be seen in **Table A1-1**.

Table A1-1 Coastdown Test Procedure Matrix

	Task
(1)	Record Vehicle Details (Registration, Model, Odometer, engine, etc.)
(2)	Ensure vehicle is clean
(3)	Check tyre pressures
(4)	Record tyre make/model/size
(5)	Record tyre tread depths
(6)	Weigh vehicle with driver and any ballast required to reach a target of curb weight from the stated manufacturer figures in the handbook plus driver
(7)	Conduct vehicle safety check
(8)	Check/adjust steering geometry is at manufacturer specifications
(9)	Record wheel arch height in mm
(10)	Record effective tyre diameter
(11)	Record brake type on each axle (disc/drum)
(12)	Ensure there is wear on the brakes
(13)	Check track conditions (dry/wind speed less than 3m/s)
(14)	Close all air vents
(15)	Warm up vehicle on track at 120km/h
(16)	Conduct a minimum of 12 north and 12 south coast down runs from >130kmh to <5km/h

The coastdown times from all ten runs were averaged in order to allow each vehicle to be 'matched' on the chassis dynamometer. These can be seen in **Table A1-2**.

Table A1-2 Matrix of averaged north and south coastdown test results from all vehicles

Target speeds (km/h)	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6
125-115	6.86	6.23	4.59	5.13	4.25	4.36
115-105	7.86	7.35	5.34	5.99	4.92	5.12
105-95	8.81	8.31	6.16	6.93	5.71	5.85
95-85	9.87	9.38	7.06	7.96	6.72	6.67
85-75	11.16	10.70	8.20	9.25	7.78	7.67
75-65	12.45	12.25	9.58	10.69	9.15	8.83
65-55	14.09	14.05	11.37	12.81	10.85	10.24
55-45	15.83	16.19	13.27	15.17	13.00	11.92
45-35	17.86	18.41	15.63	18.43	15.74	13.98
35-25	19.92	20.93	18.33	21.61	19.37	16.54
25-15	22.12	23.39	21.28	25.99	23.28	19.55
15-5	23.28	24.71	23.32	29.77	25.49	22.08

The match process involves the dynamometer driving the vehicle up to a speed higher than that of the fastest coastdown time and allowing the inertia to run the vehicle down. The dynamometer software will try to match the times input to the computer. Once matched to within 5% at all points (with the exception of the two slowest points, which have a tolerance of +/-10%) the vehicle was assigned a set of coefficients. These coefficients, when input to the control computer, will create an accurate model of the vehicles rolling resistance, frictional losses, and aerodynamic drag throughout all driven cycles. This is in line with the legislative procedure.

Because two dynamometers were to be used at varying temperatures it was necessary to carry out multiple matches. Each of the vehicles were matched to the above times on both of the dynamometers, in addition each was matched on the VTEC dynamometer with each of the times reduced by 10% - this was in line with legislation to generate a vehicle model to test at -7°C. The final dynamometer coefficients can be seen in **Table A1-3**.

Table A1-3 Matrix of all vehicle dynamics coefficients generated from on-road coastdowns for all vehicles and all tests conducted

	Coefficient	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6
Mass (kg)		1590	1470	1130	1360	910	1020
>0°C Testing Light Duty Dyno	F^0 (N)	104.1	78.9	48.2	69.4	52	58.1
	F^1 (N/km/h)	-0.707	-1.068	-0.559	-1.375	-0.38	-1.494
	F^2 $(N/km/h)^2$	0.03999	0.04599	0.04222	0.05555	0.036773	0.054174
	F^3 $(N/km/h)^3$	-0.000053	-0.000056	-0.00002307	-0.00007485	-0.00001755	-0.0000975
>0°C Testing Heavy Duty Dyno	F^0 (N)	105.546	70	48	26	25	35
	F^1 (N/km/h)	1.0145	1.6638	0.0747	1.3831	1.4	2.4239
	F^2 $(N/km/h)^2$	0.0125	0.00418	0.03429	0.02178	0.0134	-0.00557
	F^3 $(N/km/h)^3$	0.000073	0.000127	0.000009	0.000038	0.00007	0.000162
<0°C Testing Heavy Duty Dyno	F^0 (N)	125.991	82.783	48	44	31	46.862
	F^1 (N/km/h)	1.2463	2.1157	1.6316	2.2248	1.7502	2.97
	F^2 $(N/km/h)^2$	0.0136	0.00099	0.01664	0.00979	0.01086	-0.01005
	F^3 $(N/km/h)^3$	0.000077	0.000158	0.000088	0.000135	0.000103	0.0002

A1.3 BENCHMARK VEHICLE TESTING AGAINST TYPE APPROVAL

Using the vehicle road load models generated for the chassis dynamometers, the vehicles were run through the legislated European emission approval process. It was understood that vehicles were unlikely to exactly match their type approval emissions and fuel consumption levels due to production variations, however, comparisons were made in order to ensure that there were no major issues with the vehicles, which caused unreasonable deviation from the approval results submitted by the vehicle manufacturer.

The results of benchmarking emissions tests can be seen in **Table A1-4** compared to the appropriate Euro standard limit values.

Table A1-4 Pre-instrumentation NEDC benchmark test results for Vehicle 1

Vehicle 1 Benchmarking Results								
								Fuel Cons
Odo at SOT:	**23354**	UNITS	**HC**	**CO**	**NOx**	**CO2**	**PM**	l/100km
Phase 1	*EEC CYCLES*	g/km	0.084	0.480	0.038	315.7	N/A	13.65
Phase 2	*EUDC CYCLE*	g/km	0.001	0.019	0.002	166.8	N/A	7.19
Combined result		**g/km**	**0.031**	**0.187**	**0.015**	**221.2**	**N/A**	**9.55**
Euro 4 Limits		g/km	0.100	1.000	0.080	N/A	N/A	**N/A**
Percentage of Euro 4 Limit		%	31%	19%	19%	N/A	N/A	**N/A**

Table A1-5 Pre-instrumentation NEDC benchmark test results for Vehicle 2

Vehicle 2 Benchmarking Results									
									Fuel Cons
Odo at SOT:	**8917**	UNITS	**HC**	**CO**	**NOx**	**CO2**	**PM**		l/100km
Phase 1	*EEC CYCLES*	g/km	0.116	0.199	0.147	255.8	0.011		11.05
Phase 2	*EUDC CYCLE*	g/km	0.002	0.103	0.007	145.9	0.002		6.29
Combined result		**g/km**	**0.044**	**0.138**	**0.059**	**186.4**	**0.005**		**8.05**
Euro 5 Limits		g/km	0.100	1.000	0.060	N/A	0.005		**N/A**
Percentage of Euro 5 Limit		%	44%	14%	98%	N/A	1.064		**N/A**

Table A1-6 Pre-instrumentation NEDC benchmark test results for Vehicle 3

Vehicle 3 Benchmarking Results									
									Fuel Cons
Odo at SOT:	**21496**	UNITS	**HC**	**CO**	**NOx**	**CO2**	**PM**		l/100km
Phase 1	*EEC CYCLES*	g/km	0.085	0.386	0.090	210.3	N/A		9.10
Phase 2	*EUDC CYCLE*	g/km	0.004	0.158	0.036	136.0	N/A		5.87
Combined result		**g/km**	**0.034**	**0.241**	**0.056**	**163.0**	**N/A**		**7.05**
Euro 4 Limits		g/km	0.100	1.000	0.080	N/A	N/A		**N/A**
Percentage of Euro 4 Limit		%	34%	24%	70%	N/A	N/A		**N/A**

Table A1-7 Pre-instrumentation NEDC benchmark test results for Vehicle 4

Vehicle 4 Benchmarking Results									
									Fuel Cons
Odo at SOT:	**15004**	UNITS	**HC**	**CO**	**NOx**	**CO2**	**PM**		l/100km
Phase 1	*EEC CYCLES*	g/km	0.229	0.733	0.069	246.8	N/A		10.72
Phase 2	*EUDC CYCLE*	g/km	0.011	0.185	0.003	158.1	N/A		6.83
Combined result		**g/km**	**0.090**	**0.385**	**0.027**	**190.5**	**N/A**		**8.25**
Euro 4 Limits		g/km	0.100	1.000	0.080	N/A	N/A		**N/A**
Percentage of Euro 4 Limit		%	90%	38%	33%	N/A	N/A		**N/A**

Table A1-8 Pre-instrumentation NEDC benchmark test results for Vehicle 5

Vehicle 5 Benchmarking Results									
									Fuel Cons
Odo at SOT:	**13704**	UNITS	**HC**	**CO**	**NOx**	**CO2**	**PM**		l/100km
Phase 1	*EEC CYCLES*	g/km	0.135	0.702	0.050	139.0	N/A		6.05
Phase 2	*EUDC CYCLE*	g/km	0.002	0.080	0.001	101.3	N/A		4.37
Combined result		**g/km**	**0.052**	**0.310**	**0.019**	**115.2**	**N/A**		**4.99**
Euro 4 Limits		g/km	0.100	1.000	0.080	N/A	N/A		**N/A**
Percentage of Euro 4 Limit		%	52%	31%	24%	N/A	N/A		**N/A**

Figure A1-9 Pre-instrumentation NEDC benchmark test results for Vehicle 6

Vehicle 6 Benchmarking Results									
									Fuel Cons
Odo at SOT:	**15678**	UNITS	**HC**	**CO**	**NOx**	**CO2**	**PM**		l/100km
Phase 1	*EEC CYCLES*	g/km	0.177	0.692	0.046	192.8	N/A		8.38
Phase 2	*EUDC CYCLE*	g/km	0.009	0.106	0.013	120.3	N/A		5.19
Combined result		**g/km**	**0.071**	**0.322**	**0.025**	**147.0**	**N/A**		**6.36**
Euro 4 Limits		g/km	0.100	1.000	0.080	N/A	N/A		**N/A**
Percentage of Euro 4 Limit		%	71%	32%	31%	N/A	N/A		**N/A**

A1.4 VEHICLE INSTRUMENTATION

There were four different vehicle configurations. All vehicles were fitted with thermocouples to measure temperatures in the engine oil sump, coolant top hose, air intake, fuel rail surface, fuel tank surface, pre catalyst temperature, and post catalyst temperature. UEGO sensors were also installed before the catalyst on all vehicles with the exception of Vehicle 6, where the sensor was installed post-catalyst due to space restrictions. An engine speed sensor was fitted to each vehicle and, with the exception of Vehicle 5 where it was unavailable, CAN (Controlled Area Network) data were logged throughout using a Racelogic VBox. It is also worth noting that Vehicle 2 had a small catalyst close coupled to the exhaust manifold, which did not leave enough room for instrumentation – in this case the ‘pre-catalyst’ instrumentation was actually installed between the close coupled and main catalyst. Vehicle 1 had additional instrumentation due to the exhaust being split into two banks at the manifold; one bank for each set of three cylinders. All of this can be seen in the instrumentation diagrams below.

Figure A1-1 Instrumentation Configuration 1 for Vehicles 3, 4 and 5

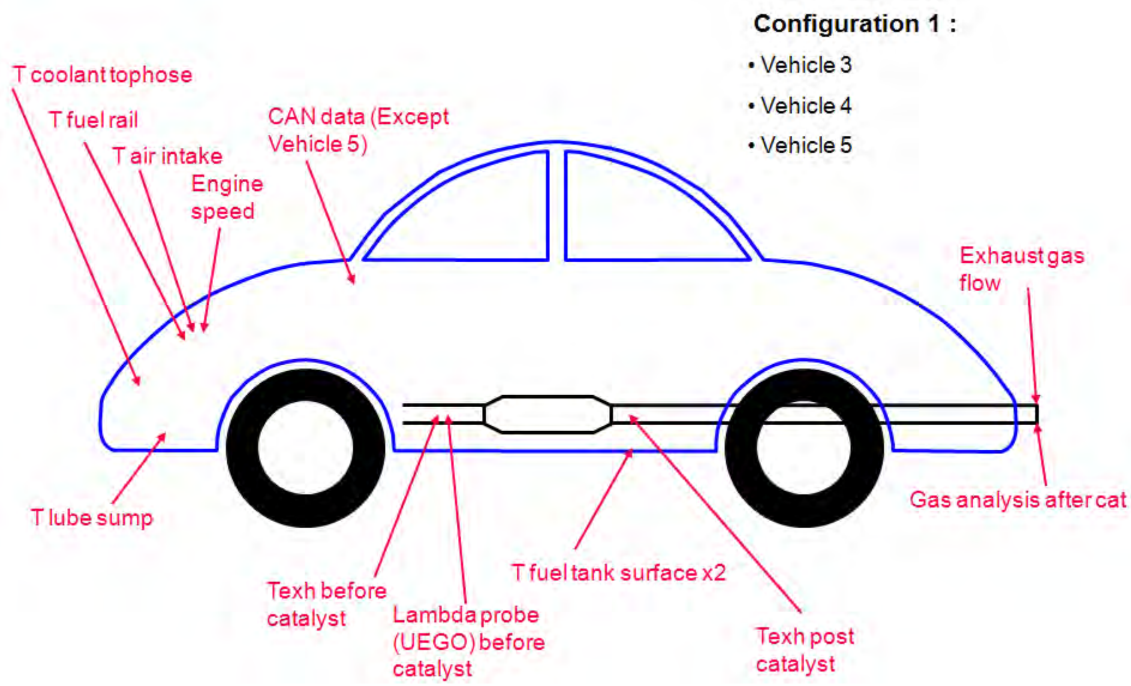


Figure A1-2 Instrumentation Configuration 2 for Vehicle 2

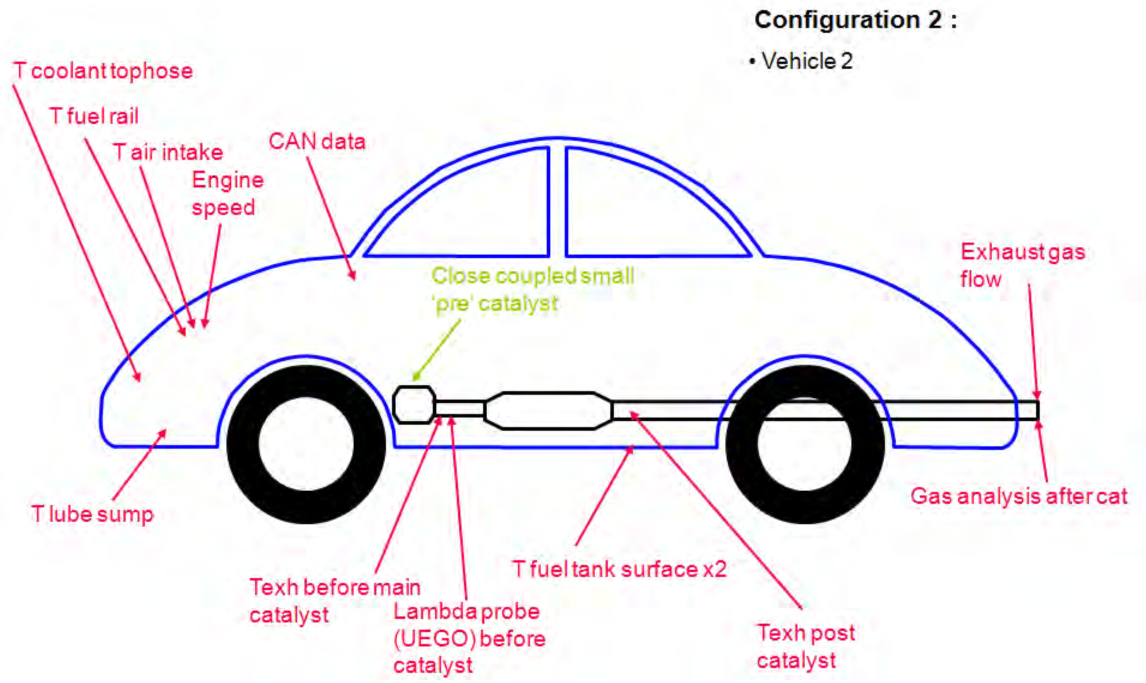


Figure A1-3 Instrumentation Configuration 3 for Vehicle 6

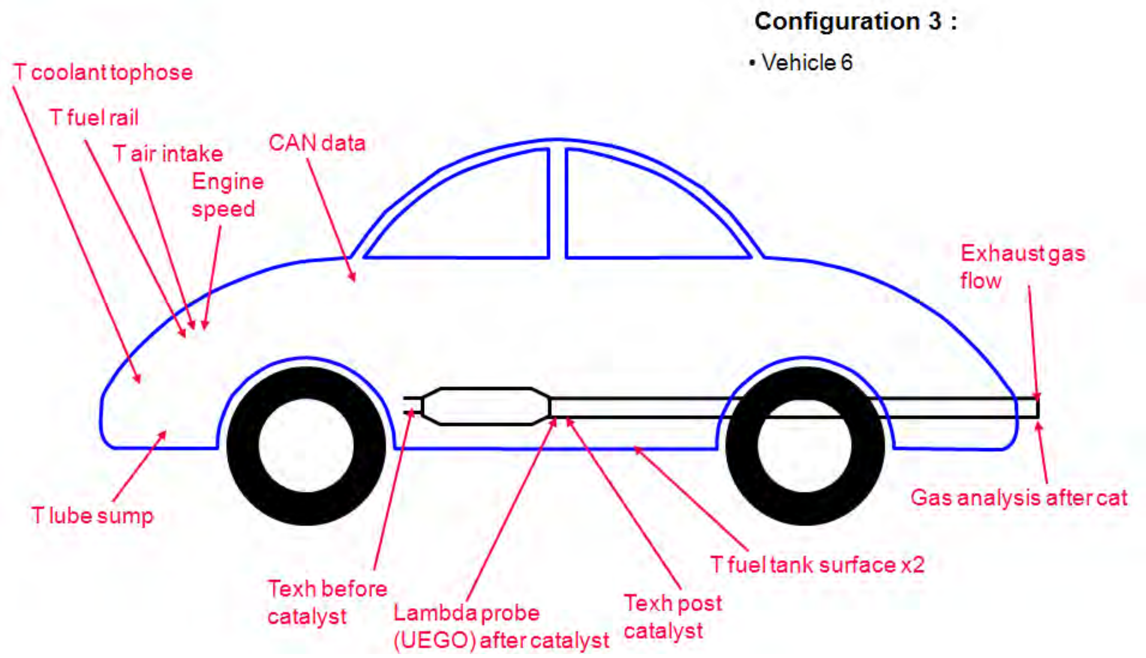
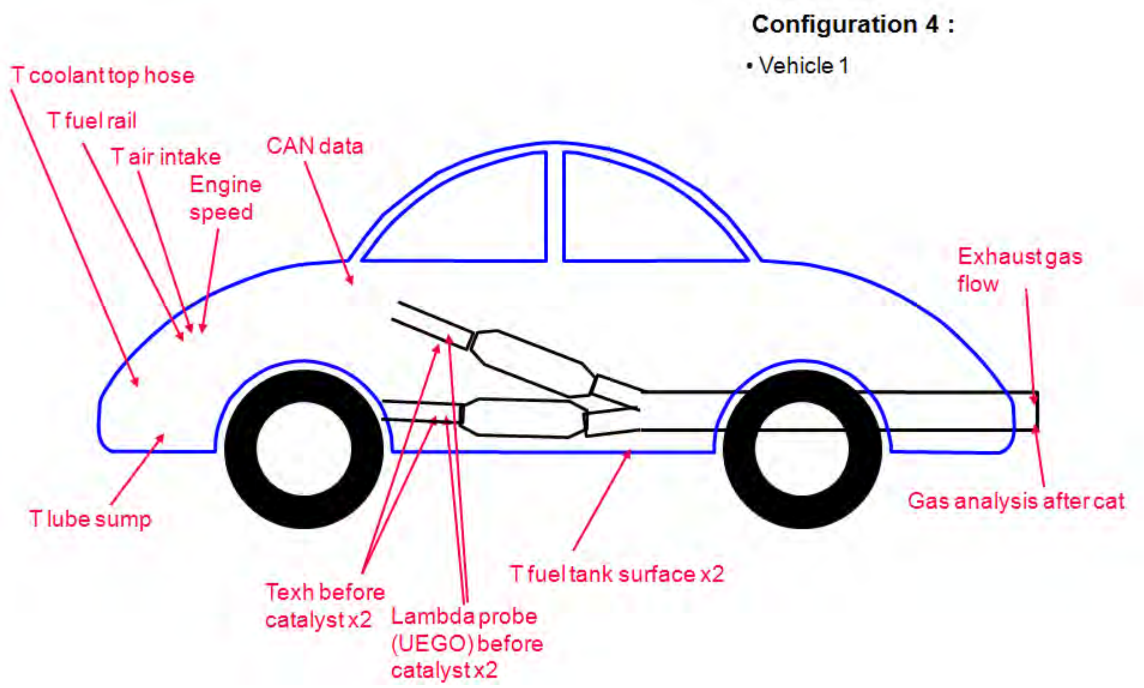
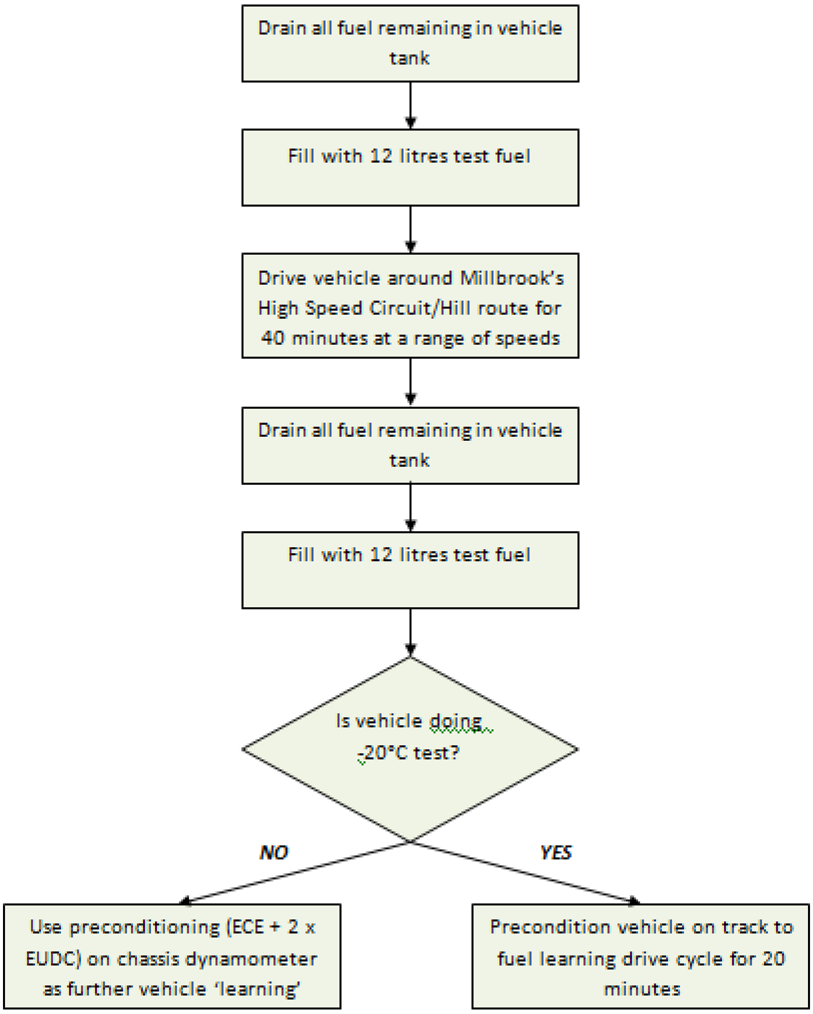


Figure A1-4 Instrumentation Configuration 4 for Vehicle 1



A1.5 FUEL DRAIN/FLUSH PROCEDURE

Figure A1-5 Flowchart for vehicle preparation and fuel flush and drain



A1.6 CANISTER PREPARATION

Evaporative carbon canisters were purchased especially for evaporative emissions testing and hot weather driveability assessments. All other tests used the carbon canister fitted to the vehicle at the time of purchase. Each of the vehicles evaporative emissions pipes, leading to and from the carbon canister, were fitted with quick connects in order to prevent any damage caused by wear to the vehicle connectors, which are not designed for repeated use.

In order to allow some conditioning on the new canisters, prior to any use each was filled to breakthrough with butane before being fully purged. This process was repeated a total of three times.

Pre-test preparation differed for evaporative and HWD assessments. For evaporative testing the canister was conditioned as follows:

- Any remaining hydrocarbon material purged from canister as much as reasonably possible.
- Butane used to load canister until breakthrough of at least 2g achieved.
- Canister fitted to vehicle less than an hour prior to start of preconditioning drive cycle.

For HWD assessments each canister was conditioned as follows.

- Any remaining hydrocarbon material purged from canister as much as reasonably possible.
- Butane used to load canister until breakthrough achieved.
- Drain butane out until remaining makes up 50% operating capacity of carbon sites.
- Canister fitted to the vehicle prior to start of warm up cycle.

