gasoline volatility and ethanol effects on hot and cold weather driveability of modern european vehicles

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ABSTRACT

A joint test programme has been carried out by CONCAWE and GFC to evaluate the impact of gasoline volatility and ethanol on the driveability performance of modern European vehicles. Eight vehicles, three with DISI fuel systems and five with MPI, were tested for hot driveability performance. The same eight vehicles were tested for cold driveability, although only a subset of four vehicles was tested in depth. The latest test procedures developed by GFC were used for both hot (20, 30 and 40°C) and cold (+5 and -10°C, representative of moderate winter conditions) weather testing on climate controlled chassis dynamometers. A matrix of four hydrocarbon test fuels at two levels of DVPE and E70 was blended for the hot weather testing, and three fuels with varying E100 but essentially parallel distillation curves for the cold weather tests. For each hydrocarbon fuel, two other fuels containing 10% ethanol were tested, one splash blend and one with matched volatility. Some tests were also carried out using 5% ethanol fuels made by blending the hydrocarbon and 10% ethanol fuels.

This report describes the results obtained for both hot and cold weather driveability.

KEYWORDS

gasoline, volatility, vapour pressure, DVPE, E70, E100, ethanol, driveability, hot weather driveability, cold weather driveability, direct injection, vehicle, GFC

INTERNET

This report and detailed results spreadsheets are available on the CONCAWE website (www.concawe.org).

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SUMMARY

A joint test programme has been carried out by CONCAWE and GFC to evaluate the impact of gasoline volatility and ethanol on the driveability performance of modern European vehicles. Eight vehicles, three with DISI fuel systems and five with MPI, were tested for hot driveability performance. The same eight vehicles were tested for cold driveability, although only a subset of four vehicles was tested in depth. The latest test procedures developed by GFC were used for both hot (20, 30 and 40°C) and cold (+5 and -10°C, representative of moderate winter conditions) weather testing on climate controlled chassis dynamometers. A matrix of four hydrocarbon test fuels at two levels of DVPE and E70 were blended for the hot weather testing, and three fuels with varying E100 but essentially parallel distillation curves for the cold weather tests. For each hydrocarbon fuel, two other fuels containing 10% ethanol were tested, one splash blend and one with matched volatility. Some tests were also carried out using 5% ethanol fuels made by blending the hydrocarbon and 10% ethanol fuels.

The work has confirmed that the GFC test procedures are capable of identifying fuel, vehicle and temperature effects on hot and cold weather driveability with modern vehicles. The procedures appear to be more discriminating than the former CEC test procedures.

For hot weather driveability, four of the eight vehicles tested (three MPI and one DISI) gave good performance under all fuel/temperature conditions tested. A fourth MPI vehicle only exceeded 24 demerits on the highest volatility, 10% ethanol splash blend at 30°C. The final MPI vehicle showed substantial demerits on high volatility fuels at high temperatures, especially for ethanol splash blends. Two of the DISI vehicles showed poor driveability performance with very high demerits on high DVPE fuels at high temperatures. In all cases substantial increases in demerits were only seen at high temperatures on fuels with volatility beyond the summer limits of EN228.

Analysis of the hot weather driveability data suggested that DVPE and temperature were the variables that influenced driveability most, followed by E70 then ethanol content. Ethanol splash blends generally increased demerits and overall severity rating. Matched volatility ethanol blends gave similar performance to equivalent hydrocarbon fuels, suggesting that the effects seen were a consequence of the increase in volatility caused by the addition of ethanol, rather than ethanol per se.

With the new GFC cold-weather test, substantially higher demerit levels were seen than would be expected with the former CEC procedure, especially at -10°C. Most vehicles showed sensitivity to fuel volatility with higher demerits on the less volatile fuels. Several vehicles showed a sharp increase in demerits on the least volatile E-series fuels (E100 <~50%v/v) at -10°C (though not at +5°C). One DISI vehicle gave very high demerits on all fuels at both temperatures but showed no sensitivity to fuel volatility, ethanol content or temperature. The other two DISI vehicles gave demerits in the same range as the MPI vehicles. One of the MPI vehicles showed consistently high demerits at -10°C but no sensitivity to fuel volatility.

The effects of ethanol on cold weather driveability were varied, though in several cases splash blends of ethanol into the lowest volatility fuel at -10°C improved driveability. It is likely that the main effects seen are a consequence of the increase in volatility caused by the addition of ethanol rather than the presence of ethanol per se.

1. INTRODUCTION

The driveability performance of gasoline vehicles and their response to fuel volatility, under both hot and cold weather conditions, has been studied for many years. Industry groups were set up to assess the performance of large numbers of vehicles in USA (CRC) and Europe (Oil Industry Intercompany Group and GFC). Standard driveability test procedures were developed for these groups, by CRC in USA and by CEC in Europe, and large-scale test programmes were carried out in the 1970s and 1980s. A crucial difference between the two is that US CRC have always used on-road testing, while in Europe all work since 1970s has been carried out on climate controlled chassis dynamometers. In the 1990s interest in driveability was overtaken by concerns over the effect of fuel quality on exhaust emissions, which led to the US AQIRP and European EPEFE test programmes. Since that time, driveability studies in Europe have been limited.

CONCAWE last looked at driveability and fuel volatility in its 1999 report "Proposal for revision of volatility classes in EN 228 specification in light of EU Fuels Directive" [1]. This report looked at hot-weather driveability only using test work generated by the Oil Industry Intercompany Group on vehicles up to 1996, as input to the 2000 Fuels Directive that also modified sulphur, aromatics and olefins content. Further reductions in sulphur and aromatics content are legislated for 2005, which may increase the constraints on fuel volatility in refining. Also there is now interest in the use of renewable fuels, encouraged by the recent Biofuels Directive, with increasing use of ethanol in gasoline being one of the likely effects. Vehicle technology is also changing to meet new emission standards, as well as the CO_2 targets which ACEA has committed to meet from 2008. New direct injection spark ignition (DISI) engines are now available in Europe which may have different fuel volatility responses.

Therefore CONCAWE felt it was appropriate to take a fresh look at the driveability performance of modern fuels and passenger cars. As the existing CEC driveability test procedures were developed when the majority of the European vehicle fleet were non-catalyst carburettor cars, it was felt that more modern procedures should be used. The only more recent procedures available were a cold weather procedure developed by Shell [2] and a hot-weather procedure developed by the French GFC [3] that is referenced by CEC. From contacts with GFC, CONCAWE learned that a new cold-weather procedure had also been developed, but not formally published. Following a meeting with GFC, a joint CONCAWE-GFC test programme was agreed. This would be funded by CONCAWE and run in a contractor laboratory, but would use the GFC hot and cold weather test procedures, with four of the test vehicles provided by GFC. The main emphasis of this programme was on hot-weather driveability, but it was agreed to also conduct a limited programme to assess cold-weather performance.

2. TEST PROGRAMME DEVELOPMENT

2.1. TEST PROTOCOL

The main emphasis of the programme was on hot driveability testing, so a suitable test protocol had to be developed for this. The former CEC test procedure was "conditional", wherein a vehicle would be tested on a given severe fuel/temperature combination and allocated a rating of "Pass", "Borderline" or "Fail". Further tests would then be carried out on other fuel/temperature combinations depending on this rating. In this way the fuel volatility – temperature envelope of acceptable performance could be established. The French GFC however used a statistical approach where a vehicle is tested on all available fuel/temperature combinations, and a number of demerits are assigned for each test. From this data, relationships can be developed between demerit levels, fuel volatility and temperature.

After some discussion, a modified test protocol was developed as discussed in **Section 5.1**. A basic matrix of four test fuels (A,B,C,D) was chosen with high and low values for DVPE (100 and 60 kPa) and E70 (55 and 40 %v/v) (see **Section 4.1**). Fuel D, similar to the emissions test regulatory fuel on which the vehicles would have been homologated, was taken as the reference fuel for determining the reference acceleration time, which is used to calculate acceleration demerits. In addition to the hydrocarbon fuels, two sets of ethanol blends were produced, one set of four "splash" blends and a further set with matched volatility levels. These fuels were to be tested at three temperatures, 40, 30 and 20°C, though only the 60 kPa DVPE fuels (B, D) were tested at 40°C and only the highest volatility fuel (A) and the reference fuel D at 20°C, with other fuels tested if substantial demerits were seen. Other fuels would be tested, including interblends with intermediate volatility levels, depending on test results on the main matrix, as explained in **Section 5.1**. All vehicles were tested initially on fuels A and D at 30°C as a screening exercise. These tests were then repeated during the programme and some other repeat tests were also run to allow an estimate of test repeatability to be made.

The original plan was to test ten vehicles, but as the GFC procedure is of long duration, only two tests per day could be conducted, so due to budget constraints, only eight cars were tested. A subset of four cars was selected for testing with ethanol fuels, and for cold driveability. However as the programme evolved and results became available, a more flexible approach was adopted, so that additional cars were tested also on ethanol-containing fuels.

The cold weather test protocol was more straightforward as the test procedure was shorter so all fuel/temperature combinations were tested on the selected vehicles. It was decided to conduct cold weather driveability tests at +5°C and -10°C, as representative of moderate European winter conditions. Three fuels were blended with approximately parallel distillation curves as high (A), medium (G) and low (E) volatility fuels. As with the hot weather tests two matching fuel matrices with 10% ethanol splash blended and with matched volatility were tested. All eight vehicles were tested on fuels E and G at -10°C as a screening exercise, then four of these chosen for the full test programme. As for the hot-weather programme, a number of repeat tests were included.

All tests were performed at the Shell Global Solutions Laboratory PAE Labor in Hamburg. Hot weather tests were carried out first, followed by the cold tests.

2.2. TEST PROCEDURES

2.2.1. Hot Weather Driveability Testing

The GFC hot weather procedure has not been formally adopted by CEC, but was published by them, together with the BTC procedure [3]. The procedure comprises three test sequences as shown in **Table 1**:

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 meant to simulate stop and go driving in heavy traffic, which may overload the carbon canister and hence affect engine air/fuel ratio (AFR).

Table 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*Vmax (max. 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 2a**.

Table 2a 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 programme 2 seconds was considered 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 and 5.

The total demerit rating for each test is then the sum of all individual faults, starting and acceleration demerits recorded during the complete test. Thus for example, one test on vehicle 2 had a total of 144 demerits made up as follows:

Table 2b 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**

2.2.2. Cold Weather Driveability Testing

At the time of writing, the GFC test procedure had not been formally published or adopted by the GFC or CEC. It consists of a test cycle comprising five phases, which is executed immediately after engine start and is repeated six times. The detailed cycle is shown in **Figure 1**.

Phase 1: 1^{st} gear acceleration to 16 km/h
Phase 2: 1^{st} and 2^{nd} gear acceleration to 18km/h
Phase 3: 1^{st} and 2^{nd} gear acceleration to 37.5 km/h
Phase 4: multiple acceleration and decelerations, max speed 37.5 km/h
Phase 5: full throttle acceleration from 30 to 68 km/h

Demerits are assigned to driveability faults using the same scale as shown in **Table 2a**. Starting times and demerits were calculated in the same way as for the hot-weather test, taking the longest start time in any test. However acceleration demerits are not included in the cold-weather test.

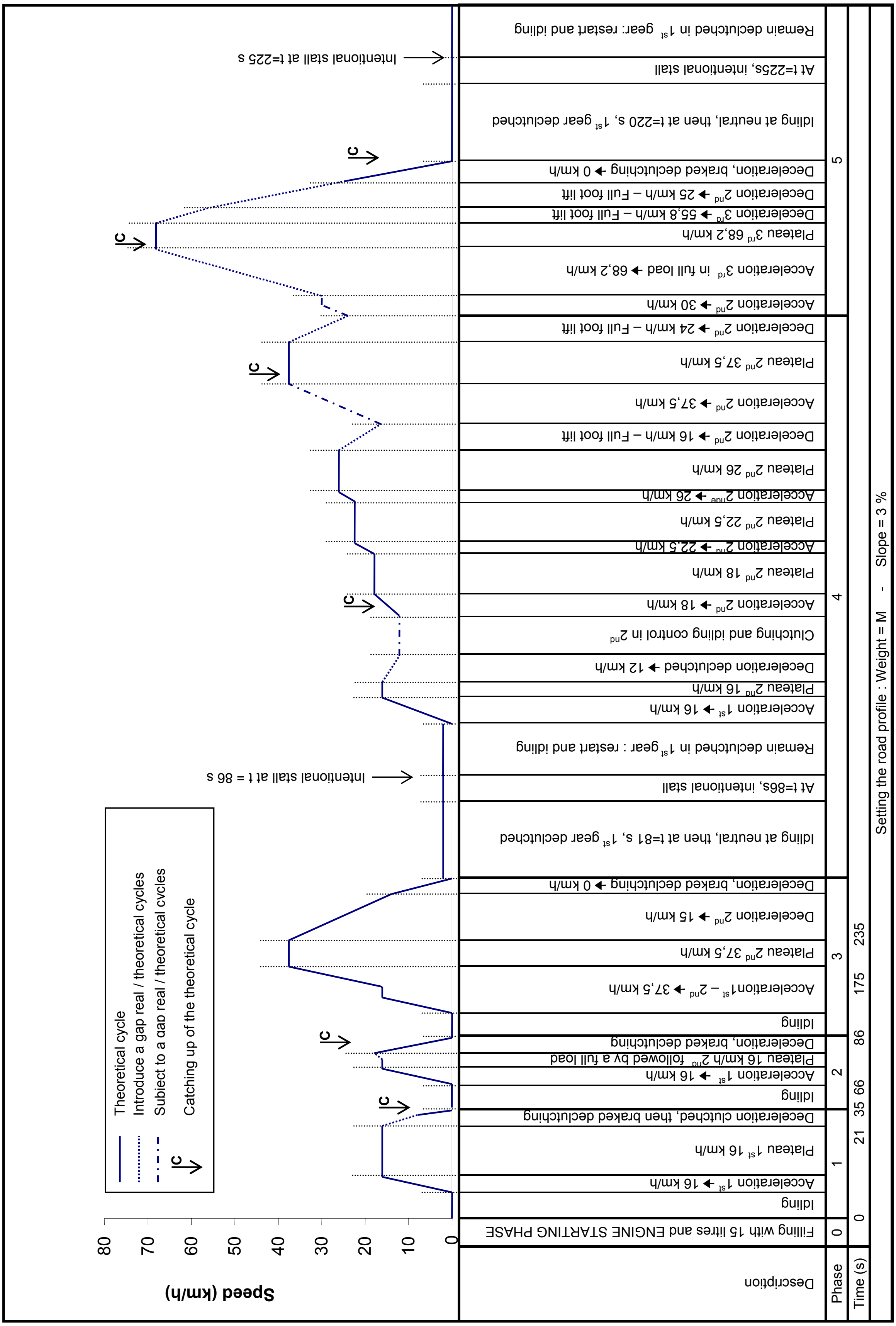
2.2.3. Fault Type Severity Coding

The demerit total recorded for a particular test shows the level of driveability for a particular vehicle/fuel/temperature combination on an arbitrary scale. However this does not indicate the level of Customer Acceptance of this level of performance. In the past this has been established by Consumer Reaction road tests where customers are asked to subjectively rate the driveability performance of their vehicles in normal operation. This can then be compared to the driveability demerit level recorded for the same vehicle/fuel/temperature combination. However such an exercise has not been done recently and there was no opportunity or budget to do such a test in this programme.

An alternative approach was adopted in this programme for both hot and cold weather driveability, based on members' in-house experience of driveability assessment. This approach considers each fault type separately and assigns it a colour-coded "severity category", in addition to a demerit level, i.e.:

None **Trace** **Moderate** **Customer Unacceptable** **Safety Unacceptable**

Figure 1 Cold Weather Driveability Cycle



The rating scale for this is shown in **Table 3(a)**, which also shows the associated demerits. Based on the ratings for individual faults in a given test, plus rating for starting and acceleration times, an overall rating is given to the test, as shown in **Table 3(b)**. Note that the overall rating is based on the most severe faults that occurred during a test, not the sum of demerits. Thus a test that had three moderate hesitations would have 36 demerits, but only be coded as "Moderate" by this rating scale. In contrast a test with one severe roughness and one moderate hesitation would also have 36 demerits but would be coded as "Customer Unacceptable". This scale was used to code the severity of all hot and cold driveability tests in addition to the demerit totals.

Table 3 Scale for Coding of Driveability Fault Type Severity

(a) Individual Fault Rating

Fault	Slight	Moderate	Severe	Yes
Stalling when starting				18
Stalling when idling				21
Stalling under load				42
Stalling when decelerating				42
Fail				42
Roughness	4	12	24	
Hesitation	4	12	24	
Stumble	4	12	24	
Surge	3	6	9	
Backfire	4	8	12	
Odour				2

Notes:

(1) Severity rating for each fault type is determined by the worst instance of that fault, not by the demerit sum.

(2) Backfire and odour are included in the GFC test demerits, but not in the severity rating

(b) Overall rating

Colour	Severity	Cycle Faults	Starting time	Accel. time
	None	No faults	$t_s < 1$	
	Trace	Only slight faults recorded	$1 \le t_s < 2$	$0 \le DM < 80$ $1.1{*}t_{CR5} \le t_{CRref5} < 1.5{*}t_{CR5}$
	Moderate	At least 1 moderate fault	$2 \le t_s < 4$	$80 \le DM < 180$ $1.5{*}t_{CR5} \le t_{CRref5} < 2.0{*}t_{CR5}$
	Customer unacceptable	• At least one severe fault • Stalls (all other than unacceptable ones) • Any FAIL	$t_s \ge 4$ HWD - ≥ 2 attempts CWD - ≥ 3 attempts	$DM \ge 180$ $t_{CR5} \ge 2{*}t_{CRref5}$
	Safety unacceptable	a) Stall under acceleration b) Stall under deceleration c) Severe hesitation under acceleration		FAIL

Note: The overall severity rating for the test as a whole is determined by the worst cycle faults, start and acceleration times and not by the sum of demerits.

3. VEHICLES

Eight vehicles were selected for the test programme, intended to represent current and advanced engine and fuel system technology. These were all production vehicles homologated to meet Euro 3 or 4 emission limits. Four of the vehicles were supplied by GFC and the other four were leased commercially for the programme. **Table 4** shows the essential data for these test vehicles.

Three test vehicles (1-3) were fitted with direct injection spark ignition (DISI) engines, two of which were lean burn, the other stoichiometric. The other vehicles had Multi-Point Injection (MPI) fuel systems of which three were returnless. One vehicle had MPI but no throttle, using variable inlet valve to lift control power.

Table 4 Test Vehicles

Vehicle Reference	**1**	**2**	3	4	5	**6**	**7**	8
Features	**Lean DISI**	**Lean DISI**	Stoich. DISI	MPI no throttle	Small MPI returnless	**MPI**	**Returnless MPI**	Returnless MPI
Engine Capacity, litres	**1.6**	**2.0**	2.0	1.8	1.2	**1.6**	**1.8**	2.0
No. of Cylinders	**4**	**4**	4	4	4	**4**	**4**	4
Fuel Injection system	**DISI**	**DISI**	DISI	MPI no throttle	MPI	**MPI**	**MPI**	MPI
Fuel return to tank?	**Yes**	**No**	Yes	No	No	**Yes**	**No**	No
Fuel Rail Pressure, bar	**50-100**	**100**	80-130	3.5	2.5-3	**3.0**	**2.8-3.2**	3.5
Air-Fuel ratio control	**Lean**	**Lean/ Stoich.**	Stoich.	Stoich.	Stoich.	**Stoich.**	**Stoich.**	Stoich.
Max Power, kW	**81**	**103**	110	85	55	**77**	**85**	99

It was originally planned to test a subset of four of these vehicles (shown in bold in **Table 4**) for hot driveability on the ethanol fuels and on all fuels for cold driveability. In the light of programme results however it was decided to carry out a few hot driveability tests with ethanol fuels on most of the vehicles, though more tests were done on vehicles 2, 3, 4, and 7 because of their interesting responses to changes in fuel volatility.

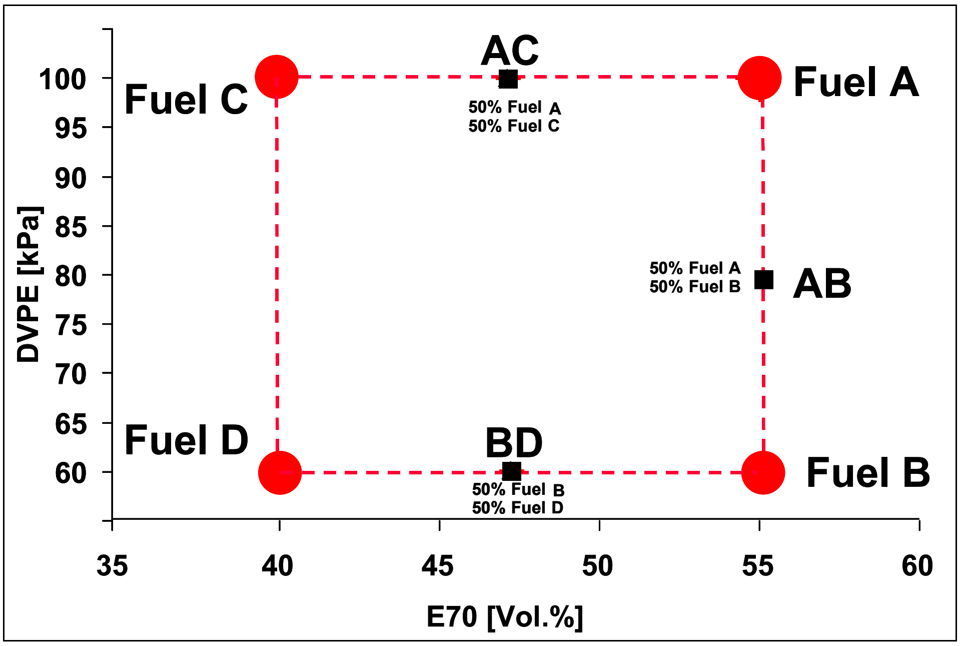
For the cold weather testing, screening tests were conducted on all vehicles, then a subset chosen for further work (vehicles 1, 2, 6, 7).

4. FUELS

4.1. HOT WEATHER TEST FUELS

Four key corner fuels were chosen with high and low target values of DVPE (95-100 and 60-65 kPa) and E70 (55 and 40 %v/v +/-1), coded A, B, C and D as shown in **Figure 2**. These were to be used to create interblends as required such as AB, AC, BD, etc.

Figure 2 Main Test Fuel Matrix



E100 values were closely controlled in line with E70, so 76 +/-1 (A, B) and 61 +/-1 (C, D). E150 targets were left wider at 90-95 (A, B) and 80-90 (C, D). FBP was simply controlled at 210°C max. Sulphur was controlled within 40-50 mg/kg using sulphur compound doping as required, though this was not a key property for this exercise. The octane target was deliberately set high at RON 97.0 and MON 87.0 min. to avoid any effect of knock sensors on acceleration performance during driveability testing. However in practice it was not possible to meet these targets for all fuels, and some were nearer to 96 RON and 86 MON. Benzene, aromatics and olefins were limited to 1.0, 35 and 18 %v/v max respectively, the EU limits from 2005.

For each corner fuel target, three different fuels were blended:

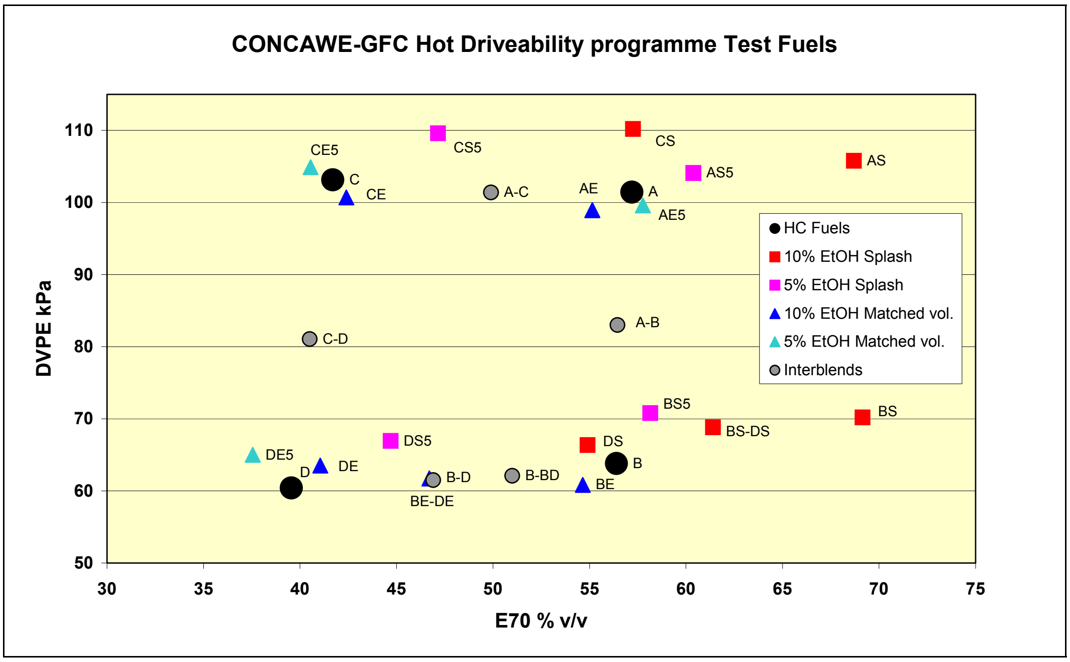
- Hydrocarbon only fuels (A, B, C, D)
- 10% Ethanol "splash blends" (AS, BS, CS, DS) where ethanol was simply blended with the Hydrocarbon fuels (A, B, C, D), consequently increasing their volatility
- 10% Ethanol blends with matched volatility (AE, BE, CE, DE)

At the end of the programme, it was decided also to test some 5% ethanol blends. These were made by simply blending HC and 10% ethanol blends, so for example AE5 = 50%A+50%AE. Inevitably the matched volatility 5% blends were not an exact match to HC or 10% blends due to the non-linear blending characteristics of ethanol. Fuel BE5 was not made.

