Shell Global Solutions

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The Effect of Fuel Cetane Quality on Light-Duty Diesel Performance

prepared by

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The Effect of Fuel Cetane Quality on Light-Duty Diesel Performance

Executive Summary[1,2]

Cetane number is a measure of the ignition quality of diesel fuel based on ignition delay in an engine. The higher the cetane number, the shorter the ignition delay. Conventional wisdom states that higher cetane number diesel fuels generate a less violent increase in cylinder pressure during compression ignition, which, in turn, results in more complete combustion and lower noise emissions.

Historically, the performance of diesel vehicles has been found to be sensitive to cetane number, particularly during cold start and cold operation. Under such conditions, injected fuel with a low cetane number will be more reluctant to vaporise and subsequently combust than a high cetane fuel would under similar conditions.

Diesel engine technology has been subject to significant advancement over recent years. Developments in fuel injection systems in particular have been key in this evolution. Fuel injection metering and fuel/air mixture preparation, where cetane quality was of key importance in older types, has been greatly improved with the introduction of high pressure solenoid controlled common rail and unit injector fuel systems.

Testing commissioned by the Coordinating Research Council, (CRC) undertaken by Shell Global Solutions in the UK entailed a programme of tests designed to determine the effect of fuel cetane number on light-duty diesel performance.

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In particular, this study used a climate controlled chassis dynamometer to test a matrix of 8 fuels with cetane numbers varying from 41 to 58, in four modern technology, High Speed Direct Injection (HSDI) passenger vehicles, (a Mazda 6, a VW Golf, a VW Lupo and a Toyota Avensis). Single tests were run using each car and fuel combination at three ambient temperatures, -10°C, 0°C and +10°C. Performance was evaluated using the following procedures:

- CEC-M-11-T-91, Cold Weather Performance Test Procedure for Diesel Vehicles to appraise cold start up and
- CEC-M-08-T-83, Cold Weather Driveability Test Procedure for cold driveability performance. (For details of test methods used and parameters evaluated see Appendices 4 and 8.)

In addition to the measurements detailed in the above procedures, the following were also measured: -

- engine noise and vibration during cold idle after start up
- tailpipe smoke opacity throughout the test. No other tailpipe emissions were evaluated.

The results of this study, designed to determine vehicle responses to the variables of cetane number and cold ambient temperatures, are summarised in the following paragraphs.

- **Time to start**

Attempts to record this variable were made using a stopwatch, by recording engine speed determined from a pulse generated by crankshaft rotation and via interpretation of battery voltage. Time to start was at worst, in the order of 1 second in the tests. Consequently, given the start up efficiency of the modern vehicles tested during this work, it was not feasible to differentiate vehicle response to cetane number using this measure, over the fuel and temperature ranges used.

- **Time for Engine Speed Rise**

The time taken for the engine speed to rise to 2000r/min from start up with full throttle applied was determined from engine speed data generated from crankshaft rotation. This was affected by temperature and cetane number in some tests. Impact of cetane varied dependent on vehicle model. The geometric fleet average results show that there is a statistically significant impact of cetane at –10°C, at the 95% confidence level, and no statistically significant effect at the warmer temperatures.

- **Sound Measurements**

Sound pressure was recorded using a microphone positioned in the vicinity of the cylinder head during the first 25 seconds of engine operation. The sound data were logged across the audible spectrum. Frequency ranges exhibiting correlation to combustion effects (100Hz – 4kHz), recorded during cold idle, were selected for further analysis and conversion to dB(A). Similar responses to temperature were seen in sound pressure levels recorded from all vehicles, with higher sound pressure levels occurring at lower temperatures. The response to cetane was vehicle model dependent. A trend in the fleet average sound pressure levels, (SPLs), at –10°C, is apparent which links higher cetane with higher SPLs, which is not statistically significant. At 0°C there is a trend in the same direction which is statistically significant at the 99% confidence level. There is no trend apparent in the data collected at +10°C.