A1.7 HOT WEATHER DRIVEABILITY TRAINING

It was considered necessary to train the drivers who would be responsible for the HWD testing. Due to the nature of assessing subjective demerits and the inevitable difference in driver opinion of issues encountered during vehicle operation, each vehicle would be driven by the same driver on all fuels. An external consultant in HWD assessment and familiar with the GFC procedure visited Millbrook in order to train the drivers on each of their respective vehicles. Training was conducted using the test facility that would be used throughout and with the vehicle fuelled with an unadditised European, Euro 4 grade gasoline. The complete drive cycle was carried out under actual test conditions so that the technician would be familiar with their vehicle, the demerits requiring assessment, and the testing procedure.

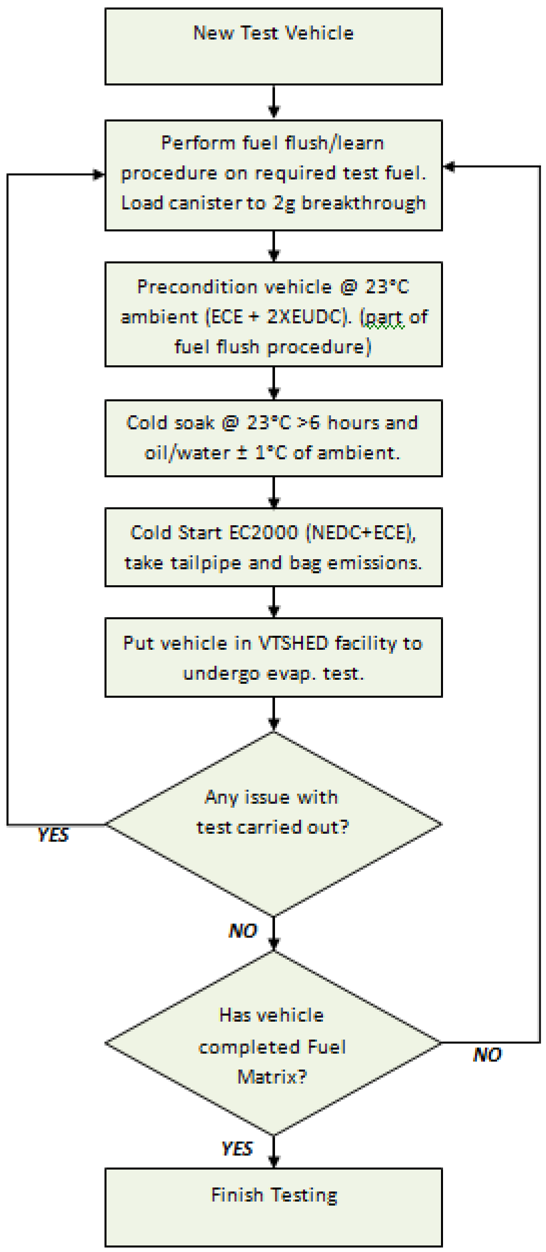
APPENDIX 2 REGULATED EMISSIONS AT +23°C

A2.1 BACKGROUND TO NEDC REGULATED EMISSIONS AT +23°C

Regulated emissions were measured over the NEDC at +23°C during the legislative evaporative emissions test procedure.

A2.2 TEST PROCEDURE

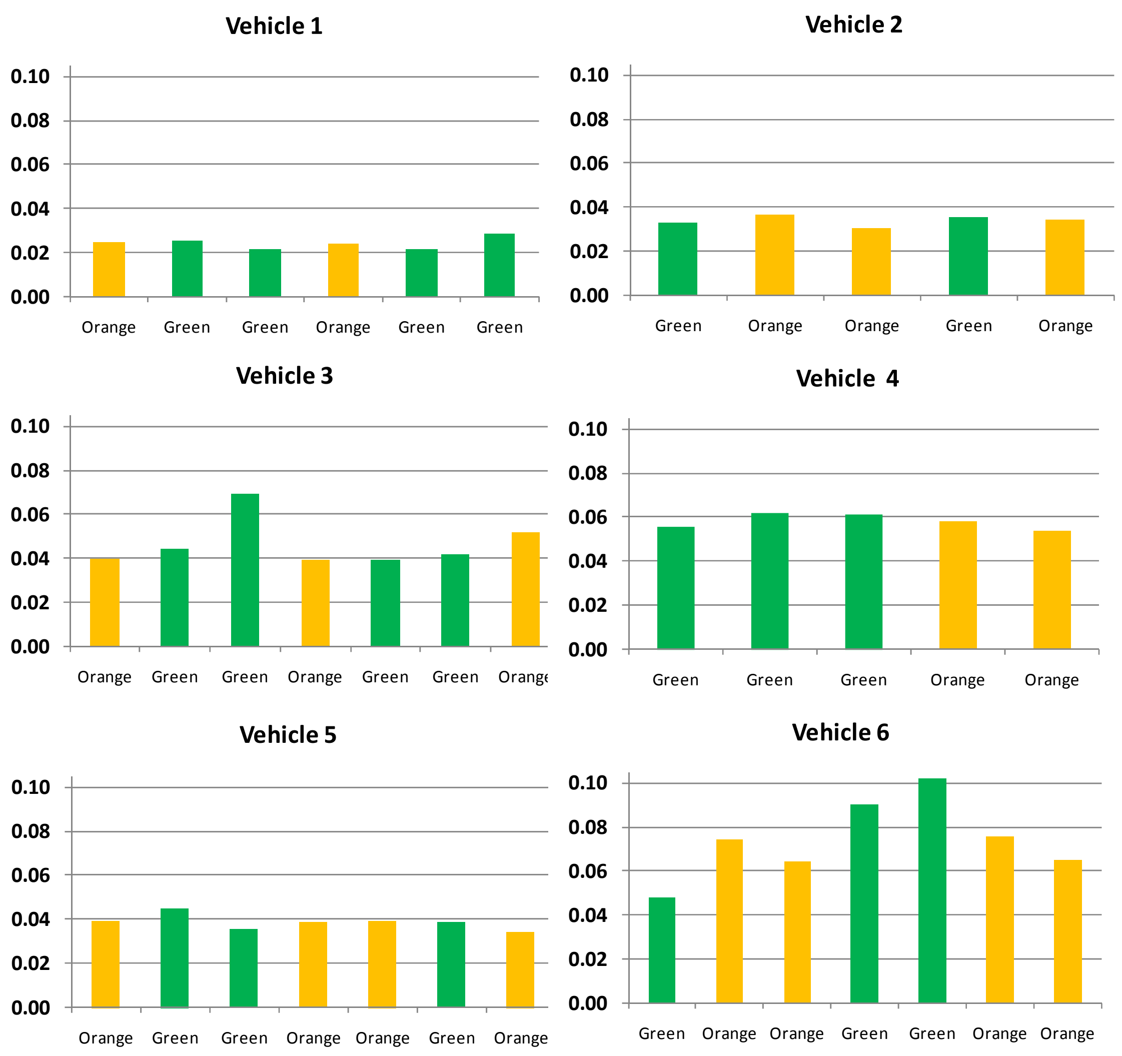
Figure A2-1 Flow chart for NEDC and Evaporative Emissions Testing



A2.3 RESULTS

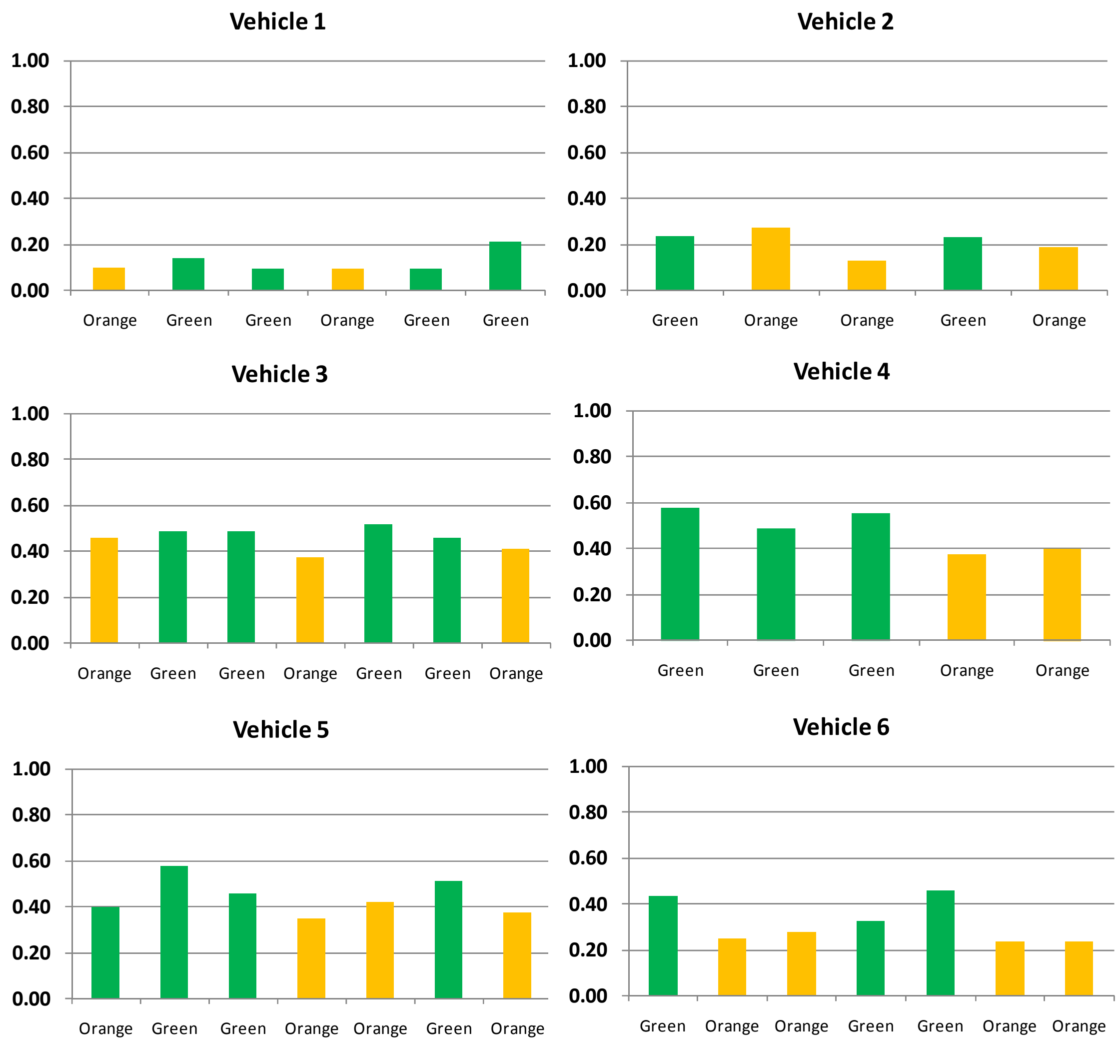
The results are shown in date order for two summer grade test fuels: Baseline E10-A (ORANGE) and Step 2 E10-A (GREEN).

Figure A2-2 HC emissions (in g/km) over the NEDC at +23°C



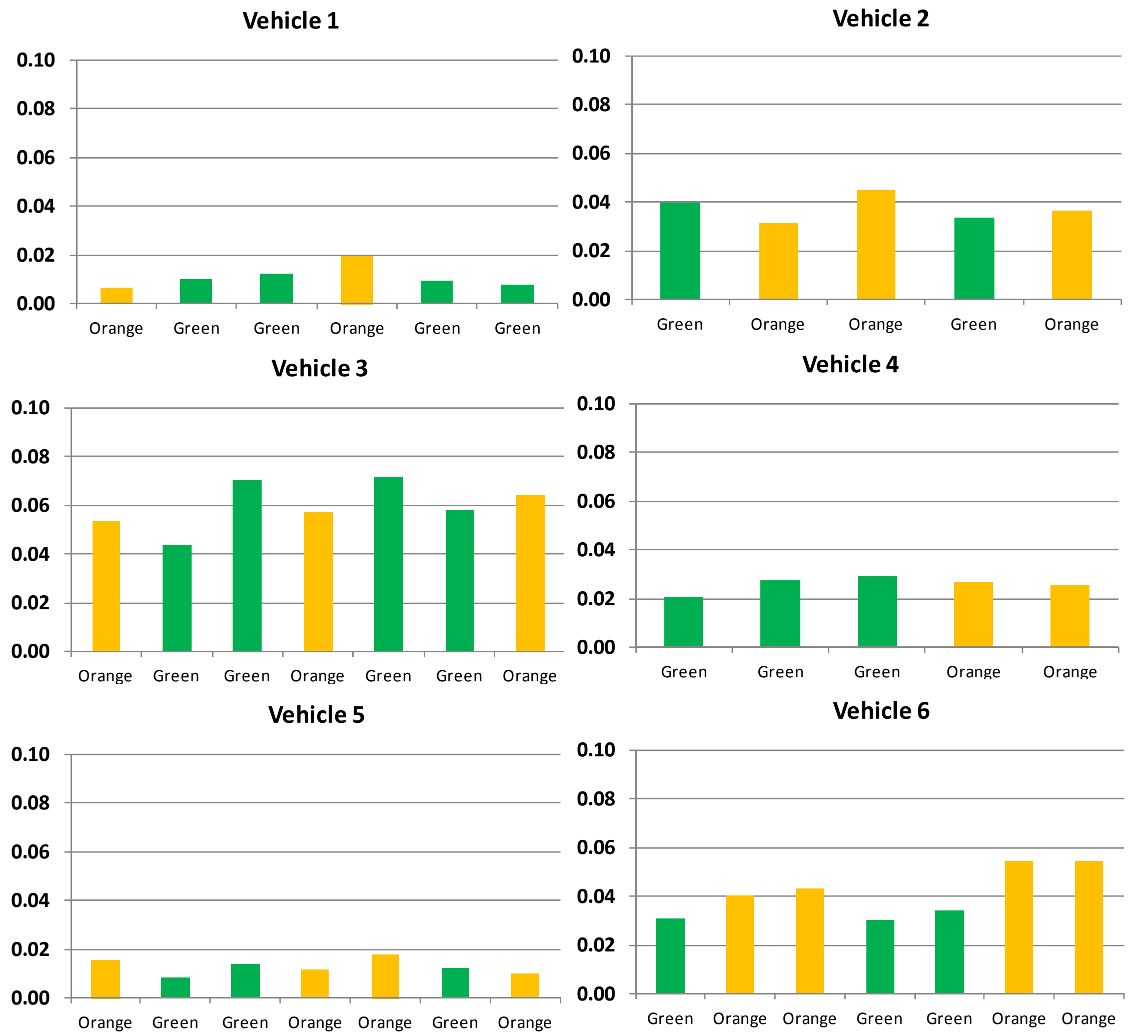
ORANGE: Baseline E10-A
GREEN: Step 2 E10-A

Figure A2-3 CO emissions (in g/km) over the NEDC at +23°C



ORANGE: Baseline E10-A
GREEN: Step 2 E10-A

Figure A2-4 NOx emissions (in g/km) over the NEDC at +23°C



ORANGE: Baseline E10-A
GREEN: Step 2 E10-A

Figure A2-5 CO_2 emissions (in g/km) over the NEDC at +23°C

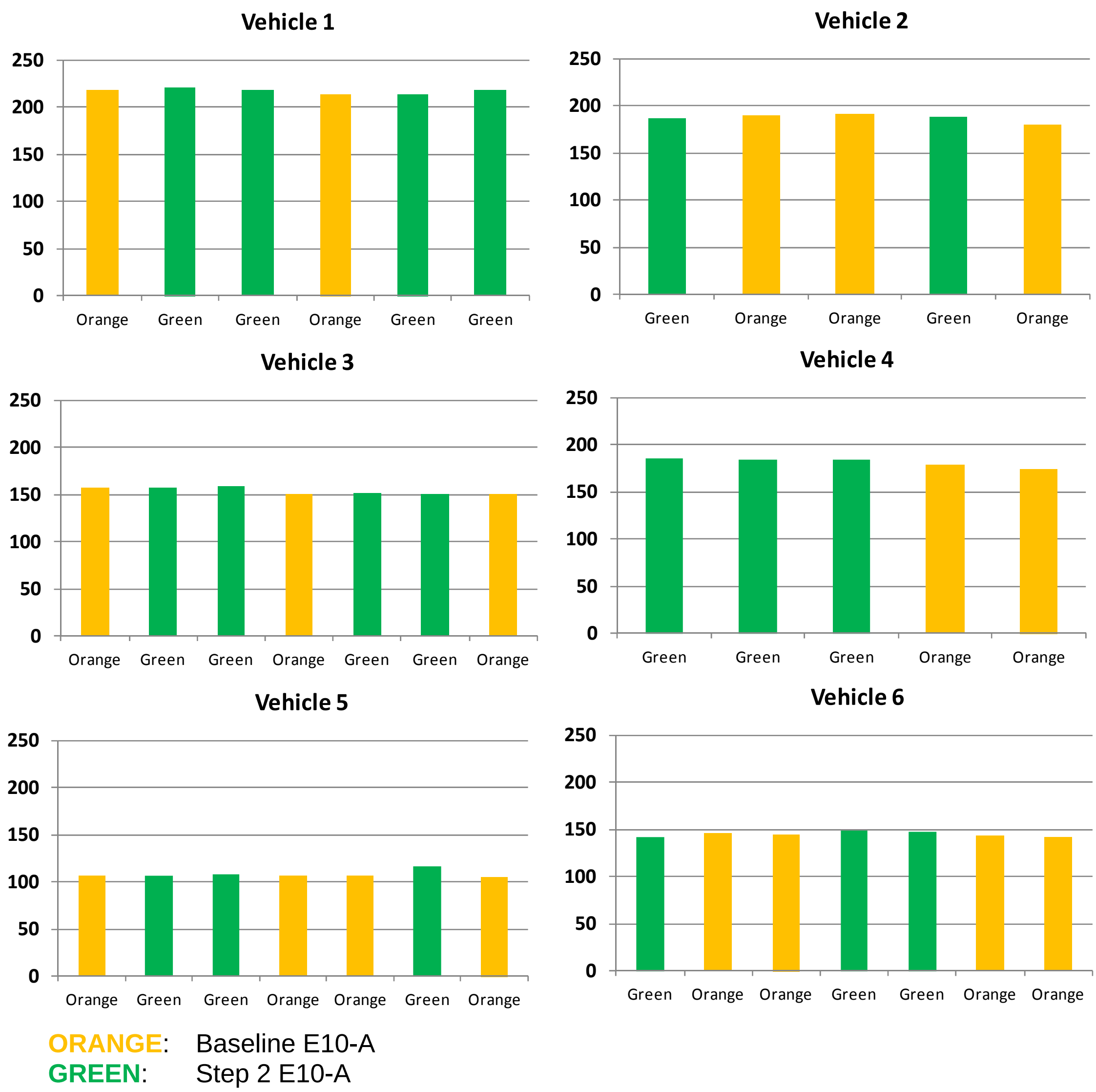
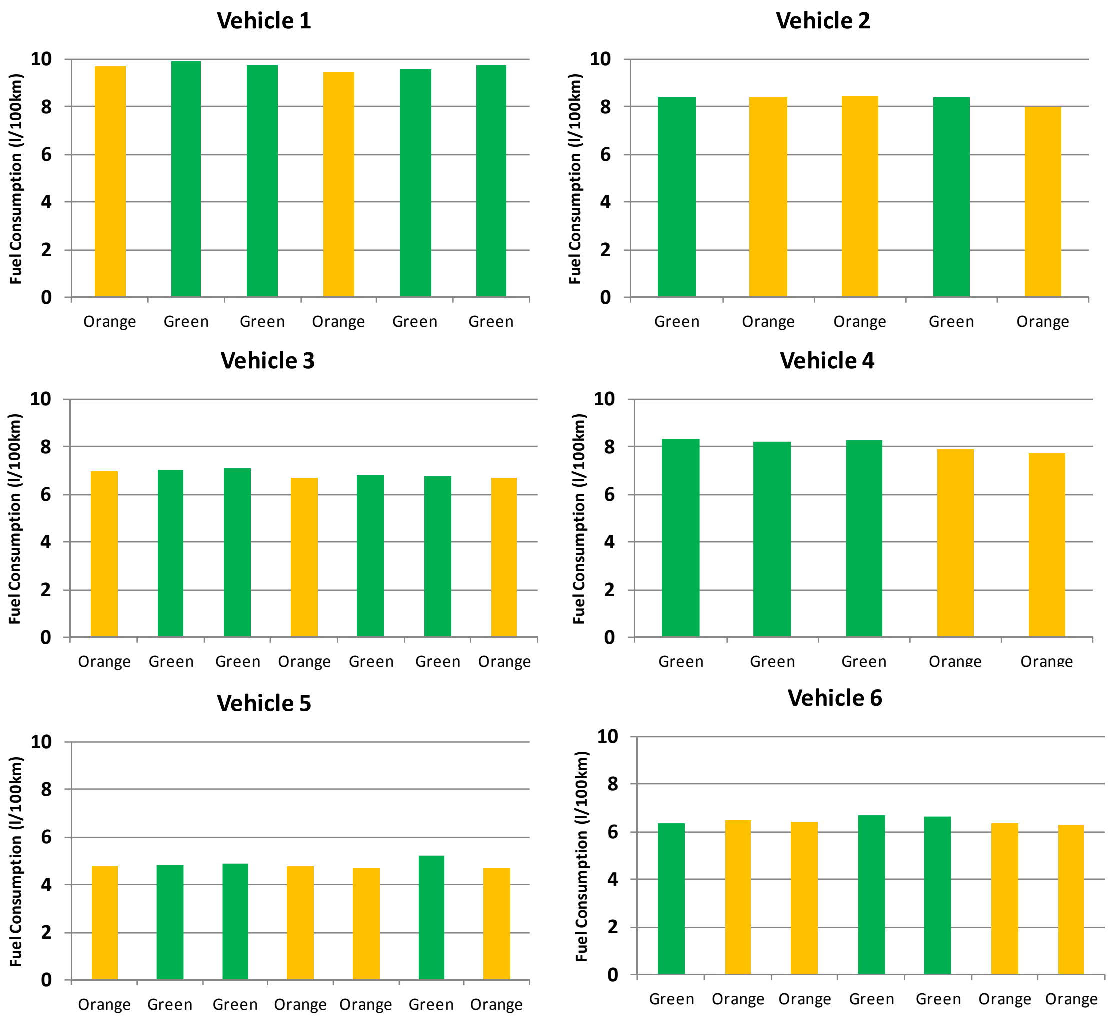


Figure A2-6 Fuel consumption (in l/100km) over the NEDC at +23°C



ORANGE: Baseline E10-A
GREEN: Step 2 E10-A

APPENDIX 3 COLD STARTING & IDLING AT -20°C

A3.1 BACKGROUND TO COLD STARTING AND IDLING TESTING

In preliminary test results presented to CEN, other experts reported cold engine starting tests, where performance was monitored as the engine was started at -20°C and warmed up at idle to a cooling water temperature of 90°C. When using fuels with higher E70 (52% and 58% volume), lambda values richer by about 10% and higher CO emissions were observed during the warm-up phase compared to results using EN 228 gasoline. The results presented covered the first 6000 engine revolutions after starting, equivalent to 6 minutes idling at 1000rpm. They expressed concern that the richer lambda values could risk problems of increased starting time, engine stalling, smoke, fouling of spark plugs and deterioration of vehicle driveability.

The CONCAWE programme therefore included similar cold start and idling tests to gather more detailed information.

A3.2 TEST PROCEDURE

Before each test, a careful fuel change and conditioning procedure was followed as outlined in **Figure A3-1**. Following flushing and fuel change, the vehicle was operated on a test track for 20 minutes to allow the engines control system to adapt to the new fuel. Vehicles were conditioned at -20°C ambient temperature for a minimum of 6 hours, and oil/water temperatures checked to be within 1°C of ambient before the cold start test was performed.

All six test vehicles were evaluated on two winter grade fuels: Baseline E10-E (BLUE) and Step 2 E10-E (RED). Two tests were performed on each fuel. The full conditioning procedure was carried out between each test and the test fuel order randomized. To provide some intermediate data the Step 1 E10-E (PURPLE) fuel was tested on Vehicles 5 and 6. Since these tests were performed after the main test series, repeat tests on the Baseline E10-E (BLUE) fuel were also performed.