All fuels were blended in one location (Shell PAE Labor Hamburg). However the fuels were also analysed by Kuwait Petroleum Research and Technology laboratory in Rotterdam and Total in Le Havre, though not all tests were carried out by each laboratory. A Round Robin exercise for DVPE and Distillation was carried out with three "Golden Standard" Reference fuels. All three laboratories were within acceptable reproducibility limits except one point from Shell PAE. In general, Shell PAE TxxE values were slightly higher, and Kuwait Petroleum and Total slightly lower than the Standard values. Shell PAE and Kuwait Petroleum data were used for the final results as Total did not test the 5% ethanol blends. The key analytical data for the main test fuels are given in **Appendix 1,** also full distillation curves. All data are the mean of two test values, except ethanol contents for the 5% ethanol blends. Octane, composition and sulphur were not determined for these blends. Full inspection data are available from the CONCAWE website (www.concawe.org).

A number of interblends were also made for testing various vehicles, and their distillation properties are also shown in **Appendix 1**. $T_{V/L20}$ values were calculated for all fuels using the Linear Equation given in ASTM D4814[1], as attempts to measure values were unsuccessful. Vapour pressure measurements were made at higher temperatures up to 95°C for the main fuel blends, but not 5% ethanol blends, and are shown in **Appendix 1**.

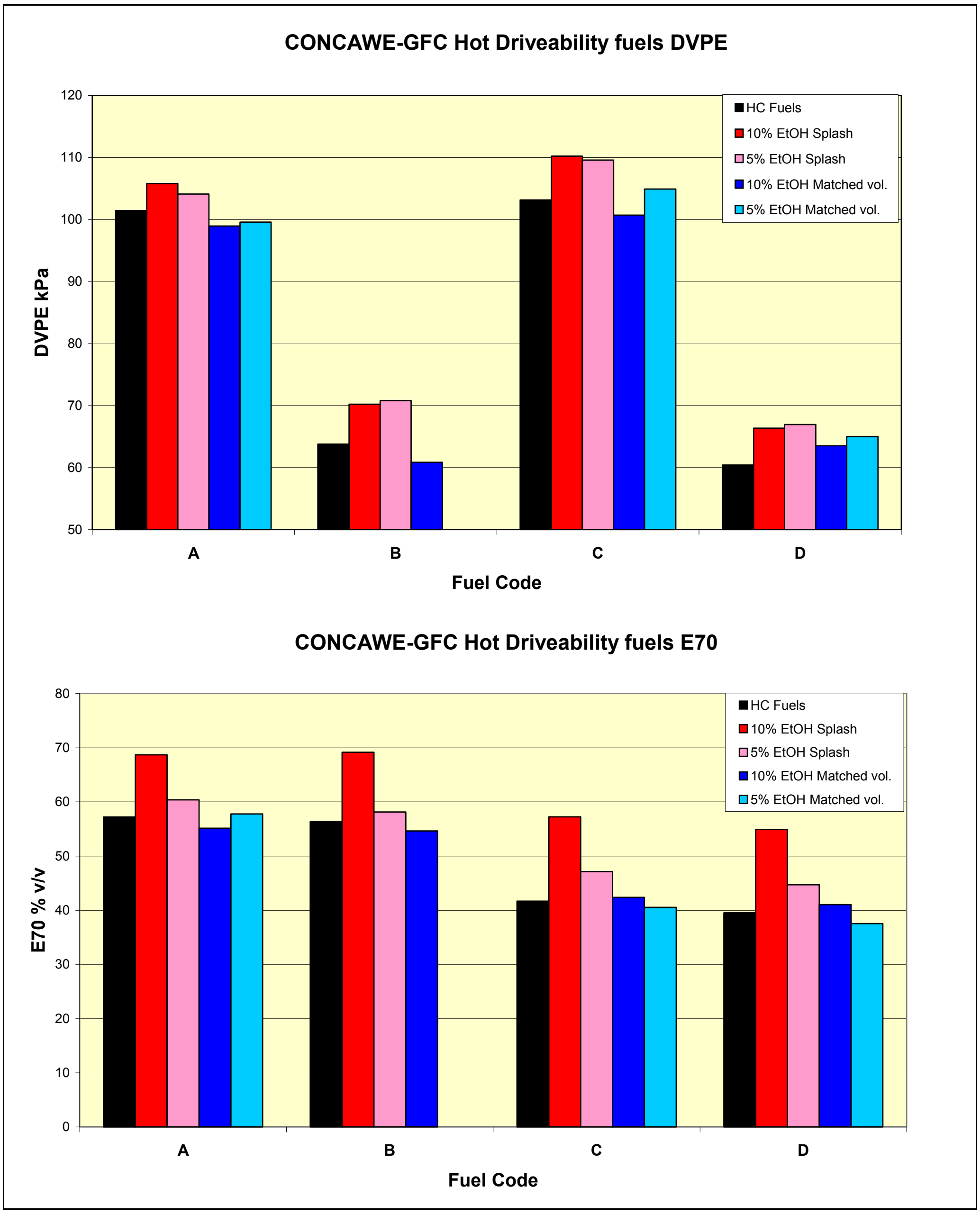
Figure 3 DVPE and E70 values for all Hot Driveability Test Fuels



[1] The Linear Equation in ASTM D4814 has been used for all fuels even though it is officially only valid for "gasolines" (hydrocarbon only), not ethanol blends.

The actual values of DVPE and E70 for all fuels tested are shown in **Figure 3**, and values of DVPE and E70 for the four fuel series compared in **Figure 4**.

Figure 4 DVPE and E70 Comparison of Hot Driveability Fuels

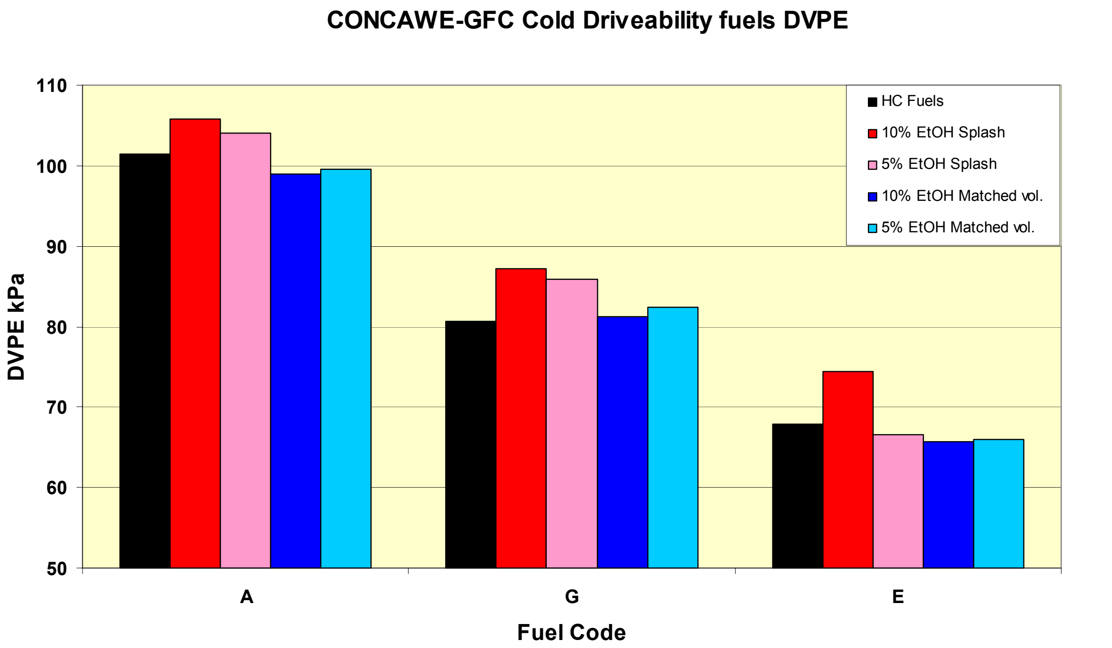


These figures clearly show the substantial increase in both DVPE and E70 with 10% ethanol splash blends. The DVPE increase is also seen for the 5% blends, but the increase in E70 is much smaller. All the matched volatility blends are close to the equivalent hydrocarbon fuels, as would be expected. However it is interesting to note that the DVPE of the 5% matched volatility blends can be *higher* than either the hydrocarbon or 10% ethanol blend from which it was made. This is not the case for E70.

4.2. COLD WEATHER TEST FUELS

As the cold driveability tests were only intended as a screening exercise, no attempt was made to separate effects of different volatility parameters. Three fuels were made with essentially parallel distillation curves of high, medium and low volatility, with E100 targets of 76, 56 and 46 %v/v respectively. Fuel A from the hot weather matrix was used as the high volatility fuel, and two other fuels (E, G) were blended specifically for the cold weather programme. All other fuel properties were kept at the same levels as for the hot-weather fuels. As for the hot-weather programme, three sets of fuels were made comprising hydrocarbon only, 10% ethanol splash and 10% ethanol matched volatility blends. Again at the end of the programme 5% ethanol blends were made by blending 50/50 hydrocarbon and 10% ethanol fuels. Key distillation and other data are given in **Appendix 1, Table A.1.3** and **Figure A.1.3**. **Figure 5** shows DVPE, E70, E100 and E150 values of the three different fuel series.

Figure 5(a) DVPE and E70 values for the Cold Driveability Fuels



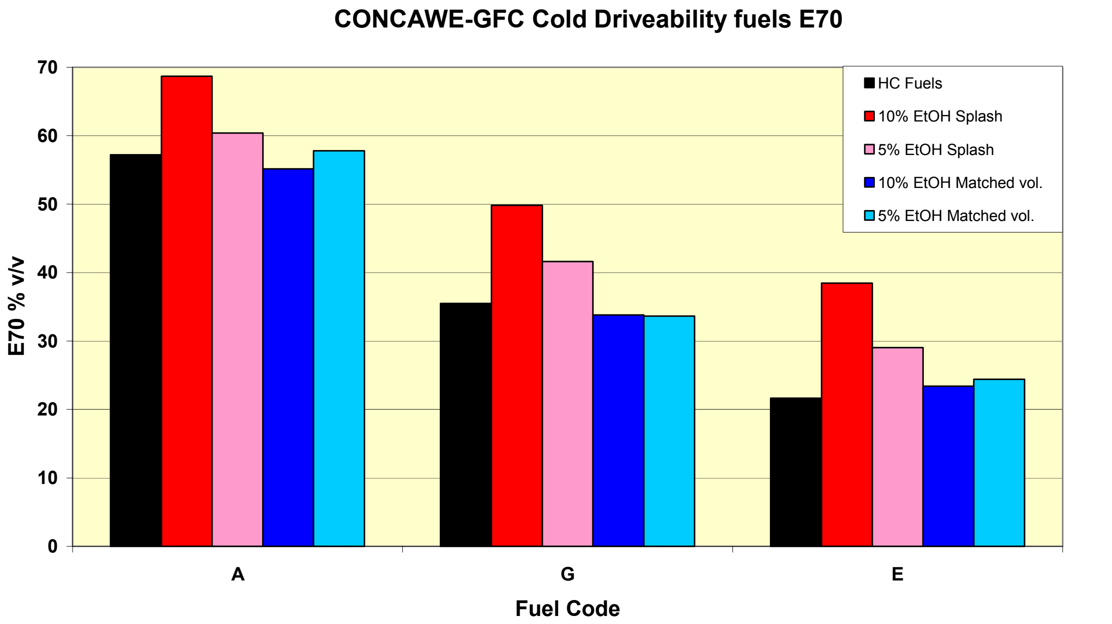
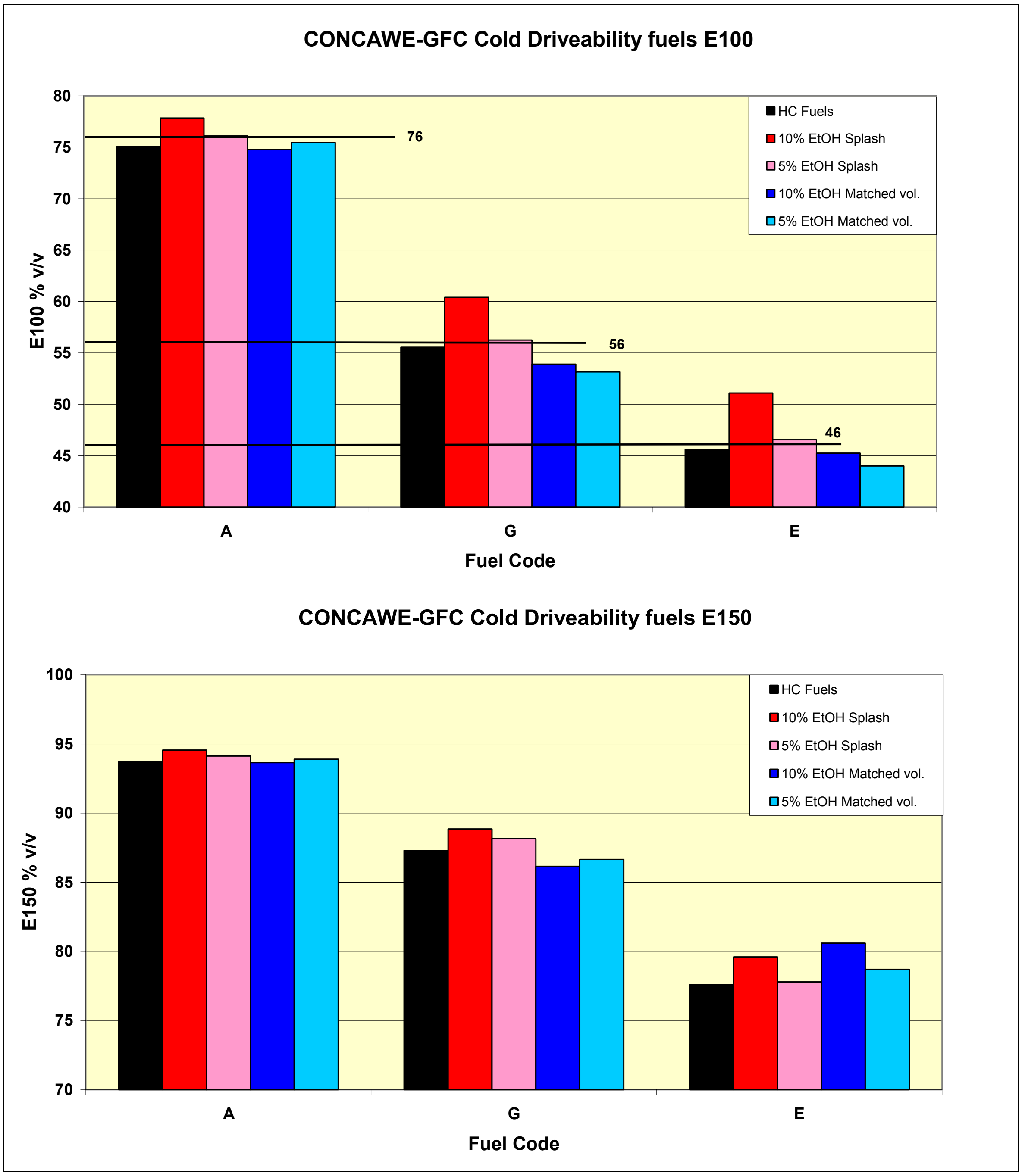


Figure 5(b) E100 and E150 values for the Cold Driveability Fuels



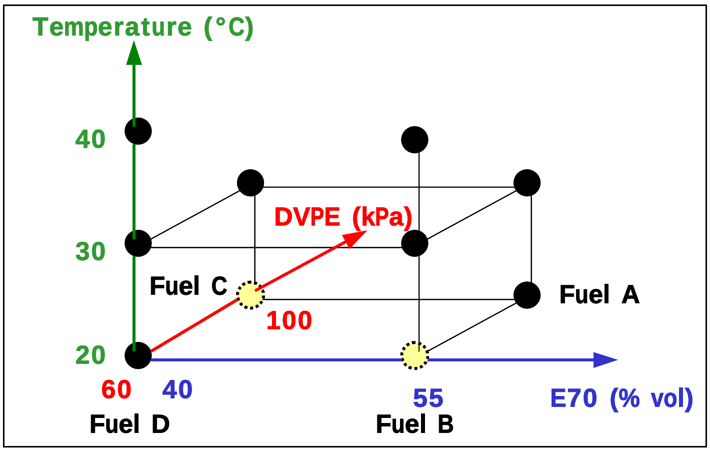
5. HOT DRIVEABILITY TESTING

5.1. TEST DESIGN

Initially a screening programme was carried out where all vehicles were tested on fuels A and D at 30°C. These results were used to select vehicles for more detailed testing, especially with the ethanol fuels. Using a single climate controlled chassis dynamometer it was only possible to carry out two tests per day, and to change the fuel and precondition one vehicle. In the main hot driveability programme the various fuel x temperature conditions for each vehicle were examined as far as was practicable as a single continuous block of tests. Usually the two tests conducted each day were on the same vehicle, changing temperature or fuel between them. However the conditional nature of the test sequence (discussed below) reduced the scope for randomisation to reduce drift. There were also interruptions while decisions were made about repeat tests and tests on ethanol fuels. There was little opportunity for repeat testing, though some repeats were carried out including a repeat of fuels A and D at 30°C for all vehicles.

The full test design was based on a rectangular 3x2x2 matrix with three temperatures and two levels of DVPE and E70, as shown in **Figure 6**. Tests were carried out at three temperatures, 40, 30 and 20°C. Fuels A, B, C and D were tested at 30°C. At 40°C only fuels B and D were tested, as fuels A and C are unrealistic at this temperature. At 20°C, fuel A was tested first and other fuels tested only if there were Substantial Demerits on fuel A at this temperature. Substantial Absolute Demerits are defined as ≥ 24 DM, which is equivalent to 2 moderate, or one severe, driveability malfunction (see **Table 2**). At all temperatures, interblends were tested as needed, according to the decision sequence defined below. Fuel D was selected as the standardisation fuel to determine baseline vehicle demerits and reference acceleration times.

Figure 6 Hot Driveability Test Design



Test Decision Sequence:

Lack of prior knowledge about the likely responses of the eight vehicles necessitated the use of a sequential experimental design for this programme. This ensured that the test effort was concentrated in interesting areas, and that excessive resources were not wasted testing vehicle × fuel × temperature combinations showing no demerits, or on combinations that were unrealistic in practice.

At 40°C test fuels B and D. Also test interblend BD if there is a Substantial Demerit Difference (Substantial Demerit Difference defined as ≥ 16 DM, which is equivalent to changing two trace driveability malfunctions into 2 moderate, or one severe, driveability malfunction). Also test further interblends BBD or BDD if there is a Substantial Demerit Difference between BD and B or D. Three vehicles (5, 6, 7) which showed very good driveability performance were also tested at 40°C on fuel A.

At 30°C test all four fuels, A, B, C, D. 50:50 interblends of A/C, A/B should also be tested if there are Substantial Demerit Differences (≥ 16) between the corner fuels.

At 20°C test fuel A. Fuel D was also tested as Standardisation fuel on all vehicles. Fuels B and C should also be tested if there are Substantial Absolute Demerits (≥ 24) on Fuel A. Also test 50:50 interblends A/C or A/B if there are Substantial Demerit Differences (≥ 16) between A-C or A-B.

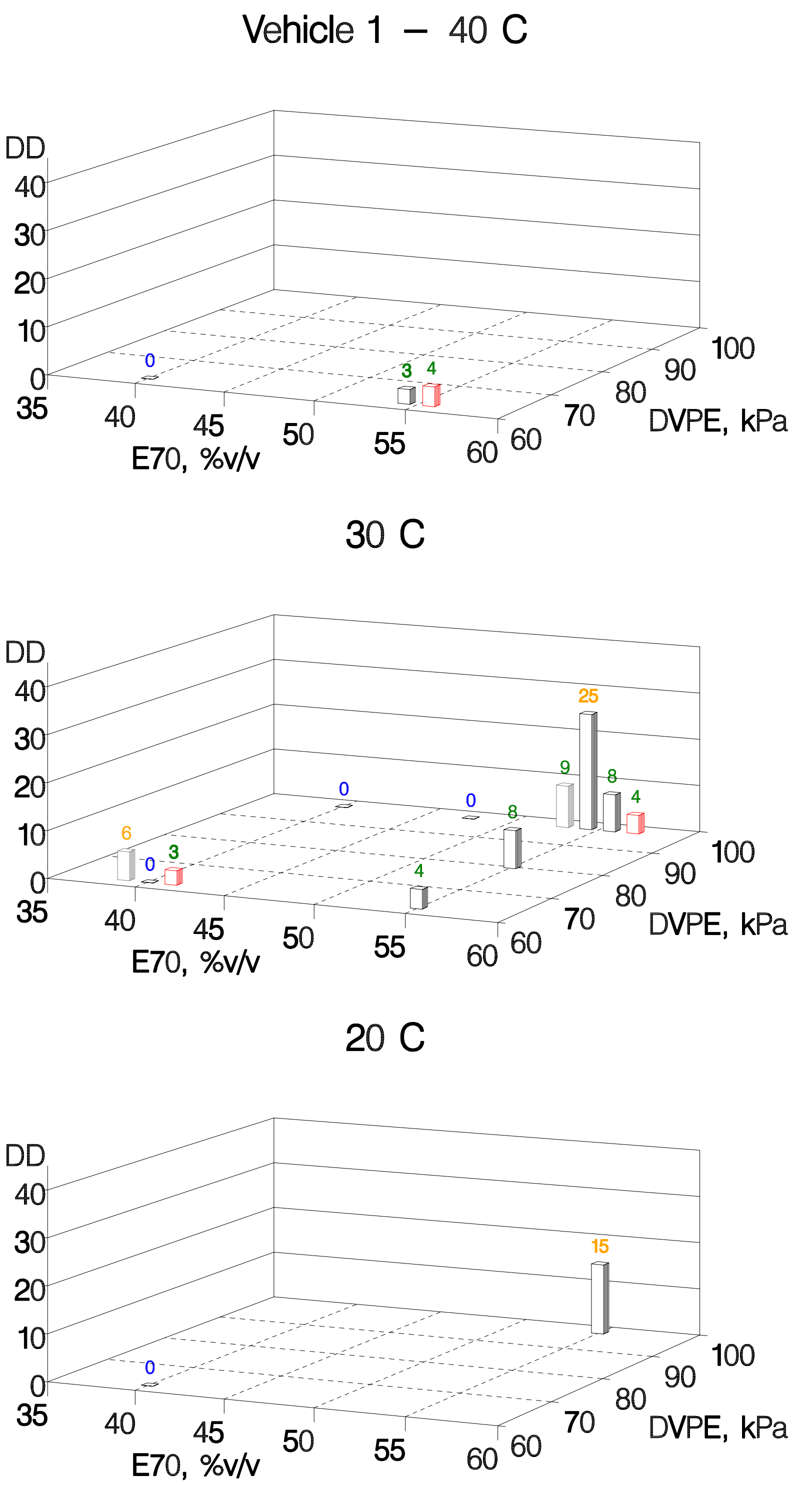
Four vehicles (2, 3, 4, 7) were tested in depth on the ethanol fuel blends. Three further vehicles (1, 5, 8) had a few tests with either 10% or 5% splash blends, to check for an ethanol effect. For each vehicle, conditions for testing the ethanol blends were chosen, some of which showed substantial demerits on the test vehicle, some which showed low demerits but were close to conditions where demerits increased on the hydrocarbon fuels. At each selected condition the relevant ethanol splash blend was tested. If there was a Substantial Demerit Difference (≥ 16) between the ethanol splash blends and the equivalent HC fuels, the matched volatility ethanol fuel was also tested.

5.2. TEST RESULTS

The total demerits recorded for each vehicle test are shown in **Figures 7-14**. These figures show total demerits on each fuel at each temperature, the colour of the bar denotes the fuel type, but bars are NOT plotted at their exact RVP/E70 values to aid clarity. The number above the bar is the total demerits, but the colour of this number gives the overall severity rating as defined in **Table 3**. Note that the scales are different for different vehicles, 500 Demerits max. for vehicles 2 and 3, 100 max for vehicle 4, and 40 max. for all others.