Data recorded over the complete usable frequency range, (100Hz – 20kHz), over the entire testing period, (0-25 seconds), were also appraised. These data were influenced greatly by the engine speed rise section of the test and showed little correlation between cetane and sound levels.

A true market representation of average vehicle response would require a much larger selection of vehicle models to be tested.

- **Vibration**

Engine block vibration acceleration was measured using an accelerometer, over a frequency range of 20Hz – 20kHz during the first 25 seconds of engine operation. The data were analysed in the range where sensitivity to combustion effects was comparable in all vehicles (1 - 6kHz, 10-20 seconds), and converted to vibration velocity.

In the fleet average data, a trend linking higher cetane to increasing vibration can be seen at 0°C which is significant at the 95% confidence level. No trend can be identified at either the warmer or colder testing temperatures.

An appraisal of the data collected over the entire usable range (100Hz - 20kHz, 0-25 seconds) was also made. Little correlation between cetane and vibration levels could be seen in this data.

A larger selection of representative vehicle models would need to be tested to determine with certainty whether vibration tends to worsen with increasing cetane, and indeed whether this effect is only seen over a limited temperature range.

- **Smoke**

Smoke opacity was measured using a full flow opacimeter throughout each test. Reducing cetane number was found to correlate with increasing smoke at cold start, (0-10 seconds). This correlation is stronger at lower temperatures, a statistically significant relationship exists in the fleet average data at the 99% confidence level for tests run at –10°C. As each test progressed, the smoke/cetane relationship changed. Smoke values from a partially warmed engine were more likely to be higher with fuels of higher cetane number. In the fleet average data collected between start up and the end of the third drive cycle (0-327 seconds), at 10°C there is a relationship correlating increasing smoke with increasing cetane that is statistically significant at the 99% confidence limit. For the period spanning 90-327 seconds a similar trend exists at –10°C which is statistically significant at the 95% limit; trends in the same dataset at 0°C and 10°C are significant at the 99% confidence limit.

- **Measured Idle Quality**

This was defined as the standard deviation in idle speed recorded during the cold idle phase of the test, (10-25 seconds). This was determined from engine speed data generated from crankshaft rotation. More variation in idle speed occurs at lower temperatures. Not all of the vehicles tested showed idle quality sensitivity to cetane. Analysis of the fleet average data recorded between 10 and 20 seconds show that increasing cetane leads to improving idle quality at the two lower testing temperatures, this is significant at the 99% confidence limit. No relationship is detectable in the data at the +10°C testing temperature.
Idle quality was also assessed in the period where electrical load is applied (20-25 seconds). The data in this period contains no substantial relationship between cetane and idle quality.

- **Subjective Performance Ratings**

Subjective driveability malfunctions were logged in accordance with CEC M-08-T-83, (Cold Weather Driveability Test Procedure) throughout the test. The modern vehicles tested suffered few driveability faults during the tests. Of those recorded, the majority of the performance demerits were logged during tests run at -10°C. It was not possible to identify a statistically significant correlation between total weighted merits or driveability demerits and cetane. It was only possible to identify a correlation between cetane number and idle quality demerit ratings at –10°C. The correlation linking decreasing cetane with increasing idle quality demerits is statistically significant at the 95% confidence level.

- **Perceivable Vehicle Response to Cetane Number and Temperature Variations**

In general, it would be difficult for an untrained operator or bystander to identify any differences in the performance of the vehicles tested when subjected to the variations in fuel cetane number applied during this work. Two exceptions are in time to 2,000r/min and idle quality, where it is possible that an untrained operator or bystander might recognise the differences in performance caused by varying cetane at the lower test temperature. Some differences in noise levels between tests at the lower and higher test temperatures with the same vehicle and fuel combination narrowly exceeded the recognised limit of human perception, (3dB). It is possible that an untrained operator or bystander might recognise the differences in performance caused by varying temperature.
None of the vehicles were rendered inoperable by the use of the fuel set, (cetane number varying from 41 to 58) and temperature ranges, (-10°C to +10°C) employed.