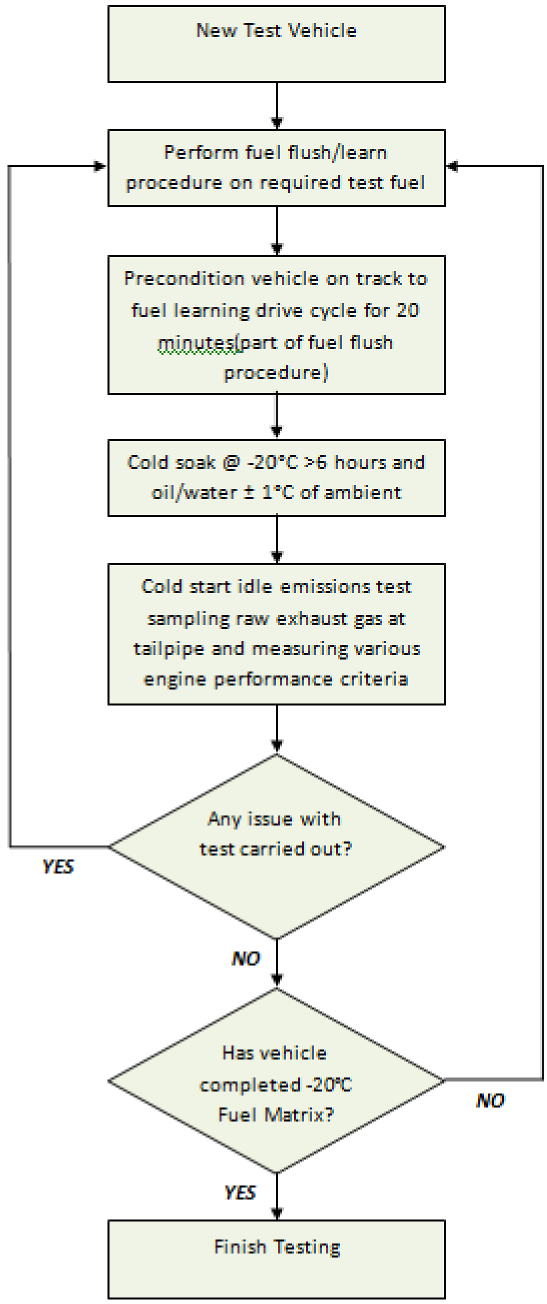
The engine was started at -20°C following the manufacturer’s procedure, and allowed to idle for 1200 seconds (20 minutes). In practice, it was found that the first 400s (about 6½ minutes) provided the most useful information, even though the engine coolant was not fully warmed up at this point.

The following measurements were taken:

- Tailpipe modal emissions (HC, CO, NOx, CO_2). Bag emissions were also measured, but were found not to be reliable, so are not reported here.
- Modal air-fuel ratio (lambda) from a pre-catalyst UEGO sensor.
- Engine speed
- Temperatures of coolant, oil sump, pre and post catalyst exhaust, fuel supplied to the rail, rail surface, fuel tank surface were recorded. As a check on test consistency, temperatures of intake air, manifold pressure and throttle position were also recorded.

- A basic driveability evaluation was carried out in terms of engine stability through driver assessment of engine speed variations or other events.

Figure A3-1 Flowchart for cold engine starting and idling performance at -20°C



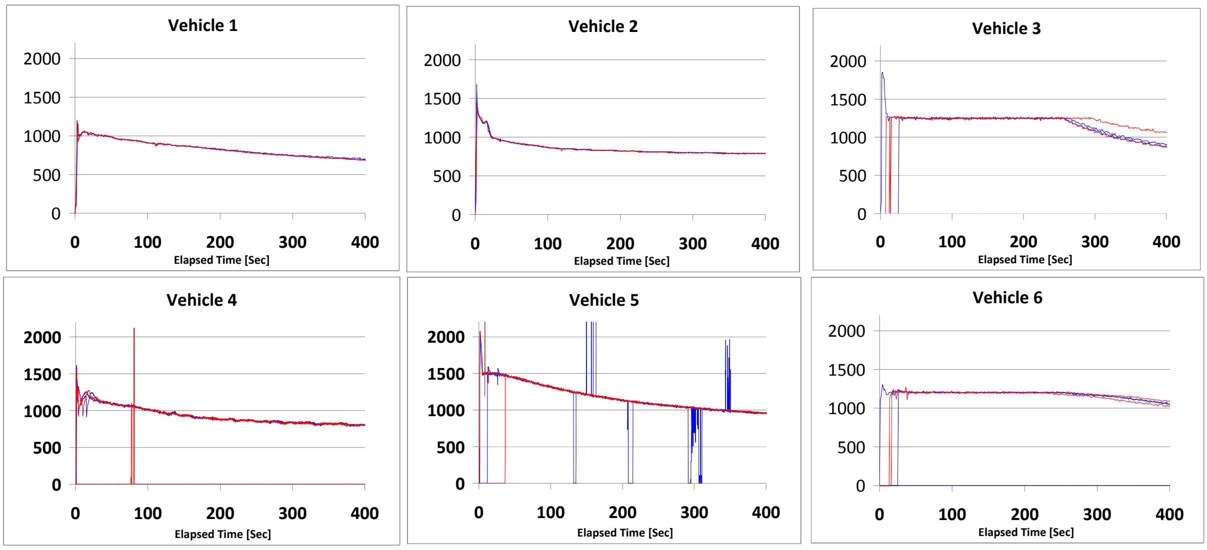
A3.3 RESULTS

Results are presented and discussed in **Section A3.3.1** to **A3.3.4** comparing the Baseline E10-E (BLUE) fuel with the Step 2 E10-E (RED) fuel. These fuels have E70 values of 51.9% (BLUE) and 60.6% (RED), with other parameters held constant as much as possible.

In **Section A3.3.5**, the more limited tests on the E10-E Step 1 (PURPLE) fuel are presented for completeness.

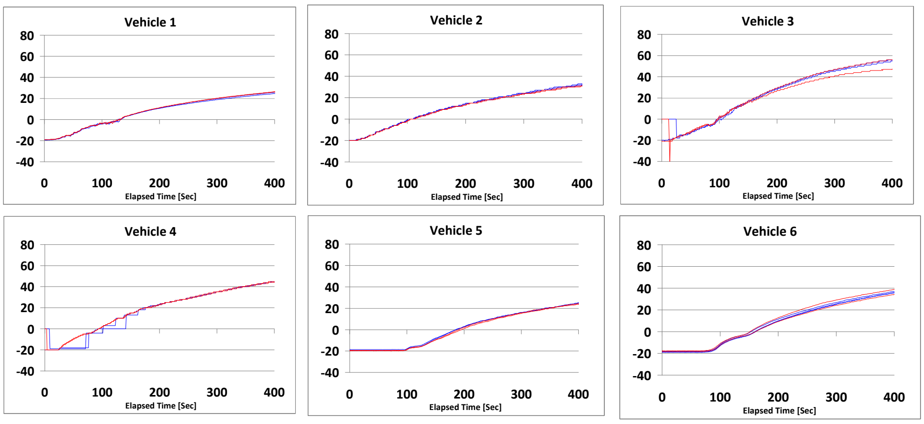
A3.3.1 Engine speed and temperature

Figure A3-2 Engine speed at idle following start at -20°C



Results are shown for the first 400s of the test. All the vehicles started easily (<1.6s) on both fuels and followed the same profile of high initial idle speed which decreased steadily as the engine warmed up. Engine speed profiles were consistent between tests (the occasional spikes in the traces represent temporary noise in the measuring system). Where there was some evidence of test to test variation (Vehicles 3 and 6), it appeared randomly and there was no evidence of a fuel effect.

Figure A3-3 Engine coolant temperature at idle following cold engine starting at -20°C



Coolant thermocouples were located in the top hose of the test vehicles (i.e. the 'cold' side of the thermostat). In spite of this, recorded temperatures started to rise very shortly after engine start and had reached 25-50°C after 400s. Temperatures generally followed consistent profiles for each test. Vehicles 3 and 6 again showed a small degree of test-to-test variability but this was not related to the fuel type.

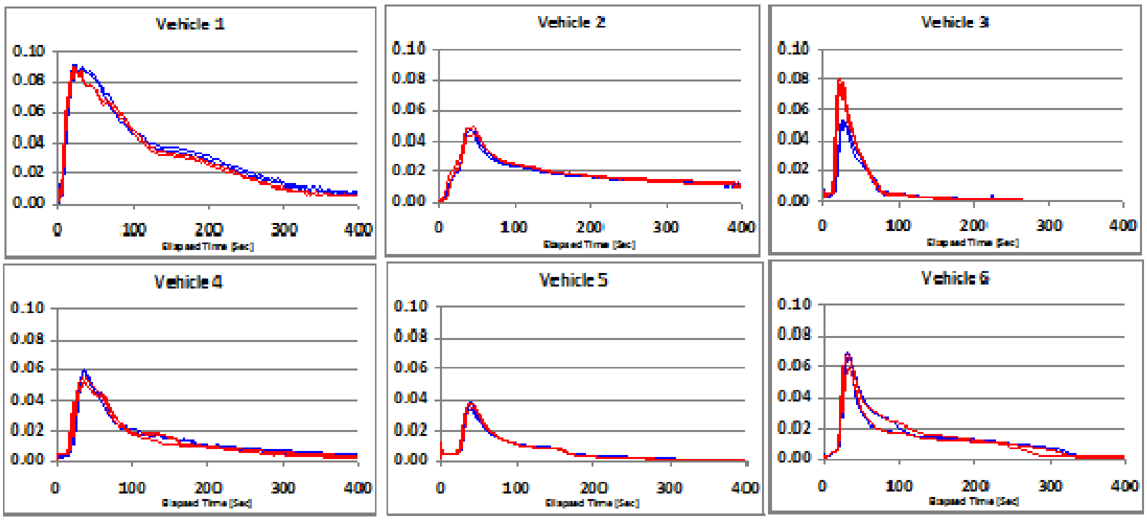
A3.3.2 Exhaust Emissions

Under these cold start and warm-up conditions, we may expect to see significant levels of unburned or partially burnt fuel in the exhaust gases, particularly in the period of open loop operation before the lambda sensor and catalyst have warmed sufficiently to bring them under control.

Figure A3-4 shows that HC emissions rose to an initial peak, followed by a slow decay as the engines warmed up. The peak of the profiles is truncated, because emissions were higher than the maximum limit (just below 6000ppm propane equivalent) that could be measured by the analyser. There was good consistency between the individual tests.

Differences between the fuels were variable and relatively small: the more volatile red fuel gave lower emissions on Vehicles 1 and 4, but higher emissions on Vehicles 2 and 3 while there was no clear difference in Vehicles 5 and 6.

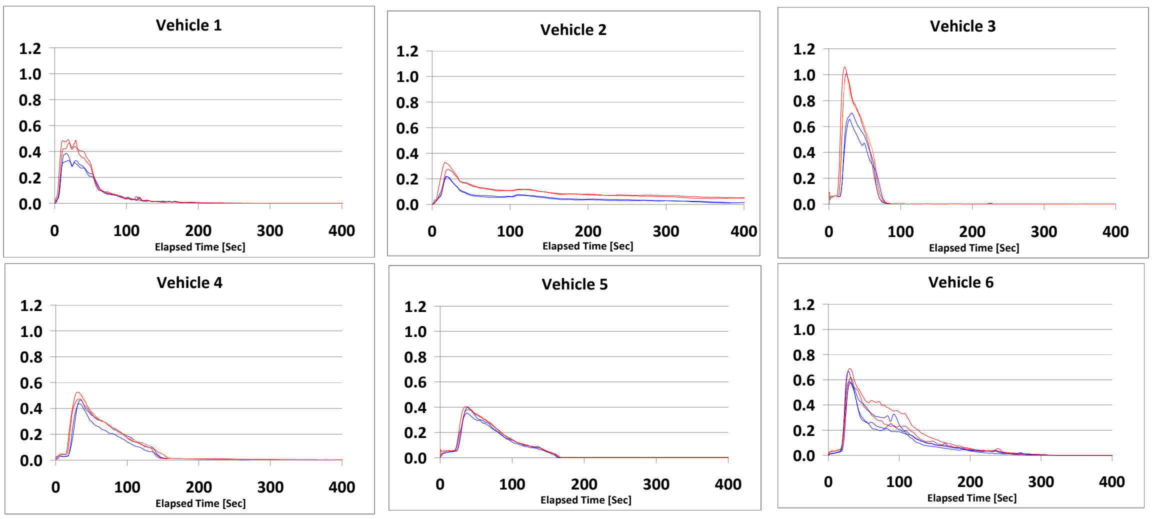
Figure A3-4 Exhaust HC emissions (in g/sec) at idle following cold engine starting at -20°C



For the CO emissions, peak values ranged from 7% to 11% and were all within the range of the exhaust analyser. Results in g/second are shown in **Figure A3-5**.

There were clear differences between the fuels, with the Step 2 E10-E (RED) fuel giving higher emissions on all the test vehicles compared to the Baseline E10-E (BLUE) fuel. The difference was very small for Vehicle 5.

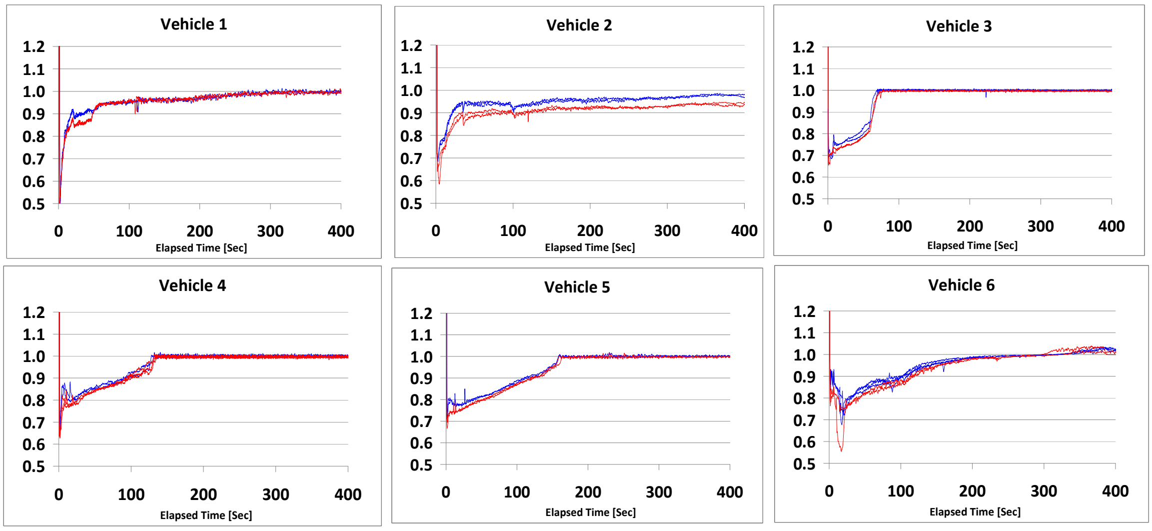
Figure A3-5 Exhaust CO emissions (in g/sec) at idle following cold engine starting at -20°C



A3.3.3 Air-Fuel Ratio (lambda)

Exhaust AFR was measured using a heated UEGO sensor specially fitted to the vehicle. Because it was heated, the sensor could monitor lambda from the beginning of the test, whereas the vehicle's own sensor takes time to warm up and establish lambda control. The vehicle's own oxygen sensor was monitored but it was not disturbed and controlled the vehicle in the normal way.

Figure A3-6 Exhaust lambda values at idle following cold engine starting at -20°C



A clear transition from open-loop operation to lambda control was seen for Vehicles 3, 4, and 5 while the other vehicles approached lambda=1 in a more ambiguous way. Vehicle 2 appeared to reach lambda control around 50s but remained slightly rich of lambda=1 throughout the 1200s test. Vehicle 6 appeared to trend lean after a period of lambda=1 operation. The fuel did not affect the time taken to reach lambda control.

During the open-loop period, which varied between vehicles from below 50 to 300s, measured exhaust lambda values were lower (richer) on the Step 2 E10-E (RED) fuel.

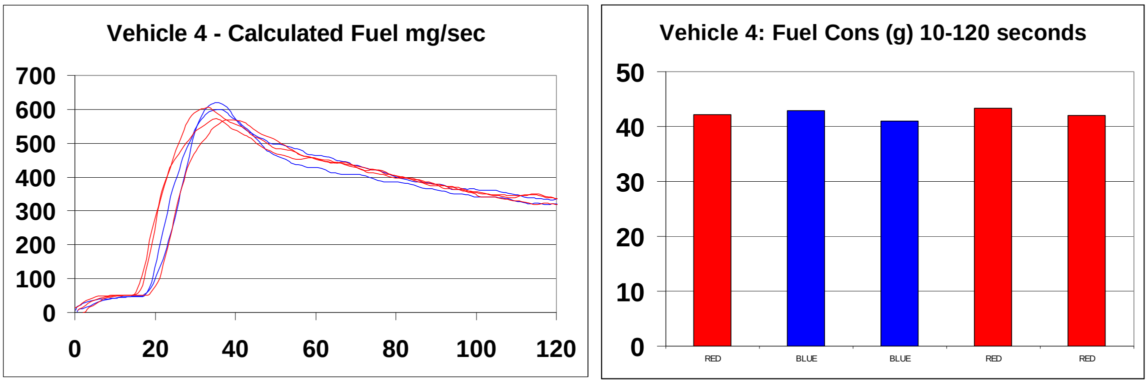
A3.3.4 Discussion of the lambda and emission measurements

These lambda values are measured in the exhaust, whereas what we really want to understand is what differences occur inside the combustion chamber when the fuel volatility changes. To better understand the UEGO results, the data from the first 120s of the test have been analysed in more detail.

The engine's control system will inject a specified volume of fuel according to the engine's instantaneous needs. Since the BLUE and RED test fuels differ in energy content by only 0.12% per litre and by 0.02% per mg, we would expect the amount of fuel passing through the engine to be independent of which of the two fuels was used. **Figure A3-7** shows that this is indeed the case. The fuel flow is calculated from the exhaust emission measurements, taking full account of unburned hydrocarbons and CO emissions.

Small amounts of unburned fuel can enter the engine crankcase and over time dilute the lubricating oil. Apart from this, because gasoline is a light and volatile fuel, we do not expect any unburned fuel to remain in the combustion chamber or exhaust system, so it should all reach the exhaust analysers. **Figure A3-7** suggests that any fuel passing to the crankcase is not significant in the overall fuel balance, and no difference between the fuels can be detected.

Figure A3-7 Calculated fuel flow in the first 120s after starting



During open-loop operation, the ECU will calculate the fuel demand based on engine speed and either mass air flow or manifold pressure. Direct measurements of mass air flow from the CAN system on Vehicles 1 and 2 (the only two vehicles where it was possible) confirmed this to be the case. Throttle positions and spark advance were measured for all vehicles except Vehicle 5 and showed no measureable differences between tests. Under these conditions, the amount of air drawn through the engine should be identical for the two fuels.

How can we then understand the exhaust lambda measurements, which showed differences between the fuels?

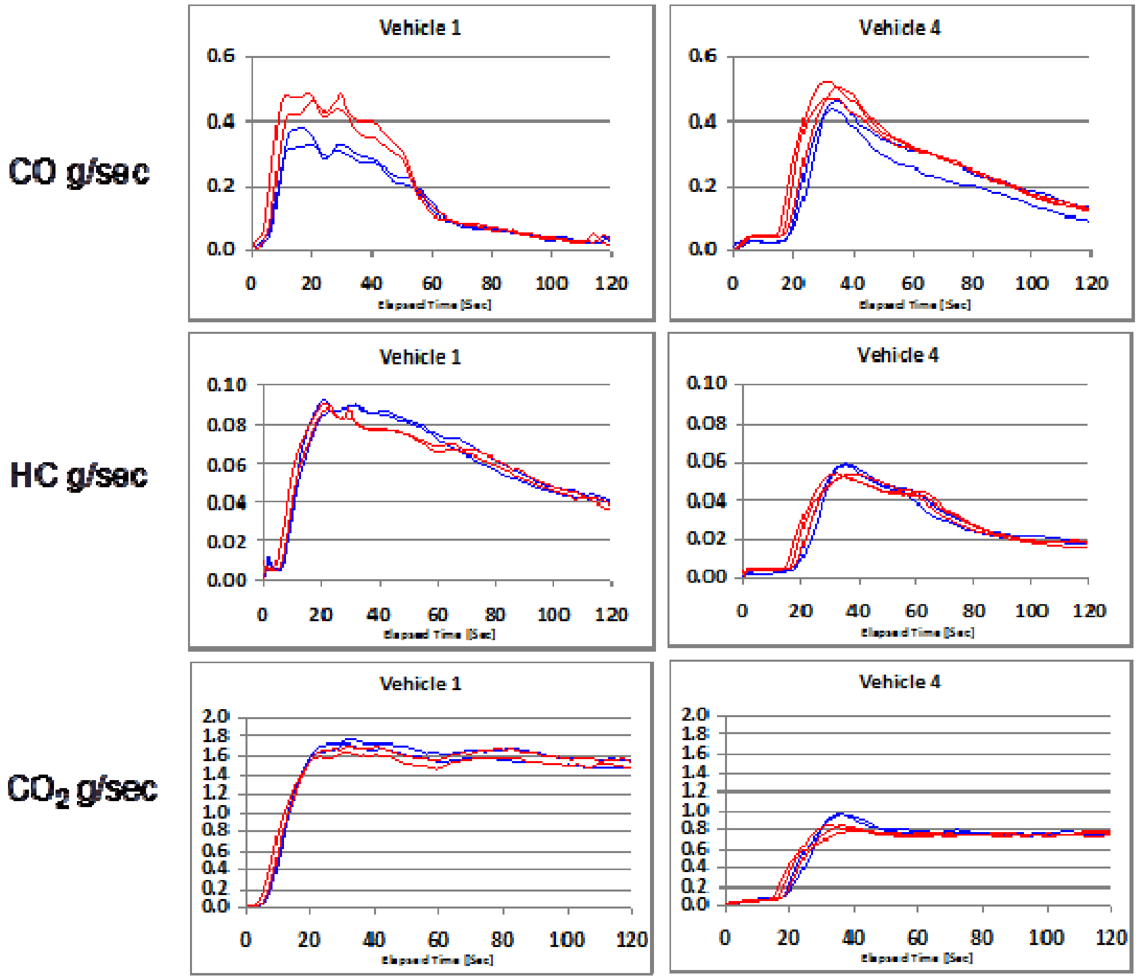
- If the amount of fuel injected is the same for the two fuels, and the air flow the same, then the overall air-fuel ratio or lambda in the combustion chamber should also be the same.

Figure A3-8 shows emissions of CO, HC and CO_2 during the first 120s for Vehicles 1 and 4. The increased CO emissions for the Step 2 E10-E (RED) fuel can be clearly seen, especially during the period from 20 to 60s after starting. At the peak, the difference is about 0.2 g/sec for Vehicle 1 and 0.1 g/sec for Vehicle 4.

For these vehicles, the RED fuel produced slightly lower HC emissions but the difference is only about 0.01g/sec, enough to produce about 0.02g/sec of CO, so this alone cannot explain the higher CO emissions. The CO_2 emission traces show lower emissions on the RED fuel of 0.1g/sec for Vehicle 1 and 0.2 g/sec for Vehicle 4. While the precision of the measurements does not support a detailed analysis, it appears that combustion of the RED fuel is less complete, with more fuel carbon being emitted as CO rather than being completely converted to CO_2.

For Vehicle 1, which shows the greatest difference, the amount of fuel carbon converted to CO rather than to CO_2 may be as much as 10%, which would imply a 3% difference in energy output between the fuels. This is to some extent balanced by the lower unburned hydrocarbon emission for the RED fuel (about 1%), but it is nevertheless surprising that the difference in energy output does not seem to affect the throttle position or manifold air flow needed to maintain the idle speed required by the closed-loop control. One possible explanation could be that less fuel is retained in the combustion chamber and lube oil at higher volatility but a more complete study would be needed to investigate this.

Figure A3-8 Exhaust CO, HC, and CO_2 measurement in the first 120s after starting



This leaves the question of how we should interpret the exhaust lambda differences between the fuels. How the UEGO works is explained in [23]. The UEGO contains a zirconia measuring cell, and the air-fuel ratio is calculated by measuring the amount of oxygen that has to be electrochemically pumped in or out to achieve stoichiometry.

Under rich conditions, the air-fuel ratio is proportional to the amount of oxygen required to complete the oxidation of the unburned species (HC, CO and H_2). In our tests, since the RED fuel is less completely burned than the BLUE fuel, the RED fuel should require more oxygen input to completely combust and hence be recorded by the UEGO as richer than the BLUE fuel. However, the diffusion rates of HC, CO and H_2 are different and can affect the results. CO and HC tend to bias the sensor lean, while H_2 (which we did not measure) biases it rich. The sensor calibration is typically based on an artificial gas mixture with fixed proportions of CO, CO_2, H_2 and water so cannot adjust for compositional variations at the same AFR.

If we consider the conditions in the combustion chamber, we can say that there is no clear evidence that the more volatile fuel does have an overall richer mixture. However, the distribution of fuel in the chamber will be different as evidenced by the compositional differences in the exhaust gases. The Step 2 E10-E (RED) fuel will evaporate more quickly and hence mix more thoroughly than the Baseline E10-E (BLUE) fuel. We cannot clearly deduce the conditions around the spark plug or at the cylinder wall, although better evaporation and mixing might be expected to reduce the degree of coking and deposit formation. The overall energy balance might suggest a higher lube oil dilution for the RED fuel, but a more extensive test would be needed to evaluate this.

In summary:

- The fuel flow and air flow through the engines are the same for both fuels, which implies that the air-fuel ratio and lambda should be the same. However the exhaust UEGO measurement calculates a different lambda for the two fuels.

- The RED fuel produces more CO and less CO_2 in the exhaust than the BLUE fuel, while unburned hydrocarbon levels are slightly lower on the RED fuel. This should require a higher fuel flow for the RED fuel to sustain idle speed but this does not seem to be the case in reality.