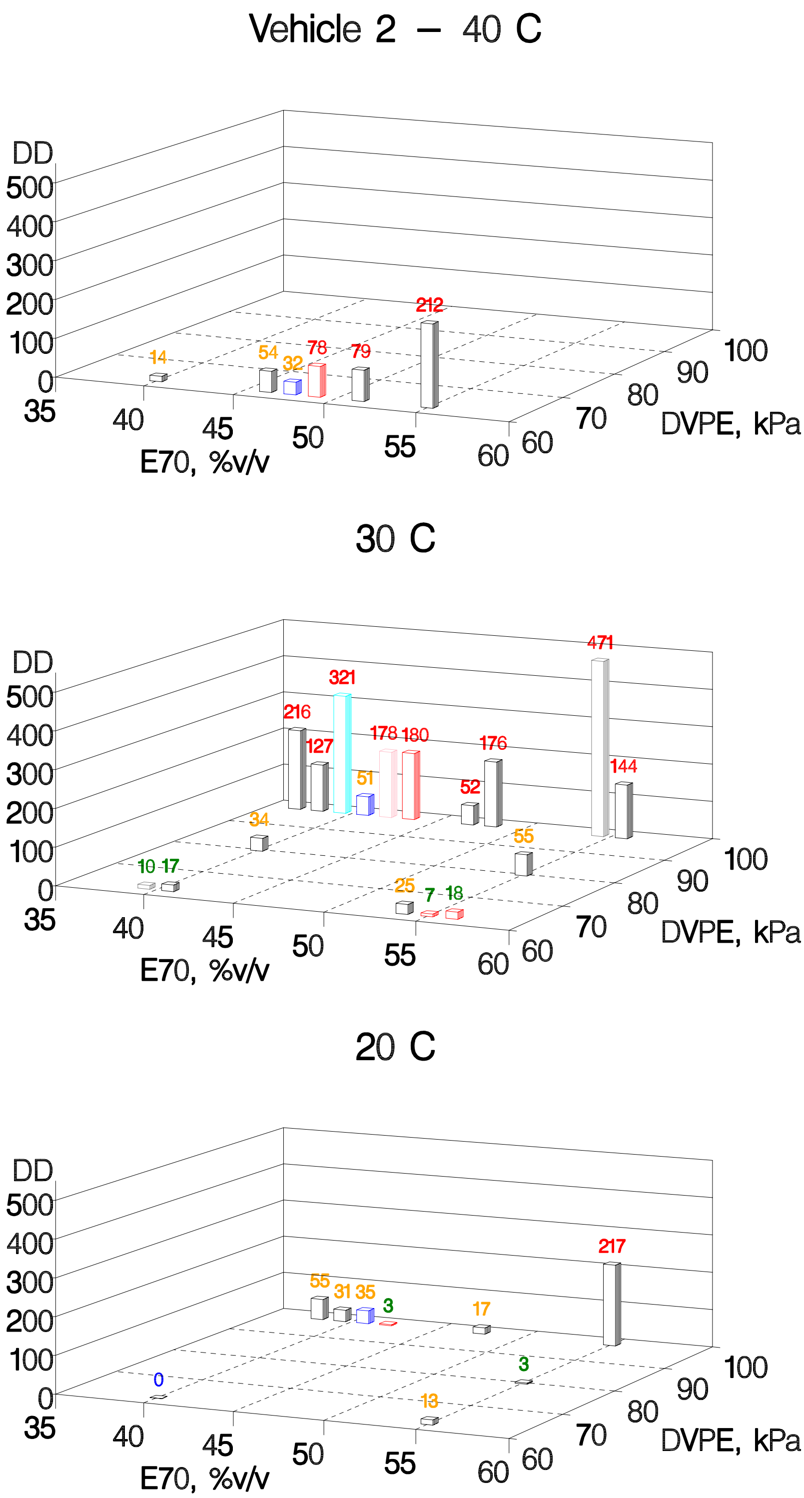
Four of the eight vehicles tested (5,6,8-MPI and 1-DISI) exhibited good hot driveability performance (≤24 demerits) under all fuel/temperature conditions tested. A fourth MPI vehicle (7) only exceeded 24 demerits on the highest volatility, 10% ethanol splash blend at 30°C. Two of the DISI vehicles however (2, 3) gave very high demerits on fuels A and C at 30°C and fuel B (vehicle 2) or BS (vehicle 3) at 40°C. Vehicle 3 showed a fault code indicating low fuel pressure on a number of these tests, indicating vapour lock in the fuel system. The remaining vehicle (4) showed substantial demerits (≤100) on the A fuels at 30°C but very low demerits under all other conditions. In the case of the vehicles 2 and 3, demerits varied widely on high DVPE fuels (A and C series) at 30°C and on lower DVPE B series fuels at 40°C. This suggests that those fuel/temperature combinations are critical, producing unstable responses from the vehicles. Similar unstable responses were observed for these two vehicles when tested under cold weather conditions, at the lowest temperature tested (-10°C), with the lowest volatility fuel E.

Figure 7 Total demerits – Vehicle 1



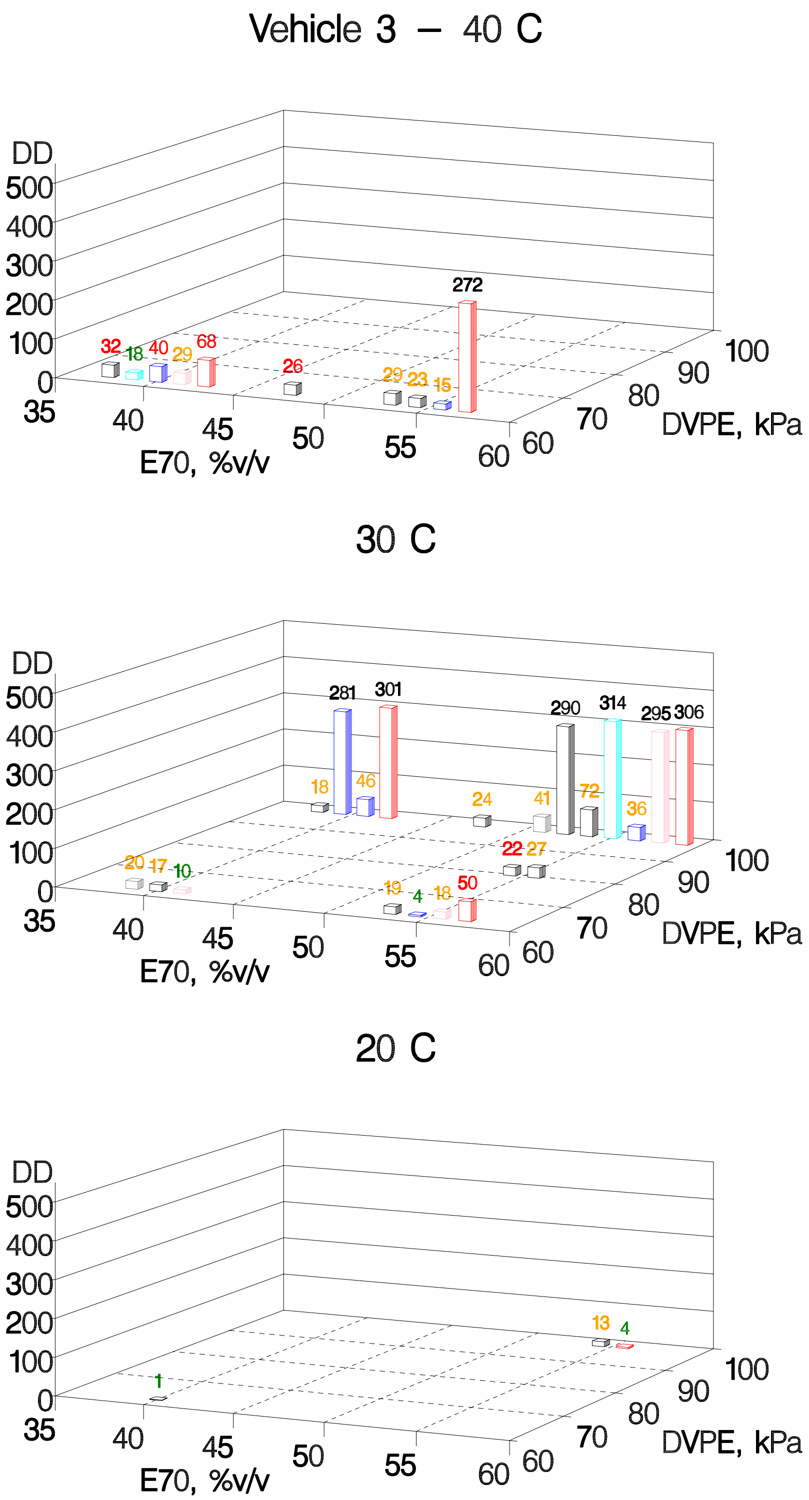
Bar Colour						
Fuel Type	HC (screening)	HC	5% EtOH (matched)	10% EtOH (matched)	5% EtOH (splash)	10% EtOH (splash)
Severity Colour (Number above bar – see **Section 2.2.3**)	**None**	**Trace**	**Moderate**	**Customer unacceptable**	**Safety unacceptable**	
Note: Demerit scales on Figures 10–17 are not all comparable						

Figure 8 Total demerits – Vehicle 2



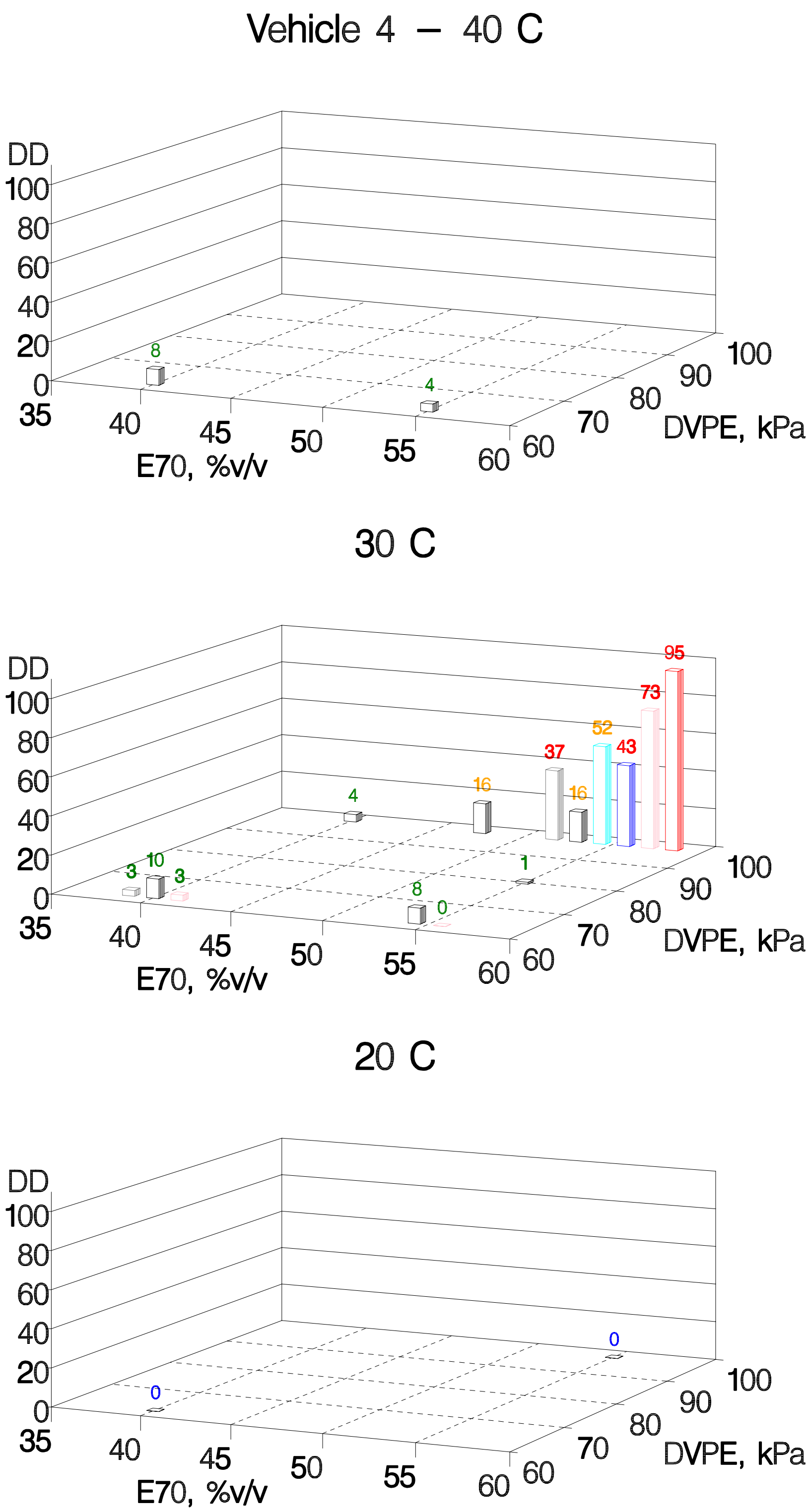
Bar Colour						
Fuel Type	HC (screening)	HC	5% EtOH (matched)	10% EtOH (matched)	5% EtOH (splash)	10% EtOH (splash)
Severity Colour (Number above bar – see **Section 2.2.3**)	**None**	**Trace**	**Moderate**	**Customer unacceptable**	**Safety unacceptable**	
Note: Demerit scales on Figures 10-17 are not all comparable						

Figure 9 Total demerits – Vehicle 3



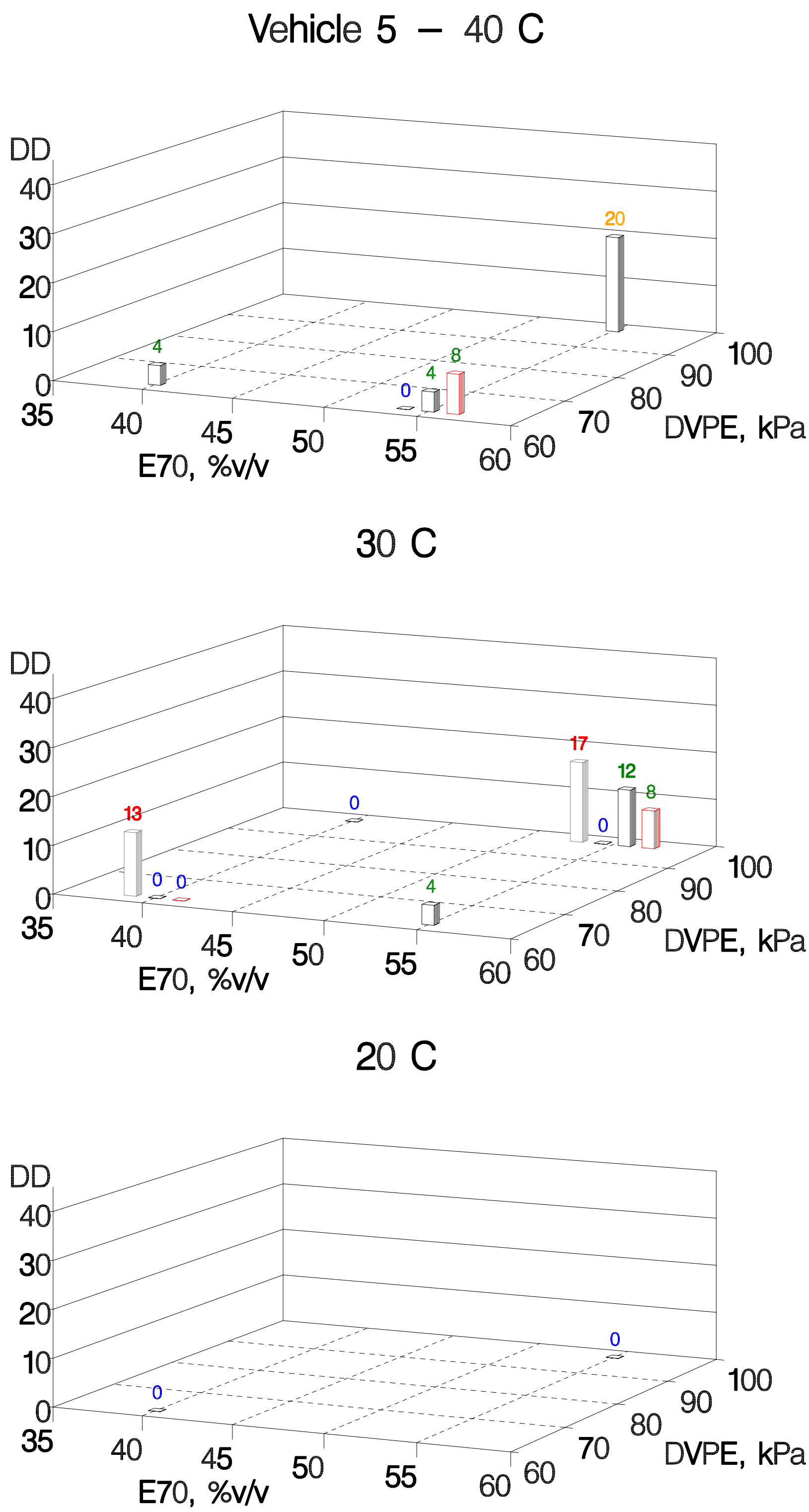
Bar Colour						
Fuel Type	HC (screening)	HC	5% EtOH (matched)	10% EtOH (matched)	5% EtOH (splash)	10% EtOH (splash)
Severity Colour (Number above bar – see **Section 2.2.3**)	**None**	**Trace**	**Moderate**	**Customer unacceptable**	**Safety unacceptable**	
Note: Demerit scales on Figures 10-17 are not all comparable						

Figure 10 Total demerits – Vehicle 4



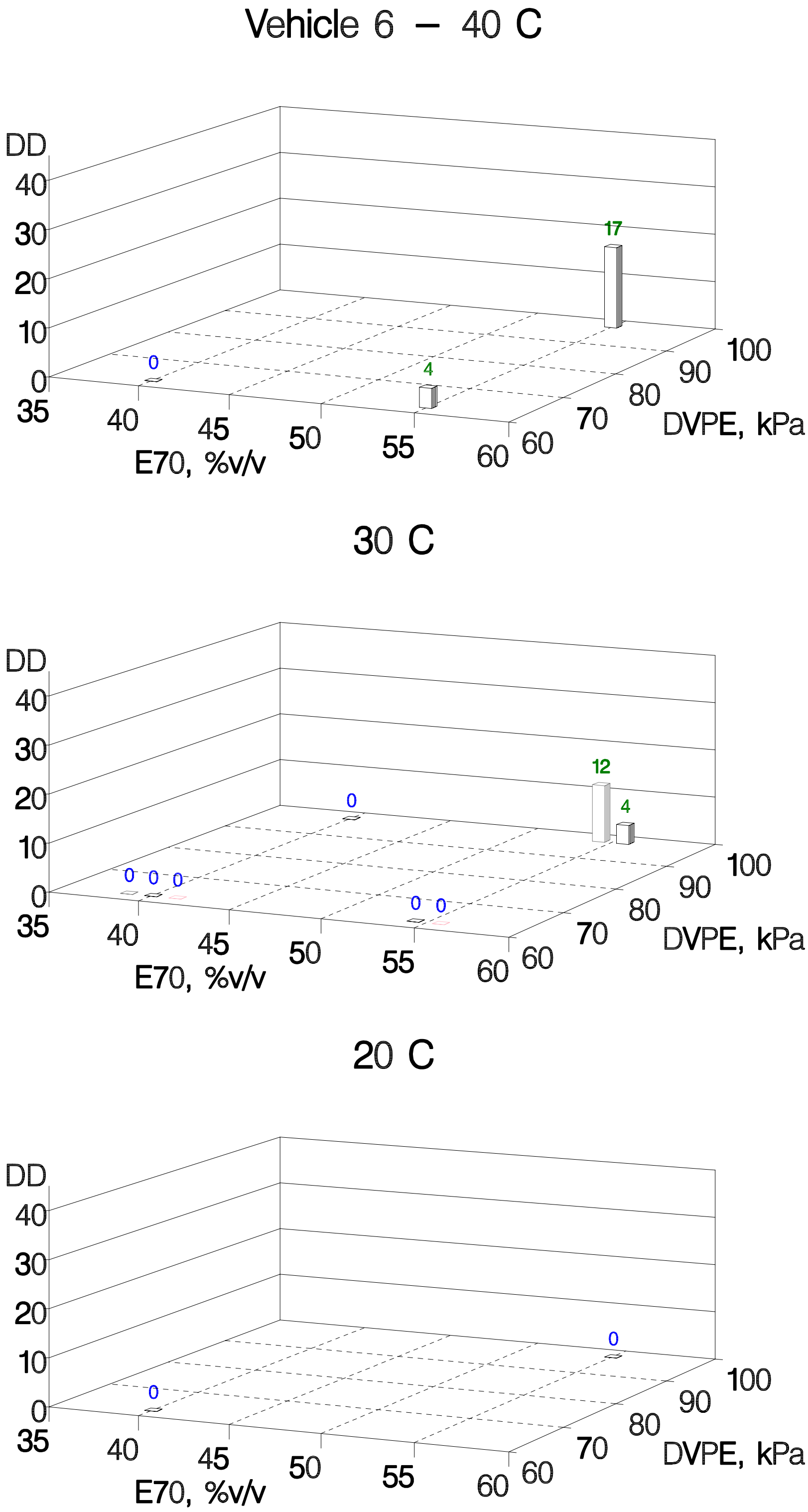
Bar Colour						
Fuel Type	HC (screening)	HC	5% EtOH (matched)	10% EtOH (matched)	5% EtOH (splash)	10% EtOH (splash)
Severity Colour (Number above bar – see **Section 2.2.3**)	**None**	**Trace**	**Moderate**	**Customer unacceptable**		**Safety unacceptable**
Note: Demerit scales on Figures 10-17 are not all comparable						

Figure 11 Total demerits – Vehicle 5



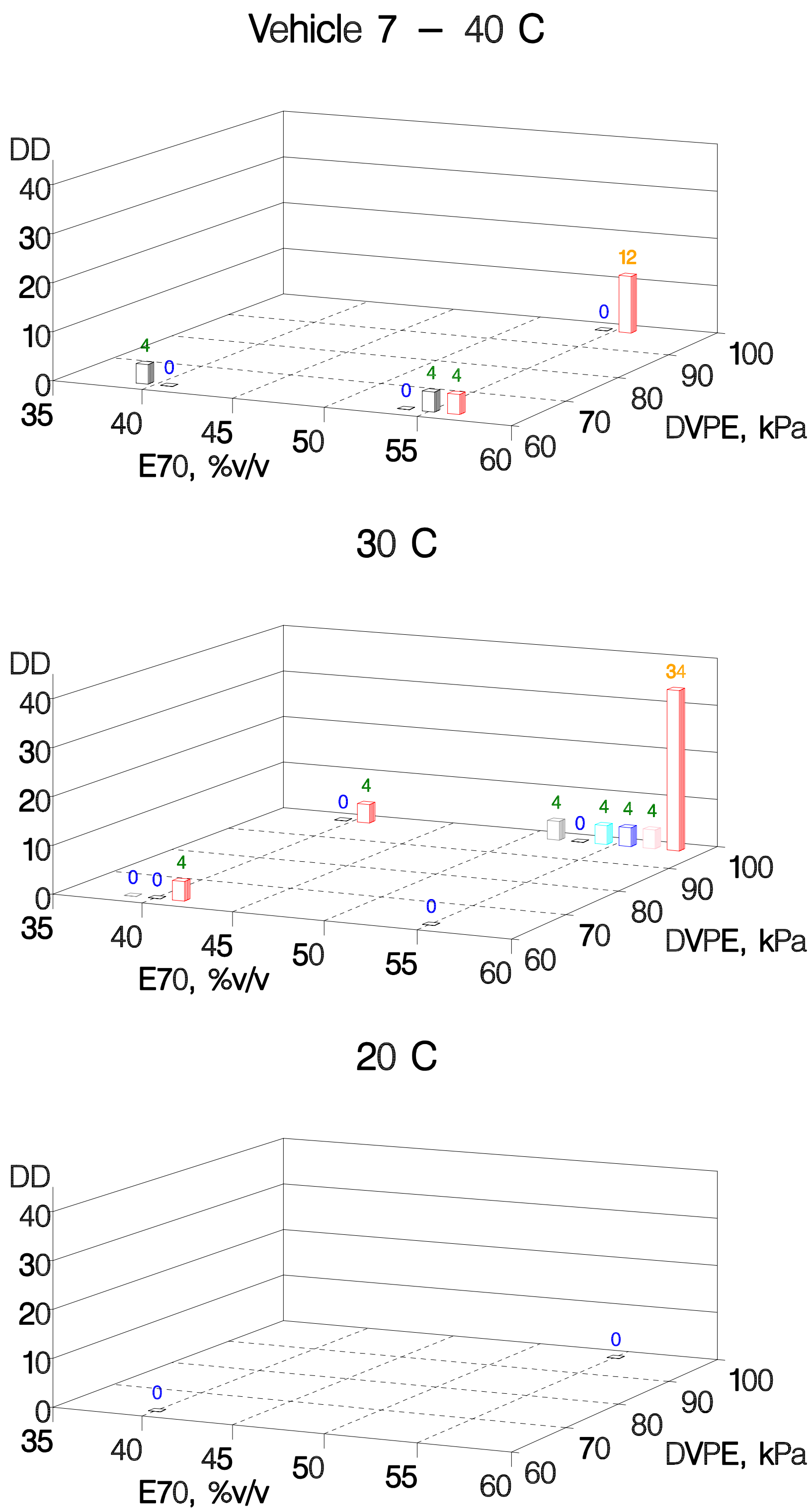
Bar Colour						
Fuel Type	HC (screening)	HC	5% EtOH (matched)	10% EtOH (matched)	5% EtOH (splash)	10% EtOH (splash)
Severity Colour (Number above bar – see **Section 2.2.3**)	**None**	**Trace**	**Moderate**	**Customer unacceptable**	**Safety unacceptable**	
Note: Demerit scales on Figures 10-17 are not all comparable						