- **Impact of Fuel Variables other than Cetane Number**

An appraisal of the data generated under this study showed that there was no impact of any fuel property other than cetane number apparent in the data, despite there being some variation in distillation and viscosity in the fuel set.

- **Impact of Natural versus Additised Cetane Quality**

Fuels of both natural and additised cetane quality were used in the study. To investigate whether this would impact on the results, an appraisal of the data was carried out. A substantial difference in only two data subsets was seen between fuels of natural and additised cetane. In both cases, fuels of additised cetane quality outperformed fuels of natural cetane quality. As this trend is only seen in a proportionately small amount of data, and is counter intuitive, it is concluded that this is a coincidental occurrence.

- **Overview of Vehicle Sensitivity to Cetane Number**

Based on the results from the 4 vehicles tested, it is concluded that modern diesel passenger cars equipped with solenoid controlled, high pressure DI fuel systems are less sensitive to variations in cetane number than older technology vehicles equipped with mechanical injection systems.
Further work and a larger fleet would be required to identify the temperature and cetane number ranges that would constitute the limits of acceptable operation for these vehicles. It

is technically possible to increase the range of testing temperatures, but engine damage could occur if cetane number was dropped much below the lower limit employed in this work. The limit of the lower testing temperature employed in this study was dictated by the highest CFPP (Cold Filter Plugging Point) identified in the test fuel matrix.

Tests recording in-cylinder pressure data would be necessary to determine the reasons for the counter intuitive impact on vibration and noise emissions with increasing cetane.

Contents

Statistical Analysis

Statistical significance - The standard convention of quoting significance at one of three confidence levels, viz. 95% (i.e., P < 5%), 99% (P < 1%) or 99.9% (P < 0.1%) as appropriate, is adopted throughout. Effects are deemed to be "not significant" if they are not significant at 95% (i.e., P < 5%).

Extent of statistical analysis – due to limitations on the scope of the study, statistical analysis, (as described in section 4.8), has been carried out on the following key datasets only:

Variable	**Dataset(s) analysed**
Time for engine speed rise, 0 – 2000 r/min	By car and fleet average, all temperatures
Cold idle sound pressure level, 100Hz - 4kHz, 10 – 20 seconds	By car and fleet average, all temperatures
Cold idle vibration, 1 – 6kHz, 10 – 20 seconds	By car and fleet average, all temperatures
Smoke opacity, 0 – 10 seconds	By car and fleet average, all temperatures
Smoke opacity, 0 – 120, 0 – 327 and 90 – 327 seconds	Fleet average, all temperatures
Measured idle quality, 10 – 20 seconds	By car and fleet average, all temperatures
Total weighted driveability demerits	By car and fleet average, -10°C only
Idle quality demerits	By car and fleet average, -10°C only

1. Scope

The work summarised in this report entailed a series of 96 cold start-ability and driveability tests using:

- Four modern high speed direct injection diesel passenger vehicles.
- A climatically controlled chassis dynamometer facility.
- Three cold ambient testing temperatures.
- Eight test fuels blended to have similar properties except for cetane number, which ranged from 41 to 58.

This work falls under the research agreement between the CRC and Shell Research to conduct the subject study under CRC Contract No. AVFL-11.

2. Objectives

The objectives of this study are to determine the effect of cetane number on light-duty diesel performance in respect to:

Cold Start Up

- Noise
- Vibration
- Start-ability performance
- Smoke

Cold Driveability

- Smoke opacity

- Driveability performance

The impact of ambient temperature on engine sensitivity to cetane number was also investigated, through testing at three ambient temperature settings. The study did not include the evaluation of impact on exhaust emissions other than smoke.