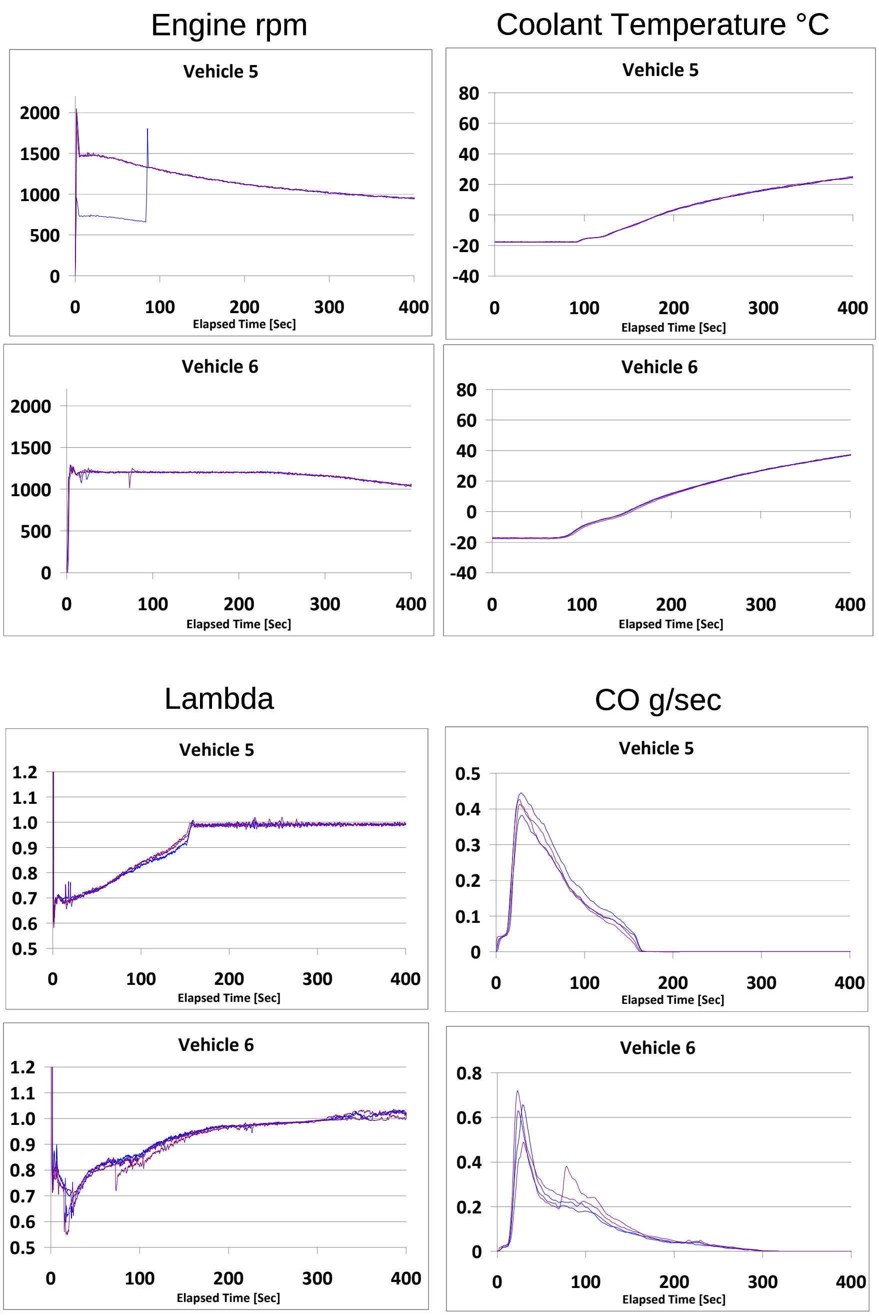
- The exhaust UEGO sensor output should be interpreted with caution. It is not surprising that the UEGO records a richer mixture for the RED fuel, because it is less completely burned than the BLUE fuel. However, the UEGO calibration is unlikely to compensate fully for compositional differences in the exhaust due to fuel changes and these may account for some of the differences seen.

- Although we cannot directly measure conditions in the combustion chamber, we can deduce that the more volatile fuel gives better evaporation and mixing. It is not clear whether the effects of this are beneficial or detrimental.

A3.3.5 Results on Step 1 E10-E (PURPLE) fuel

The Step 1 E10-E (PURPLE) fuel was tested on Vehicles 5 and 6. Since these tests were performed after the main test series, repeat tests on the Baseline E10-E (BLUE) fuel were also performed. Key results are presented here for completeness. These fuels have E70 values of 51.9% (BLUE) and 54.9% (PURPLE), with other parameters held constant as much as possible. Differences between the fuels are smaller than those for the Step 2 E10-E (RED) fuel, in line with the smaller change in E70.

Figure A3-9 Results for Vehicles 5 and 6 on the Step 1 E10-E (PURPLE) fuel



APPENDIX 4 REGULATED EMISSIONS AT -7°C

A4.1 BACKGROUND TO REGULATED EMISSIONS AT -7°C

In preliminary test results presented to CEN, other experts presented exhaust emissions results from the -7°C legislated test over the NEDC. When using an E10 fuel with higher volatility (E70 = 58% volume), they measured higher CO emissions – about 40% higher than a Reference E10 which had an E70 = 44% volume. The CONCAWE programme therefore included this lower ambient temperature emissions test to gather comparable data.

A4.2 TEST PROCEDURE

The -7°C emissions test is specified within the European passenger car emissions Directive 98/69/EC as the Type VI tests: *"verifying the average low ambient temperature carbon monoxide and hydrocarbon tailpipe emissions after a cold start"*. The test consists of the four elementary urban driving cycles of part one of the Type I test, generally known as the ECE phases of the test, and last a total of 780 seconds (or 4 x 195s per ECE). Limits were set in Directive 98/69/EC for category M vehicles as 15.0 g/km for CO and 1.8 g/km for HC. These limits were left unchanged in Regulation (EC) No 715/2007, but with the comment that the Commission shall review the emissions limits and present a proposal to the European Parliament and Council with a view to tightening the emission limits.

Before each test, a careful fuel change and conditioning procedure was followed as outlined in **Figure A4-1**. Following flushing and fuel change, the vehicle was driven over the precondition cycle consisting of one ECE and two EUDC driving cycles. This preconditioning was performed at 23°C, prior to moving the vehicle to the cold soak condition of -7°C for a minimum of 6 hours. Exhaust emissions were sampled from key-on, as in the Type I NEDC test. The vehicle was driven through a complete NEDC test cycle, with bag emissions collected separately for the ECE and EUDC phases. Only the results from the legislated ECE phase of the test were used in the overall analysis.

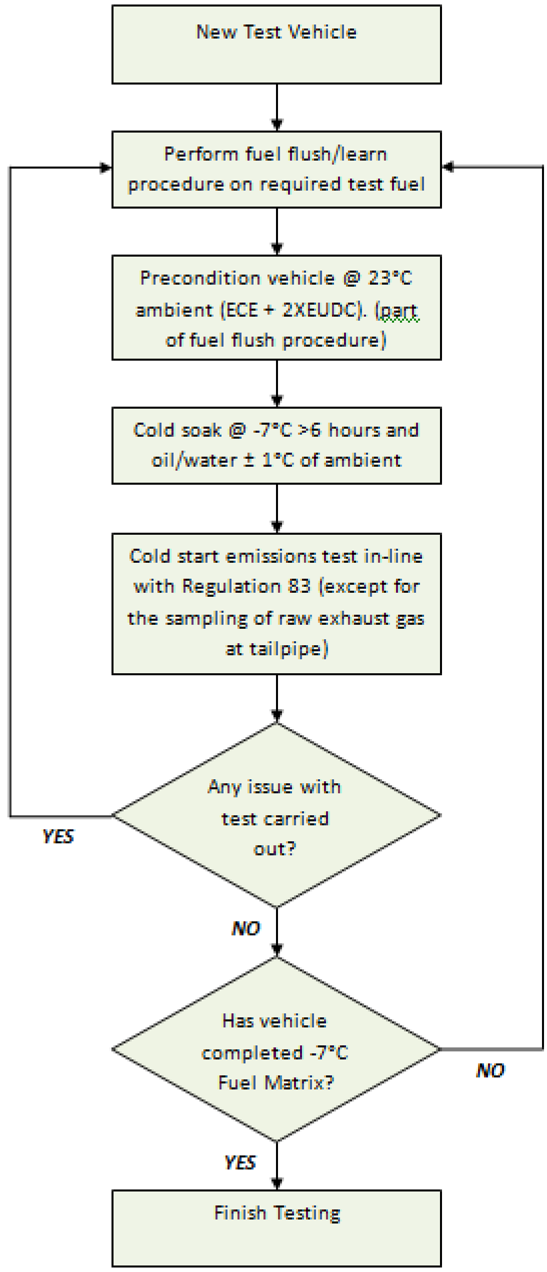
All six test vehicles were evaluated on the Baseline E10-E (BLUE) and Step 2 E10-E (RED) winter grade fuels. A minimum of two tests were performed on each fuel. The full conditioning procedure was carried out between each test and the test fuel order randomized.

The following measurements were taken:

- Tailpipe modal emissions (HC, CO, NOx, CO_2). Bag emissions were also measured over the ECE and EUDC phases.
- Modal air-fuel ratio (lambda) from a pre-catalyst UEGO sensor.
- Engine speed
- Temperatures of coolant, oil sump, pre and post catalyst exhaust, fuel supplied to the rail, rail surface, fuel tank surface were recorded. As a check on test consistency, temperatures of intake air, manifold pressure and throttle position were also recorded.

- A basic driveability evaluation was carried out in terms of engine stability through driver assessment of engine speed variations or other events.

Figure A4-1 Flowchart for NEDC testing at -7°C



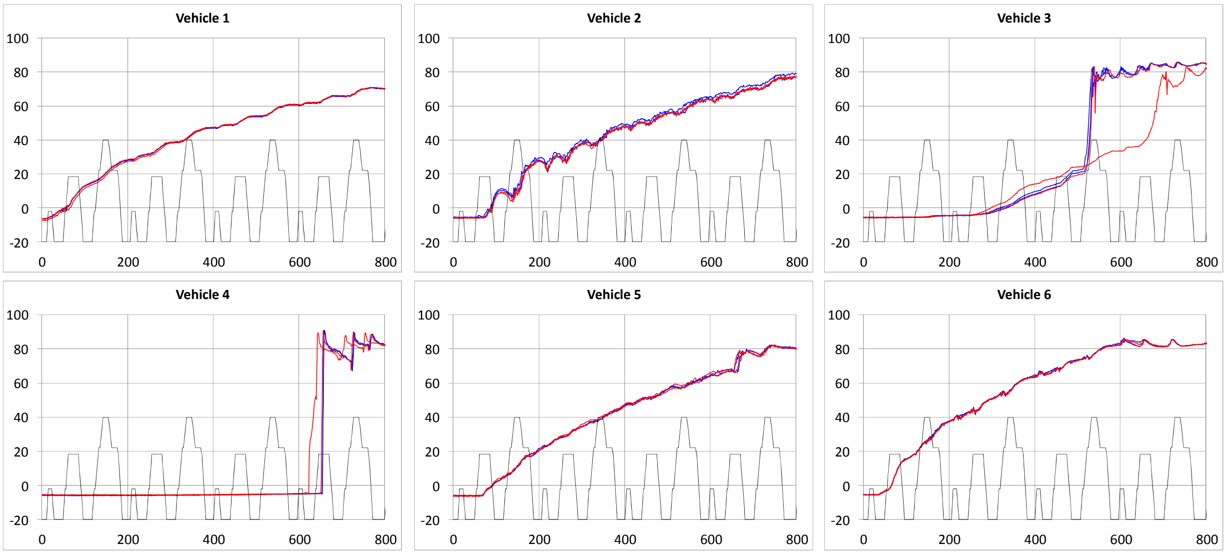
A4.3 RESULTS

Results are presented and discussed in **Sections A4.3.1** to **A4.3.4** comparing the Baseline E10-E (BLUE) fuel with the Step 2 E10-E (RED) fuel. These fuels have E70 values of 51.9% (BLUE) and 60.6% (RED), with other parameters held constant as much as possible.

A4.3.1 Water and oil temperatures

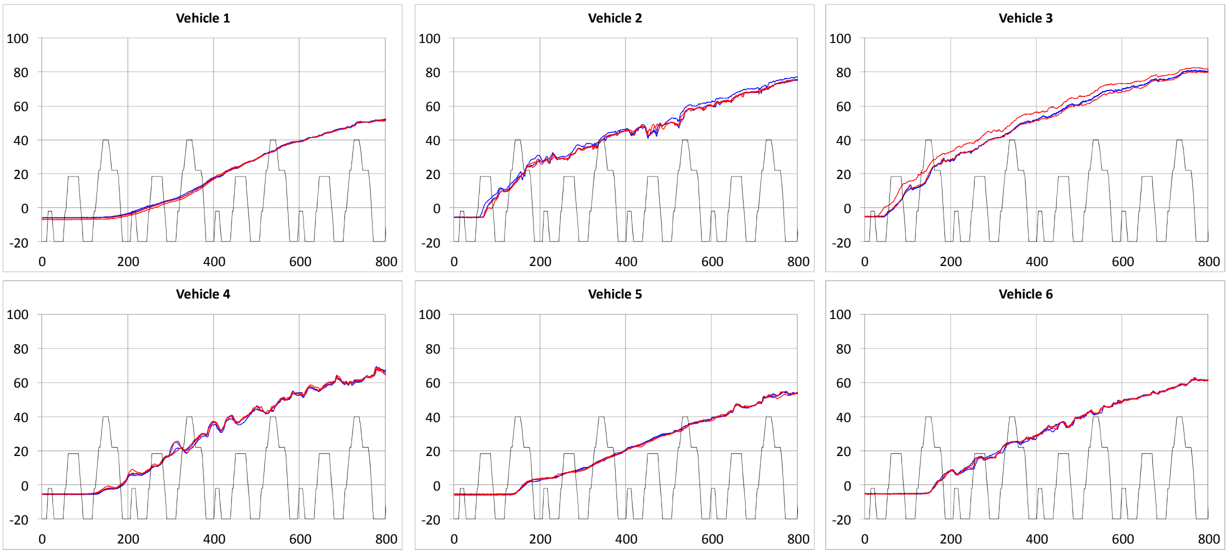
Coolant thermocouples were located in the top hose of each of the test vehicles. In the majority of cases, these thermocouples registered steadily increasing temperatures throughout the ECE phase of the test cycle, as shown in **Figure A4-2**. However, for Vehicle 4, there is a clear temperature step when the thermostat opens after 600 seconds, while for Vehicle 3 there is a gradual temperature rise between 300 and 500s followed by a larger temperature step.

Figure A4-2 Engine coolant temperature during ECE following cold engine starting at -7°C



The measured oil temperature shows more comparable responses between the vehicles, and is generally slower than the coolant temperature rise, apart from Vehicle 2 where the two temperatures follow very similar profiles. The temperatures at the end of the ECE phases ranked the vehicles in the following order: Vehicles 3, 2, 4, 6, 5 and 1. This ranking does not generally correlate with any simple vehicle metric such as size or inertia class. The temperature responses were not fuel dependent.

Figure A4-3 Engine oil temperature during ECE following cold engine starting at -7°C



A4.3.2 Exhaust gas temperatures

The pre-catalyst exhaust gas temperature (**Figure A4-4**) rises rapidly in the first 100s of the cycle (to the end of the first 32 km/h steady state condition), and then follows a pattern related to the vehicle accelerations and decelerations. The initial peak at 100 seconds is around 400°C for most vehicles, closer to 500°C for Vehicle 3 and 550°C for Vehicle 6. These are two of the small vehicles in the fleet, the latter having a close-coupled catalyst.

Figure A4-4 Pre-catalyst temperature during ECE following cold engine starting at -7°C

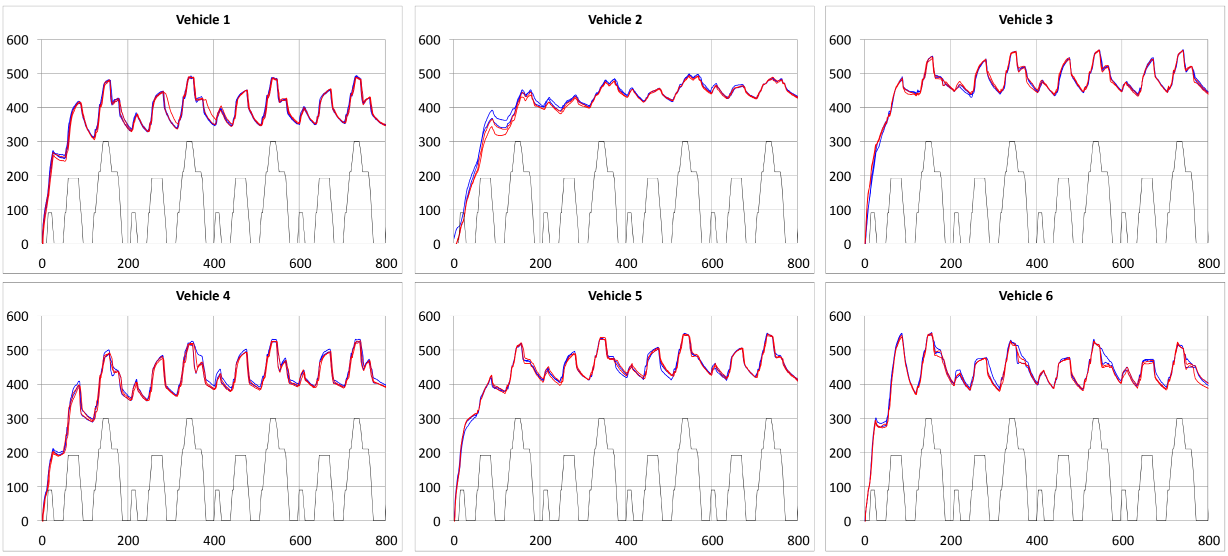
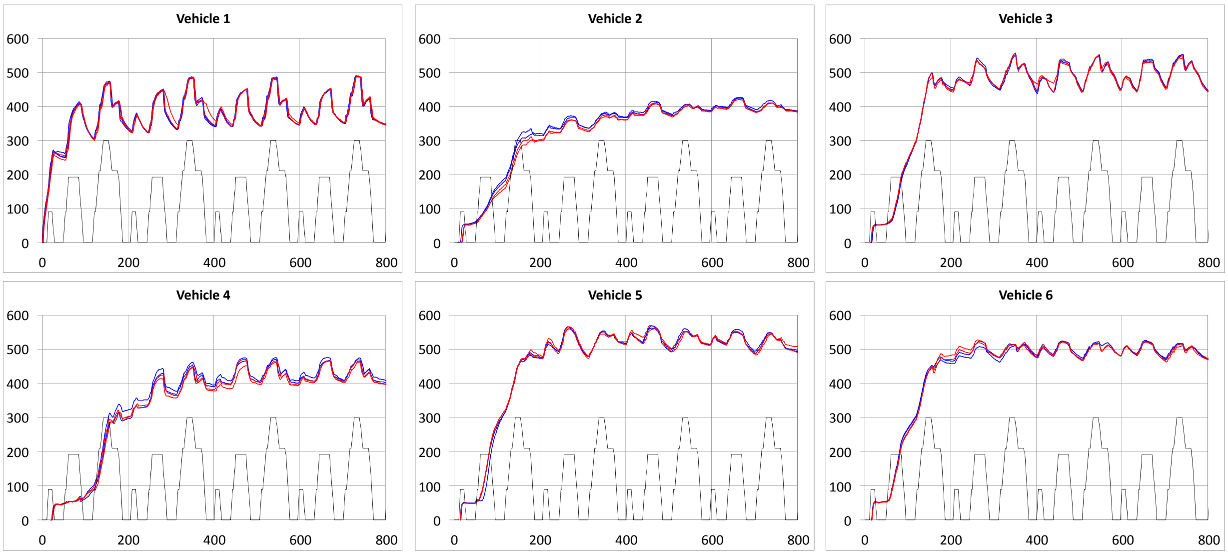


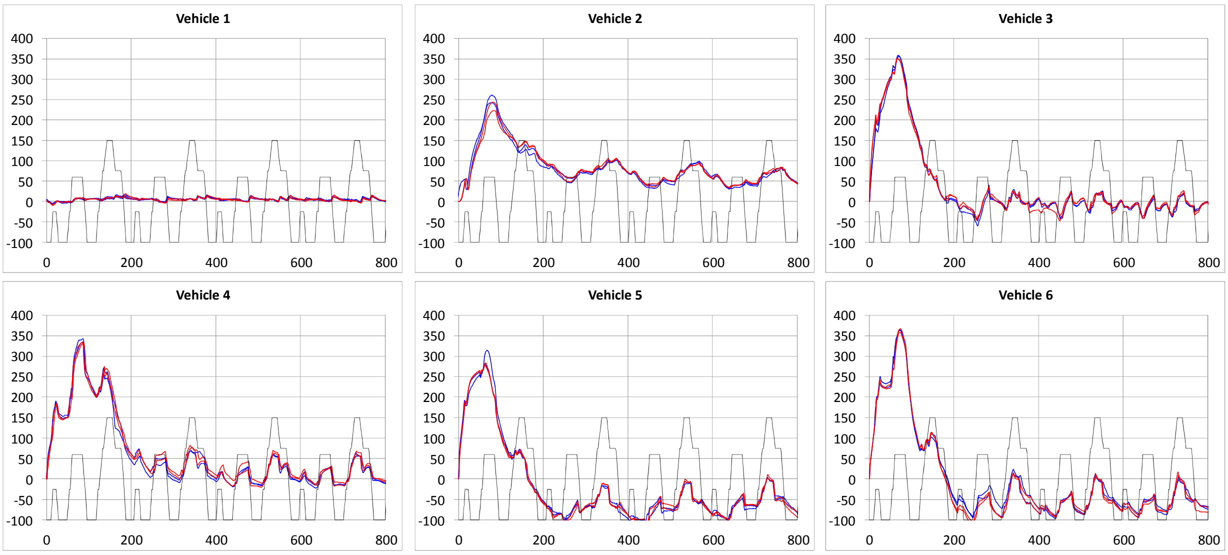
Figure A4-5 Post-catalyst temperature during ECE following cold engine starting at -7°C (except for Vehicle 1 – see text)



Vehicle 1 (6 cylinder) was fitted with a twin-pipe exhaust system. For the instrumentation of this vehicle, pre-catalyst thermocouples were fitted to both systems, with no post-catalyst thermocouples. Therefore, **Figure A4-5** shows the pre-catalyst temperature for vehicle 1, while the post-catalyst temperatures are shown for the other five vehicles. The post-catalyst temperatures generally lag the pre-catalyst temperatures and don't reach their initial peak until about 150s after the start of the test, at the end of the first 50 km/h steady state condition. By this point in time the catalyst will be fully warmed-up and tail-pipe emission rates should be negligible.

The calculated temperature drop across the catalyst (T_{inlet} minus T_{outlet}) is shown in **Figure A4-6**. Again, for Vehicle 1, this shows the difference in the pre-catalyst temperatures in the twin exhaust systems, with a maximum difference of about 20°C. For the other 5 vehicles, the peak temperature drop across the catalyst is between 250°C and 350°C, which occurs at the end of the first 32 km/h steady state condition. By the end of the first ECE phase (195s), most of the warm-up has taken place, and the temperature across the catalyst follows a consistent pattern, related to the vehicle speed, for the remaining part of the ECE. However, there are subtle vehicle differences: Vehicle 2 averages about 50°C temperature drop across the catalyst, Vehicles 3 and 4 show periods of both temperature drop and temperature rise across the catalyst, while Vehicles 5 and 6 show consistent temperature rises across the catalyst.

Figure A4-6 Temperature drop across the catalyst during ECE following cold engine starting at -7°C (except for Vehicle 1 – see text)

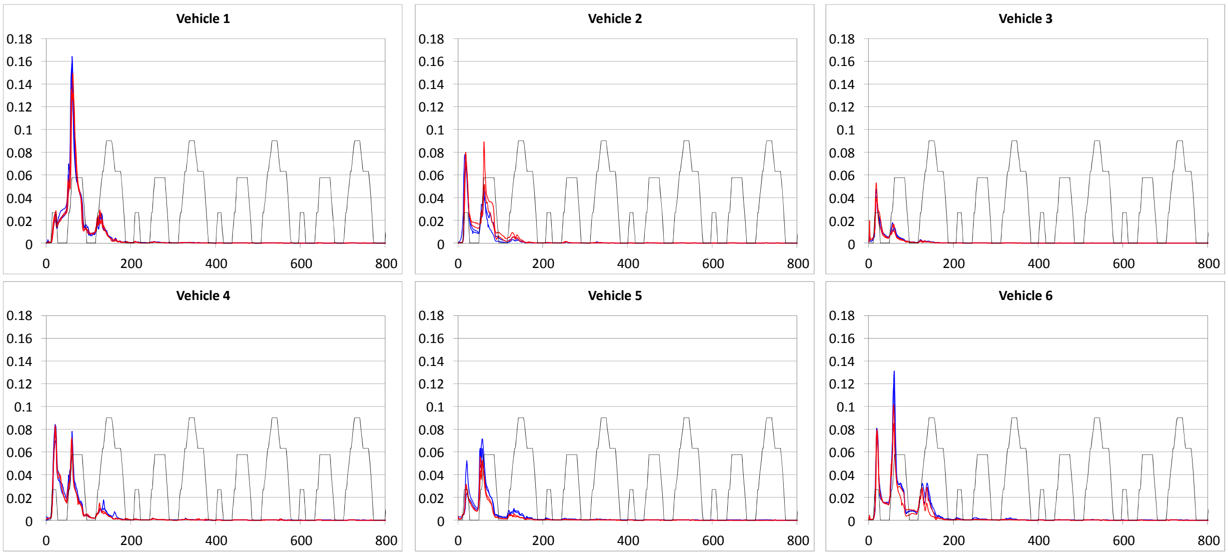


A4.3.3 Exhaust emissions and lambda

The exhaust emission traces (g/s) are shown in **Figures A4-7** to **A4-10** for the entire 780s of the ECE phase of the test, which is the legislated phase of the cycle. Catalyst warm-up and mixture strength should be well optimised in this test in order to achieve compliant emissions along with acceptable driveability. Further analysis of these results is contained in **Section 3.4** of the main report.