Figure 12 Total demerits – Vehicle 6



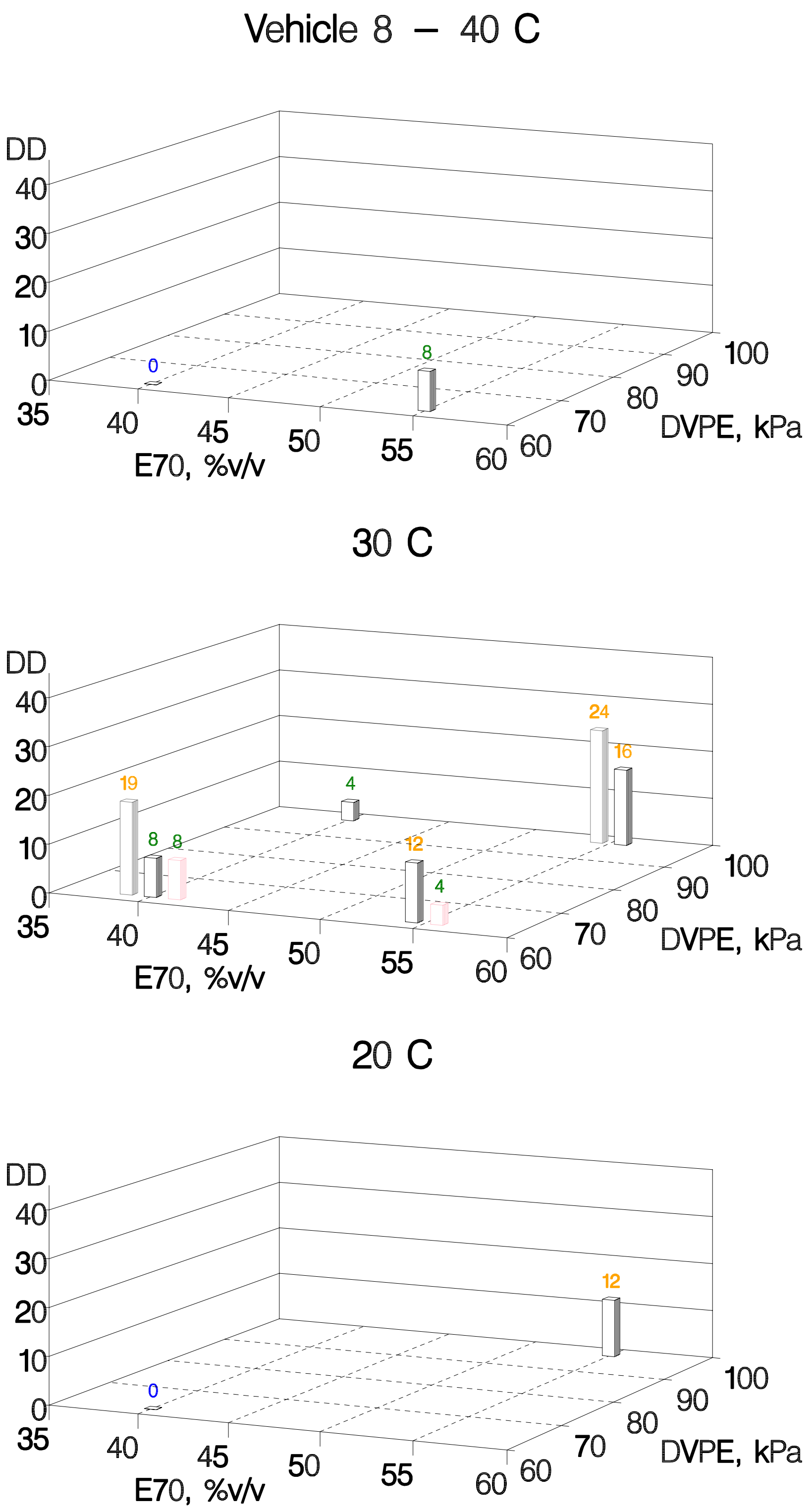
Bar Colour						
Fuel Type	HC (screening)	HC	5% EtOH (matched)	10% EtOH (matched)	5% EtOH (splash)	10% EtOH (splash)
Severity Colour (Number above bar – see **Section 2.2.3**)	**None**	**Trace**	**Moderate**	**Customer unacceptable**	**Safety unacceptable**	
Note: Demerit scales on Figures 10-17 are not all comparable						

Figure 13 Total demerits – Vehicle 7



Bar Colour						
Fuel Type	HC (screening)	HC	5% EtOH (matched)	10% EtOH (matched)	5% EtOH (splash)	10% EtOH (splash)
Severity Colour (Number above bar – see **Section 2.2.3**)	**None**	**Trace**	**Moderate**	**Customer unacceptable**	**Safety unacceptable**	
Note: Demerit scales on Figures 10-17 are not all comparable						

Figure14 Total demerits – Vehicle 8



Bar Colour						
Fuel Type	HC (screening)	HC	5% EtOH (matched)	10% EtOH (matched)	5% EtOH (splash)	10% EtOH (splash)
Severity Colour (Number above bar – see **Section 2.2.3**)	**None**	**Trace**	**Moderate**	**Customer unacceptable**	**Safety unacceptable**	
Note: Demerit scales on Figures 10-17 are not all comparable						

5.3. DISCUSSION OF RESULTS

5.3.1. Data handling and statistical analysis

The number of vehicles tested (8) and their wide variation in demerit levels and response to fuels meant it was not practicable to perform fleet analysis, so individual vehicles were analysed. This is shown below considering total demerits, the test sequence (1, 5 or 6) in which they occurred and individual fault demerits. In addition the fault severity coding described in **Section 2.2.3** and **Table 3** has been applied to individual faults and an overall rating given for each vehicle test.

The conditional nature of the design (see **Section 5.1**) resulted in a final data set that was rather irregular with different fuel sets tested at different temperatures and in different vehicles. This irregularity and the arbitrariness of the demerit scale limited the scope for rigorous statistical analysis. Therefore, for the most part, the results are presented in graphical form and the discussion is based on those visualisations.

In previous driveability studies [4] the variability in demerits has typically been found to increase as the number of demerits increases. This suggests that the data should be analysed on a log(DD+B) scale, an offset B being essential due to the presence of tests with DD = 0. Standard deviation vs. mean plots based on the available pairs of repeat measurements suggested a transform of the form $\log_{10}(DD+4)$ would stabilise the variability and render the data more amenable to standard statistical analysis techniques such as multiple regression (see **Appendix 2**). Therefore to investigate fuel effects, models of the following form

$$\log_{10}(DD+4) = a + b \times E70 + c \times DVPE + d \times TEMP + e \times \%v/vEtOH + \ldots$$

(or some subset thereof) were fitted to the demerit data for vehicles 2 and 3 only, where large enough numbers of tests were conducted and substantial driveability problems were encountered for several temperature × fuel combinations. The measured values of E70, DVPE and %v/v EtOH were used throughout rather than the targets. Such models were found to capture the non-linear responses to fuel properties and temperature reasonably well and allowed us to perform some simple significance tests. More complex model forms did fit some data sets better, but added little value to interpretation of the results.

Only a small number of vehicle × fuel × temperature combinations were repeat tested. This meant that the only way to detect possible outliers was to inspect studentized residuals (residuals divided by their standard errors) after fitting models such as the above. Time trends were sought by adding a TestDate term and checking its significance. In practice, several pairs of repeat tests showed poor levels of repeatability, so conclusive affirmation of individual outliers and trends was difficult.

5.3.2. MPI vehicles

Three of the MPI vehicles (5, 6, 8) showed good hot weather driveability on all fuels tested, with ≤24 demerits. Vehicle 7 also showed <24 demerits in all tests, except for fuel AS at 30°C, which gave 34 demerits. In view of these low demerit levels, three of the vehicles (5, 6, 7) were also tested on fuel A at 40°C. Despite this extreme combination of temperature and volatility, all had ≤20 demerits, which confirms the excellent hot driveability of other MPI vehicles seen in previous work [1]. Vehicle 5 had very low demerit levels except for the first two screening tests that showed severe surge in Sequence 5 resulting in “Customer Unacceptable” ratings. This was not seen in any other tests and cannot be explained. This vehicle was equipped with a powerful cooling fan that remained on for some time after engine shutdown, and probably contributed to its good driveability performance. Vehicle 8 had several “Moderate” severity ratings, but almost all other vehicle tests were “None” or “Trace”. Most of the demerits for these vehicles occurred in Sequence 5, though vehicle 8 had idle roughness demerits during sequence 6 for the screening tests only. Generally the highest demerits were seen on fuel A at 30 or 40°C, showing a slight sensitivity to volatility.

Vehicle 4 had an MPI fuel system but no throttle; instead inlet valve lift is varied to control engine power. This vehicle showed low demerits (<12) under all test conditions except A series and A-C interblend fuels at 30°C, when demerit levels of 16-95 were seen. Here again the majority of the demerits occurred in Sequence 5, mainly starting and idle roughness. The highest demerits occurred on fuel AS which had highest volatility, and under these conditions the vehicle shows increased demerits on ethanol fuels as shown in **Figure 10**. It is unclear whether the increase in demerits in fuels AS5 and AS is due to the presence of ethanol per se or is simply a consequence of the increase in volatility that is caused by the addition of ethanol.

5.3.3. DISI vehicles

One DISI vehicle (1) showed good driveability performance with ≤25 demerits in all test conditions, similar to the four MPI vehicles. The highest demerit figure of 25 was generated on fuel A at 30°C, where over half the demerits occurred in Sequence 6, mainly moderate cruise surge. Fuel A was tested at 30°C three times in this vehicle, giving 9, 25 and 8 demerits with cruise surge observed in only the one test. In general this vehicle had demerits in all test sequences. The other two DISI vehicles (2, 3) showed much poorer driveability, with many tests giving 100-500 demerits.

Vehicle 2 showed high demerits on fuel A at 20°C, on all A and C fuels at 30°C and on fuel B at 40°C, with highest demerits of 471 in the screening test on fuel A at 30°C. Substantial demerits were seen in all test sequences, with the highest number often in sequence 6, mainly due to idle roughness. In Sequences 1and 5, problems were mainly due to poor starting and idle roughness. Tests on D-series fuels had low demerits (≤17) at all temperatures.

Vehicle 3 also had many tests with 270-314 demerits on high DVPE fuels A and C at 30°C and on fuel BS at 40°C, mostly in Sequence 5 with some in Sequence 6. Most of the very high demerits in Sequence 5 were caused by acceleration time fail, i.e. the vehicle would not accelerate, and was classified as SAFETY – UNACCEPTABLE. These high demerits were accompanied by an engine warning message saying fuel pressure was out of range, too low. This suggests classical vapour lock was taking place somewhere in the fuel system, but the phenomenon was not very reproducible, as shown in the following table.

Fuel - Temp	A - 30	D - 30	CE - 30	B - 40	AB - 30
Test 1 (screening)	41	20			
Test 2	*290**	17	*281**	29	22
Test 3	72		46	23	27

** Engine warning message*

5.3.4. Volatility effects

For five of the vehicles (1,5,6,7,8) with low overall demerits, no analysis or modelling was possible. The only conclusion to be made is that demerits were highest on the highest volatility A series fuels at 30°C and 40°C. Most of these tests were rated as “None” or “Slight” by the Fault Severity scale, though a number were “Moderate”, generally corresponding to 15-25 demerits. Vehicle 5 had two “Customer unacceptable” ratings as described above, with only 13 and 17 demerits, but these were the first scouting tests showing severe surge which was never repeated.

Vehicles 2, 3 and 4 show clear effects of increasing volatility. **Figures 15a-b** show tests at 30 and 40°C plotted against volatility as “bubbles”, with the area of the bubble proportional to the number of demerits, and its colour the severity rating, as in **Figures 10-17**. Increasing DVPE at 30°C and E70 at 40°C showed a clear increase in demerits for vehicle 2, while vehicles 3 and 4 at 30°C only show an increase on the most volatile fuel A. Vehicles 3 and 4 also show a small effect of E70 for high DVPE fuels at 30°C. In all cases substantial increases in demerits were only seen at high temperatures on fuels with volatility beyond the summer limits of EN228.

Fitting simple statistical models in E70 (%v/v), DVPE (kPa) and Temperature (°C) to the hydrocarbon fuels first, as discussed in **Appendix 2**, yielded the equations[2]:

$$log_{10}(DD+4) = -2.53 + 0.020^{*} \times E70 + 0.022^{***} \times DVPE \quad + 0.051^{***} \times T \qquad (adj\ R^2 = 0.70) \quad (vehicle\ 2)$$

$$log_{10}(DD+4) = -0.81 + 0.009^{NS} \times E70 + 0.011^{*} \times DVPE \quad + 0.032^{*} \times T \qquad (adj\ R^2 = 0.40) \quad (vehicle\ 3)$$

The results were directionally similar with DVPE and Temperature effects having greater significance levels than E70. The absence of a significant effect does not mean that the variable does not have an effect, rather that its effect is too small to see above the noise within the available data.

2 * Regression coefficient significantly different from zero at P < 5%, i.e. we are 95% confident that the effect is real
** Coefficient significant at P < 1%
*** Coefficient significant at P < 0.1%
NS Coefficient not significant at P < 5%

In previous studies [4] VLI (= DVPE + 0.7 E70) and T_{VL20} were found to be good predictors of driveability. Fitting models in VLI or T_{VL20} and Temperature yielded the following equations:

$$\log10(DD+4) = 3.00 - 0.060^{***} \times TVL20 + 0.051^{***} \times T \quad (\text{adj } R^2 = 0.69) \quad (\text{vehicle 2})$$

$$\log10(DD+4) = 1.86 - 0.030^{**} \times TVL20 + 0.034^{*} \times T \quad (\text{adj } R^2 = 0.47) \quad (\text{vehicle 3})$$

$$\log10(DD+4) = -2.40 + 0.022^{***} \times VLI + 0.052^{***} \times T \quad (\text{adj } R^2 = 0.71) \quad (\text{vehicle 2})$$

$$\log10(DD+4) = -0.80 + 0.011^{**} \times VLI + 0.032^{*} \times T \quad (\text{adj } R^2 = 0.45) \quad (\text{vehicle 3})$$

with similar or better adjusted R^2 values than the above models in E70, DVPE and temperature. Thus VLI and T_{VL20} are marginally better predictors of driveability than E70 or DVPE for hydrocarbon fuels.

Restricting the vehicle 2 models to 30°C yielded:

$$\log_{10}(DD+4) = -0.55 + 0.011^{NS} \times E70 + 0.022^{***} \times DVPE \quad (\text{adj } R^2 = 0.75)$$

$$\log_{10}(DD+4) = 4.37 - 0.056^{***} \times T_{VL20} \quad (\text{adj } R^2 = 0.80)$$

$$\log_{10}(DD+4) = -0.65 + 0.021^{***} \times VLI \quad (\text{adj } R^2 = 0.78)$$

Overall it appears that these three critical vehicles, which did show substantial driveability problems and variation with volatility, are more sensitive to fuel DVPE than to E70. The effect of DVPE over the range 60-100 kPa was more than double that of E70 over the range 40-55 %v/v.

Figure 15a Effect of DVPE and E70 of HC fuels on Hot Driveability of Vehicle 2
Bubble area represents total demerits plotted at true DVPE and E70 values

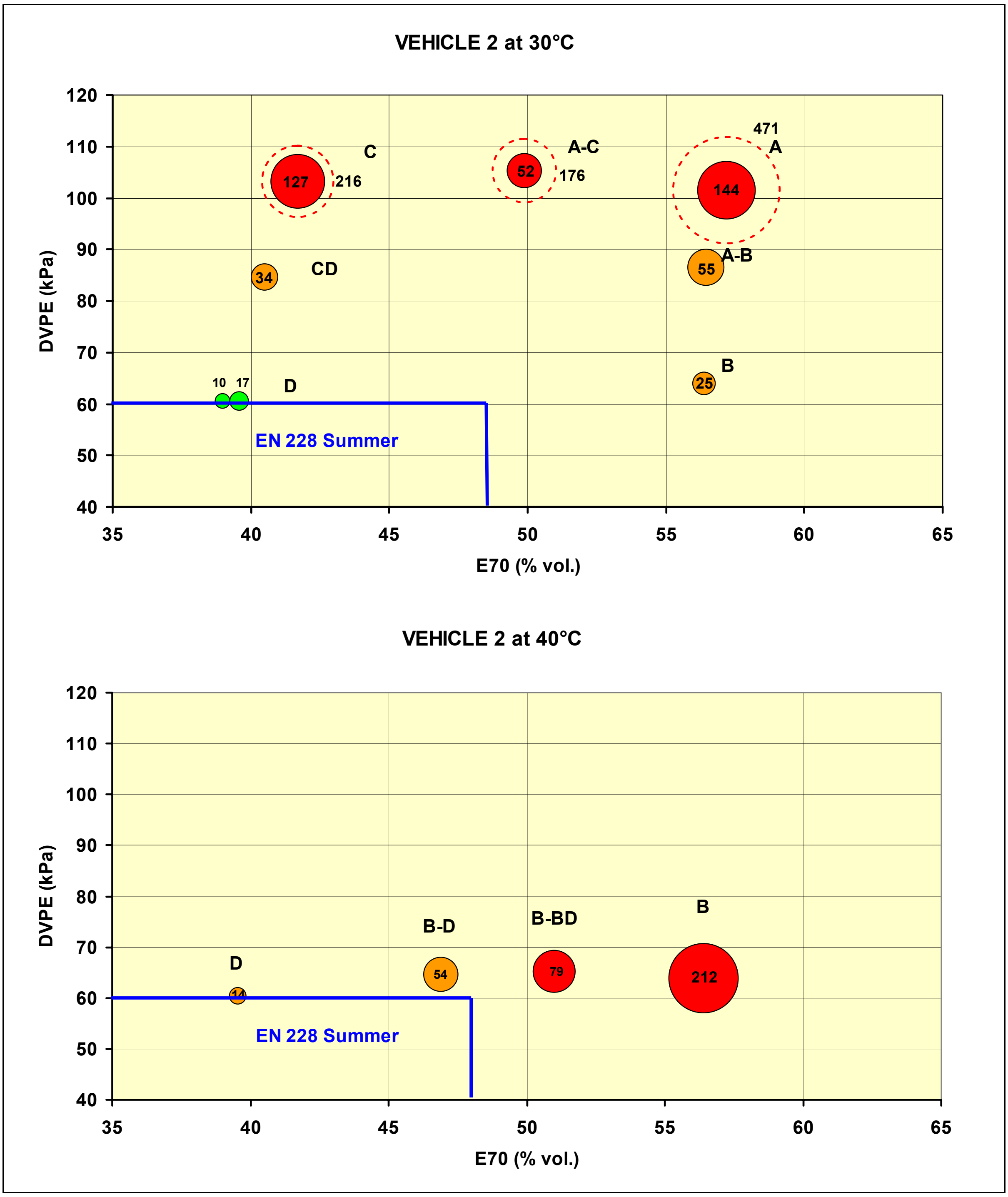
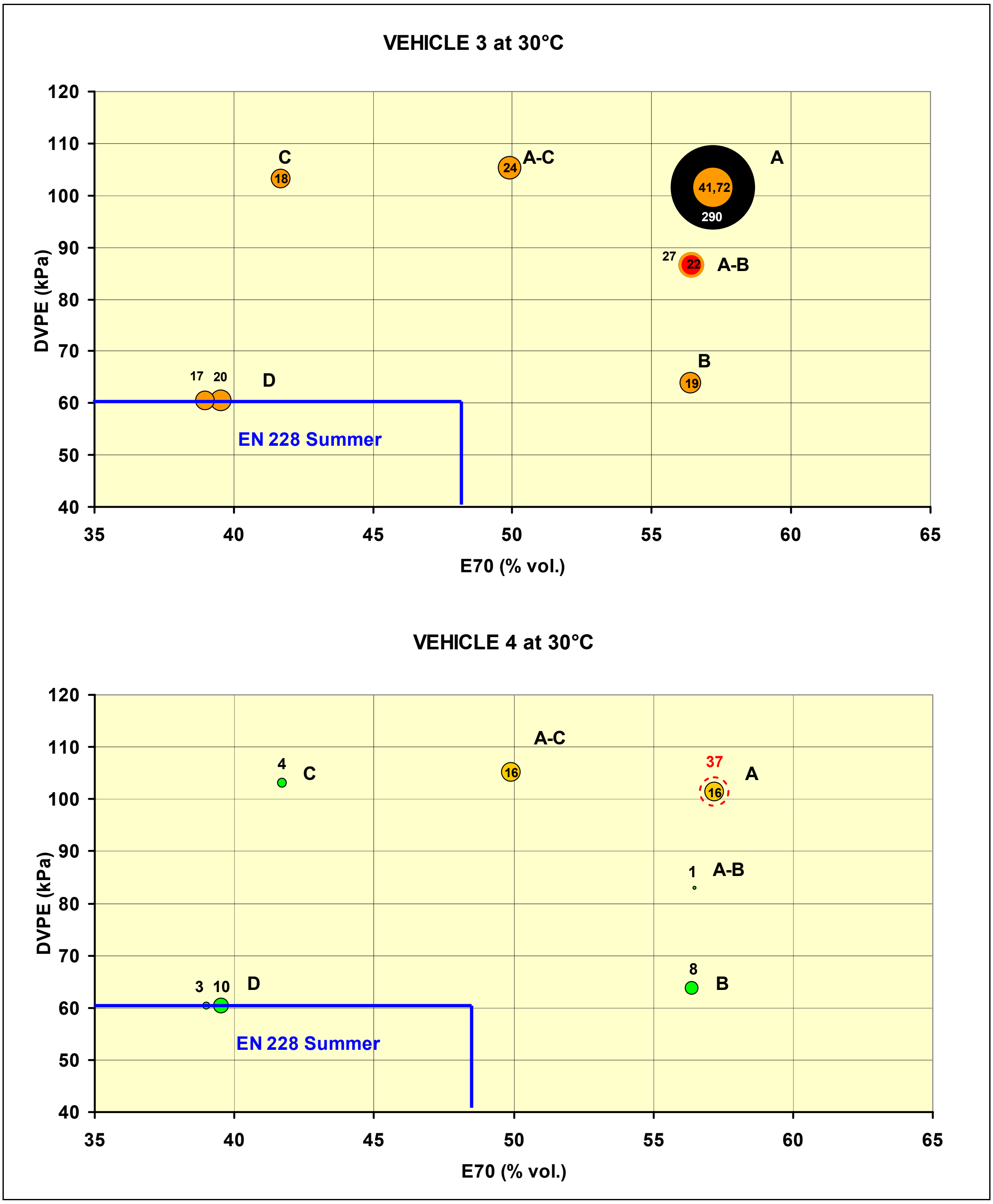


Figure 15b Effect of DVPE and E70 of HC fuels on Hot Driveability of Vehicles 3 and 4
Bubble area represents total demerits plotted at true DVPE and E70 values



5.3.5. Ethanol effects

As for the volatility effects, there were relatively few vehicles where enough demerits were seen to perform a meaningful analysis, in this case only vehicles 2, 3, 4 and 7 (**Figures 8, 9, 10 and 13**). In all cases vehicles were tested first on ethanol splash blends, and if there was a significant difference to the equivalent hydrocarbon fuel, then the matched volatility fuel was also tested. Ethanol splash blends were tested on three other vehicles (1, 5, 8) at one or two temperatures as seen in **Figures 7, 11 and 14**. Demerits and test severity for these last three vehicles on the ethanol fuels were generally the same or lower, but all demerit levels were very low.

Figures 16a-b show demerits plotted by fuel type, with the test severity indicated by the colour of the boxes above the bars. Vehicle 2 showed no clear effect of ethanol fuels at 20°C or 30°C. Vehicle 4 showed a clear effect on the A-series fuels at 30°C, with the splash blends giving higher demerits as might be expected from their higher volatility, and the matched volatility blends giving slightly higher demerits than the hydrocarbon fuels. Vehicle 3 showed a similar trend at 40°C on the D and B series fuels, but at 30°C results were hard to interpret with some high and some low demerit values, corresponding with the presence or absence of a fuel pressure warning message. Overall splash blends gave worse performance in this vehicle. A similar picture was seen for vehicle 7, though here again demerit levels are very low and differences very small, apart from fuel AS.

Fitting simple statistical models in E70 (%v/v), DVPE (kPa), temperature (°C) and ethanol content (%v/v) yielded the equations:

$$log_{10}(DD+4) = -2.26 + 0.008^{NS} \times E70 + 0.023^{***} \times DVPE + 0.058^{***} \times T - 0.036^{*} \times EtOH$$
(adj R^2 = 0.64) (vehicle 2)

$$log_{10}(DD+4) = -1.99 + 0.009^{NS} \times E70 + 0.019^{***} \times DVPE + 0.049^{***} \times T + 0.011^{NS} \times EtOH$$
(adj R2 = 0.49) (vehicle 3)

The large DVPE and temperature effects are still evident but there is not much evidence of E70 or ethanol effects. Splash blending ethanol into a hydrocarbon base fuel substantially increases its E70. The negative ethanol term for vehicle 2 indicates that splash blend demerits were lower than one might expect given the increase in E70.

The parameters VLI (= DVPE + 0.7 E70) and T_{VL20} had similar predictive performance to DVPE when modelling the combined results from hydrocarbon and ethanol fuels.

In general, except for vehicle 2, ethanol splash blends increased demerits and in some cases overall severity rating. Matched volatility blends gave similar driveability to the equivalent hydrocarbon fuels. This suggests that the effects seen are not due to the presence of ethanol per se but are a consequence of the increase in volatility that is caused by the addition of ethanol.