3. Introduction

3.1. The Impact of Cetane Number on Combustion Quality[1,2]

Cetane number is a measure of how readily a fuel ignites in a compression-ignition engine. A fuel with a high cetane number will give a shorter ignition delay; i.e., the period between initial fuel injection and initial combustion will be reduced. When the fuel is first injected into the cylinder, it will be in the form of a tiny droplet, the surface of the droplet will then vaporise due to the high temperature environment. The vaporised fuel will then ignite, which then speeds up the vaporisation and combustion of the remainder of the fuel droplet. As injection continues, the fuel entering the cylinder will meet fuel already combusting and will therefore vaporise and ignite.

When ignition delay is reduced via higher cetane, the rate of increase in cylinder pressure is reduced, because there is a smaller amount of the final injected fuel quantity in the cylinder when combustion commences. A steeper rise in cylinder pressure is tantamount to a more explosive combustion event, and this in turn can impact on noise emissions and engine vibration.

The delay in combustion commencement associated with lower cetane fuel can lead to combustion being incomplete. This then means products of partially burnt fuel will be ejected during the exhaust stroke. This can result in higher gaseous hydrocarbon, carbon monoxide, particulates and black smoke emissions. Under cold start conditions, un-burnt fuel can be ejected, resulting in an increase in white smoke.

3.2. Misfire

In extreme cases of low cetane impacting combustion quality, a partial or complete misfire can be caused. This would occur when a considerable part of the fuel/air charge in the cylinder fails to combust, either in the normal crank angle range or at all. In such cases, some or all of the charge would be ejected un-burnt and the stroke of the engine for which the misfire occurred would not deliver the torque to the crankshaft that would maintain the expected engine output. Symptoms of the misfire would be engine stumble or roughness, which could be measured by means of vibration, noise, engine speed or subjectively as a driveability fault. The misfire would also have a detrimental impact on exhaust emissions.

3.3. Engine Technology[3,7]

Historically, the performance of diesel vehicles has been found to be sensitive to cetane number, particularly during cold start and cold operation. This has been documented in several research papers over the years and has formed one of the drivers for the development of the Coordinating European Council (CEC) test procedure M-11-T-91, Cold Weather Performance Test Procedure for Diesel Vehicles.

A test programme executed in the early 1990s at Shell Global Solutions' UK laboratory, CIP considered the influence of cetane boost on cold start-ability and operability. This work used 6 trios of contemporary light-duty diesel vehicles, four IDI types and two DI types in tests conducted at –5°C. EHN (2-ethylhexyl nitrate) was added at a concentration of 300ppmw to create a test fuel with cetane boosted by approximately 2 numbers. The testing concluded the following:

- Time to start – values ranging from 0.9 to 9 seconds were recorded. An improvement was seen for tests run on the higher cetane fuel.
- No improvement in cold start smoke or cold acceleration smoke was evident for the higher cetane fuel.
- Cold acceleration vehicle performance was improved with the use of the higher cetane fuel.
- Cold start noise and vibration increased with the higher cetane fuel.

Diesel engine technology has undergone phenomenal advancement over recent years. Evolution has been driven by evermore stringent emission and performance requirements. Developments in fuel injection systems in particular have been key in this evolution. Fuel injection metering and fuel/air mixture preparation have been greatly improved with the introduction of high pressure solenoid controlled common rail and unit injector fuel systems. These systems have largely replaced the traditional mechanically actuated rotary and in-line pump designs.

Given that one of the key drivers in diesel engine evolution has been to improve combustion – therefore reducing emissions, it is feasible that the modern diesel engine would be less sensitive to the cetane number of fuel. Conversely it is also feasible that European diesel engine technology has evolved such that optimum performance is only achievable with relatively high cetane fuel, as found in the European market. To determine which is the case, this programme was designed to determine whether a selection of modern European diesel passenger cars are sensitive to cetane number variation, and if so to what extent.

4. Experimental Details

4.1. Test Vehicles

The vehicles selected for testing are modern diesel passenger cars from the European market.