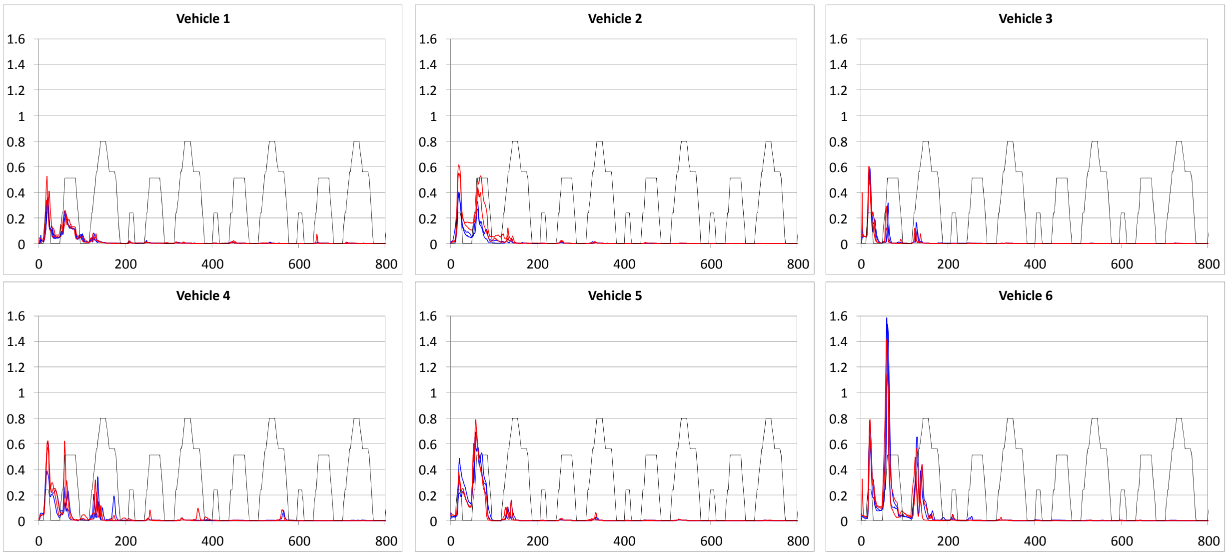
The Total Hydrocarbon (THC) emissions are shown in **Figure A4-7**. All vehicles tend to show two or three peaks in emissions corresponding with the first three acceleration phases of the ECE. Within the first 200s, catalyst light-off has occurred in all vehicles, and the THC emissions are negligible. There are no obvious fuel effects on THC emissions in any of the vehicles.

Figure A4-7 THC Emissions [g/s] during ECE following cold engine starting at -7°C



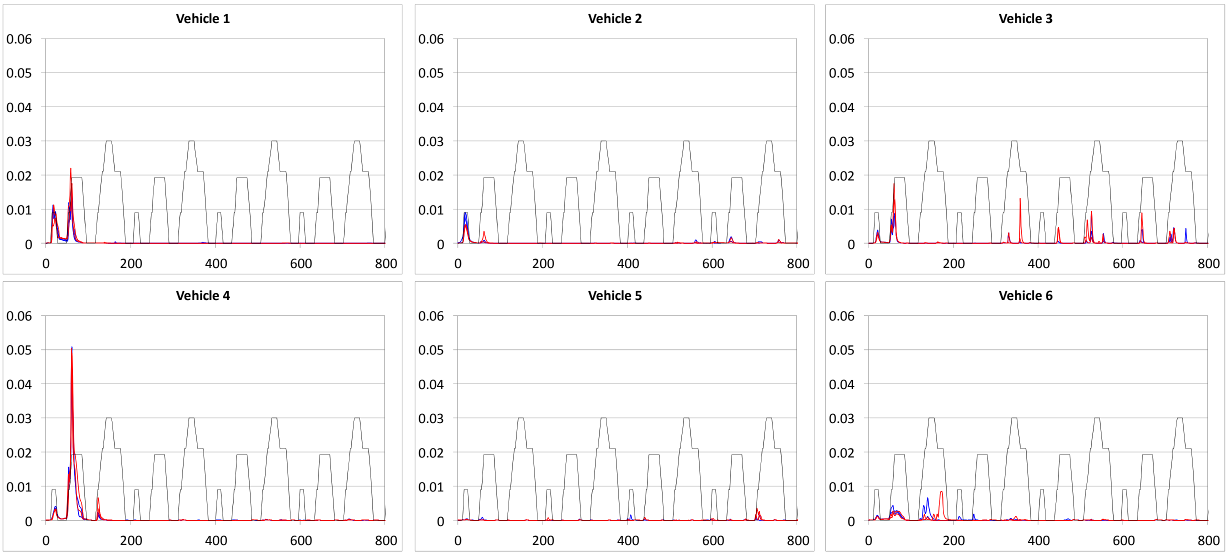
The CO emissions are shown in **Figure A4-8**. Similar to THC, the vehicles tend to show two or three peaks in CO emissions corresponding with the first three acceleration phases of the ECE. After the first 200s, the CO emissions are generally low, although a couple of vehicles show some small spikes during transients, suggesting over-rich combustion mixture. Vehicle 2 shows higher CO emission rates from the more volatile RED fuel.

Figure A4-8 CO emissions [g/s] during ECE following cold engine starting at -7°C



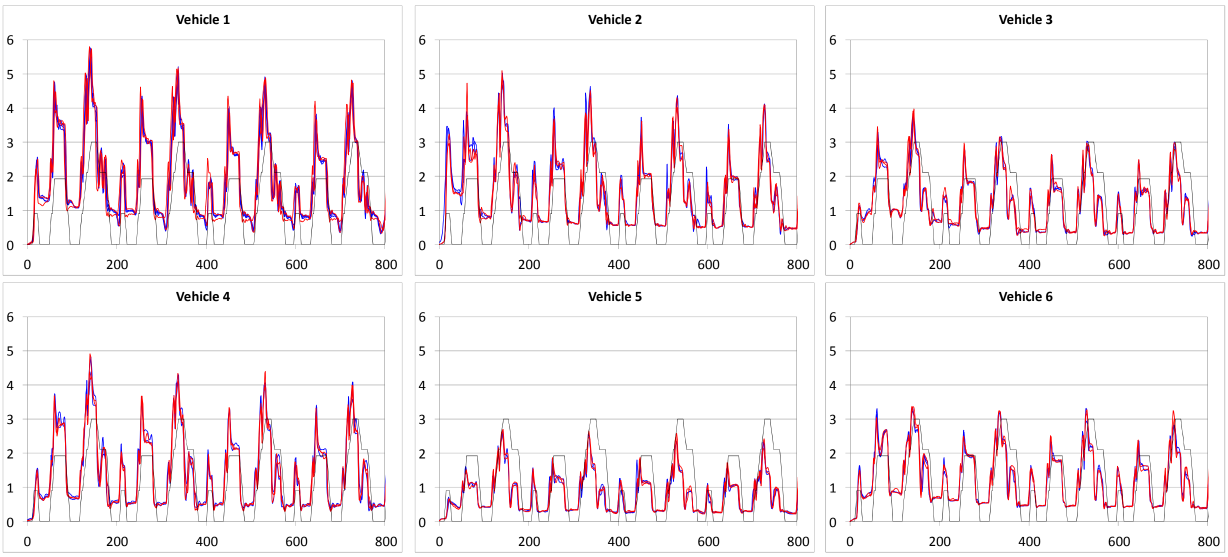
The NOx emissions are shown in **Figure A4-9**. The results are more vehicle dependent than the THC and CO, so no general trends are evident. Several of the vehicles show the highest NOx emissions within the first 100 seconds, beyond which the NOx emissions are negligible. However, Vehicle 3 shows spikes of NOx emissions throughout the test and Vehicle 5 shows extremely low levels of emissions at all times. There were no obvious fuel effects on NOx emissions in any of the vehicles.

Figure A4-9 NOx emissions [g/s] during ECE following cold engine starting at -7°C



The CO_2 emissions are shown in **Figure A4-10**. Since this is predominantly an indication of fuel consumption rate, the profile is directly related to the work required to drive the cycle. Vehicle comparisons therefore reflect the differences in vehicle inertia and road load. A steady reduction in CO_2 emissions across the 4 repeat ECE phases reflects the increased engine efficiency as it warms up. There are no obvious fuel effects on CO_2 emissions in any of the vehicles.

Figure A4-10 CO_2 emissions [g/s] during ECE following cold engine starting at -7°C



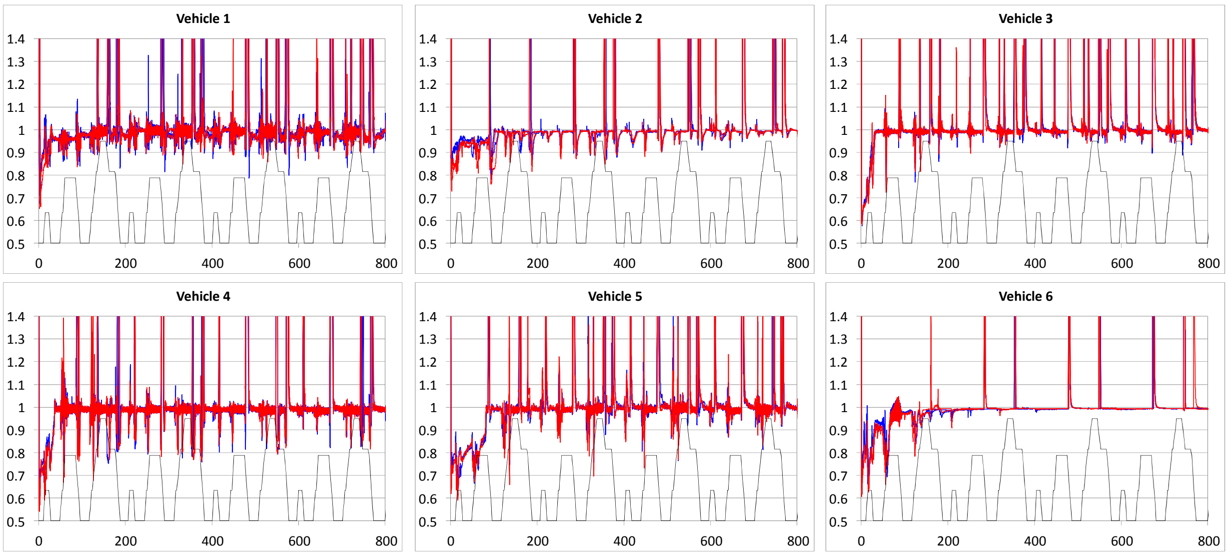
Exhaust air-fuel ratio was measured using a heated UEGO sensor specially fitted to the vehicle. The locations of these sensors were different in some vehicles, especially Vehicles 2 and 6 (see **Appendix A1.4**), depending upon the available space. On Vehicle 2, the UEGO sensor was located between the close-coupled pre-catalyst and the main oxidation catalyst while the sensor on Vehicle 6 was located downstream of the catalyst. For the other four vehicles, the sensor was located between the engine and the catalyst.

The exhaust air-fuel ratio results measured by the UEGO sensors are shown in **Figure A4-11**. The time to reach lambda=1 varied significantly from vehicle to vehicle. The shortest times were shown by Vehicle 3 (~30s) and Vehicle 4 (~40s). Vehicle 5 (~80s) was slightly ahead of Vehicle 2 (~100s). Vehicle 6 almost achieved lambda=1 before 100s, but it was after 150s when it appeared to control at stoichiometric. Vehicle 1 took a similar time to reach lambda=1, and then showed continuous lambda oscillations on both sides of stoichiometric. A UEGO sensor was also fitted into the second exhaust system of Vehicle 1 and this showed a very similar response.

Throughout the remainder of the ECE cycle, there were also vehicle to vehicle differences. Vehicles 2 and 6 showed fewer high frequency lambda variations due to the downstream location of their UEGO sensors. Relatively few lean spikes (fuel cut-off) were observed during decelerations. The other vehicles showed lean spikes at the end of the acceleration phases as well as during the deceleration events.

From these figures, there is some evidence of a fuel effect on lambda with Vehicle 2 during the first ~100s. This is discussed in more detail in **Section 3.4**.

Figure A4-11 Lambda during ECE following cold engine starting at -7°C



Lambda was also calculated from the exhaust emission measurements, and these traces are shown in **Figure A4-12**, for two of the vehicles. These calculated values are mainly controlled by the exhaust gas CO_2 concentration, and the corresponding results are shown in **Figure A4-13**. Generally, when the exhaust CO_2 is at about 13% (130000 ppm CO2), the lambda is 1, and if the CO_2 concentration is lower, then lambda > 1 (lean). **Figure A4-12**, Vehicle 2, shows that the emission calculated Lambda values are unable to follow the true nature of the lean spikes, and although there is a rapid leaning of the mixture at the start of the deceleration phases, the return to lambda=1 is apparently much slower than the response shown by the UEGO. It is assumed that this is an artefact introduced by the transport of the exhaust gas to the emissions analysers, as well as the analyser response. The CO_2 traces (**Figure A4-13**) confirm the inverse relationship between measured CO_2 concentration and lambda. For Vehicle 5, the calculated lambda showed an apparent lambda of ~1.2 after each deceleration, which is not shown by the UEGO data. Again, the same effects may explain this artefact.

Figure A4-12 Emissions calculated lambda during ECE following cold engine starting at -7°C

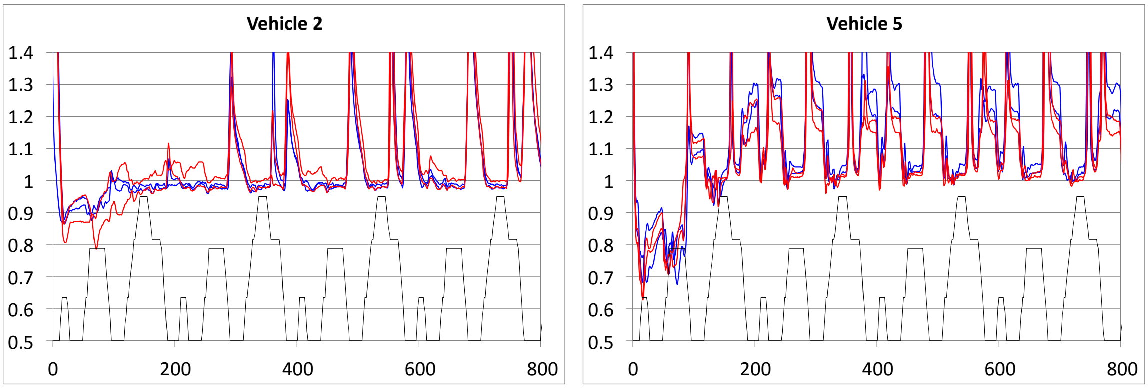
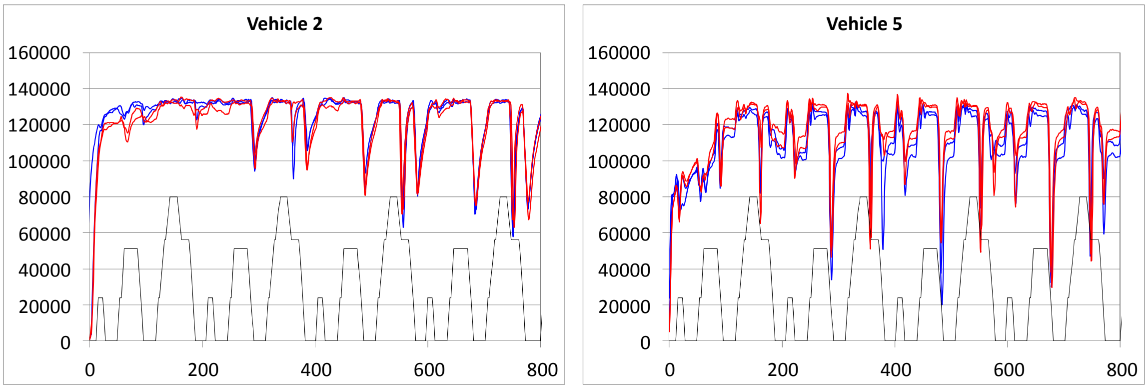


Figure A4-13 Exhaust gas CO_2 concentration [ppm] during ECE following cold engine starting at -7°C



APPENDIX 5 EVAPORATIVE EMISSIONS

A5.1 BACKGROUND TO EVAPORATIVE EMISSIONS TESTING

Evaporative emissions testing was carried out on all six vehicles in the Millbrook SHED using the current EU test procedure as described below. Duplicate tests were carried out on two fuels, the Baseline E10-A (ORANGE) and Step 2 E10-A (GREEN). Hot Soak Loss (HSL) and Diurnal emissions were determined. Test order was randomised as far as possible within the constraint of only four tests per vehicle, i.e. GREEN-ORANGE-ORANGE-GREEN or ORANGE-GREEN-ORANGE-GREEN, etc.

During the testing, high emissions were observed for three vehicles, well above the regulatory limit of 2g/test. To establish whether this was due to canister breakthrough or to leakage or permeation from the fuel system, extra diurnal tests were carried out with a second canister connected to the outlet of the main vehicle canister. This allowed determination of the source of the emissions.

A5.2 TEST PROCEDURE

Testing was carried out according to the protocol described in EU Directive 98-69 EC, Emissions from Light Duty Vehicles, as shown in **Figure A5-1**. A full fuel change and conditioning drive (see previous section) was carried out between each test to prevent loss of “light ends” during testing affecting results.

Separate, new canisters were used for each test fuel, two for each fuel for logistical reasons. Before testing these were conditioned by loading to breakthrough with butane, and then purging to constant weight, three times. Between tests canisters were purged to constant weight, and then loaded to 2g breakthrough with butane.

Where possible canisters were fitted with quick-release connectors, so they could be removed and weighed at several points during the testing:

- Canister loaded to breakthrough before testing
- After the pre-conditioning drive (ECE + 2*EUDC)
- After overnight soak, before ECE Type 1 cycle
- After ECE Type 1 cycle, before going into SHED
- After Hot Soak and Diurnal tests in SHED

However, this weighing was not always carried out and some weighings were carried out with or without connecting pipework so not all canister weight data are available.

Exhaust emissions were also measured over the NEDC during the Type 1 test drive, as permitted by the Directive and described in **Appendix A2**.

Figure A5-1 Evaporative Emissions Testing Flowchart

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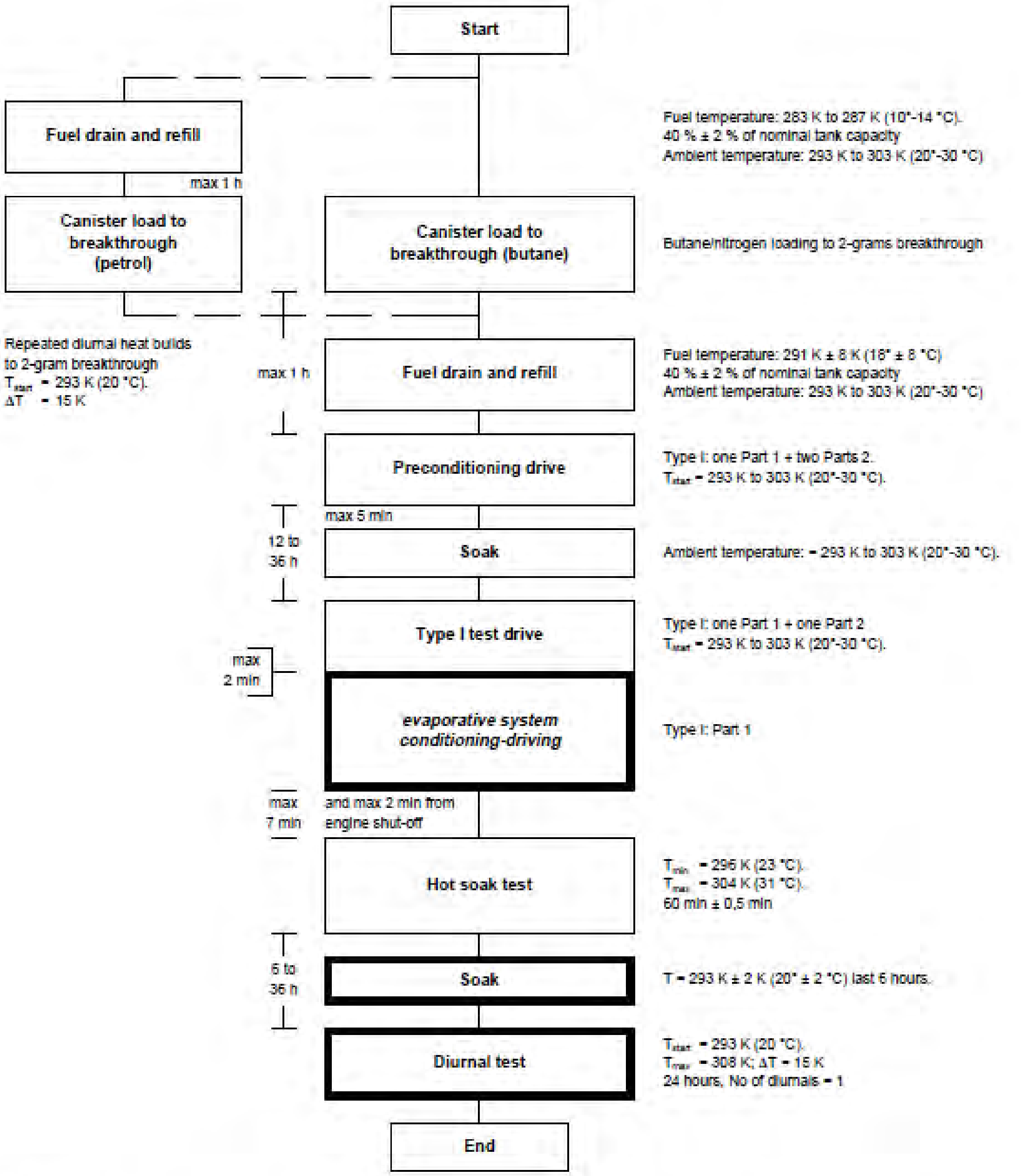
Figure VI.1

Evaporative emission determination

3 000 km run-in period (no excessive purge/load)
Ageing of canister(s) verified
Steam clean of vehicle (if necessary)



Note: 1. Evaporative emission control families — details clarified.
2. Tailpipe emissions may be measured during type I test drive, but these are not used for legislative purposes. Exhaust emission legislative test remains separate.

A5.3 CANISTER CONDITIONING

Figure A5-2 shows canister weights after purging and loading to breakthrough for the conditioning cycles, plus some later breakthrough weights. For most vehicles, the purged and breakthrough weights continued to increase with time, as the canisters built up "heels" of heavier hydrocarbons and ethanol. This is consistent with the earlier JRC/EUCAR/CONCAWE study [20]. Canister working capacity is shown in **Figure A5-3** which is the difference between the purged and breakthrough canister weights. Working capacity varies from around 50g for the two smaller Vehicles 5 and 6 to over 100g for the largest Vehicles 1 and 2, as would be expected. Working capacity varies surprisingly little over time, though there is little data from the later tests on ethanol fuels. This is because, surprisingly, the breakthrough loaded weight increases with time as the "heel" in the carbon canister builds up, as well as the purged weight.