Figure 16a Effect of Ethanol on Vehicles 2 and 4

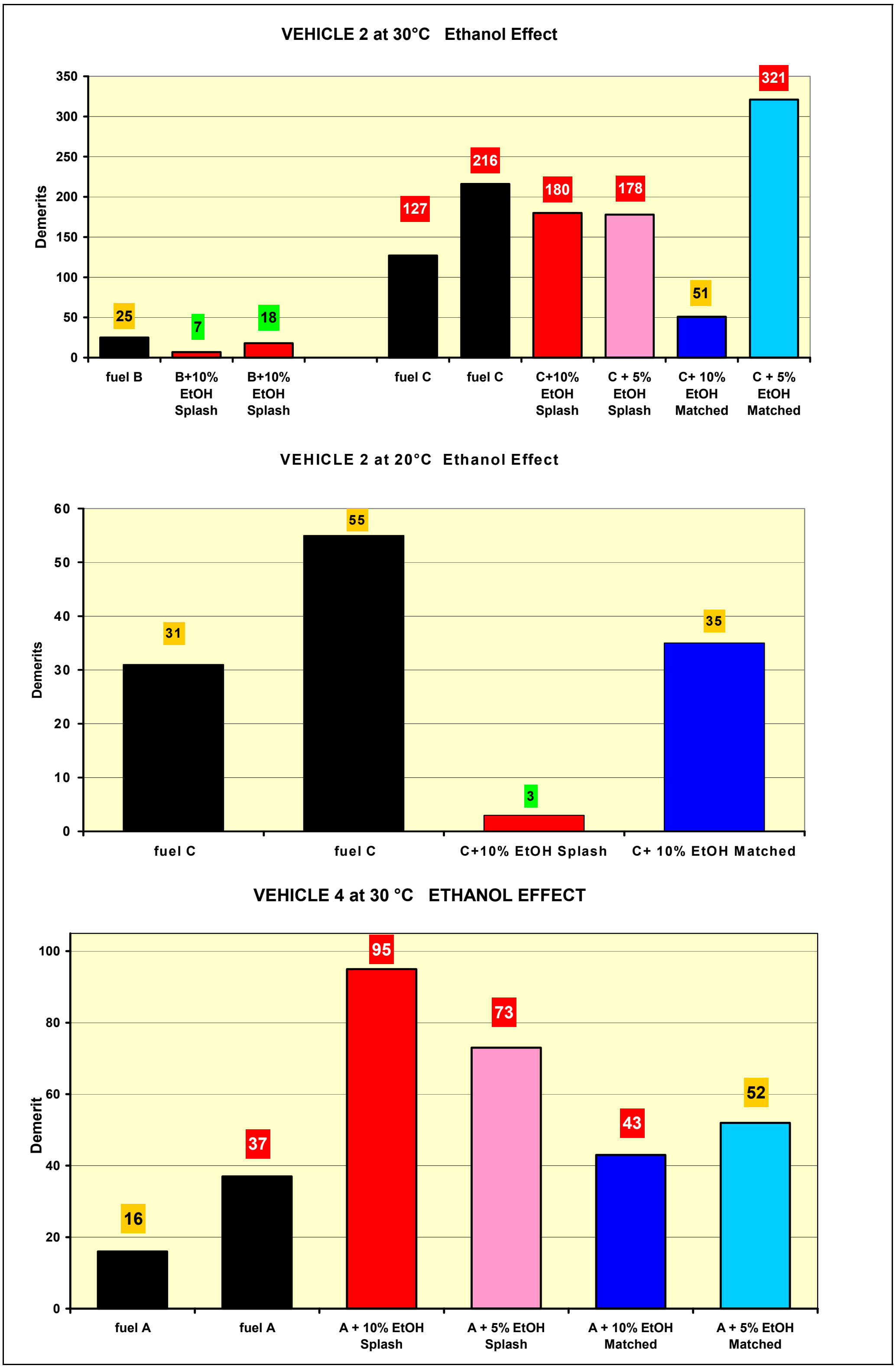
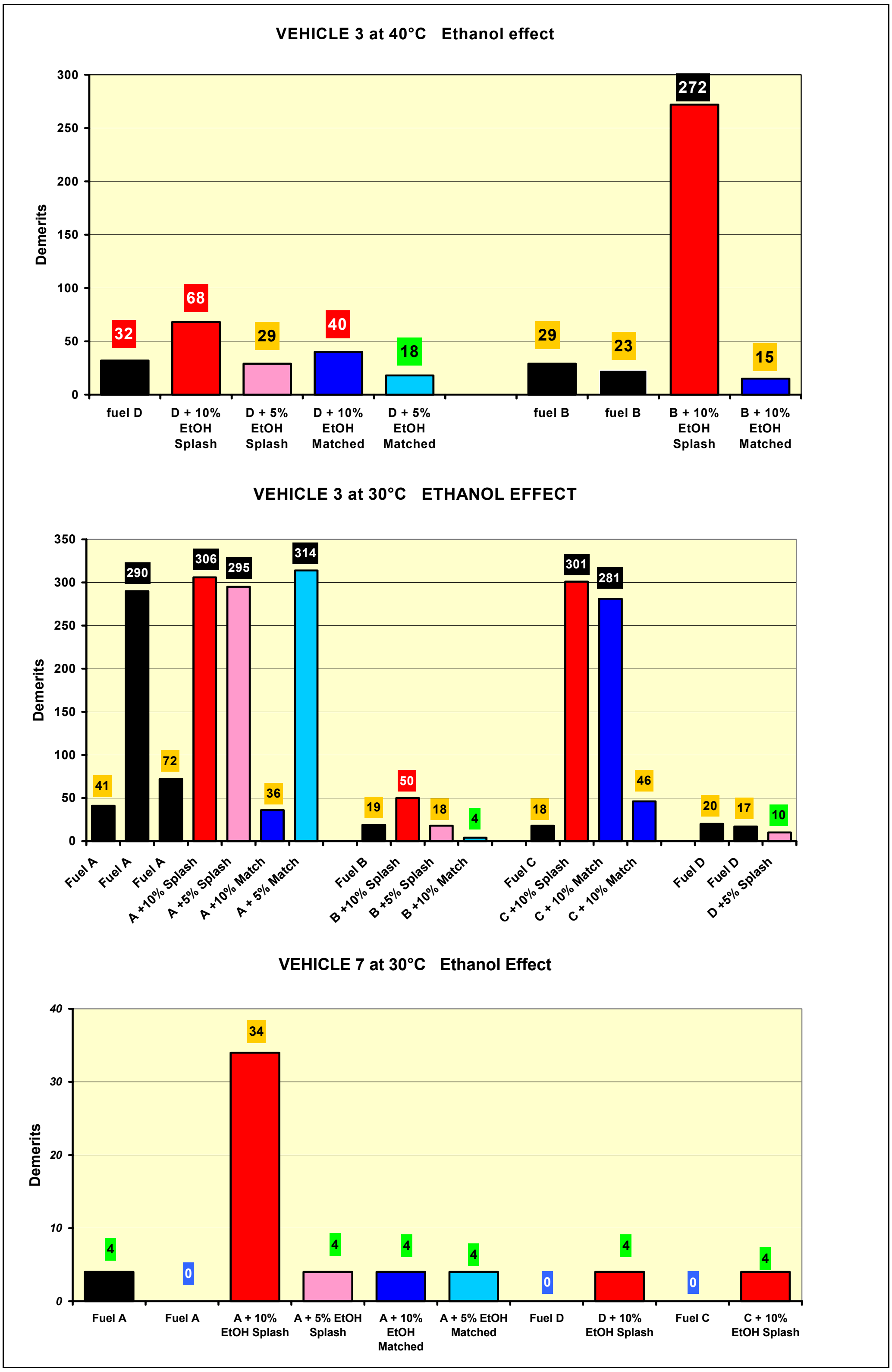


Figure 16b Effect of Ethanol on Vehicles 3 and 7



6. COLD DRIVEABILITY TESTING

6.1. TEST DESIGN

As for the hot driveability tests a screening programme was initially carried out, in this case with all eight vehicles tested on fuels G and E at -10°C. On the basis of these test data, a subset of four vehicles (1, 2, 4, 7) was chosen for further testing on the full range of fuels. However during subsequent tests, vehicle 4 showed a consistent high level of demerits at -10°C on all fuels. This was due to persistent engine stalls in second gear when accelerating from idle, and believed to be due to an engine calibration problem at low temperature as it did not occur at +5°C. It was decided to stop testing on vehicle 4 and substitute vehicle 6, so the final vehicle subset tested was changed to 1, 2, 6, 7.

Each of these vehicles was tested on 9 fuels (A, AE, AS, G, GE, GS, E, EE, ES) at two temperatures (-10°C, +5°C). The fuels were tested in a different randomised order in each vehicle to minimise any possible effects of drift. To avoid unnecessary flushing, the two tests on each fuel were conducted back-to-back with the order of the test temperatures (-10°C, +5°C) being randomised. A small number of tests were conducted on 5% ethanol matched and splash blends in vehicles 1 (-10°C and +5°C), 6 (-10°C) and 7 (-10°C) at the end of the programme.

The final cold weather data set included a full single-replicate 4 vehicle × 9 fuel × 2 temperature factorial design and so was more amenable to statistical analysis than the hot weather data.

6.2. TEST RESULTS

Total demerits for each vehicle at both test temperatures (-10°C only for vehicles 3, 5 and 8) are shown in **Figures 17 to 24** plotted against fuel E100. In these figures, the colour of the central data-point shows the fuel type, while the colour of the outer circle indicates the test severity according to **Table 3**.

All of the vehicles showed substantial demerits (>100 but generally <200) under some conditions, so the majority of Figures are plotted with a demerit scale of 0-160. Vehicle 2 however showed very high demerit levels (200-500) on all fuels so this figure has been plotted with a scale of 0-500 demerits. Vehicle 4 had substantial demerits at -10°C as discussed above, as did vehicle 8. These are both plotted with a scale of 0-250 demerits.