Type	Cylinders / displacement (l)	Max. Power (kW)	Fuel Injection System	Emissions Specification	Model Year	Odometer reading at start of test (miles)
Toyota Avensis D-4D	4/2.0	85	Common Rail	Euro IV	2003	5580
Mazda 6 TS	4/2.0	100	Common rail	Euro III/D4	2003	13934
VW Lupo TDi PD	3/1.2	45	Unit Injector	Euro III/D4	2003	8330
VW Golf TDI PD	4/1.9	74	Unit injector	Euro III/D4	2003	9345

Table 1: Test Vehicles (Note the vehicles are not listed in the order that the car number designations appear through the report).

Figure 1: Test vehicles, from left: VW Lupo, VW Golf, Mazda 6 and Toyota Avensis

4.2. Test Fuels

The test fuels have been blended taking into account:

- the currently available fuel quality in Europe and the US, (details in Appendix 1)
- the ability to blend fuels with constant properties and satisfactory cold flow performance for the testing conditions

The fuel matrix covers a range of 17 cetane numbers and was constructed as follows:

Fuel set 1: 4 fuels with cetane numbers of nominally 40, 45, 50 and 55.
Fuel set 2: based on the 2 fuels from set 1 with cetane numbers of 40 and 45, adjusted as follows:
Each of the fuels was dosed with 2 levels of the cetane improver 2-Ethyl Hexyl Nitrate, (EHN), to give increased cetane of 4 and 8 numbers. Therefore, fuels in set 2 should have cetane numbers of nominally 44, 48, 49 and 53.
The fuels are identified in accordance with ascending cetane number as given in the following table, other properties are shown in Appendix 1. The fuels containing EHN are highlighted in yellow in this table, while those having natural cetane quality remain white:

Fuel Number	Cetane number Target (Measured, ASTM D613)	Natural or EHN	Fuel Identifier
1	40 (40.7)	Natural	DBR 0216 Low CN (4c)
2	44 (43.2)	EHN	DBR 0219 Boosted 45 CN
3	45 (44.7)	Natural	DBR 0222 45 CN Base
4	48 (46.8)	EHN	DBR 0220 Boosted 48 CN
5	49 (48.9)	EHN	DBR 0223 Boosted 50 CN
6	50 (52.3)	Natural	DBR 0221 50 CN Base
7	53 (53.2)	EHN	DBR 0224 Boosted 54 CN
8	55 (57.7)	Natural	DBR 0218 High CN (4c)

Table 2: Fuel Details

It should be noted that it has been possible to formulate the four base fuels so that the aromatics and density are well matched, but there is a considerable spread in viscosity and some spread in boiling range across the fuel set.

4.3. Test Procedure

The testing uses CEC-M-11-T-91 (cold weather performance test procedure for diesel vehicles), subsequently referred to as M11, to evaluate cold start-ability and CEC M-08-T-83 (cold weather driveability test procedure), subsequently referred to as M08, directly after the cold start to evaluate cold driveability. The two procedures are merged as in Figure 2; i.e., the operability part of CEC-M-11-T-91 is omitted.