Figure A5-2 Canister weight gain during conditioning and some later tests

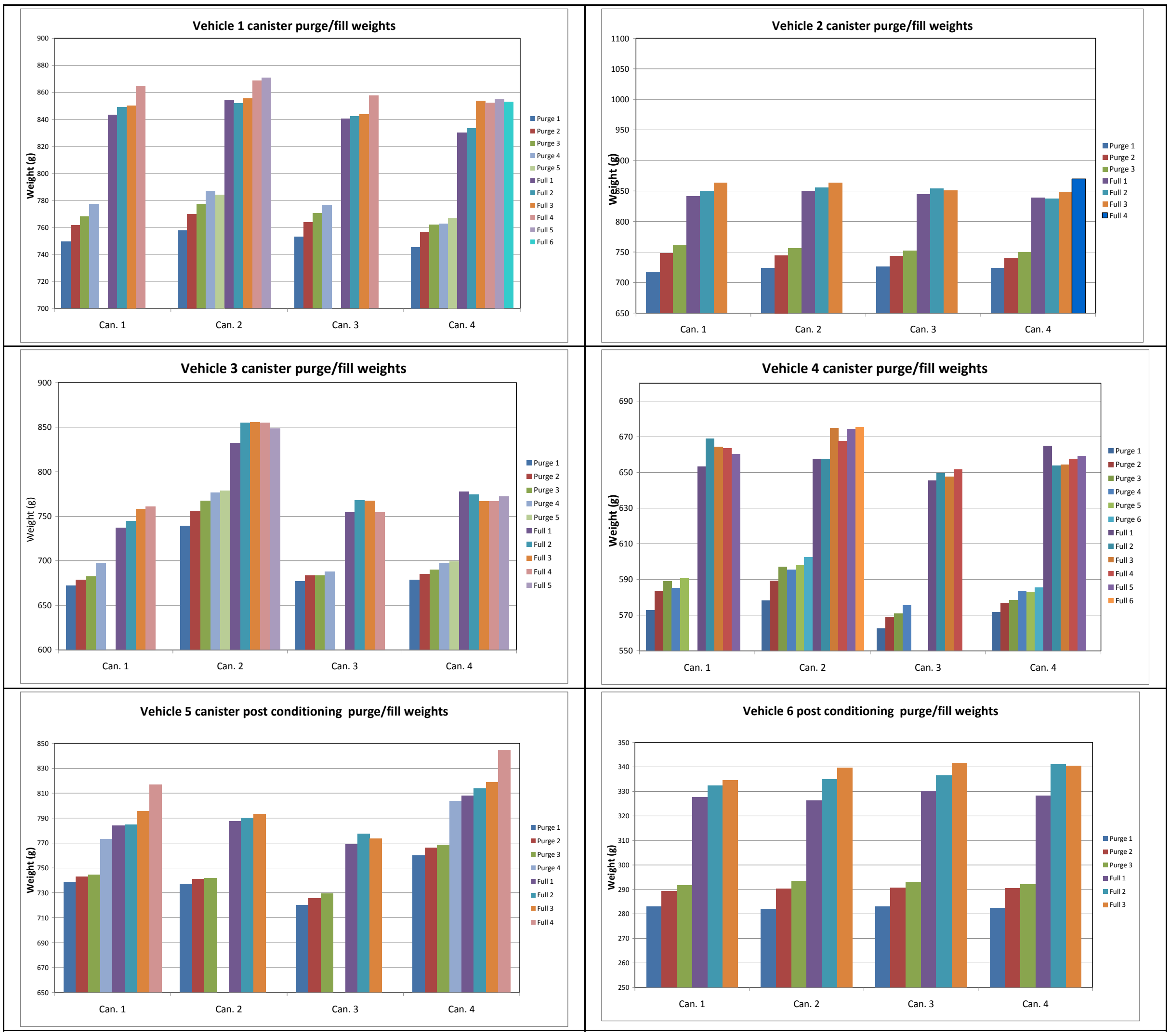
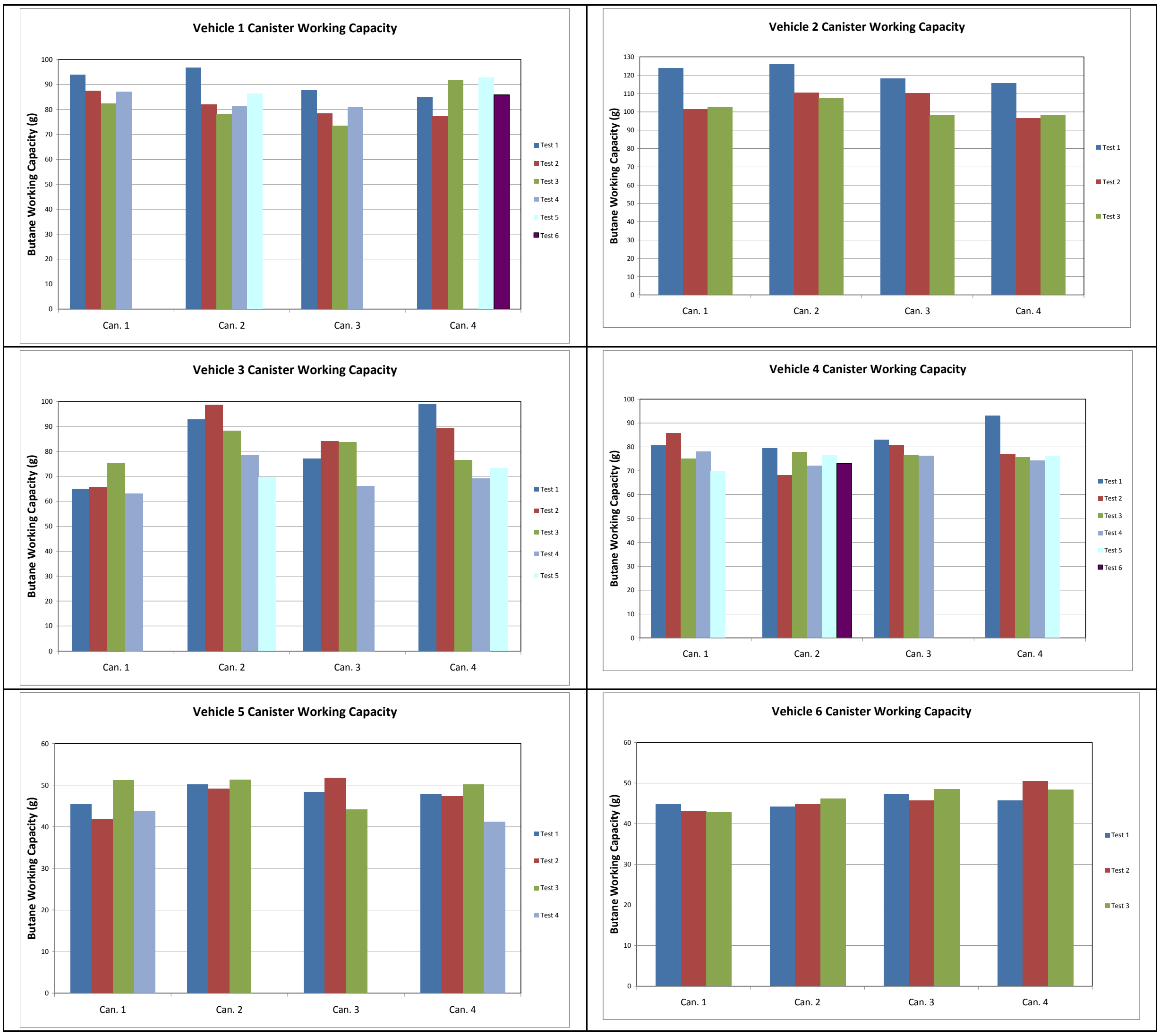


Figure A5-3 Canister working capacity



A5.4 RESULTS

Full test results for all tests completed are given in **Table A5.1** including canister weight data. Evaporative emissions data are discussed in **Section 3.5** and shown in **Figures 3.5.1** to **3.5.3** with tests arranged in date order.

Table A5.1 Evaporative emissions and canister weight data

Fuel	Vehicle Ref	Test Date	1 Hr Hot Soak HC (g)	24 Hr Diurnal HC (g)	TOTAL HC Emissions (g)	% of Limit (2g)	Loaded CAN weight prior to Precon (g)	Immediate Post precon CAN weight (g)	Can weight loss from precon	Pre EC2000 cycle CAN weight (g)	CAN weight between EC2000 and SHED (g)	Can weight loss from EC2000	CAN weight following SHED (g)	Can weight gain in SHED	TOTAL = Evap + can wt gain g	Canister No Used	Test Notes / Comments
Orange	1	17/02/2011	0.263	0.572	0.835	42%										1	
Green	1	22/02/2011	0.150	1.046	1.195	60%										2	Requires repeat due to power cut
Green	1	26/02/2011	0.302	1.202	1.503	75%										3	
Orange	1	04/03/2011	0.358	1.194	1.552	78%	852.4	801.6	50.8	805.6	783.8	21.8	-			4	
Green	1	07/03/2011	0.322	1.222	1.544	77%	1006.6	960.4	46.2	962.2	937.4	24.8	959.2	21.8	23.3	2	Repeat of ML03000575
Green	1	03/06/2011	0.126	1.220	1.345	67%	961	914.6	46.4	908.1	903.2	4.9	920.9	17.7	19.0	3	Investigation with fuel system standard - can external
Green	1	18/10/2011	0.000	1.101	1.101	55%	1379	1331.2	47.8	1331.8	1321.2	10.6	1338.4	17.2	18.3		
Green	1	18/10/2011		1.444	1.444	72%					908.8		908.8	-1			Extra Diurnal with additional canister
Green	2	15/02/2011	0.056	0.610	0.666	33%										1	
Orange	2	19/02/2011	0.060	0.945	1.004	50%										2	
Orange	2	24/02/2011	0.061	0.526	0.587	29%										3	
Green	2	02/03/2011	0.105	0.859	0.964	48%	869.6	832	37.6	833.6	814	19.6	-			4	
Orange	2	01/06/2011	0.111	1.196	1.307	65%	1230.2	1194.8	35.4	1197	1186.2	10.8	1198.8	12.6	13.9	3	Investigation with fuel system standard - can external
Orange	3	20/04/2011	0.264	2.630	2.894	145%	838.6	808.4	30.2	808.6	799.8	8.8	-			3	
Green	3	04/05/2011	0.167	2.124	2.290	115%	842.6	810.2	32.4	776.4	763.2	13.2	-			1	
Green	3	09/05/2011	0.128	3.932	4.060	203%	784.6	758.4	26.2	800.6	827.2	-26.6	-			4	
Orange	3	13/05/2011	0.183	2.860	3.043	152%	943.8	901.4	42.4	866	897.6	-31.6	907.6	10	13.0	2	
Green	4	18/04/2011	0.179	2.066	2.245	112%										2	
Orange	4	06/05/2011	0.217	2.911	3.128	156%	740.6	707	33.6	667.6	650.2	17.4	-			1	
Orange	4	11/05/2011	0.164	2.064	2.229	111%	739	703.8	35.2	706	650	56	658.6	8.6	10.8	4	
Green	4	17/05/2011	0.178	2.424	2.601	130%	751.6	718.2	33.4	720	666.4	53.6	721.6	55.2	57.8	2	
Orange	5	02/08/2011	0.183	2.843	3.025	151%										1	Canister weights unreliable
Green	5	09/08/2011	0.206	2.996	3.202	160%										2	Canister weights unreliable
Green	5	09/08/2011		3.099	3.099	155%					761.2		761.4	0.2		3	Extra Diurnal with additional canister
Orange	5	31/08/2011	0.245	3.381	3.626	181%	916.8	884.6	32.2	888.8	881.4	7.4	892.4	11	14.6	4	
Green	5	16/09/2011	0.516	4.118	4.635	232%	867	843	24	844.5	834.2	10.3	845	10.8	15.4	3	
Green	6	04/08/2011	0.168	1.543	1.712	86%										2	Canister weights unreliable
Orange	6	16/08/2011	0.105	1.578	1.683	84%	656.4	639.4	17	640.6	636.0	4.6	644.2	8.2	9.9	1	
Orange	6	06/09/2011	0.106	1.095	1.200	60%	539.8	521.4	18.4	521.2	516.2	5	523.2	7	8.2	4	
Green	6	13/09/2011	0.094	1.569	1.663	83%	549.4	537.6	11.8	537.4	532.2	5.2	539.4	7.2	8.9	3	
Green	6	13/09/2011		1.166	1.166	72%					374.6		376.2	1.6		3	Extra Diurnal with additional canister

APPENDIX 6 HOT WEATHER DRIVEABILITY AT +40°C

A6.1 BACKGROUND TO HWD TESTING

All six vehicles were tested at 40ºC on the summer grade (Class A) fuels, Baseline E10-A (ORANGE) & Step 2 E10-A (GREEN). Tests were run using the GFC test procedure [24], the same as was used for a previous CONCAWE Hot Weather Driveability Study [7,8]. The GFC procedure has three “sequences” that represent motorway, mountain climbing and heavy city traffic driving, as discussed below. Duplicate tests were run on each fuel with the test order randomised as far as is possible with only four tests per vehicle. Some GFC test requirements for full throttle accelerations were adjusted to keep vehicles stable on the dynamometer.

A6.2 TEST PROCEDURE

A European test procedure developed by the CEC in the 1970s had been in use for many years, the final version CEC M-09-T-84, dated 1984. This was a “conditional” procedure, where a vehicle was tested over four “sequences” on a given fuel/temperature combination. Each malfunction was allocated a rating of “Trace, Moderate or Severe” leading to a rating of “Pass”, “Borderline” or “Fail” for each sequence. Further tests would then be carried out on other fuel/temperature combinations depending on this first rating. In this way the fuel volatility versus temperature envelope of acceptable performance could be established. The British Technical Council (BTC) had developed and used an updated version of this procedure in the 1990s. However this procedure was developed for non-catalyst carburettor cars and was not considered appropriate for modern vehicles.

In the 1990s, the French GFC developed a procedure for catalyst-equipped vehicles that had three sequences[12]:

- **Sequence 1** is a motorway hot-soak test and is essentially the same as the old BTC and CEC procedures;
- **Sequence 5** is a mountain climbing test with increased dynamometer load;
- **Sequence 6** is a “canister loading” test which is meant to simulate stop-and-go driving in heavy traffic. This sequence may overload the carbon canister and hence affect the engine’s air/fuel ratio (AFR).

A number of demerits is assigned to each recorded driveability malfunction - “slight, moderate or severe” as shown in **Table 2** below. Thus a total number of demerits is calculated for each test, and from these data for a number of tests, relationships could be developed between demerit levels, fuel volatility and temperature.

The CEC were unable to develop a new HWD procedure due to lack of support from the Auto Industry who saw driveability as a commercially sensitive issue, and the Driveability Group was formally closed in 2001. The GFC Hot Weather Driveability procedure has not been formally adopted by CEC, but was published by them, together with the BTC procedure in a final report [24].

[12] There were no Sequences 2-4 because these were part of the older BTC/CEC procedure and were no adopted into the GFC procedure.

The GFC procedure was used in the previous CONCAWE study [7,8] and in the absence of any more recent developments was chosen for this programme also.

The procedure comprises three test sequences as shown in **Figure A6-1** and **Table A6.1**.

Figure A6-1 Speed vs. time profile for the Hot Weather Driveability test procedure

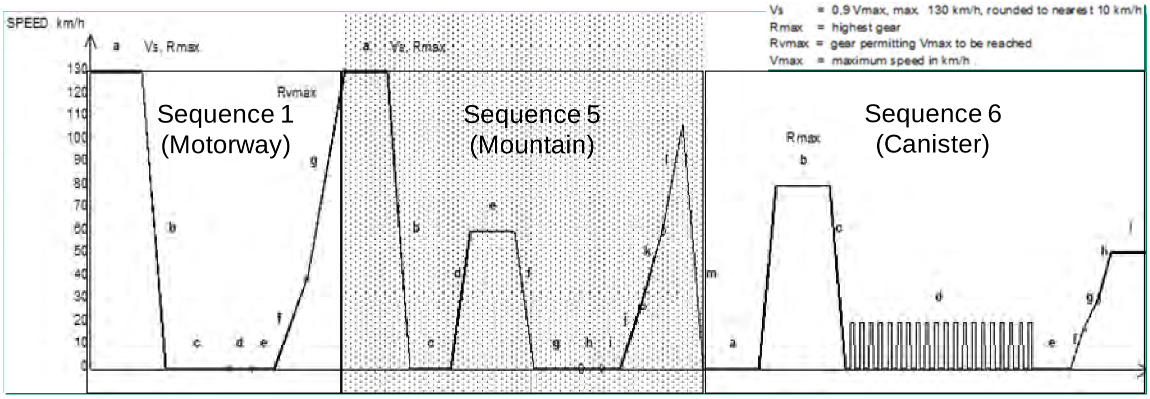


Table A6.1 GFC Hot Weather Driveability Procedure

Sequence	Stage	Summarised Description
Preconditioning	-	Drain, rinse then fill the tank (5 litres fuel)
	-	Carry out 4 cycles ECE15 then 2 cycles EUDC at 20°C
Adjust Test Temperature		
Sequence 1 (motorway)		Add 20 litres fresh fuel for the 1st test temperature, 10 litres for the following temperatures
	a	Stabilisation of temperatures at Vs*
	c	Engine stopped for 15 minutes
		Take 0.5 litre fuel sample from tank
	f	Part throttle acceleration up to 40 km/h
	g	Full throttle acceleration from 40 km/h to Vs with measurement of the acceleration time from 50 km/h to Vs*
Sequence 5 (mountain)	a	Stabilisation of temperatures at Vs*
	e	Up slope P=10% with 0.7 PTRA** during 7 minutes
	g	Engine stopped 30 minutes
	i	Idling 30 seconds
	j, k, l	Full throttle acceleration in the first three gears to 4500 rev/min (Slope P=5%) at 0.7 PTRA** with measurement of the acceleration time
Sequence 6 (canister)	a	Add 10 litres of fresh fuel
	b	Cruise at 80 km/h during 15 minutes in the highest gear
		Take 0.5 litre fuel sample from tank
	d	20 cycles STOP and GO made up as follows: - 40 sec idling - 20 sec 20 km/h in first gear
	e	Idling for 5 minutes
	f, g, h	Part-load acceleration to 50 km/h in top gear
	i	Cruise at 50 km/h for 5 minutes
If the same fuel is to be tested at another temperature, resume from “adjust test temperature”		
If another fuel is to be tested, resume from pre-conditioning		

*Vs is the “cruising speed” defined as 0.9*V_{max} (maximum speed), but limited to 130 km/h
** PTRA = maximum authorised running weight

Demerits are assigned to each occurrence of a driving fault observed during each of the three test sequences according to **Table A6.2**.

Table A6.2 Assignment of Demerit points to driving faults

Fault	Slight	Moderate	Severe	Yes
Stalling when starting				18
Stalling when idling				21
Stalling under load				42
Stalling when decelerating				42
Fail*				42
Instability when idling (roughness)	4	12	24	
Hesitation	4	12	24	
Stumble	4	12	24	
Surge	3	6	9	
Backfire	4	8	12	
Odour (canister breakthrough)				2

Slight: Limited fault appearance, just detectable by a trained operator
Moderate: Fault detectable by an experienced driver
Severe: Fault that is pronounced, and obvious to any driver

* Fail is defined as follows:
Starting Fail: Starting impossible after 10 attempts or 1 minute max.
Acceleration Fail: Impossible to reach Vs (see above) after 2 x (acceleration time 50km/h to Vs on reference fuel) in Sequence 1 or 4500 rev/min in 3rd gear in Sequence 5.
Cruise Fail: Cruising speed impossible to maintain longer than 4 minutes

Demerits are also calculated from starting time and acceleration time according to the following formulae:

- ***Starting Demerits = 10 x (starting time in seconds – 2)***

However, for this study, 2 seconds was considered to be an unacceptable starting time so the equation was modified to:

- ***Starting Demerits = 10 x (starting time in seconds – 1)***
- ***Acceleration Demerits = 200 x (t_{CRV} – t_{CRref})/t_{CRref} –20 (minimum 0, maximum 200)***

Where t_{CRV} is the acceleration time recorded with the test fuel and t_{CRref} is the acceleration time recorded with a specified reference fuel in a test conducted at the same temperature. This is determined for both Sequences 1 (top gear acceleration to Vs) and 5 (through-gears acceleration to 4500 rev/min in each gear up to 130 km/h).

The total demerit rating for each test is then the sum of all individual faults, starting and acceleration demerits recorded during the complete test. An example from the previous CONCAWE study is shown in **Table A6-3**:

Table A6-3 Example of test demerits

Sequence	Fault	Demerits
1	Start time - 4.4 sec: 10*(4.4-1)=34	34
	Starting stall	18
5	Start time 3.3 sec: 10*(3.3-1)=23	23
	Starting stall	18
	Severe idle roughness	24
	Acceleration Slight Stumble	4
	Cruise slight surge	3
6 phase d3	Moderate idle roughness	12
6 phase d5	Slight Idle Roughness	4
6 phase d13	Slight Idle Roughness	4
TOTAL		**144**

A6.3 RESULTS

All six vehicles were tested twice on both the Baseline E10-A (ORANGE) and Step 2 E10-A (GREEN) fuels at 40ºC. The test order was randomized as far as possible with only four tests per vehicle. **Figure A6-2** shows the steps that were used to condition and test the vehicles. A full fuel change procedure was carried out for each test, even if the same fuel was used for a subsequent test. Carbon canisters were loaded to breakthrough with butane then purged with air to 50% of their working capacity.

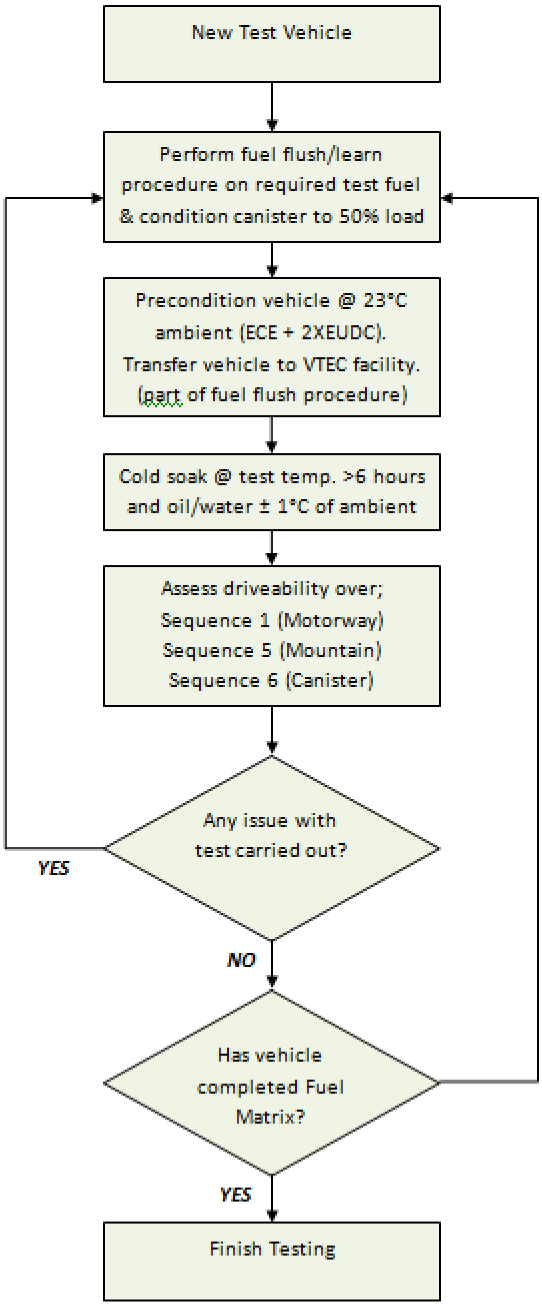
Reference acceleration times were measured (mean of at least three accelerations) on the CEC RF-02-08 fuel containing 5% Ethanol at +40ºC and are shown in **Table A6-4**. For all vehicles, the sequence 1 in-gear accelerations were carried out in 5th gear, even though Vehicles 1, 2 and 4 had six gears. The Sequence 5 through-the-gears accelerations should be a standing start through 1st, 2nd and 3rd gears to 4500 rev/min in 3rd or 130km/h. This was done for Vehicles 1, 3, 5 and 6, starting the accel time measurement at 2km/h. For Vehicles 2 and 5, however, full throttle in 1st gear generated too much wheelspin and vehicle instability on the rollers, so the accels were run for vehicle 2 from 20 – 130 km/h in gears 2-3-4 and for Vehicle 5 from 10km/h to 4500rev/min in gears 2-3-4. The same conditions were of course also used for the test runs.