Figure 17 Total Cold Driveability Demerits of Vehicle 1

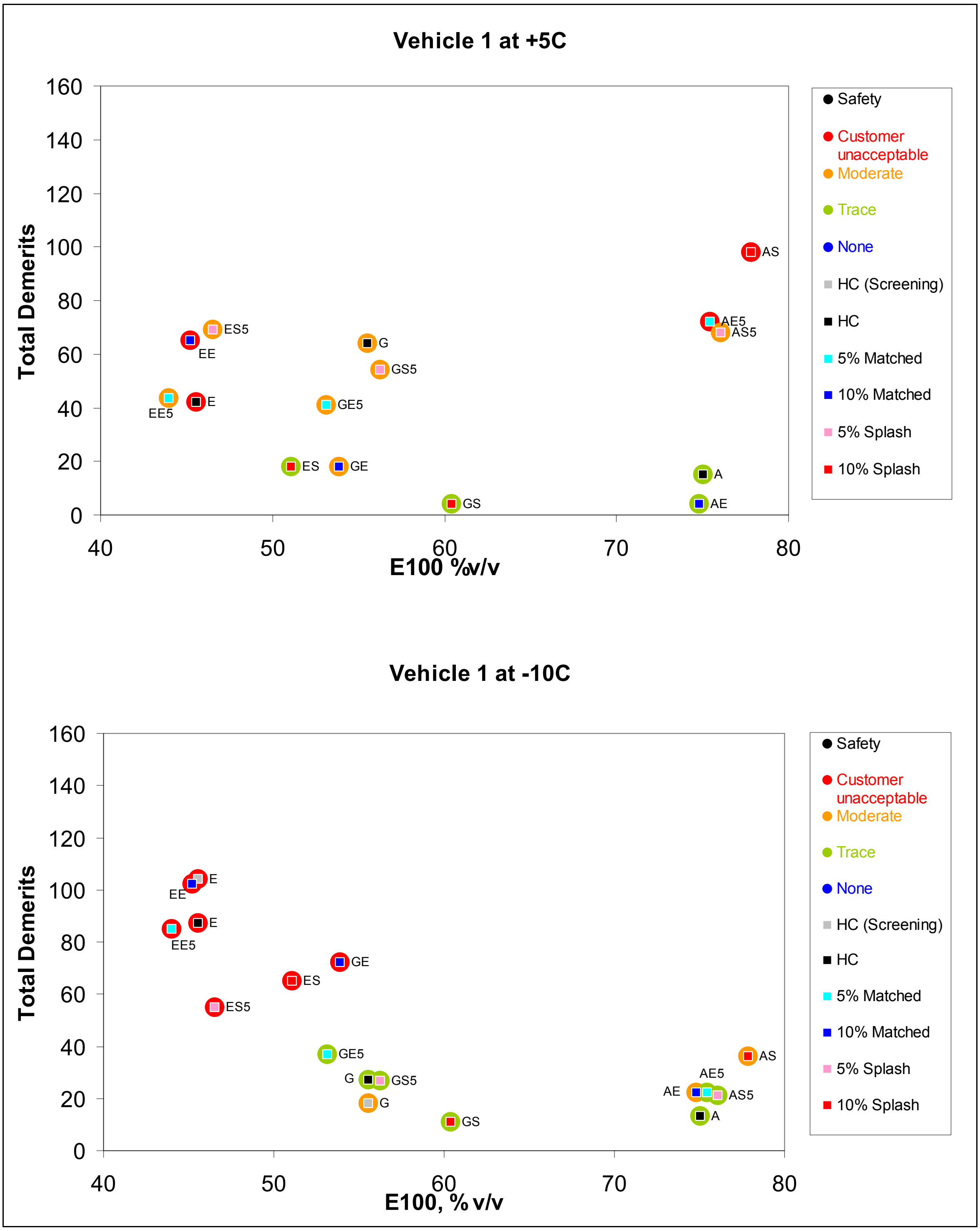


Figure 18 Total Cold Driveability Demerits of Vehicle 2

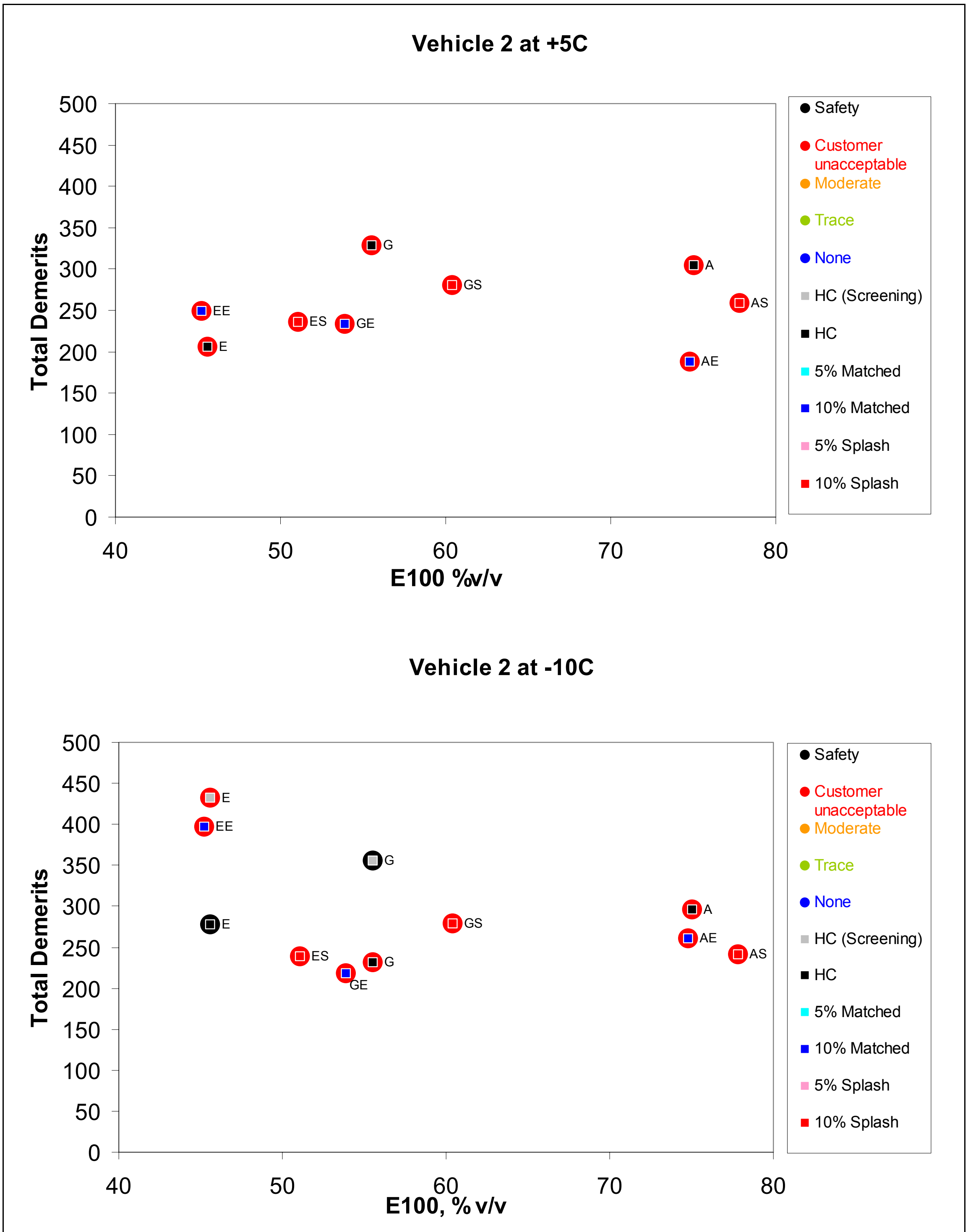


Figure 19 Total Cold Driveability Demerits of Vehicle 3

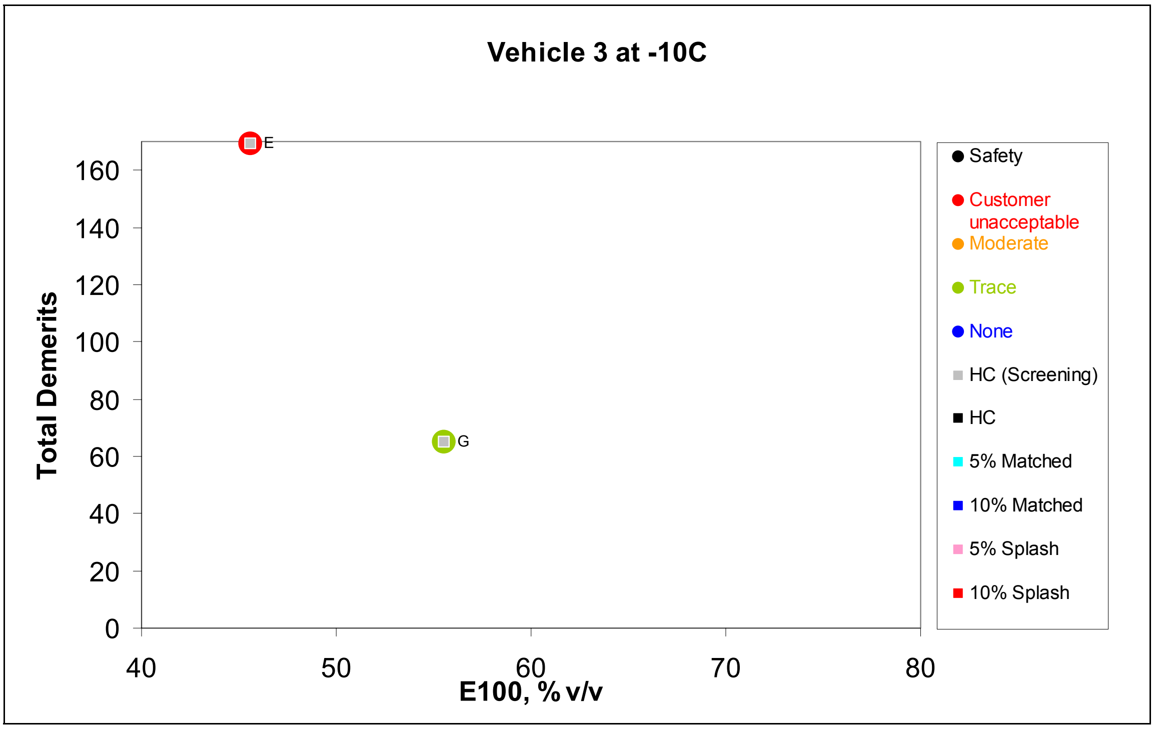


Figure 20 Total Cold Driveability Demerits of Vehicle 4

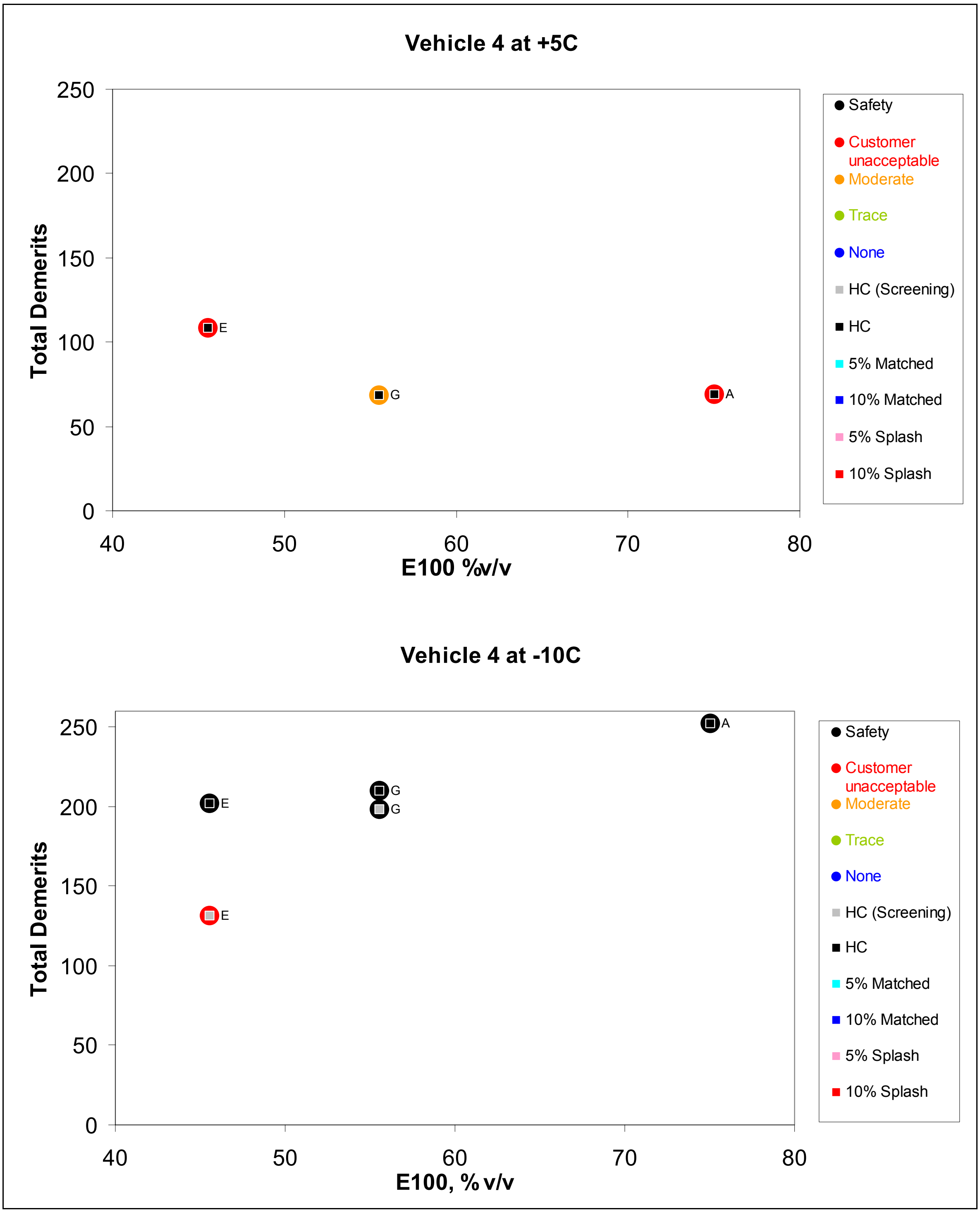


Figure 21 Total Cold Driveability Demerits of Vehicle 5

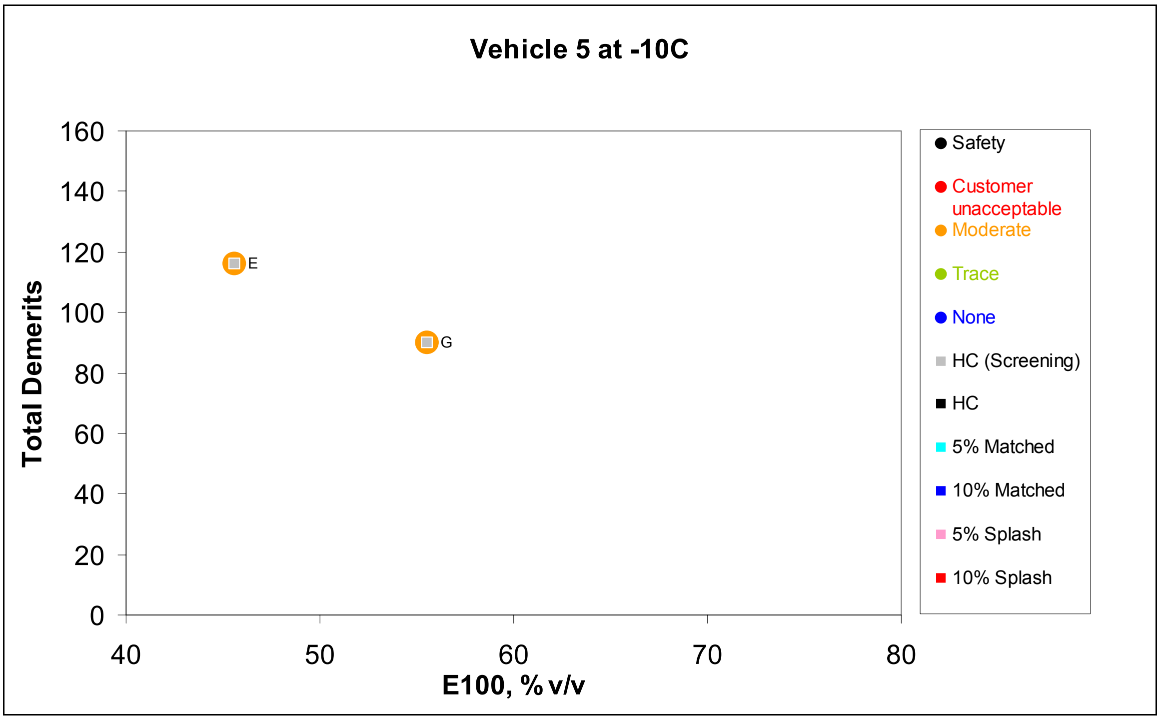


Figure 22 Total Cold Driveability Demerits of Vehicle 6

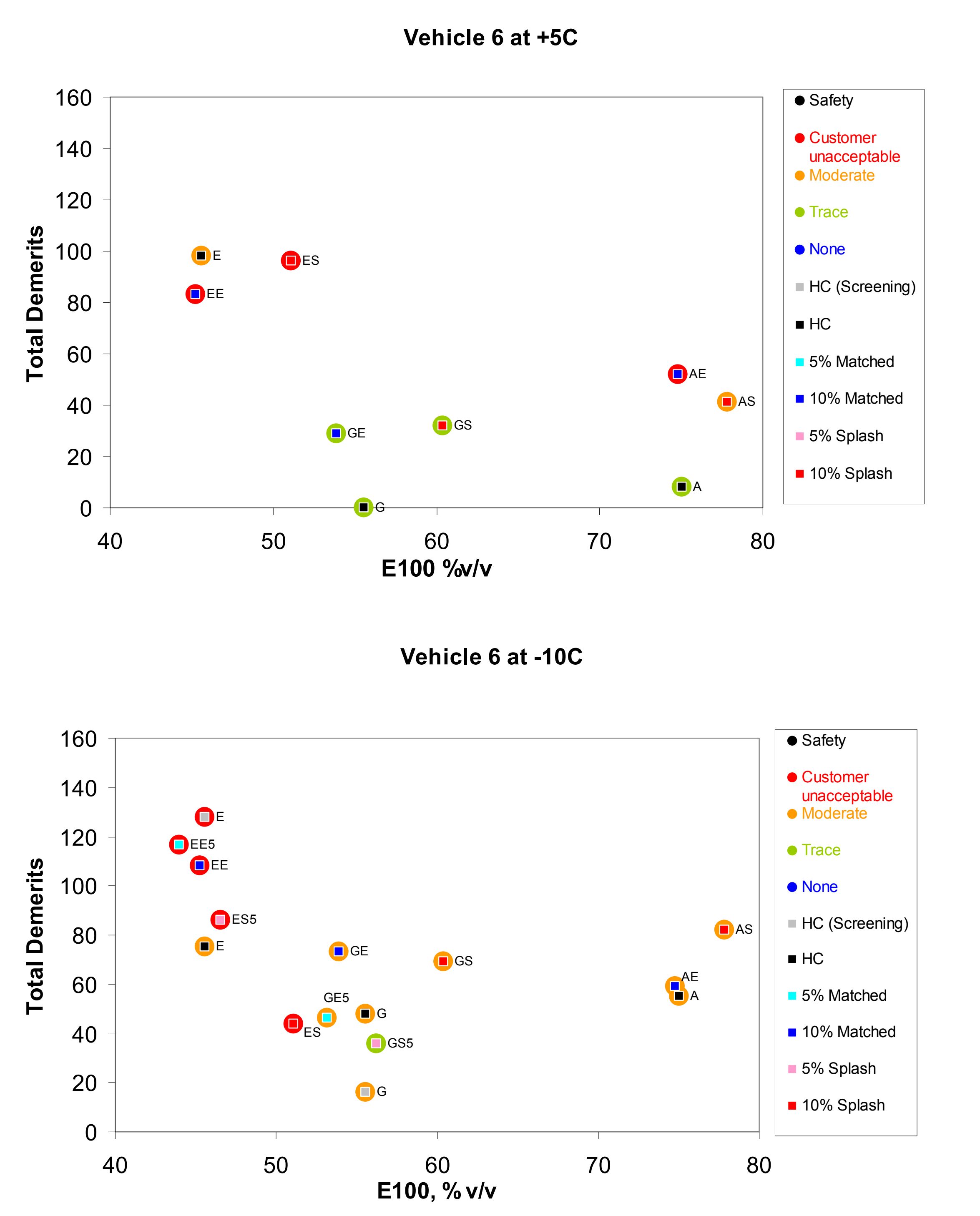


Figure 23 Total Cold Driveability Demerits of Vehicle 7

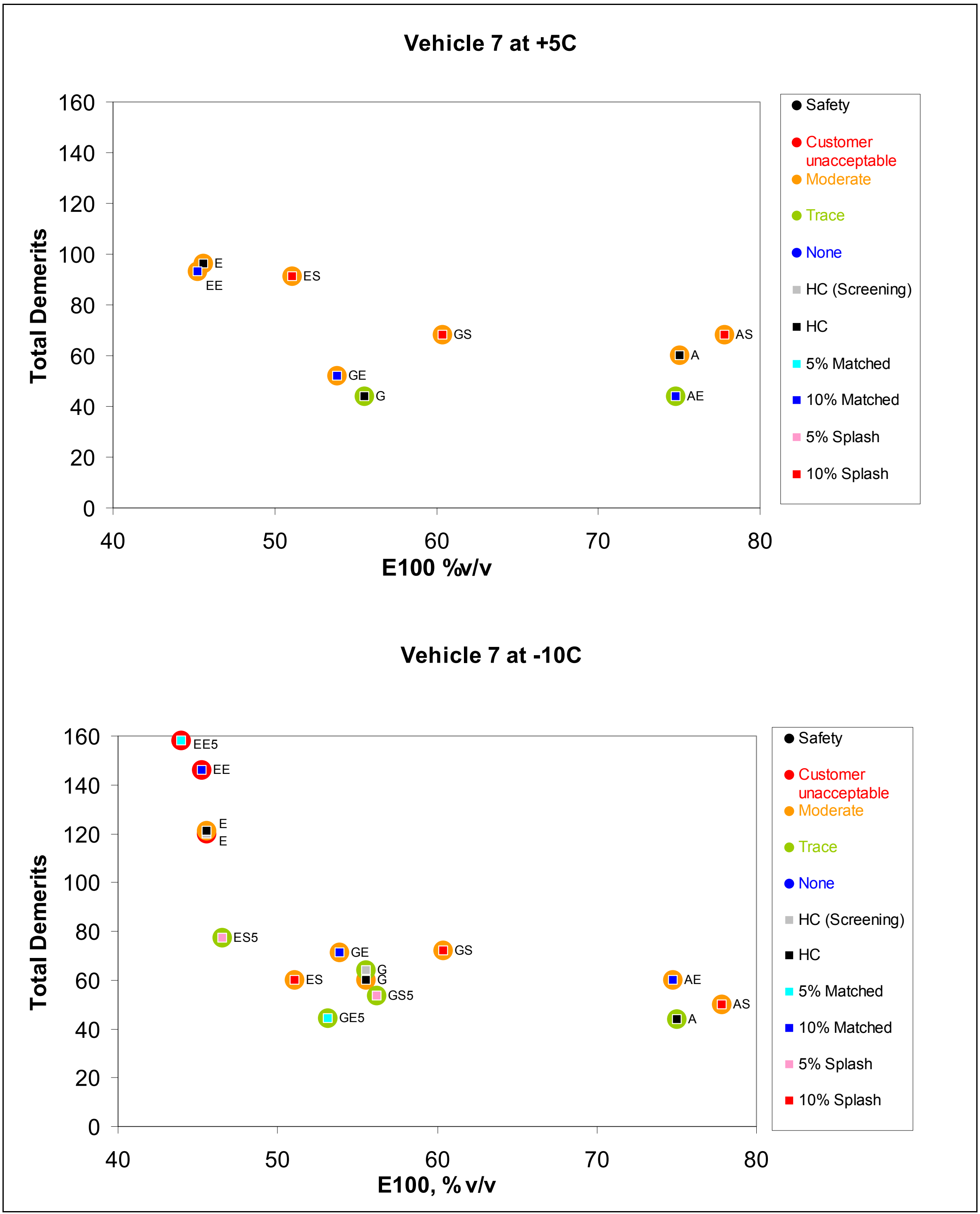
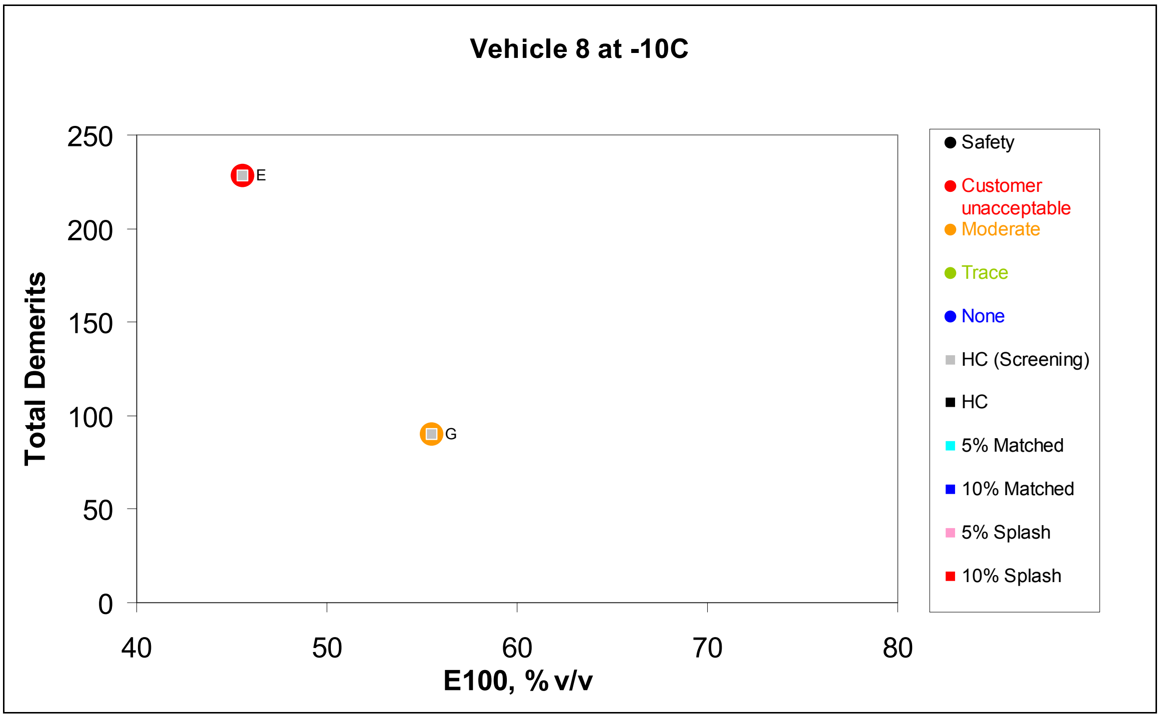


Figure 24 Total Cold Driveability Demerits of Vehicle 8



6.3. DISCUSSION OF RESULTS

6.3.1. Data Handling and Statistical Analysis

As for hot weather driveability analysis, and as discussed in **Appendix 2**, the data was analysed on a log(DD+B) scale, an offset B being essential due to the presence of tests with DD = 0. Finding a suitable transformation of the demerit data using standard deviation vs. mean plots was difficult as the only repeat tests were those conducted at the screening stage. A transform of the form $\log_{10}$(DD+4) was selected for consistency with the hot weather analysis but this was one of many possible alternatives. Thus models of the form:

$$\log_{10}(DD+4) = a + b \times E100 + c \times TEMP + d \times E100 \times TEMP + e \times EtOH + \ldots$$

(or some subset thereof) were fitted to the demerit data for the 4 vehicles selected for full testing. The measured values of E100 and %v/v EtOH were used throughout. However, as the relationships between cold-weather demerits, E100, temperature and ethanol content were not as clearly non-linear as found in the hot-weather programme, models of the form:

$$DD = a + b \times E100 + c \times TEMP + d \times E100 \times TEMP + e \times EtOH + \ldots$$

were also examined. The non-normality in the data was taken care of using iteratively re-weighted least squares (see **Appendix 2**).

Models in E70, E150 and DVPE were not considered as these varied in parallel with E100, the correlation matrix across the 9 main fuels (A, AE, AS, G, GE, GS, E, EE, ES) is shown in **Table 5**.

Table 5 Cold Driveability Fuels correlation between distillation properties

	E70	E100	E150	DVPE
E70	1.00	0.96	0.90	0.97
E100	0.96	1.00	0.95	0.99
E150	0.90	0.95	1.00	0.96
DVPE	0.97	0.99	0.96	1.00

Therefore E100 can be considered as an omnibus parameter representing the overall volatility of the fuel.

The test data are presented in **Figures 17-24** and most of the discussion is based around those visualisations. The prime purpose of the statistical analysis is to determine whether volatility, temperature and ethanol have significant effects. The absence of a significant effect does not mean that the variable does not have an effect, rather that its effect is too small to see above the noise within the available data.

Only a small number of vehicle × fuel × temperature combinations were repeat tested. This meant that the only way to detect possible outliers was to inspect studentized residuals (residuals divided by their standard errors) after fitting models such as the above. Time trends were sought by adding a TestNo term and checking its significance. In practice, conclusive affirmation of individual outliers and trends was difficult to find.

The results need to be examined on a vehicle-by-vehicle basis due to the wide differences in both vehicle design and sensitivity to fuels. Statistical modelling exercises were therefore conducted for vehicles 1, 2, 6 and 7 where the nine main test fuels (and in some cases 5% ethanol blends) were tested at both temperatures (-10°C, +5°C).

6.3.2. DISI Vehicles

Two of the DISI vehicles (1,2) were tested on all fuels; the third (3) was only tested on two fuels at -10°C.

Vehicle 1 gave relatively low demerit levels (<100) at both temperatures. At +5°C there were no clear trends, but at -10°C demerits were highest for the low E100 fuels, mostly due to poor cold starting.

Vehicle 2 gave very high demerit levels but no obvious effect of volatility or ethanol content. Demerits were mainly idle roughness, acceleration stumble and cruise surge throughout all six phases of the test. This suggests the air/fuel ratio calibration may be excessively lean for these temperatures.

Vehicle 3 showed high demerits (169) on the least volatile fuel E, but much less (65) on fuel G at -10°C.

6.3.3. MPI Vehicles

Two MPI vehicles (6, 7) were tested on the nine main fuels, whereas vehicle 4 was tested only on hydrocarbon fuels, but not ethanol blends due to the technical problem associated with this vehicle (see **Section 6.1**).

Vehicle 6 gave <130 demerits under all fuel/temperature conditions. Demerits were somewhat higher at –10 than +5°C, and highest on the lowest volatility fuels, and all demerits above 70 at +5°C were on fuels E, ES or EE. The majority of demerits in all cases were due to acceleration stumble.

Vehicle 7 gave similar demerits at +5°C and -10°C, in the range 40-100 except on the E-series fuels at -10°C when demerits were in the range 60-160, mainly due to cold start problems.

The three hydrocarbon fuels were tested at each temperature in vehicle 4. Demerit levels were more than twice as high at -10°C than at +5°C but no volatility effect was observed. The high demerits at -10°C were mainly due to acceleration stalls and stumble.

The other two MPI vehicles (5 and 8) were tested at -10°C only. Vehicle 5 gave 90 demerits on fuel G and 116 on E, while vehicle 8 also gave 90 demerits on fuel G, but this increased to a high 228 on the least volatile fuel E. This was mainly due to very poor cold starting with 9 attempts required to start the vehicle.

6.3.4. Volatility Effects

Figures 17 to 24 show driveability demerits plotted against actual measured E100. Clearly the majority of vehicles show some increase in total demerits with reducing fuel volatility. Exceptions to this are vehicles 1 and 2 at +5°C and vehicle 4 at -10°C, which showed no clear effect. A number of the vehicles showed higher demerits at -10°C on Fuels E, ES and EE, in particular vehicles 1, 6, and 7. Although further data would be needed to accurately determine a critical E100 level below which the demerits increase, it is estimated to be around 50 %v/v.

In several cases this was due largely to difficult cold starting. It is worth noting that in some cases, starting performance was worse during the test after the initial cold start, when the vehicle is stopped and restarted during each test phase.

Statistical modelling was carried out on vehicles 1, 2, 6 and 7 to look for fuel volatility and ethanol effects as discussed above, also to look for effects of temperature and any performance changes over time. In most cases however, there were too few data points and effects of E100 appeared to be non-linear, so quantification of the effects via model equations added little value.

Modelling of vehicle 1 showed that increasing E100 significantly decreased demerits at -10°C both on the original DD and $\log_{10}(DD+4)$ scales (P<0.1%). At +5°C, E100 had no significant effect but a significant upward time trend was seen in the results. Higher demerits on fuels AS, AS5 and AE5 were observed, but it is not clear if these are due to the ethanol or to the time trend observed. Apart from the different responses to E100, the temperature effect was small.

Similar patterns were seen in vehicle 7. At -10°C, raising E100 significantly decreased demerits both on the original DD and $\log_{10}(DD+4)$ (P<1%) scales. No significant E100 effect was seen at +5°C. No ethanol effect was seen and, apart from the different responses to E100, the temperature effect was small. A significant upward time trend was seen in the +5°C results.

Demerit levels were higher in vehicle 2 than in vehicles 1, 6 and 7. However, no significant volatility, ethanol or temperature effect was observed. The only significant feature was a decrease in demerits with time at -10°C.

For vehicle 6, demerit models on the original DD scale fit better than those for log_{10}(DD+4). Analysing the results at -10°C and +5°C separately, neither E100 nor ethanol showed a significant effect at either temperature, although a trend to higher demerits with low E100 is apparent in **Figure 22**. Analysing the vehicle 6 data as a whole however, all three variables showed small effects and the model[3]

$$DD = 103.9 - 1.142^{*} \times E100 - 1.758^{*} \times T + 2.807^{*} \times EtOH \quad \text{(vehicle 6)}$$

gives a reasonable data summary. These effects are now statistically significant at P<5% with increased volatility or temperature reducing demerits. The positive ethanol term indicates that, as a general trend, demerits from matched blends are higher than those from hydrocarbon fuels of the same volatility. It also indicates that splash blending ethanol does not produce the reduction in demerits that one might expect from the resultant increase in E100.

As, in contrast to the hot weather results, the vehicles selected for cold weather testing appeared to behave in a similar fashion, the data for vehicles 1, 2, 6 and 7 was analysed as a fleet at -10°C and +5°C to see if any significant patterns emerged.

At +5°C, there were significant differences between vehicles (P < 0.1%), but no evidence was found of an E100 or an ethanol effect.

At -10°C, E100 had a significant effect overall (P < 0.1%) when the following models were fitted:

$$log_{10}(DD+4) = v_i - 0.013^{***} \times E100 \qquad \text{(HC fuels only)}$$

$$log_{10}(DD+4) = v_i - 0.010^{***} \times E100 \qquad \text{(all fuels)}$$

where the intercept v_i varies from vehicle to vehicle in each case (P < 0.1%). Thus reducing E100 from 75°C to 46°C increased overall demerit levels by a factor of approximately two. No evidence was found of an ethanol effect at –10C.

6.3.5. Ethanol Effects

Splash blending ethanol into a fuel substantially increases it's mid-range volatility (E70 and E100) as measured by the ASTM equilibrium distillation test. However the higher latent heat of ethanol means that it may not vaporise as well in a cold engine where the availability of heat is limited. Matched volatility blends must have other

[3] * Regression coefficient significantly different from zero at P < 5%, i.e. we are 95% confident that the effect is real
** Coefficient significant at P < 1%
*** Coefficient significant at P < 0.1%
NS Coefficient not significant at P < 5%

light components removed, so might be expected to perform less well in engines than hydrocarbon fuels.

Figures 25-28 shows the demerit data as bar charts comparing hydrocarbon and ethanol fuels at the three volatility levels. There was substantial variability in the data, as can be seen from the few repeat tests. Thus it is not surprising that ethanol effects were not clear and often contradictory, which is confirmed by the statistical analysis described above. Vehicle 7 at -10°C was the closest to the expected trend, with the matched volatility E-blends showing higher demerits than hydrocarbon fuels or the S-blends, but this was not the case at +5°C. In contrast Vehicle 2 showed the opposite trend at both temperatures, with ethanol blends generally giving lower demerits than hydrocarbon fuels (except E-series at +5°C), with matched volatility E-blends sometimes better and sometimes worse than the splash blends. Vehicle 1 showed an improvement with ethanol splash blends on fuel E at -10°C, consistent with vehicle 7, but no other clear trends, and vehicle 6 showed conflicting behaviour of the ethanol blends for different fuel/temperature combinations.

The effects of ethanol were varied. Only on a single MPI vehicle (6) was a small statistically significant effect of ethanol seen. However, on the lowest volatility fuel, splash blending ethanol generally improved driveability at –10 C (but not at +5 C). The matched volatility ethanol blends behaved similarly to the HC fuels. It is likely that the effects seen are a consequence of the increase in volatility caused by the addition of ethanol rather than the presence of ethanol per se.