Table A6-4 Reference acceleration times in (top) gear (Sequence 1) and through gears (Sequence 5)

Test Temp. 40ºC			Acceleration Times																			
Fuel: RF02-08-E5			Temperature Stabilisation							Accel in Gear		Temperature Stabilisation							Accel Through Gears			
Vehicle	Date	Kerb Mass + 100kg	Coolant	Sump Oil	Intake Air	Pre-cat	Post-cat (or rear pre-cat)	Fuel Rail	Fuel Tank 1	**50 to 130 kph Time (tR1)**	Gear Used	Coolant	Sump Oil	Intake Air	Pre-cat	Post-cat (or rear pre-cat)	Fuel Rail	Fuel Tank 1	Gears used	Start criteria	Stop Criteria	**Accel Time (tR5)**
		kg	ºC	ºC	ºC	ºC	ºC	ºC	ºC	sec		ºC	ºC	ºC	ºC	ºC	ºC	ºC				sec
1	19/01/2011	1590	81	95	46	546	560	81	N/A	23.6	**5th***	102	117	50	775	772	89	N/A	1-2-3	2kph	4500rpm	15.8
2	27/01/2011	1470	98	113	49	769	716	74	63	17.4	**5th***	104	122	50	841	794	82	66	2-3-4	20kph	130kph	19.4
3	21/01/2011	1130	103	135	50	849	863	57	64	34.6	5th	108	135	53	795	807	61	65	1-2-3	2kph	4500rpm	18.3
4	27/01/2011	1360	90	114	47	771	753	74	66	28.5	**5th***	101	122	50	782	790	82	51	2-3-4	10kph	4500rpm	27.5
5	21/01/2011	910	96	112	52	845	851	65	61	43.4	5th	102	115	58	819	844	71	64	1-2-3	2kph	4500rpm	22.6
6	27/01/2011	1020	119	132	47	794	823	69	57	56.0	5th	115	125	48	762	792	80	60	1-2-3	2kph	4500rpm	18.0

* In-gear Accel completed in 5th gear, not Top (6th)

Figure A6-2 Flowchart for HWD testing

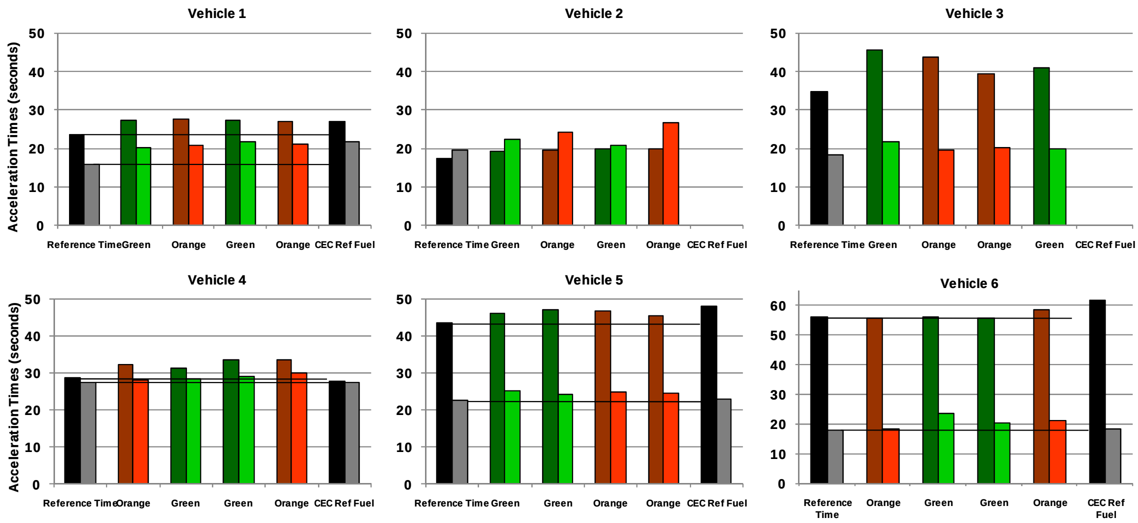


The results of all individual tests and vehicle means are shown in **Table A6-5**. These show substantial differences between the repeat tests, but no clear differences between the two fuels. During the testing it became apparent that several vehicles were producing substantial numbers of demerits, but these were mainly from increased acceleration times (Vehicles 1, 2 and 3), and idle instability (especially Vehicle 5). Demerits from traditional driveability malfunctions i.e. hesitations, stumbles and surges were relatively low.

All the vehicles had full Engine Management Systems, and all except Vehicle 5 had electronic “drive-by-wire” throttle control. This led to some problems during the two Wide Open Throttle (WOT) accelerations in the test cycle. Although the driver fully depressed the accelerator, the EMS did not fully open the throttle until around half way through the acceleration. This was probably to limit maximum torque through the transmission and/or to prevent wheelspin on the dynamometer rolls, even though the vehicle’s Traction Control systems were turned off for all tests. This led to longer acceleration times during the tests than when setting the reference acceleration times, and hence substantial “acceleration time” demerits.

Figure A6-3 shows recorded acceleration times for all tests compared with the reference acceleration times determined before the main programme. As specified by the GFC procedure, these were determined using a less arduous procedure than the full HWD test, so component (and especially tyre) temperatures could be somewhat lower. Consequently four of the six vehicles were also tested over the full HWD cycle on the CEC RF-02-08 Reference fuel, and these results are also shown in **Figure A6-3**. All vehicles show increased acceleration times over the full test cycle, even Vehicle 5 with the cable throttle, though for this vehicle the increases were small and did not lead to increased demerits. Vehicles 1, 5 and 6 clearly show increased acceleration times on the CEC reference fuel over the full test cycle, similar to the test fuels, though Vehicle 4 does not.

Figure A6-3 Through-gear (Sequence 5) and in-gear (Sequence 1) acceleration times



This behaviour had not been seen in previous studies and is considered to be an artefact of the test procedure with these vehicles while operating on a chassis dynamometer.

In addition, substantial idle stability demerits were recorded, especially during the city traffic sequence. This was found to be often due to the time taken for the engine to return to idle after a deceleration, again controlled by the EMS.

Table A6-5 HWD results at +40°C

	Baseline E10-A Gasoline				Step 2 E10-A Gasoline			
	Hesitations, Stumbles & Surges	Idle Instability	Acceleration Times	Total Demerits	Hesitations, Stumbles, & Surges	Idle Instability	Acceleration Times	Total Demerits
Vehicle 1 (average)	0	6	57	63	0	2	56	58
Test 1	0	8	59	67	0	4	46	50
Test 2	0	4	55	59	0	0	67	67
Vehicle 2 (average)	17	10	48	75	12	8	10	29
Test 1	8	12	35	55	11	8	12	31
Test 2	25	8	62	95	12	8	8	28
Vehicle 3 (average)	4	0	21	25	1	2	38	41
Test 1	4	0	32	36	0	0	60	60
Test 2	4	0	9	13	2	4	16	22
Vehicle 4 (average)	0	16	10	26	0	8	7	15
Test 1	0	12	6	18	0	4	0	4
Test 2	0	20	15	35	0	12	15	27
Vehicle 5 (average)	13	72	0	85	15	46	1	62
Test 1	17	76	0	93	18	40	2	60
Test 2	9	68	0	77	12	52	0	64
Vehicle 6 (average)	15	24	8	46	21	6	24	50
Test 1	8	44	0	52	21	8	40	69
Test 2	21	4	16	41	20	4	8	32

Increases in acceleration time had not been seen in the previous programme, except for one vehicle, which completely failed to reach cruising speed. Also no other malfunctions were reported during these accelerations, so it was decided to investigate this phenomenon further. Fortunately Millbrook had logged data at both 1Hz and 10Hz frequency from the EMS via the CAN port. This gave access to detailed data on engine and vehicle speed, throttle position, spark timing fuel and air flows etc. This data showed that during the accelerations, although the driver had “requested” full throttle via the accelerator pedal during the acceleration, the EMS had in fact not allowed the engine to operate at full throttle until well through the acceleration.

Figure A6-4 shows an example for Vehicle 1 of a full throttle acceleration on the reference fuel taken during the setting of the reference acceleration times. This gave a time of 23.5s, with the throttle only open 40-50% for the first 10s of the acceleration. Note that the full throttle signal appears as <90% on the charts. **Figure A6-5** shows a similar acceleration during a full HWD test on the Step 2 E10-A (GREEN) fuel. This gave an acceleration time of 27.7s but the throttle was open even less, below 40% for the first 10s and moving to full throttle only after almost 15s. This increased acceleration time compared to the reference fuel generated 14.8 demerits.

All of the vehicles had active Engine Management Systems (EMS) and all except Vehicle 5 had an electronic throttle, or “drive by wire”. Most vehicles, except Vehicles 5 and 6, had traction control although this was switched off during testing. It is clear that the EMS is preventing the vehicle operating at full throttle despite the driver fully depressing the accelerator. This is presumably to limit torque through the transmission and/or prevent wheelspin while accelerating on the chassis dynamometer and may not happen on the road. The vehicles and hence tyres would be hotter during full HWD tests that during the setting of reference acceleration times, which may explain why the throttle is fully open for even less time during the HWD tests. Note that Vehicle 5 with a conventional throttle cable has almost zero acceleration time demerits. It is clear from this that the acceleration time demerits are not a true reflection of driveability problems and that this type of acceleration evaluation is not suitable for modern electronically controlled vehicles.

Figure A6-4 Full Throttle Acceleration in 5th Gear for Vehicle 1 on CEC RF-02-08 reference fuel

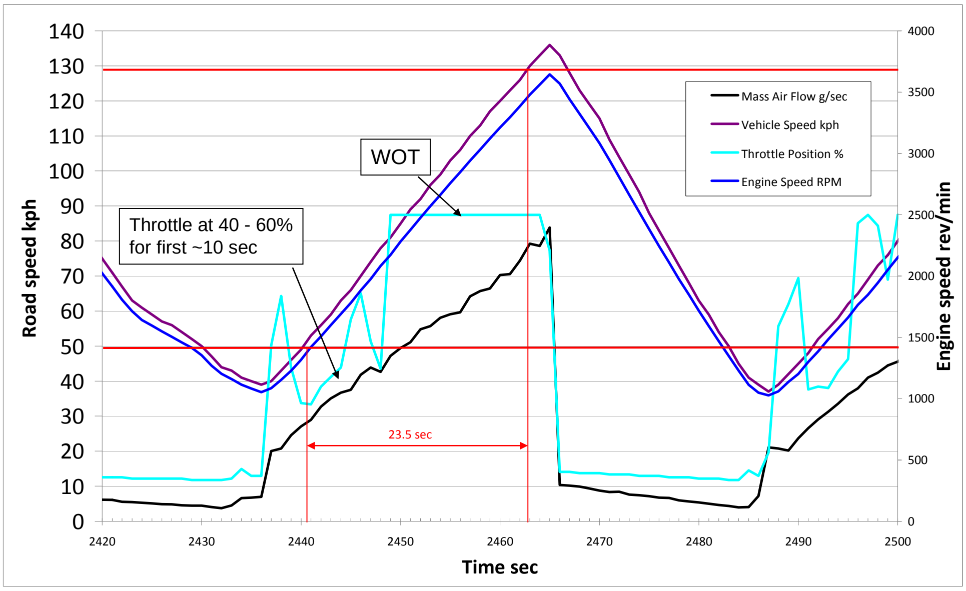
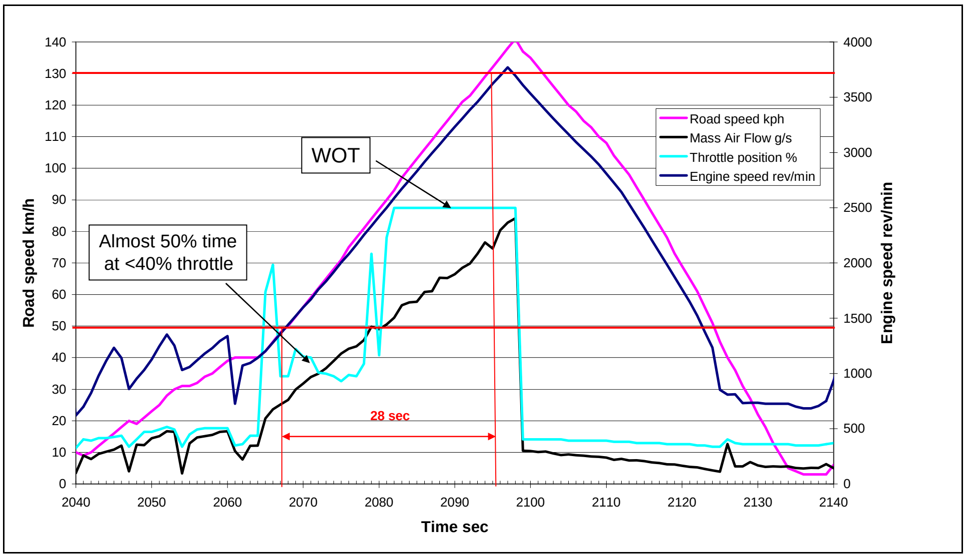
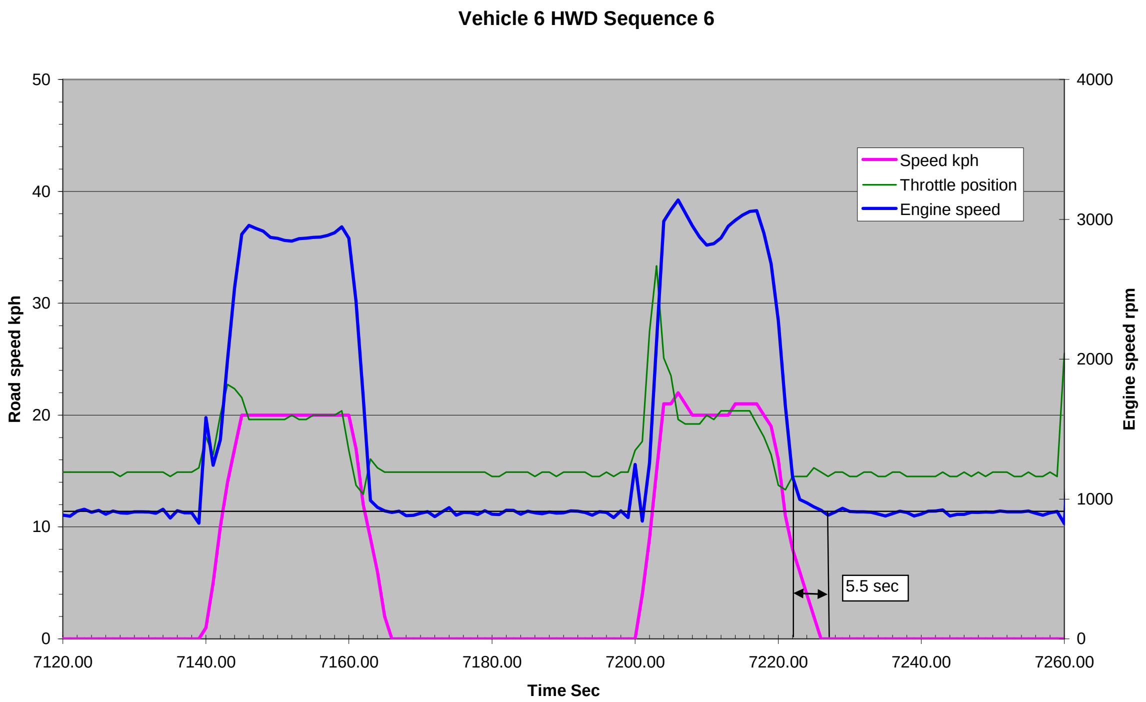


Figure A6-5 Full throttle acceleration in 5th Gear for Vehicle 1 on Step 2 E10-A (GREEN) fuel



Most of the idle instability occurred during Sequence 6 (canister test), especially during the repeated idles between part throttle accelerations to 20km/h. This appeared to be largely due to the engine speed taking some time to come down to its idling value after the cruise period, causing a significant variation in idle speed over the idle period. This is shown in **Figure A6-6** for Vehicle 6. 0n the Baseline E10-A (ORANGE) fuel. During the 3rd and 4th accelerations in Sequence 6, light idle instability was reported, which is defined as +/- 30–50rpm. This is almost entirely due to the time of >5s taken for the engine speed to come back to idle after deceleration, again controlled by the EMS.

Figure A6-6 Vehicle 6 Sequence 6 – Accelerations 3 and 4: 0–20km/h



APPENDIX 7 PROPERTIES OF TEST FUELS

A7.1 PROPERTIES OF TEST FUELS

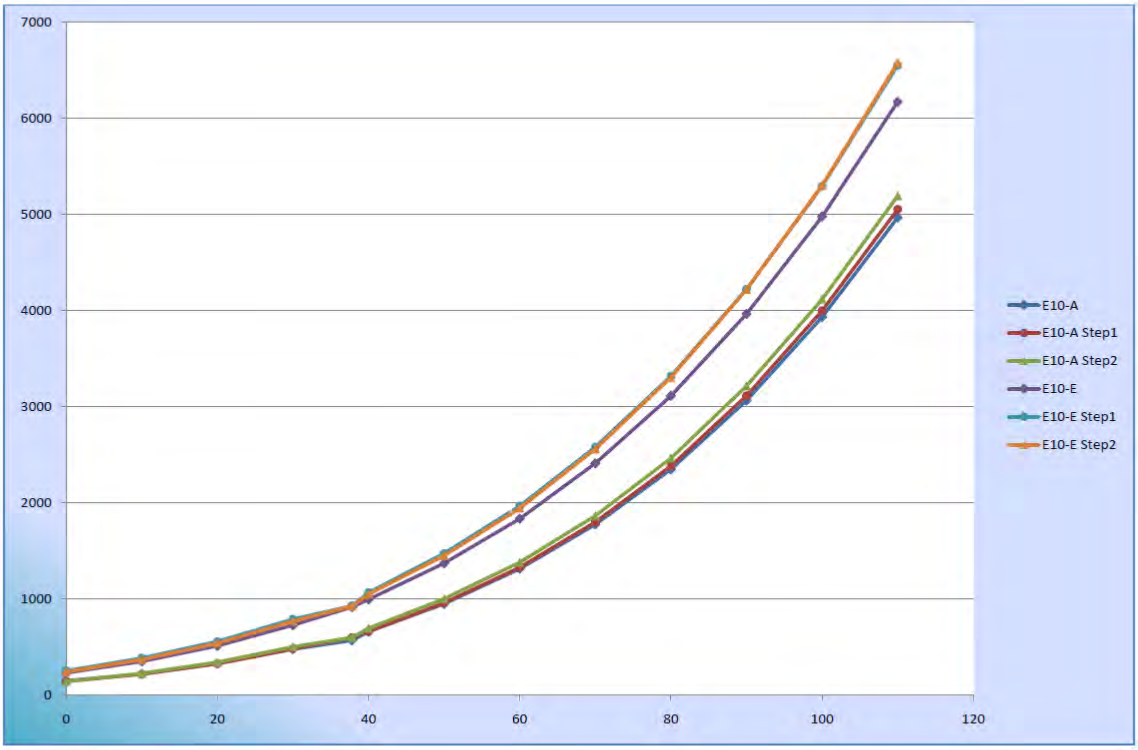
Property	Units	CEC RF-02-08 E5	Test Method
RON	==	98.8	ASTM D2699
MON	==	87.8	ASTM D2700
Density 15°C	kg/m^3	0.7488	ASTM D4052
DVPE @ 37.8°C	kPa	58.7	ASTM D323
Distillation			
IBP	°C	39.4	ASTM D86
5% vol	°C		ASTM D86
10% vol	°C		ASTM D86
20% vol	°C		ASTM D86
30% vol	°C		ASTM D86
40% vol	°C		ASTM D86
50% vol	°C		ASTM D86
60% vol	°C		ASTM D86
70% vol	°C		ASTM D86
80% vol	°C		ASTM D86
90% vol	°C		ASTM D86
95% vol	°C		ASTM D86
FBP	°C	203.0	ASTM D86
Residue	% vol	0.9	ASTM D86
Losses	% vol		ASTM D86
E70	% vol	37.0	ASTM D86
E100	% vol	53.5	ASTM D86
E150	% vol	83.9	ASTM D86
Vapour Lock Index (VLI)	index		Calculation
Combustion			
Net heat of combustion	MJ/kg	42.30	IP 12
%C/%H	% mass	84.61/13.66	ASTM D5291
Oxygen	% mass	1.73	Calculation
Sulphur	mg/kg	1.4	IP 490
Composition			
Saturates	% vol	60.7	ASTM D1319
Aromatics	% vol	30.3	ASTM D1319
Olefins	% vol	4.3	ASTM D1319
Benzene	% vol	<0.1	EN 238
Ethanol	% vol	4.7	IP 466
Methanol	% vol		EN 1601
Other Data			
Oxidation Stability	minutes	>480	ASTM D525
Copper Corrosion, 3 hrs. at 50°C	merit	1A	ASTM D130
Washed Gum	mg/100mL	<0.5	ASTM D381
Water content	ppm	0.011	IP 438
Appearance	Colour		Visual

Property	Units	Baseline E10-A	Step 1 E10-A	Step 2 E10-A	Test Method
RON	==	99.9	98.2	99.2	EN ISO 5164
MON	==	85.2	85.0	86.3	EN ISO 5163
Density 15°C	kg/m^3	746.2	748.4	738.5	EN ISO 12185
DVPE @ 37.8°C	kPa	57.1	58.7	61.0	EN ISO 13016
Distillation					
IBP	°C	37	36	40	ASTM D86
5% vol	°C	50	50	49	ASTM D86
10% vol	°C	52	52	50	ASTM D86
20% vol	°C	56	55	52	ASTM D86
30% vol	°C	60	58	55	ASTM D86
40% vol	°C	63	61	58	ASTM D86
50% vol	°C	71	66	61	ASTM D86
60% vol	°C	92	86	72	ASTM D86
70% vol	°C	102	97	92	ASTM D86
80% vol	°C	117	108	105	ASTM D86
90% vol	°C	150	134	132	ASTM D86
95% vol	°C	164	161	160	ASTM D86
FBP	°C	176	174	174	ASTM D86
Residue	% vol	0.6	0.9	0.8	ASTM D86
Losses	% vol	0.7	1.0	0.6	ASTM D86
E70	% vol	49.7	52.9	59.4	EN ISO 3405
E100	% vol	68.4	73.2	75.7	EN ISO 3405
E150	% vol	89.9	92.8	93.1	EN ISO 3405
Vapour Lock Index (VLI)	index	918.9	957.3	1025.8	Calculation
Combustion					
Net heat of combustion	MJ/kg	41.93	41.32	41.35	ASTM D240
%C/%H/%O	% mass	82.8/13.6/3.6	82.9/13.6/3.5	82.9/13.6/3.5	GC Calculated
Oxygen	% mass	3.57	3.50	3.51	EN 1601
Sulphur	mg/kg	6	5	4	EN ISO 20846
Composition					
Saturates	% vol	54.5	57.3	59.2	ASTM D1319
Aromatics	% vol	21.5	20.5	19.7	ASTM D1319
Olefins	% vol	14.3	12.7	11.6	ASTM D1319
Benzene	% vol	0.6	0.5	0.4	EN 238
Ethanol	% vol	9.7	9.5	9.4	EN 1601
Methanol	% vol	<0.17	<0.17	<0.17	EN 1601
Other Data					
Oxid. stability	minutes	>360	>960	>360	ISO 7536
Copper strip	merit	1	1A	1A	ISO 2160
Existent gum	mg/100mL	<5	1	1	ISO 6246
Water content	ppm	225	171	237	EN ISO 12937
Appearance	Colour	Clear/Bright	Clear/Bright	Clear/Bright	Visual

Property	Units	Baseline E10-E	Step 1 E10-E	Step 2 E10-E	Test Method
RON	==	99.3	98.4	98.3	ISO 5164
MON	==	87.1	85.0	86.5	ISO 5163
Density 15°C	kg/m^3	734.3	747.0	735.0	EN ISO 12185
DVPE	kPa	97.0	93.2	94.1	EN ISO 13016
Distillation					
IBP	°C	29	27	29	ASTM D86
5% vol	°C	36	39	38	ASTM D86
10% vol	°C	44	44	41	ASTM D86
20% vol	°C	52	51	46	ASTM D86
30% vol	°C	59	56	51	ASTM D86
40% vol	°C	64	61	57	ASTM D86
50% vol	°C	68	66	63	ASTM D86
60% vol	°C	94	85	69	ASTM D86
70% vol	°C	103	99	96	ASTM D86
80% vol	°C	110	109	106	ASTM D86
90% vol	°C	139	131	120	ASTM D86
95% vol	°C	162	155	141	ASTM D86
FBP	°C	174	171	170	ASTM D86
Residue	% vol	0.8	0.8	0.9	ASTM D86
Losses	% vol	3.7	2.2	1.8	ASTM D86
E70	% vol	51.9	54.9	60.6	EN ISO 3405
E100	% vol	67.1	70.9	73.9	EN ISO 3405
E150	% vol	92.3	94.1	96.0	EN ISO 3405
Vapour Lock Index (VLI)	index	1333.3	1316.3	1365.2	Calculation
Combustion					
Net heat of combustion	MJ/kg	41.86	41.90	41.87	ASTM D240
%C/%H/%O	% mass	82.6/13.8/3.6	83.0/13.5/3.5	83.0/13.5/3.5	GC Calculated
Oxygen	% mass	3.59	3.52	3.55	EN 1601
Sulphur	mg/kg	4	2	3	EN ISO 20846
Composition					
Saturates	% vol	58.7	58.2	54.4	ASTM D1319
Aromatics	% vol	20.9	22.5	24.2	ASTM D1319
Olefins	% vol	10.9	9.8	11.9	ASTM D1319
Benzene	% vol	0.4	0.2	0.3	EN 238
Ethanol	% vol	9.5	9.5	9.4	EN 1601
Methanol	% vol	<0.17	<0.17	<0.17	EN 1601
Other Data					
Oxid. stability	Minutes	>960	>960	>960	ISO 7536
Copper strip	Merit	1A	1A	1A	ISO 2160
Existent gum	Mg/100mL	<5	1	<5	ISO 6246
Water content	Ppm	184	237	190	EN ISO 12937
Appearance	Colour	Clear/Bright	Clear/Bright	Clear/Bright	Visual

A7.2 VAPOUR PRESSURE VS. TEMPERATURE

Figure A7-1 DVPE (in mbar) as a function of measurement temperature (in °C) for six test fuels



Baseline E10-A		Step 1 E10-A		Step 2 E10-A	
Temp (°C)	Pabs (mbar)	Temp (°C)	Pabs (mbar)	Temp (°C)	Pabs (mbar)
0	146	0	138	0	137
10	216	10	213	10	221
20	324	20	324	20	337
30	474	30	477	30	497
37.8	565	37.8	595	37.8	595
40	657	40	658	40	691
50	946	50	956	50	997
60	1310	60	1326	60	1378
70	1772	70	1797	70	1861
80	2345	80	2380	80	2462
90	3062	90	3111	90	3212
100	3931	100	3997	100	4115
110	4964	110	5051	110	5191

Baseline E10-E		Step 1 E10-E		Step 2 E10-E	
Temp (°C)	Pabs (mbar)	Temp (°C)	Pabs (mbar)	Temp (°C)	Pabs (mbar)
0	226	0	249	0	237
10	346	10	380	10	364
20	507	20	553	20	534
30	723	30	785	30	763
37.8	910	37.8	925	37.8	920
40	992	40	1062	40	1045
50	1367	50	1469	50	1446
60	1831	60	1964	60	1941
70	2407	70	2576	70	2555
80	3110	80	3315	80	3302
90	3962	90	4220	90	4216
100	4977	100	5293	100	5302
110	6170	110	6550	110	6577

A7.3 FUEL COMPOSITIONS

The test fuels were blended at Total ACS in Givors, France and shipped in 200 litre barrels to Millbrook Proving Ground Ltd. (Bedford, UK). Upon arrival at Millbrook, the fuel barrels were stored in a protected enclosure, avoiding heat and exposure to weather. One randomly-selected barrel of each test fuel was sampled and the fuel sample was sent to Shell Global Solutions UK in Thornton, UK for a crosscheck reanalysis. The results of these reanalyses are shown below for vapour pressure, E70, and E100 values.

Figure A7-2 Comparison of vapour pressure results on different samples of the same fuel blends, measured at Total ACS (in Givors, France) and Shell Global Solutions (UK) (in Thornton, UK)

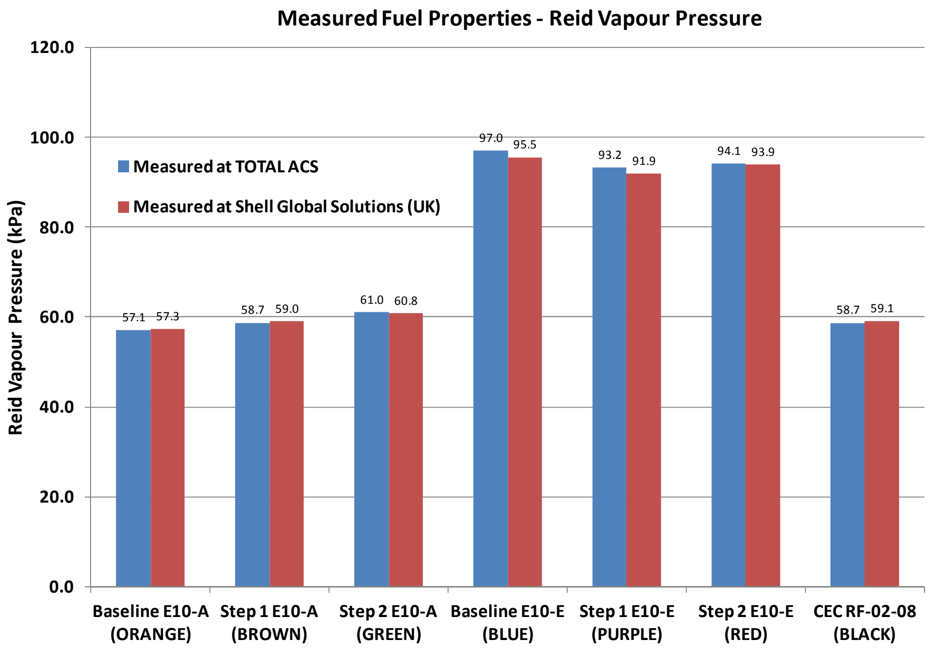


Figure A7-3 Comparison of E70 results on different samples of the same fuel blends, measured at Total ACS (in Givors, France) and Shell Global Solutions (UK) (in Thornton, UK)

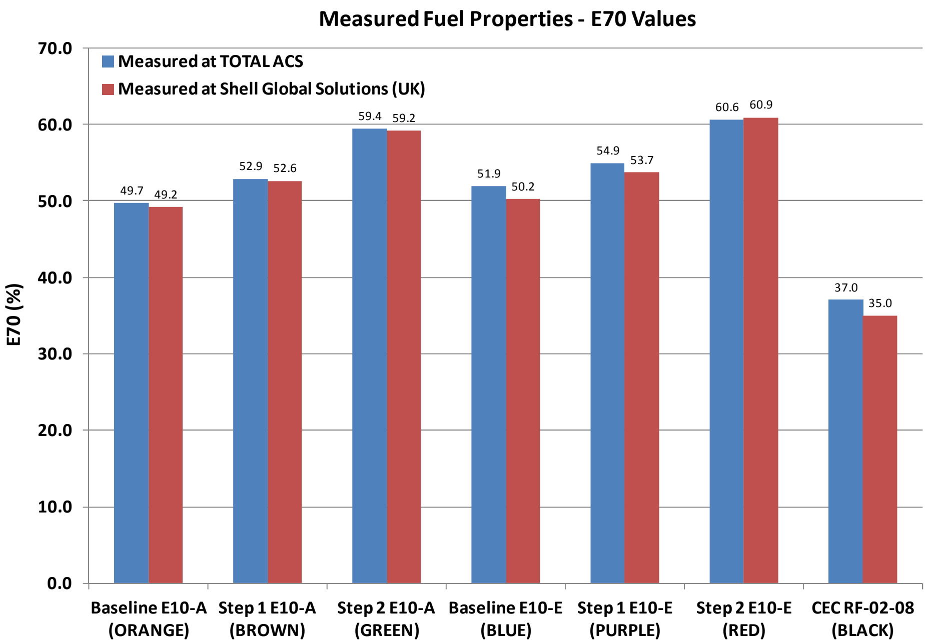
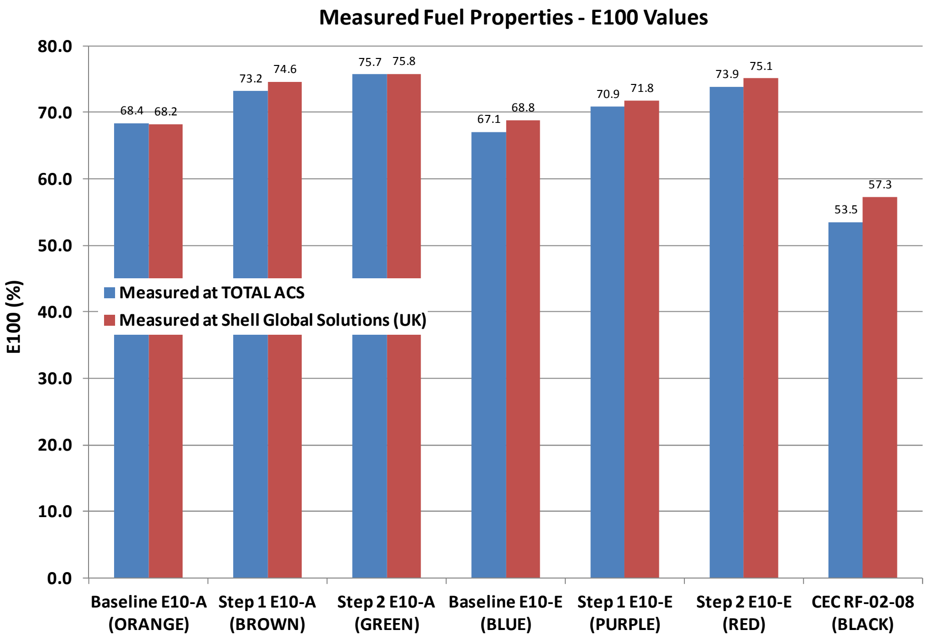


Figure A7-4 Comparison of E70 results on different samples of the same fuel blends, measured at Total ACS (in Givors, France) and Shell Global Solutions (UK) (in Thornton, UK)



APPENDIX 8 PRECISION OF E70 AND E100 FOR ETHANOL BLENDS

Appendix 5 of the BEP525 Study [10] provided estimates of the precision (repeatability & reproducibility) of E70 measurements for BOBs and 25% v/v ethanol (E25) blends. For one base fuel, it was found that the reproducibility of the E70 measurement increased from 7.84% v/v for the BOB to 11.7% v/v for its E25 blend due to the flattening of the distillation curve with ethanol addition.

The calculations in **Appendix 5** were based on the precision statement for automated distillation equipment in the 2000 version of International Standard ISO 3405. These reproducibility calculations cannot be validated using the BEP525 data as all the measurements were made at the same laboratory.

A new version of ISO 3405 was published in 2011 with a revised precision statement based on a 2006 inter-laboratory study which indicates that the precision of the method has improved.

The precision of T_{xx}[13] numbers in the new edition is shown in **Table A8-1**.

Table A8-1 Precision of the ISO 3405 test method [11] for groups 1,2, and 3 using the automated method (Table 8)

Percentage Evaporated (% v/v)	Repeatability (°C)	Reproducibility (°C)	Valid Range (°C)
IBP	0.0295(*E* + 51.19)	0.0595(*E* + 51.19)	20-70
10	1.33	3.20	35-95
50	0.74	1.88	65-220
90	0.00755(*E* + 59.77)	0.019(*E* + 59.77)	110-245
FBP	3.33	6.78	135-260
E is the temperature at the percentage evaporated within the prescribed valid temperature range			

The precision of E70 can be estimated from the precision of the corresponding T_{XX} numbers, where xx is the E70 value, by dividing the repeatability 'r'[14] or reproducibility 'R'[15] of T_{E70} by the slope of the distillation curve (dT/dV) at V=E70. This will vary from blend to blend. It is also necessary to estimate r and R for intermediate T values which has been done using the following quadratic interpolation formulae:

- $r(T_{E70})$ = 1.60719 - 0.03031 * E70 + 0.00025937 * E70 * E70
- $R(T_{E70})$ = 3.82781 - 0.06874 * E70 + 0.00059562 * E70 * E70
- $r(T_{E100})$ = 1.64250 - 0.03455 * E100 + 0.00033000 * E100 * E100
- $R(T_{E100})$ = 3.91687 - 0.07942 * E100 + 0.00077375 * E100 * E100

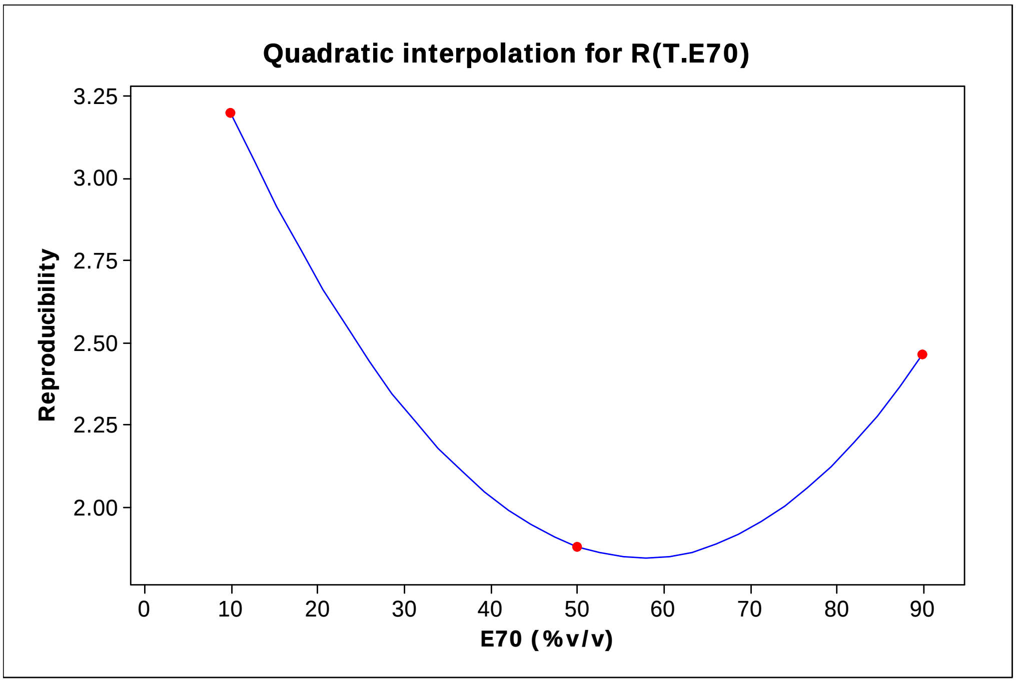
[13] T_{xx} is the temperature at which xx% v/v of the sample has evaporated.

[14] Repeatability 'r': The value equal to or below which the absolute difference between two single test results on identical material obtained by the same operator at the same laboratory using the same equipment in a short interval of time may be expected to lie with a probability of 95%.

[15] Reproducibility 'R': The value equal to or below which the absolute difference between two single test results on identical material obtained by operators in different laboratories using the standardized test method may be expected to lie with a probability of 95%.

which are valid between 10 and 90% v/v. This interpolation curve is plotted below for $R(T_{E70})$. The curves for $r(T_{E70})$, $r(T_{E100})$, and $R(T_{E100})$ show similar behaviour.

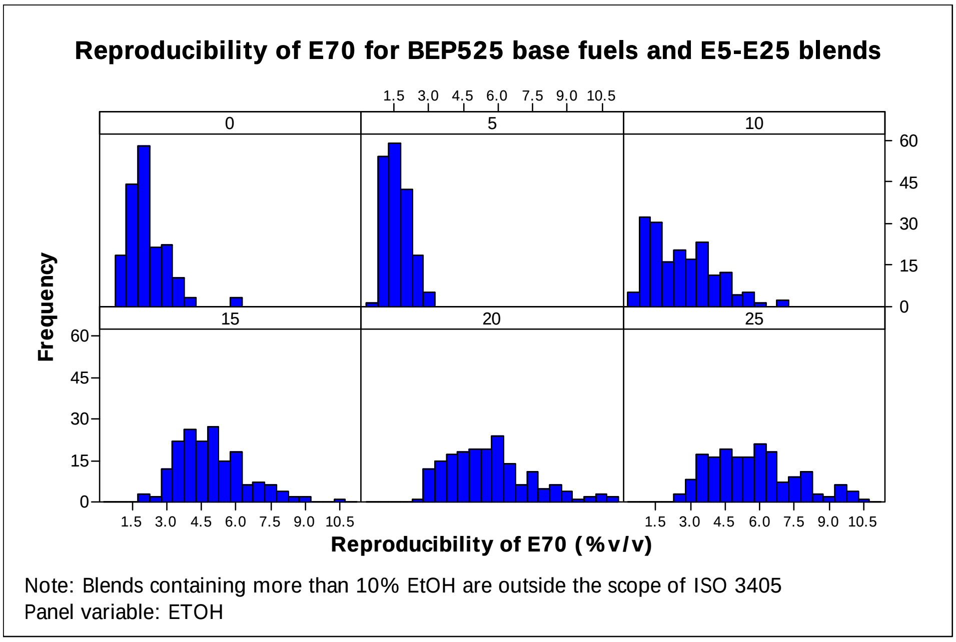
Figure A8-1 Quadratic interpolation curve for evaluating the reproducibility of T_{E70} for E70 values between 10, 50, and 90% v/v



The 1080 measured distillation curves from [10] were examined in turn, omitting curves which were missing or non-monotonic at 70°C. The slope dT/dV at V=E70 was estimated for each curve by fitting a quadratic polynomial to the six nearest points (V_i,T_i) to the 70°C point with three points on each side. The fitted equation was then differentiated and evaluated at V=E70.

The calculated reproducibility figures for E70 are summarized in the histograms below for the various base fuels and their ethanol blends from 5 to 25% v/v.

Figure A8-2 Reproducibility of E70 for BOBs and ethanol blends from the BEP525 study [10]



It can be seen that the reproducibility in general gets markedly worse as the ethanol concentration increases and the distillation curves get flatter and less precisely defined at the 70°C point. Interestingly, however, the slopes at 70°C are slightly steeper for E5 blends than they are for BOBs (see, for example, **Figure 1.1** in **Section 1.1.1**), hence the slightly better precision for E5 blends.

Annex C of ISO 3405 actually quotes a general reproducibility figure of 2.7%v/v for E70. It is clear from the above plots, however, that a single value is inappropriate for the wide range of BOBs and ethanol/gasoline blends that were studied in the BEP525 project. It should be noted, however, that many of the BOBs and ethanol blends considered in that study were outside the EN 228 limits for one or more specification parameter.

The average precision values at each ethanol concentration are:

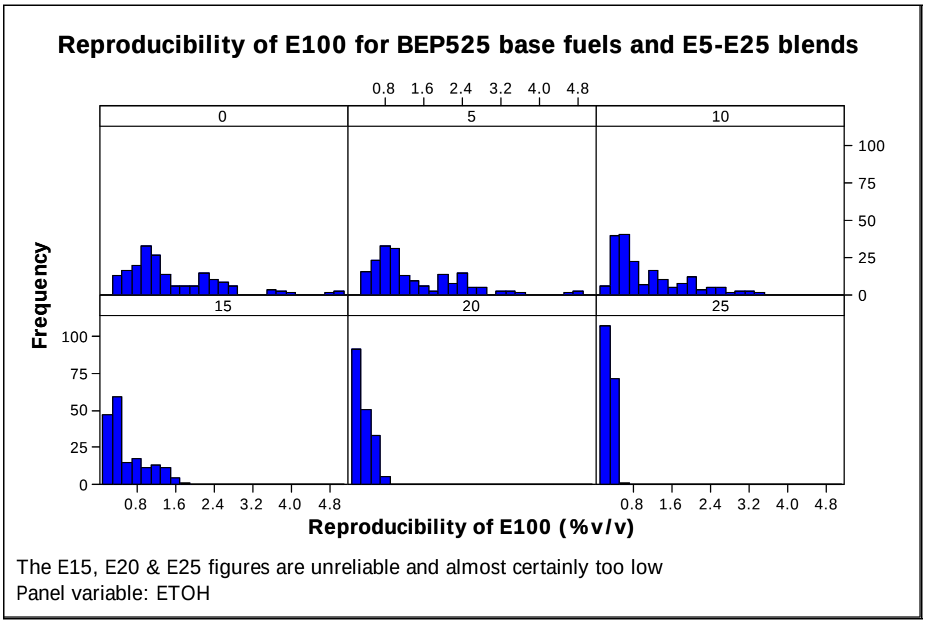
Table A8-2 Repeatability and reproducibility of E70 and E100 as a function of ethanol content

Ethanol Content	Repeatability 'r'		Reproducibility 'R'	
(% v/v)	E70	E100	E70	E100
0	0.87	0.58	2.16	1.48
5	0.64	0.53	1.60	1.35
10	1.02	0.40	2.55	1.03
15	1.96	0.24	4.93	0.60
20	2.24	0.14	5.63	0.36
25	2.27	0.11	5.70	0.28

Measurements of E70 and E100 are out of scope at these ethanol contents
Measurements of E70 and E100 are out of scope at these ethanol contents and the estimates of 'r' and 'R' are unreliable[16]

Performing a similar analysis for E100, the calculated reproducibility figures are plotted in **Figure A8-3** (note that a different x-axis scale has been used in this figure compared to **Figure A8-2**).

Figure A8-3 Reproducibility of E100 for BOBs and ethanol blends from the BEP525 study



The reproducibility 'R' is found to be very low for E20 and E25 blends and to a lesser extent for E15 blends. However, Annex C of ISO 3405 states that the method of calculation of the repeatability and reproducibility of Exxx values is not reliable when the slope dT/dV is high. From the plots in Appendix 8 of [10], it can be seen that the distillation curves are very steep at T=100°C at higher ethanol concentrations. In fact, Annex C of ISO 3405 quotes a general reproducibility figure

[16] The scope of the precision statement in ISO 3405 limits gasolines to those with oxygenates up to 10% v/v ethanol or MTBE. So, strictly speaking, the 30 base fuels with 11% or 22% MTBE or ETBE and all of their ethanol blends are also outside of the scope statement.

of 2.2% v/v for E100 which is larger than all the average values tabulated above and so raises a further concern about their reliability. Therefore, the reproducibility values for E15, E20 and E25 should not be relied upon and are almost certainly too low.

Plotting the repeatability figures in the same way, we obtain:

Figure A8-4 Repeatability of E70 for BOBs and ethanol blends from the BEP525 study

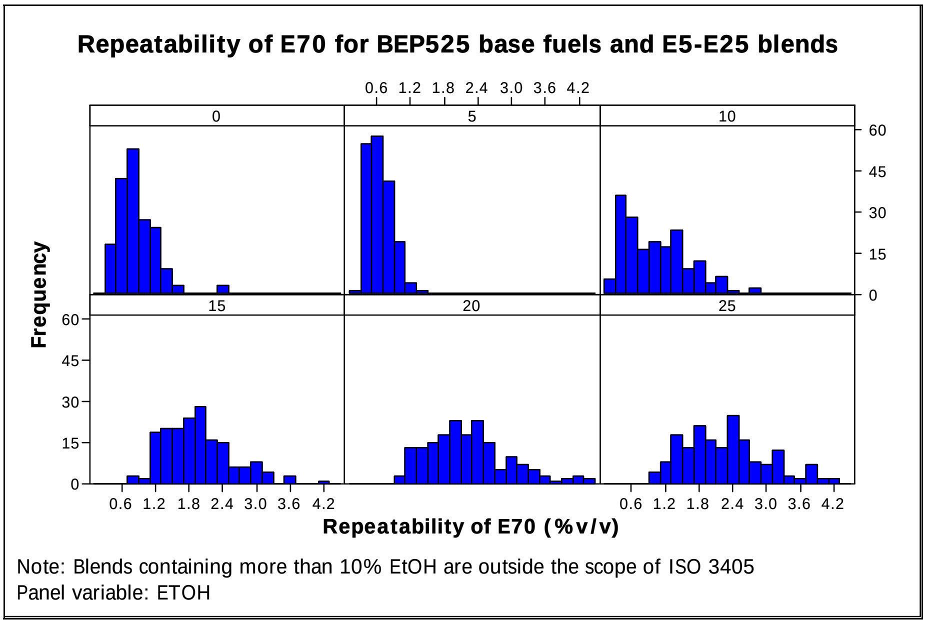
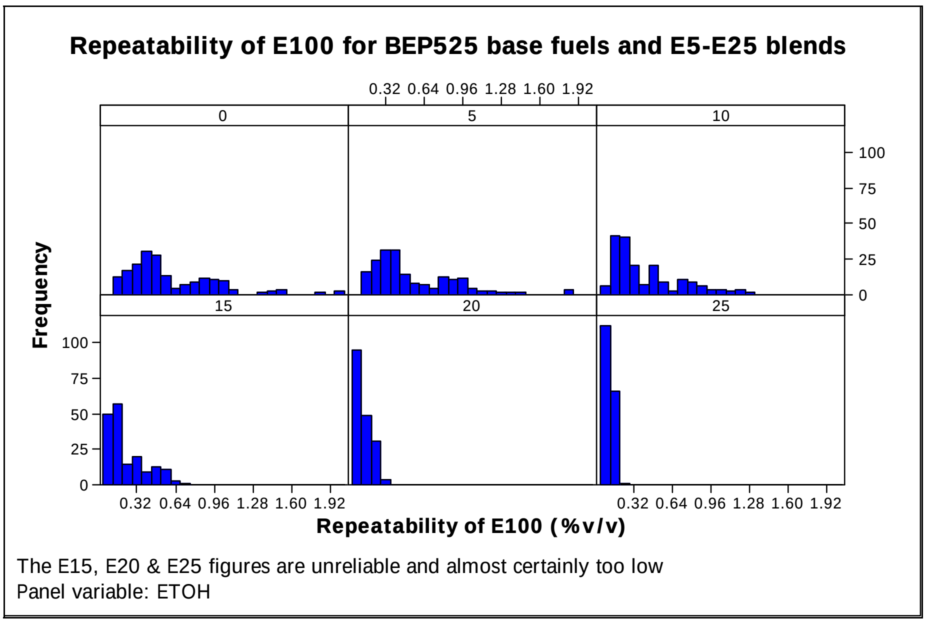


Figure A8-5 Repeatability of E100 for BOBs and ethanol blends from the BEP525 study



The patterns are very similar to those for reproducibility and the same caveats apply.

Concentrating on the calculation for the E10 blends, it can be estimated that the reproducibility of E70 is 2.55 on average, increasing to 7.06% v/v. Measurements are accurate to ±0.71R with 95% confidence meaning that the E70 values for E10 blends are measured to ±1.81% v/v on average, increasing to ±5.01% v/v in the worst case. This assumes that the laboratory is using automated distillation equipment of similar quality to that used in the 2006 ISO 3405 inter-laboratory study and its performance is similar to that of the participants.

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