Figure 25 Cold Driveability Summary of vehicle 1 at +5 and -10°C

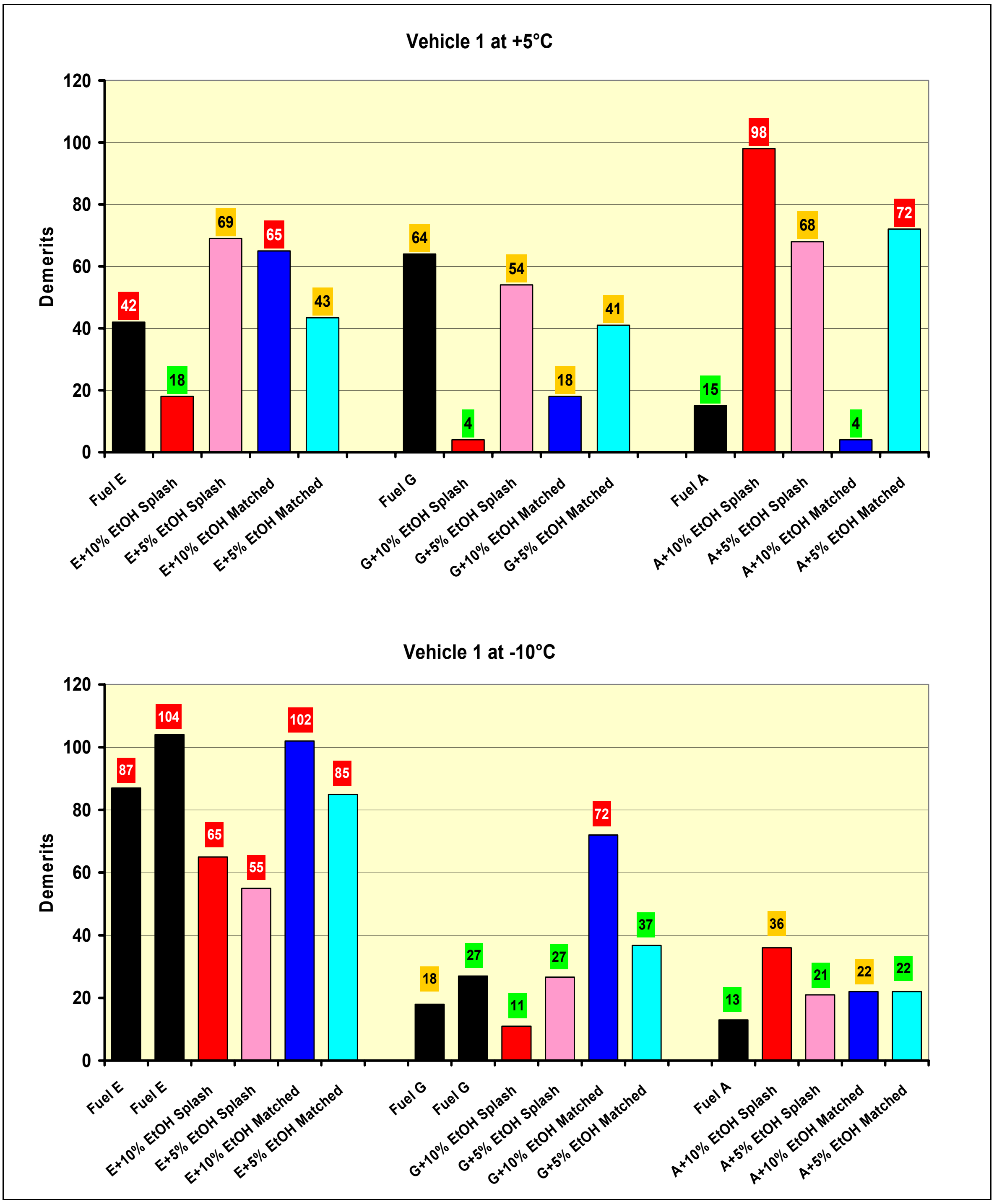


Figure 26 Cold Driveability Summary of vehicle 2 at +5 and -10°C

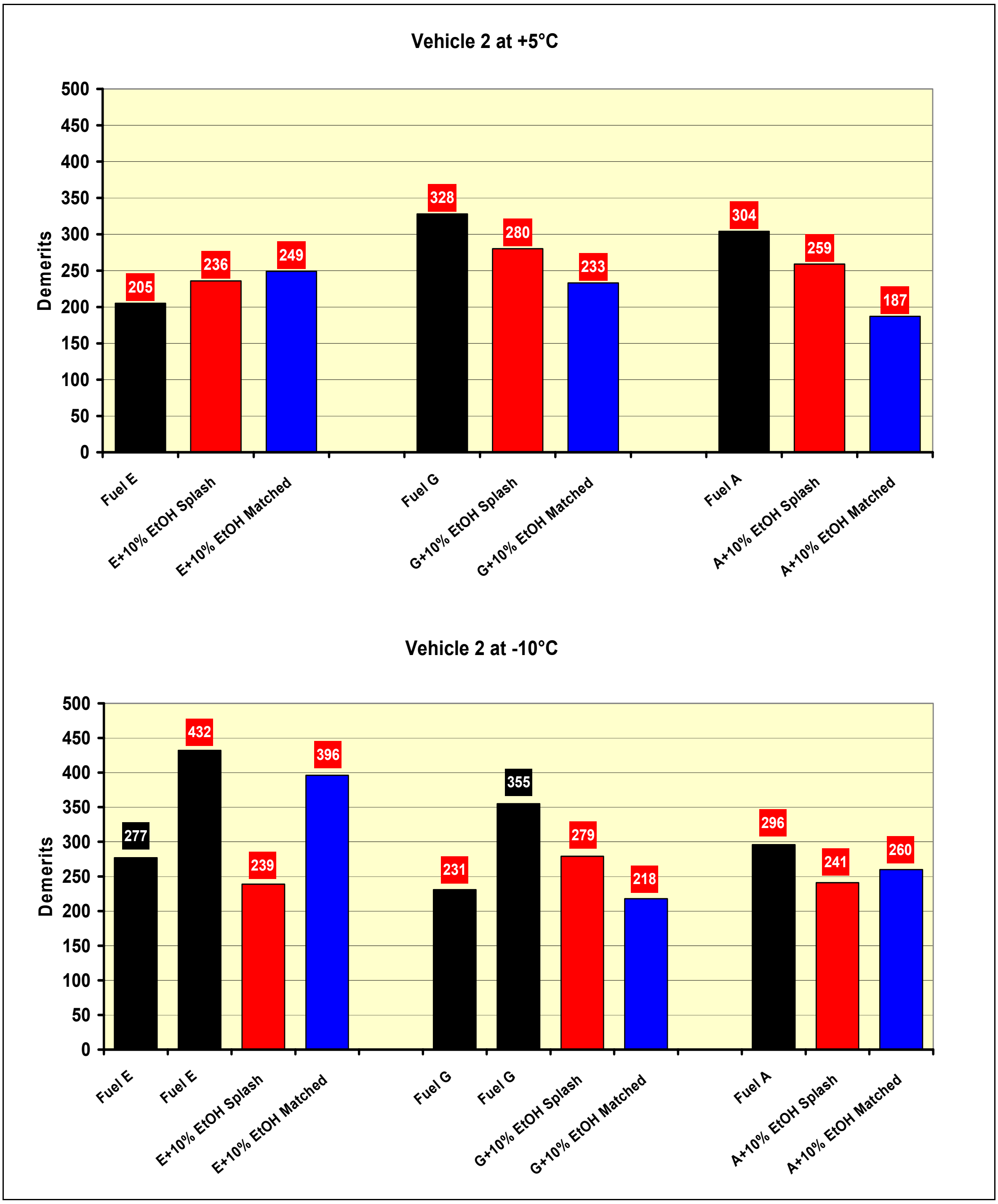


Figure 27 Cold Driveability Summary of vehicle 6 at +5 and -10°C

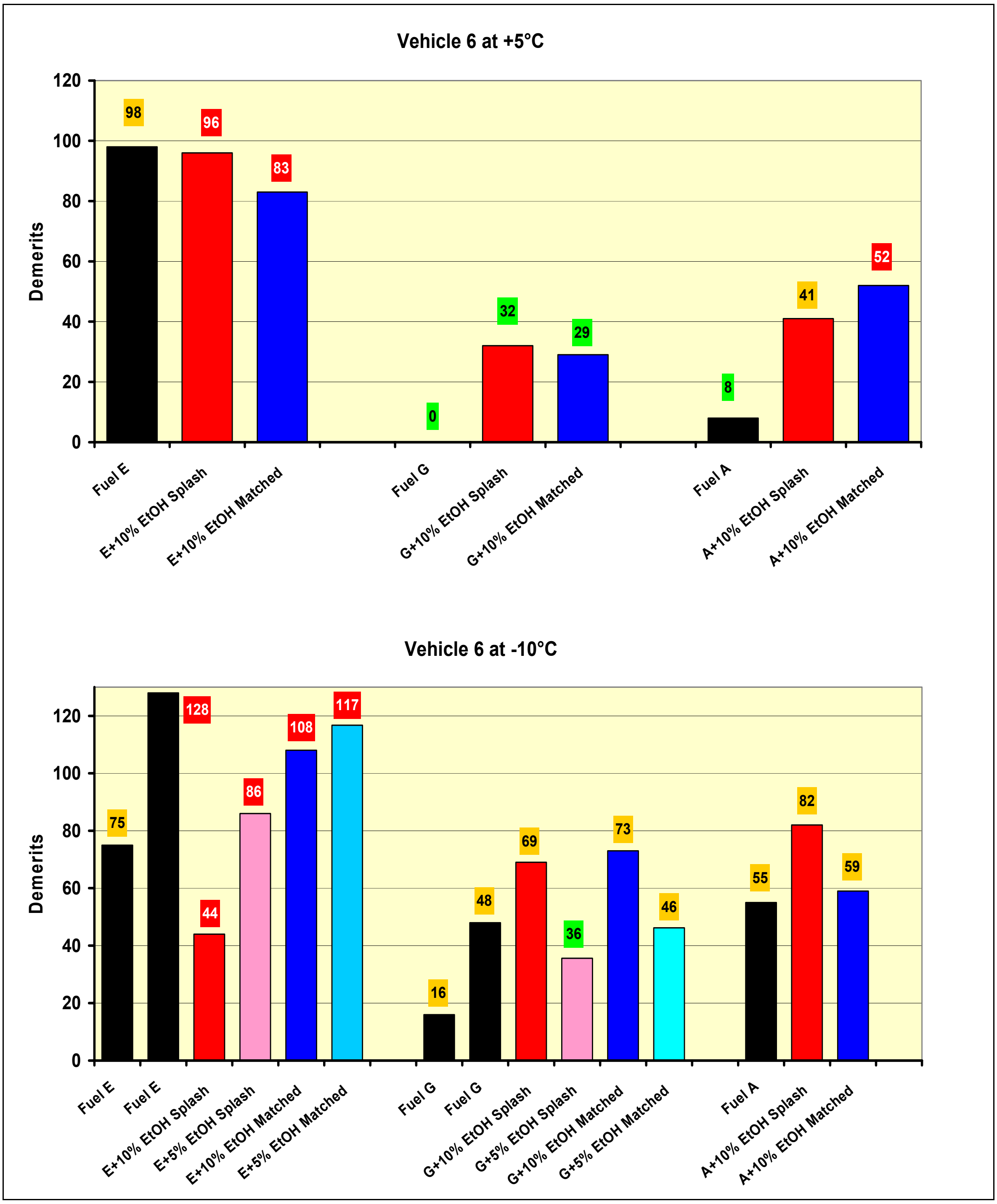
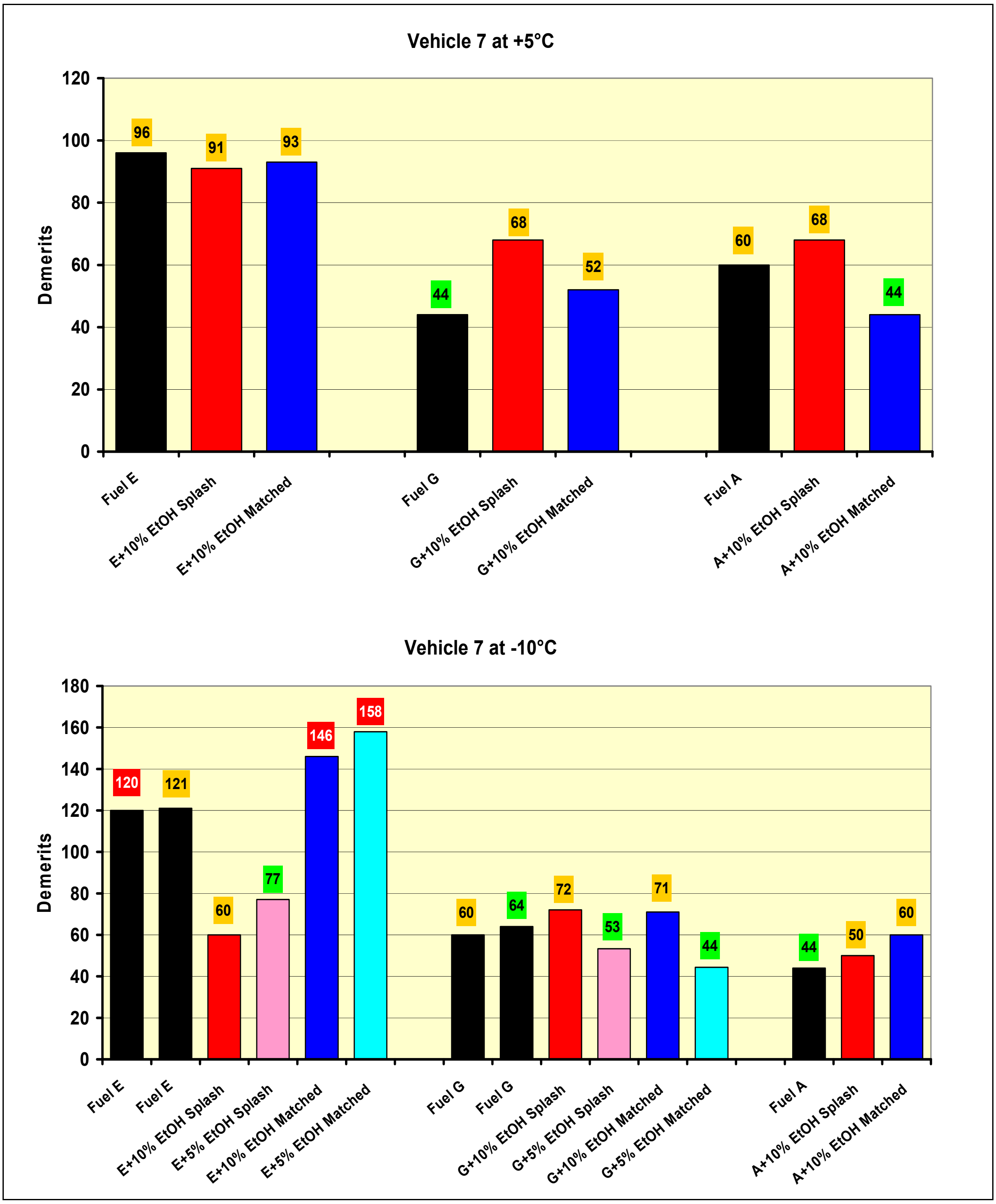


Figure 28 Cold Driveability Summary of vehicle 7 at +5 and -10°C



7. COMPARISON WITH US CRC DRIVEABILITY TEST PROGRAMMES

The US CRC (Co-ordinating Research Council) has run a number of hot and cold-weather driveability test programmes over recent years, also looking at ethanol blended fuels. It is instructive to compare their results with this programme, although there are substantial differences between GFC and CRC test procedures. All CRC procedures for both hot and cold weather testing are carried out on the road, not on chassis dynamometers. A summary of CRC procedures is given in **Appendix 3**.

7.1. Hot Driveability Programmes

The most recent CRC HFH programmes conducted in 1999 and 2001 [5,6] tested 11 fuel-injected vehicles on 14 test fuels and 20 fuel-injected vehicles using 12 test fuels respectively. None of the cars tested were direct-injection vehicles.

The 1999 programme used seven hydrocarbon-only fuels and seven corresponding 10% ethanol splash blends. The two parameters most commonly used to describe hot driveability behaviour of US MPI vehicles had been dry vapour pressure equivalent (DVPE) and the temperature for a vapour-liquid ratio of 20 (T_{VL20}). These parameters showed poor correlation with driveability of both hydrocarbon-only fuels and 10 volume percent ethanol blends. Fuel volatility measurements at higher pressures, i.e. the temperature for a vapour-liquid ratio of 1 at 500kPa pressure (TVL1-500), considered to be representative of those in fuel delivery systems, showed the best correlation with both sets of fuels:

Ln TWD regressed against TVL1-500	adjusted R^2 = 0.92
Ln TWD regressed against DVPE	adjusted R^2 = 0.25
Ln TWD regressed against TVL20	adjusted R^2 = 0.37

However, TVL1-500 is not a standard parameter (i.e. no ASTM standard), and cannot be easily measured by most laboratories. Therefore, efforts were made to develop several indices using conventional parameters such as DVPE and TVL20. Two indices showed good correlation with total weighted demerits (TWD), giving the following correlations with linear ethanol offsets:

Ln TWD regressed against DVPE + 0.234 × [Ethanol %v/v]	adjusted R^2 = 0.87
Ln TWD regressed against TVL20 − 1.01 × [Ethanol %v/v]	adjusted R^2 = 0.87

However, it was thought that these models would probably be specific to the set of fuels used in this study, so additional studies were proposed to broaden the application of these indices.

The 2001 programme used three volatility levels of four fuels each: hydrocarbon-only gasoline and 3, 6, and 10 %v/v ethanol blends, giving a total of 12 test fuels. The volatility parameter used to design the front-end volatility of each group was the TVL1-500 (see above). The results showed that again TVL1-500 was the single volatility parameter with the highest level of correlation confirming the 1999 results. However once again the T_{VL20} in combination with an ethanol offset was as good as TVL1-500 at predicting TWD. This time, the correlations were:

Ln TWD = −0.0586 TVL1-500 + 9.0458	adjusted R^2 = 0.86
Ln TWD regressed against TVL20 − 1.27 × [Ethanol %v/v]	adjusted R^2 = 0.88
Ln TWD regressed against DVPE + 0.338 × [Ethanol %v/v]	adjusted R^2 = 0.88

7.2. COLD DRIVEABILITY PROGRAMMES

Recently 2 CWD studies were conducted in 2000 and 2003 [7,8]. In the 2000 programme, the temperature range investigated was 30°F to 45°F (0°C to 7°C). Four hydrocarbon-only fuels with three concentrations of ethanol (2, 5, 10 %v/v) and MTBE (3, 7.5, 15 %v/v) were used. The base fuel volatility was as follows:

E158°F (E70°C) = 15%	E200°F (E93°C) = 30%
E300°F (E149°C) = 75%	RVP = 7psi (50kPa)

The test fleet contained 31 cars and 14 Light/Medium Duty trucks. No conclusive overall effect of Driveability Index or oxygenate content on the cold-start and warm-up driveability performance could be found.

Since the general fleet showed little evidence of sensitivity, for the 2003 programme, the vehicles were screened to identify "sensitive" vehicles. Only those vehicles were used so that more demerits, as expected, were generated. Data analysis is now complete but at the time of writing the final report had not been issued by CRC.

8. CONCLUSIONS

The work has confirmed that the new GFC test procedures are capable of identifying fuel, vehicle and temperature effects on hot and cold weather driveability with modern vehicles. The procedures appear to be more discriminating than the former CEC test procedures.

HOT DRIVEABILITY

- Four of the eight vehicles tested (three MPI and one DISI) exhibited good hot driveability performance (≤24 demerits) under all fuel/temperature conditions tested. A fourth MPI vehicle only exceeded 24 demerits on the highest volatility, 10% ethanol splash blend at 30°C.
- The fifth MPI vehicle showed substantial demerits on high volatility fuels (>100 kPa DVPE, >55% E70) at 30°C, especially for the ethanol splash blends.
- Two of the DISI vehicles showed poor driveability performance with very high demerits (>200) on high DVPE fuels (>100 kPa) at 30°C (and for vehicle 2 at 20°C), also on some less volatile fuels at 40°C. One of these vehicles clearly suffered from vapour lock in some tests as a “low fuel pressure” engine warning was displayed.
- The limited number of vehicles tested and their wide variation in demerit levels and response to fuels meant it was not practicable to perform fleet analysis. Analysis of individual vehicle data suggested that DVPE and temperature were the variables that influenced driveability most, followed by E70 and then ethanol content.
- In general, ethanol splash blends increased demerits and in some cases overall severity rating. Matched volatility ethanol blends gave similar driveability to the equivalent hydrocarbon fuels. This suggests that the effects seen are not due to the presence of ethanol per se but are a consequence of the increase in volatility that is caused by the addition of ethanol.
- In all cases substantial increases in demerits were only seen at high temperatures on fuels with volatility beyond the summer limits of EN228. Test fuels that met the existing European summer specification for DVPE and E70, showed few driveability malfunctions at 30°C, although two DISI vehicles (2, 3) exhibited a higher level of demerits at 40°C. On fuel B, with similar DVPE but higher E70 than the EN 228 standard, vehicle 2 showed high demerit levels (>200) at 40°C, as did vehicle 3 on the more volatile 10% ethanol splash blend BS.

COLD DRIVEABILITY

- The new GFC cold-weather test cycle generated substantially higher driveability demerit levels than would be expected with the former CEC procedure, especially at -10°C.
- One DISI vehicle gave very high demerits on all fuels at both temperatures but showed no sensitivity to fuel volatility, ethanol content or temperature. The other two DISI vehicles were within the same range as the MPI vehicles. One of the MPI vehicles showed consistently high demerits at -10°C (see **Section 6.1**), but with no sensitivity to fuel volatility.

- There was little difference in demerit levels between the two test temperatures, except for the low volatility E series fuels that showed higher demerits at -10°C.

- Most vehicles showed sensitivity to fuel volatility with higher demerits on the less volatile fuels. Several vehicles showed a sharp increase in demerits on the least volatile E-series fuels (E100 < 50 %v/v) at -10°C. However this was not seen at +5°C.

- The effects of ethanol were varied. Only on a single MPI vehicle (6) was a small statistically significant effect of ethanol seen. However, on the lowest volatility fuel, splash blending ethanol generally improved driveability at -10°C (but not at +5°C). The matched volatility ethanol blends behaved similarly to the HC fuels. It is likely that the effects seen are a consequence of the increase in volatility caused by the addition of ethanol rather than the presence of ethanol per se.

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8. CRC (2004) 2003 CRC intermediate-temperature volatility program. CRC Report No. 638. Alpharetta GA: Coordinating Research Council

10. GLOSSARY

AFR	Air Fuel Ratio
ASTM	American Society for Testing of Materials
AQIRP	US Air Quality Improvement Research Programme
BTC	British Technical Council
CEC	Coordinating European Council
CRC	Coordinating Research Council (USA)
CWD	Cold Weather Driveability
DI	Direct Injection
DISI	Direct Injection Spark Ignition
DVPE	Dry Vapour Pressure Equivalent
E70	%v/v of gasoline evaporated at 70°C
E100	%v/v of gasoline evaporated at 100°C
E150	%v/v of gasoline evaporated at 150°C
ECE	Urban Driving part of the European Drive Cycle
EPEFE	European Programme on Engines, Fuels and Emissions
EtOH	Ethanol (ethyl alcohol)
EUDC	Extra Urban Driving Cycle
FBP	Final Boiling Point
GFC	Groupement Français de Coordination
HWD	Hot Weather Driveability
MPI	Multi-point injection
SD	Standard Deviation
TxxE	Temperature for a fixed (xx) percentage evaporated, e.g. T50E or T90E
WOT	Wide Open Throttle

APPENDIX 1 FUEL PROPERTIES

Table A1.1 Properties of Main Hot Weather Driveability Test Fuels

Fuel name	Method	A	AS	AS5	AE	AE5	B	BS	BS5	BE	BE5	C	CS	CS5	CE	CE5	D	DS	DS5	DE	DE5
DVPE, kPa	EN 13016-1	**101.5**	105.8	104.1	99.0	99.6	**63.8**	70.2	70.8	60.9	-	**103.2**	110.2	109.6	100.7	104.9	**60.4**	66.4	66.9	63.5	65.0
DVPE + 0.7E70	Calc.	**141.5**	153.9	146.4	137.6	140.0	**103.3**	118.6	111.5	99.1	-	**132.3**	150.3	142.6	130.4	133.3	**88.1**	104.8	98.2	92.2	91.3
Tv/l20	ASTM D4814 linear equation	**37.0**	34.5	34.8	40.1	38.9	**52.4**	48.2	48.8	54.2	-	**41.0**	35.4	37.7	44.0	42.0	**56.7**	51.6	53.6	57.9	56.1
E70, %v/v	EN ISO 3405	**57.2**	68.7	60.4	55.2	57.8	**56.4**	69.2	58.2	54.7	-	**41.7**	57.3	47.2	42.4	40.6	**39.6**	54.9	44.7	41.1	37.6
E100, %v/v	EN ISO 3405	**75.1**	77.9	76.1	74.8	75.5	**75.6**	77.9	76.1	76.2	-	**60.9**	66.2	62.4	61.4	60.2	**61.8**	65.5	62.4	61.9	61.8
E150, %v/v	EN ISO 3405	**93.7**	94.6	94.1	93.7	93.9	**94.2**	94.9	94.2	94.7	-	**87.8**	89.5	88.7	88.2	88.0	**89.3**	90.3	89.5	88.4	87.8
											-										
IBP °C	EN ISO 3405	**26.8**	26.9	28.1	27.9	28.1	**36.3**	36.7	36.5	37.3	-	**25.0**	25.9	28.7	26.9	29.3	**32.2**	35.4	35.8	37.9	34.7
T10 °C	EN ISO 3405	**37.9**	37.4	37.0	44.3	40.0	**49.2**	46.0	46.2	52.8	-	**40.8**	40.2	40.4	49.7	44.3	**50.1**	48.2	47.8	56.8	50.5
T50 °C	EN ISO 3405	**61.2**	56.0	54.8	67.2	66.5	**65.5**	57.1	61.6	66.1	-	**84.9**	66.2	78.3	87.2	90.2	**83.4**	67.2	80.5	88.3	88.1
T90 °C	EN ISO 3405	**135.8**	132.4	133.9	129.4	132.3	**129.3**	125.5	127.1	120.6	-	**178.9**	170.6	172.8	177.7	177.7	**160.4**	160.0	162.9	173.9	166.0
FBP °C	EN ISO 3405	**189.5**	190.2	188.9	196.4	192.1	**193.4**	191.0	191.0	192.8	-	**201.6**	198.2	200.4	199.2	202.5	**203.7**	201.8	203.3	201.5	201.7
Density, kg/m^3 @15°C	DIN 51757/V4, EN ISO 12185	**714.3**	721.2	718.5	747.0	731.0	**723.0**	728.5	726.7	744.6	-	**721.9**	727.1	726.9	751.1	738.4	**733.5**	739.1	736.5	766.2	745.3
RON	EN 25164	**96.0**	98.8	-	98.8	-	**96.2**	100.1	-	97.6	-	**97.6**	100.5	-	100.1	-	**96.9**	100.5	-	100.4	-
MON	EN 25163	**85.8**	86.6	-	86.2	-	**87.3**	88.8	-	87.2	-	**88.9**	90.1	-	88.3	-	**88.7**	89.8	-	88.1	-
Sulphur, mg/kg	ASTM D 2622-94 ASTM D5453	**46**	43	-	41	-	**40**	36	-	39	-	**40**	35	-	45	-	**41**	35	-	37	-
Aromatics, %v/v	ASTM D 1319	**20.7**	18.0	-	22.5	-	**22.2**	20.3	-	23.1	-	**22.3**	21.7	-	22.7	-	**29.1**	25.6	-	25.3	-
Olefins, %v/v	ASTM D 1319	**5.9**	4.5	-	3.7	-	**0.5**	0.4	-	0.6	-	**0.6**	0.5	-	0.5	-	**0.5**	0.4	-	0.6	-
Saturates, %v/v	ASTM D 1319	**73.4**	67.5	-	64.0	-	**77.4**	69.3	-	66.3	-	**77.2**	67.8	-	66.8	-	**70.4**	64	-	64.0	-
Ethanol, %v/v	EN 1601	**<0.1**	9.8	4.9	9.9	5.1	**<0.1**	10.1	5.0	10.1	-	**<0.1**	10.0	5.0	10.2	5.3	**<0.1**	10.6	5.3	10.5	5.1

Table A.1.2 Properties of Interblend fuels used in Hot Driveability testing

Fuel name	Method	A-B	A-C	B-D	C-D	B-BD	BS-DS	BE-DE
DVPE, kPa	EN 13016-1	83.0	101.4	61.5	81.1	62.1	68.8	61.7
DVPE + 0.7*E70	Calc	122.5	136.3	94.3	109.4	97.8	111.8	94.4
Tv/l20	ASTM D4814	44.5	38.9	54.6	48.9	53.7	49.8	55.9
E70, %v/v	EN ISO 3405	56.5	49.9	46.9	40.5	51.0	61.4	46.7
E100, %v/v	EN ISO 3405	75.5	68.3	68.9	61.3	72.2	71.1	69.4
E150, %v/v	EN ISO 3405	94.0	90.8	91.5	88.6	92.9	92.1	91.2
IBP °C	EN ISO 3405	31.8	27.7	37.2	30.1	37.5	35.8	39.0
T10 °C	EN ISO 3405	43.1	39.2	49.9	45.1	49.8	47.5	55.0
T50 °C	EN ISO 3405	63.6	71.1	73.1	83.6	69.2	61.8	75.3
T90 °C	EN ISO 3405	130.0	148.6	137.9	171.4	131.1	133.9	138.7
FBP °C	EN ISO 3405	190.6	200.6	197.2	204.9	193.1	196.5	200.1
Ethanol, %v/v	EN 1601	<0.1	<0.1	<0.1	<0.1	<0.1	10.4	10.2

Figure A.1.1 Distillation curves for Hot Driveability Test Fuels

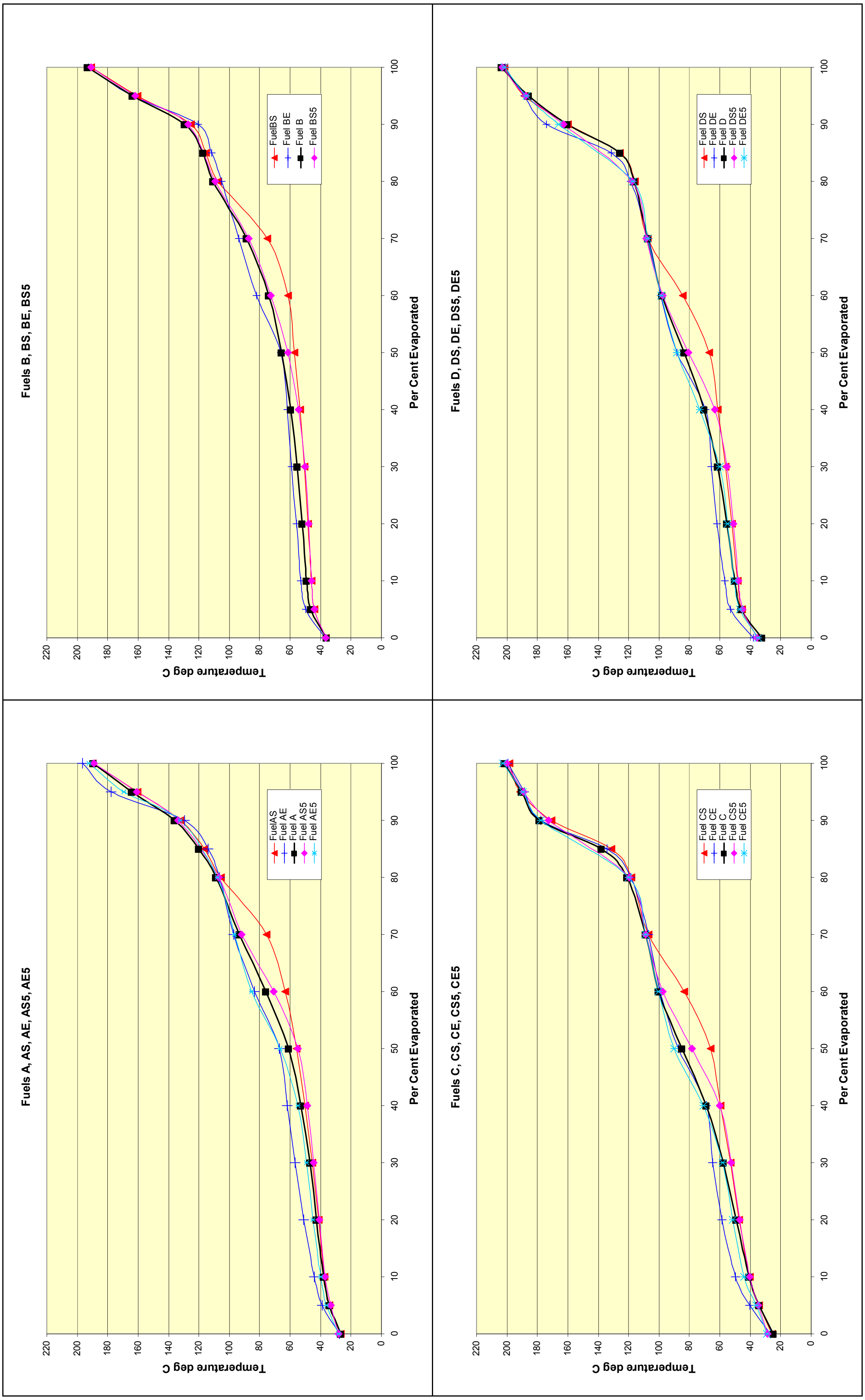


Figure A.1.2 Vapour Pressure vs. Temperature variation for Hydrocarbon and 10% Ethanol Splash and matched volatility blends:
"Power" equations have been fitted to each dataset e.g. DVPE = A(Temp)^n

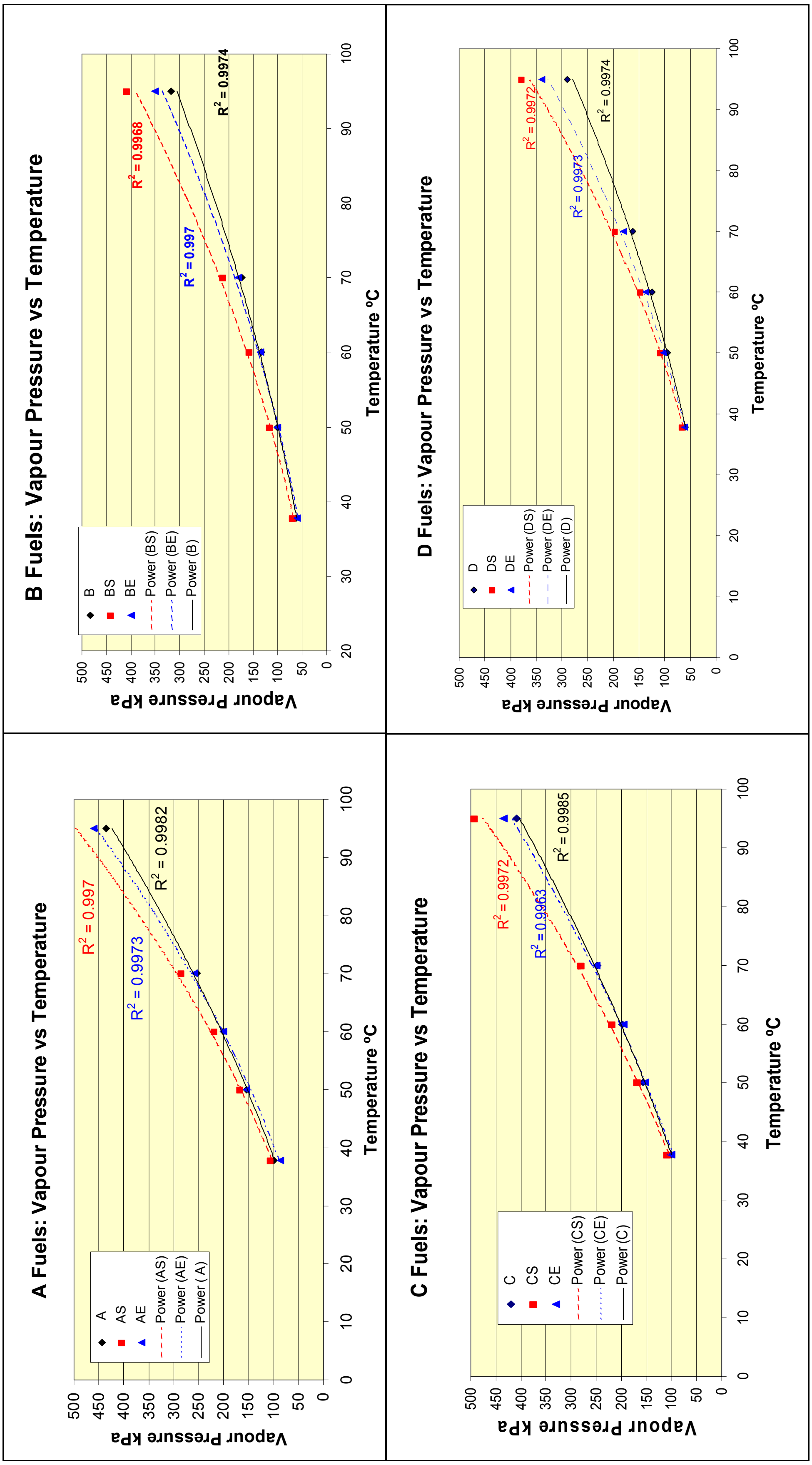
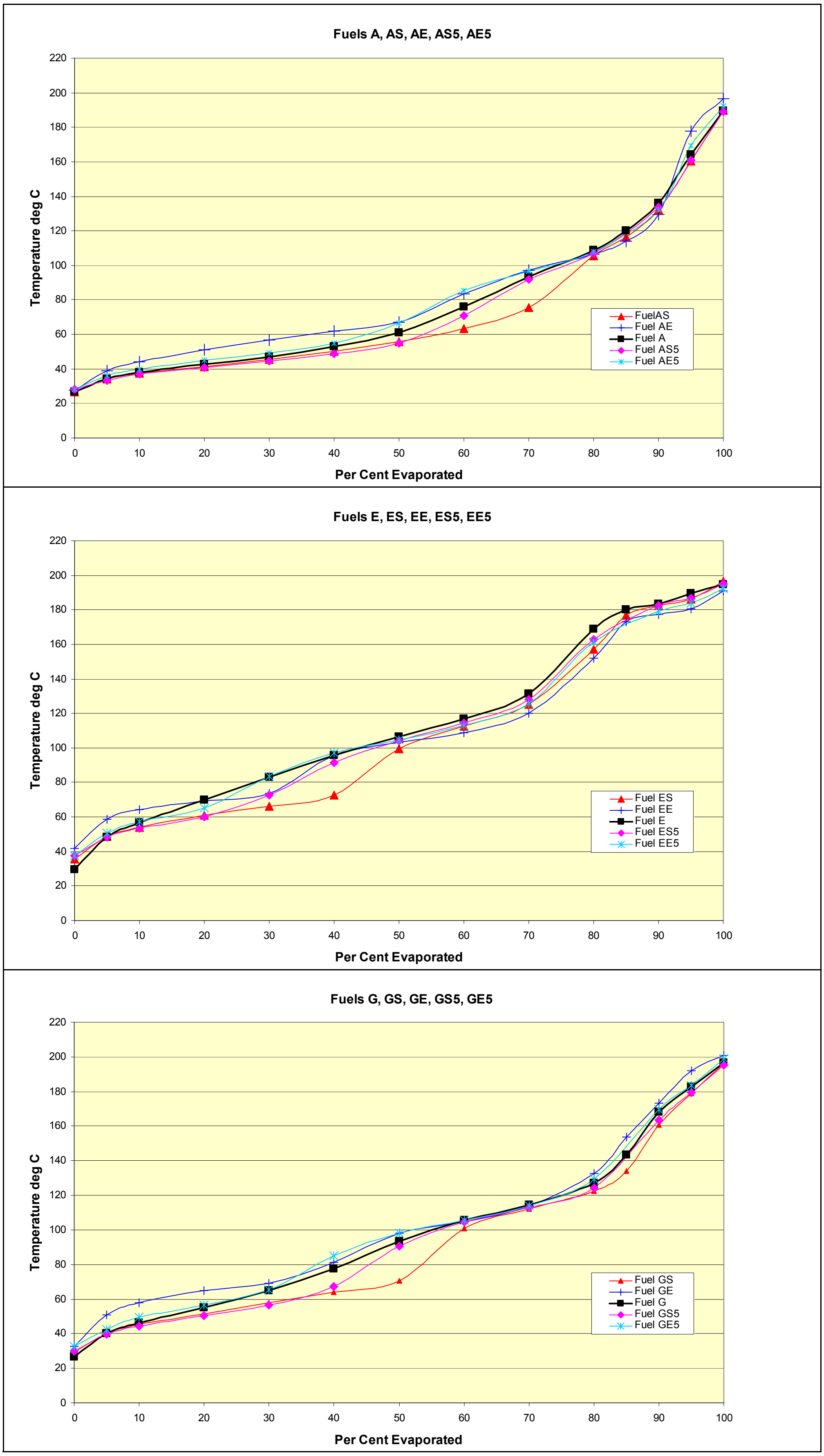


Table A.1.3 Properties of Cold Driveability Test Fuels

Fuel name	Method	A	AS	AS5	AE	AE5	E	ES	ES5	EE	EE5	G	GS	GS5	GE	GE5
DVPE, kPa	EN 13016-1	**101.5**	105.8	104.1	99.0	99.6	**67.8**	74.5	66.6	65.7	66.0	**80.6**	87.2	86.9	81.3	82.4
DVPE + 0.7E70	Calc.	**141.5**	153.9	146.4	137.6	140.0	**83.0**	101.4	87.0	82.0	83.1	**105.5**	122.0	116.0	104.9	105.9
Tv/l20	ASTM D4814 linear equation	**37.0**	34.5	34.8	40.1	38.9	**59.5**	55.6	58.9	61.2	60.0	**51.0**	44.8	48.1	53.9	51.9
E70, %v/v	EN ISO 3405	**57.2**	68.7	60.4	55.2	57.8	**21.7**	38.5	29.1	23.4	24.4	**35.5**	49.8	41.6	33.8	33.7
E100, %v/v	EN ISO 3405	**75.1**	77.9	76.1	74.8	75.5	**45.6**	51.1	46.6	45.3	44.0	**55.6**	60.4	56.3	53.9	53.2
E150, %v/v	EN ISO 3405	**93.7**	94.6	94.1	93.7	93.9	**77.6**	79.6	77.8	80.6	78.7	**87.3**	88.9	88.2	86.2	86.7
IBP °C	EN ISO 3405	**26.8**	26.9	28.1	27.9	28.1	**29.8**	35.5	37.6	42.0	37.6	**26.5**	29.3	30.0	32.8	32.7
T10 °C	EN ISO 3405	**37.9**	37.4	37.0	44.3	40.0	**56.8**	54.0	53.4	64.2	57.4	**46.2**	45.2	44.4	57.8	49.5
T50 °C	EN ISO 3405	**61.2**	56.0	54.8	67.2	66.5	**106.3**	99.4	104.2	103.2	104.7	**93.6**	70.8	90.7	98.3	98.1
T90 °C	EN ISO 3405	**135.8**	132.4	133.9	129.4	132.3	**183.2**	182.7	182.3	177.4	179.4	**168.3**	160.9	163.7	173.4	169.7
FBP °C	EN ISO 3405	**189.5**	190.2	188.9	196.4	192.1	**194.9**	196.6	195.0	190.9	192.3	**196.7**	196.3	195.4	201.0	199.2
Density, kg/m^3 @15 °C	DIN 51757/V4 EN ISO 12185	**714.3**	721.2	718.5	747.0	731.0	**761.9**	766.0	766.2	774.5	769.5	**730.4**	735.8	733.6	766.6	748.9
RON	EN 25164	**96.0**	98.8	-	98.8	-	**96.4**	99.9	-	101.0	-	**96.2**	99.4	-	99.2	-
MON	EN 25163	**85.8**	86.6	-	86.2	-	**86.9**	88.5	-	88.2	-	**88.0**	89.2	-	87.0	-
Sulphur, mg/kg	ASTM D 2622 ASTM D5453	**46**	43	-	41	-	**42**	35	-	39	-	**49**	45	-	38	-
Aromatics, %v/v	ASTM D 1319	**20.7**	18.0	-	22.5	-	**33.2**	31.3	-	26.5	-	**24.0**	22.0	-	26.7	-
Olefins, %v/v	ASTM D 1319	**5.9**	4.5	-	3.7	-	**0.6**	0.5	-	2.4	-	**0.5**	0.6	-	1.0	-
Saturates, %v/v	ASTM D 1319	**73.4**	67.5	-	64.0	-	**66.3**	58.2	-	61.2	-	**75.5**	67.4	-	62.4	-
Ethanol, %v/v	EN 1601	**<0.1**	9.8	4.9	9.9	5.1	**<0.1**	10.1	5.1	10.1	5.8	**<0.1**	10.1	5.5	10.3	5.7

Figure A.1.3 Distillation Curves of Cold Driveability Fuels



APPENDIX 2 STATISTICAL DATA ANALYSIS

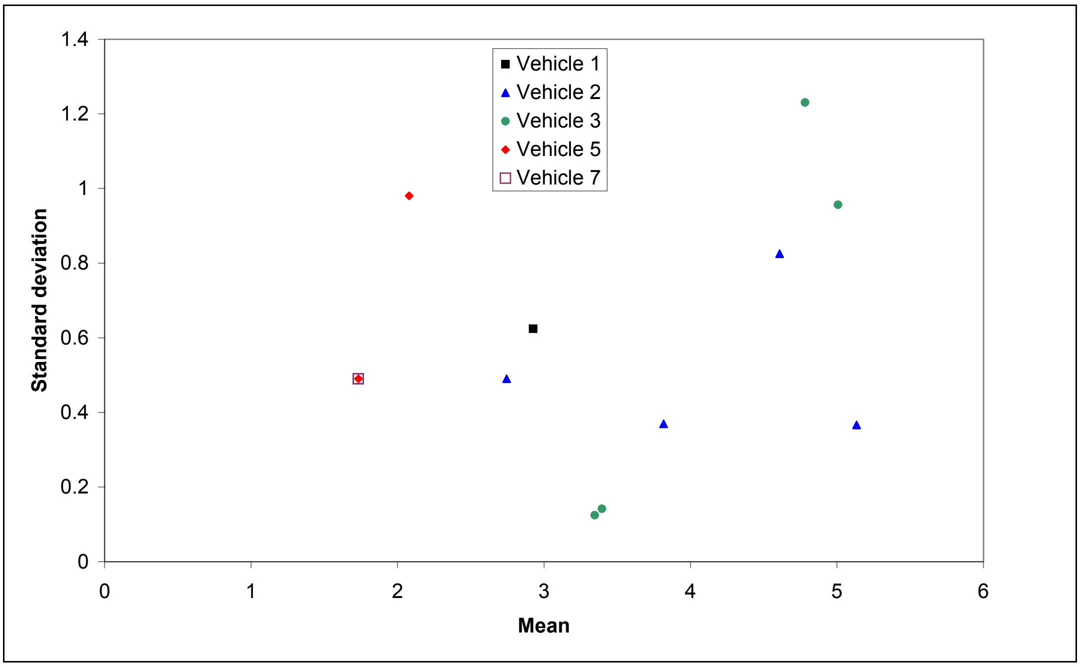
DATA TRANSFORMATION

The driveability of a vehicle on a particular fuel at a particular temperature is summarised by the total number of demerits (DD) accumulated across the various test cycles. Within each cycle, demerits are assigned to poor starting performance, stalls, stumbles, poor acceleration, etc., each measured on an arbitrarily defined demerit scale. These demerit scales are usually integer and most have an upper limit.

In previous driveability studies, e.g. [4], the variability in demerits has typically been found to increase as the number of demerits increases. This suggests that the data should be analysed on a log(DD+B) scale to stabilise the variability and render the data more amenable to standard statistical analysis techniques such as multiple regression. An offset B is essential due to the presence of tests with DD = 0.

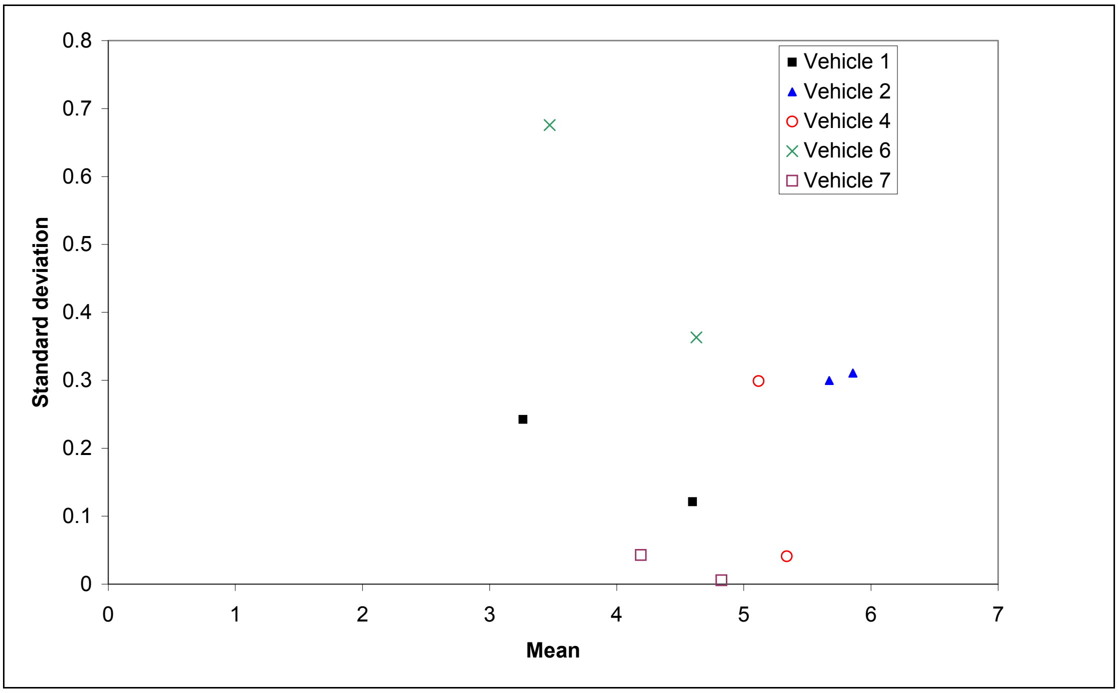
Standard deviation vs. mean plots were used to choose an appropriate value for the offset B. **Figure A.2.1** shows the standard deviation of $\log_{10}(DD+4)$ plotted against the mean for those vehicle × fuel × temperature combinations in the hot-weather programme where repeat measurements were taken (excluding the screening tests). Similar plots were produced for other values of B. The offset B = 4 was chosen as this minimised the dependence between the S.D. and the mean.

Figure A.2.1 S.D. vs. mean plot for log10(DD+4) in the hot-weather programme



Finding a suitable transformation of the cold weather demerit data using standard deviation vs. mean plots was more difficult as the only tests repeated were those conducted at the screening stage, all at –10C. **Figure A.2.2** shows a plot of the standard deviation of $\log_{10}(DD+4)$ against the mean for these pairs of cold-weather repeats. A transform of the form $\log_{10}(DD+4)$ was selected for consistency with the hot-weather analysis, but this was one of many possible alternatives.

Figure A.2.2 S.D. vs. mean plot for log10(DD+4) in the cold-weather programme



ITERATIVELY RE-WEIGHTED LEAST SQUARES

The results from both the hot- and cold-weather programmes needed to be examined on a vehicle-by-vehicle basis due to the wide differences in both vehicle design and sensitivity to fuels. Models of the following form:

Hot weather

$$\log_{10}(DD+4) = a + b \times E70 + c \times DVPE + d \times TEMP + e \times \%v/vEtOH +$$

Cold weather

$$\log_{10}(DD+4) = a + b \times E100 + c \times TEMP + d \times E100 \times TEMP + e \times \%v/vEtOH + \ldots$$

(or some subset thereof) were fitted to the demerit data for each vehicle using conventional multiple regression techniques. However such models are nonlinear when converted back to the original DD (demerit) scale and nonlinear models are not always appropriate.

Iteratively re-weighted least squares can be used to fit multiple regression models, e.g.

$$DD = a + b \times E100 + c \times TEMP + d \times E100 \times TEMP + e \times \%v/vEtOH + \ldots$$

on the original demerit scale when the dependent variable, here DD, is not normally distributed. The first step is to perform an unweighted regression analysis and calculate the fitted value for each observation. A second regression is then performed with each observation given a weight of

$$\text{weight} = 1 / (\text{predicted value} + 4)^2$$

The predicted values and weights are then recomputed and a subsequent weighted regression analysis is conducted. This process is continued until the regression coefficients have converged.

APPENDIX 3 US CRC DRIVEABILITY TEST PROCEDURES

Unlike the GFC procedure used in the current study, the US CRC (Co-ordinating Research Council) uses on-road procedures. While the fundamental principles are similar to the GFC procedure, in that demerits are assigned to similar malfunctions, there are differences in detail.

HFH Procedure (Full procedure in Ref 6)

(1) Drain vehicle fuel tank. Fill tank to 40% capacity with test fuel.

(2) Drive 15-mile warm-up cycle at 55mph and proceed to the test track entrance.

(3) Perform ten WOT accelerations from 0-35mph and park vehicle in soak tent.

(4) Turn engine off and soak for 20 minutes. Restart engine and record starting time, idle quality and the occurrence of any stalls.

(5) Ease vehicle at very light-throttle from soak tent onto test track. Stop and accelerate at wide-open-throttle to 35mph. Record any vehicle driveability malfunctions and severity.

(6) Drive back into the soak tent at 50mph and complete and repeat (3).

(7) Shift transmission into Park and idle for 20 minutes. Record any engine stalls. Attempt to restart engine immediately.

(8) After 20 minutes, record idle quality in Park and Drive.

(9) Ease vehicle at very light-throttle from soak tent onto test track. Stop and accelerate at a predetermined vacuum gauge pressure to 35mph. Records any driveability malfunctions.

(10) Proceed to soak tent at 50mph. Park vehicle in soak tent.

(11) Turn engine off and soak for 20 minutes. Restart engine and record starting time, idle quality and the occurrence of any stalls.

(12) Repeat (9).

CWD Procedure

The procedure that was used in the 2000 CWD program [7]) consists of a series of light, moderate and WOT manoeuvres mixed with idles to obtain as many evaluations of driveability in a cold engine as possible. Malfunctions recorded are hesitation, stumble, surge, stall and backfire, evaluated as being trace, moderate, heavy or extreme. The full procedure has CRC designation of E-28-94 .

(1) Turn key on for 2 sec. before cranking to pressurise fuel system. Record start time.

(2) There may be a total of three starting attempts recorded. If the engine fails to start within 5 seconds on any of these attempts, stop cranking at 5 seconds.

(3) Apply brakes and shift to Drive for 5 second idle and record idle quality. Record number of any stalls. A maximum of three stalls may be recorded.

(4) After idling 5 seconds, make a brief 0-15 mph light-throttle acceleration. Light-throttle accelerations will be made at a constant throttle opening beginning at a predetermined manifold vacuum. Use moderate brake to stop and idle for approximately 3 seconds without rating it. Make a brief 0-15 mph light-throttle acceleration. Use moderate brake to stop and idle for approximately 3 seconds without rating it. Both accelerations together should be made within 0.1 mile.

(5) Make a 0-20 mph WOT acceleration beginning at the 0.1-mile marker. Use moderate braking to achieve 10 mph and hold 10 mph until the 0.2-mile marker. Use moderate brake to stop and idle for approximately 3 seconds without rating it.

(6) Make a brief 0-15 mph light-throttle acceleration at the 0.2-mile marker. Use moderate brake to stop and idle for approx. 3 seconds without rating. If accelerations are completed before the 0.3-mile marker, cruise at 10mph to the 0.3-mile marker.

(7) Make a 10-20 mph light-throttle acceleration at the 0.3-mile marker. Use moderate braking to make a complete stop at the 0.4-mile marker and idle for approximately 3 seconds without rating it.

(8) Accelerate from 0-20 mph at the 0.4-mile marker, brake moderately and pull to the side of the roadway. Idle in Drive for 5 seconds and record idle quality.

(9) Repeat steps (4) through (8).

At colder temperatures,

(10) Accelerate (at constant vacuum) from 0-45mph. 0.4 mile is provided for this manoeuvre. Decelerate from 45 to 25 mph before the 0.4-mile marker.

(11) At the 0.4-mile marker, make a 25-35 mph acceleration.

(12) At the 0.5-mile marker, brake moderately. Idle for 30 sec. in Drive, recording idle quality after 5 sec. and after 30 sec. record any stalls that occur.