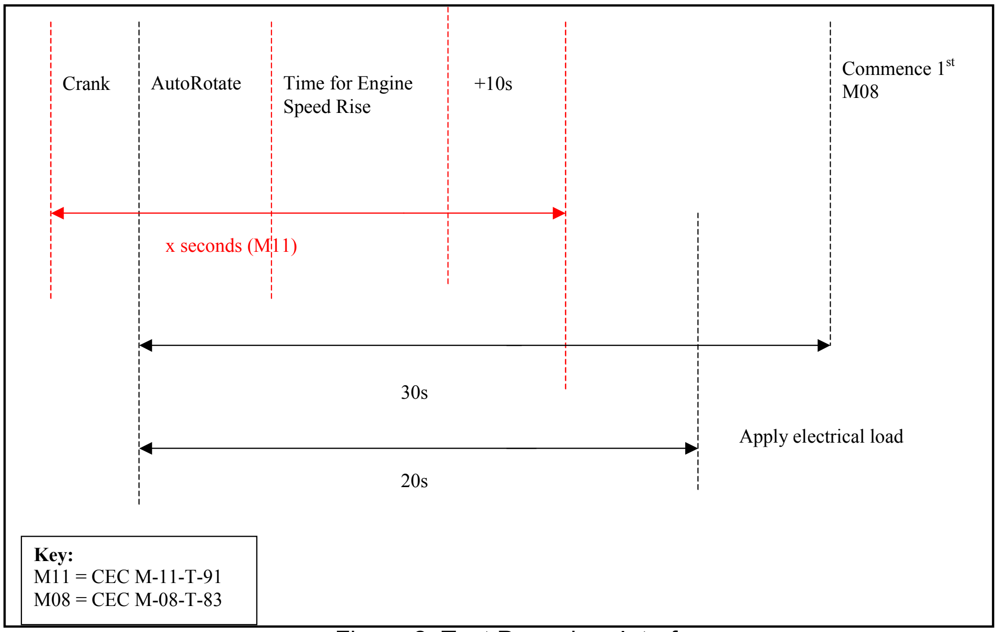


Figure 2: Test Procedure Interface

4.4. Test Measurements

A full list of parameters measured and some detail of the test procedures is given in Appendices 4 and 8. The following key measurements were made during the testing:

4.4.1. Standard CEC Method Measurements

The measurements stated in the M-11 and M-08 test procedures were made. These consist of rating vehicle performance, logging engine and rolls speed, various temperatures and pressures and battery voltage.

- Start-ability - time to start was measured with a stop watch operated by the driver, and recorded by an OROS OR36 real time analyser at a rate of 20Hz. The speed input signal for the OROS unit was from the vehicle's own crank or camshaft speed sensor, the unit also logs time.
- Time for engine speed rise is the time elapsed between start of cranking and the point at which 2000 r/min is attained.
- The number of attempts to start, number of stalls etc. would have been logged by the driver.
- Driveability malfunctions were rated as per CEC-M11-T-91.
- Pressure and temperature measurements were made as per CEC-M08-T-83.

4.4.2. Smoke

Cold start and cold driveability smoke opacity were logged using a Celesco C107 full flow opacimeter. Smoke was recorded using the test cell logging system at a rate of 1 Hz.

4.4.3. Cold Start Noise

This was measured using a GRAS-40AE measurement microphone, with GRAS-26CA microphone pre-amplifier. This is positioned under the vehicle hood in the vicinity of the engine block, but avoiding proximity to vehicle ancillaries. A photographic record of the position of the microphones is shown in Appendix 2. Noise was recorded in the audible spectrum, 20Hz – 20kHz, over which 200 discrete frequencies were sampled. The data on which the results in this report are compiled were logged at a rate of 20Hz. The microphone was calibrated prior to each test. Noise data were logged via an OROS OR36X real time analyser, start of logging was triggered when the OROS analyser registered an engine speed signal and then continued for a nominal 25 second period.

4.4.4. Cold Start Vibration

This is measured using an MMF-KS76/01 accelerometer. The accelerometer is attached magnetically to a ferrous surface on the engine block in the vicinity of the cylinder wall, perpendicular to the axis of the crankshaft. All of the test cars have transversely mounted engines, the accelerometer is sited on the face of the engine block nearest the front of the vehicle. A photographic record of the position of the accelerometers can be seen in Appendix 2. Vibration was recorded over a frequency range of 20Hz -20 kHz. Logging strategy was as for noise. Vibration data were logged via an OROS OR36X real time analyser, measurement was triggered from the engine speed signal and data were recorded for a nominal 25 second period.

4.5. Test Preparation

4.5.1. Vehicle Preparation

Prior to test, the vehicles were prepared in accordance with M11. At start of test, each vehicle had accumulated at least 5,000 miles since new.

4.5.2. Checking Noise and Vibration Measurement Sensitivity

In order to check that the noise and vibration equipment set up would be capable of detecting differences in combustion quality, a sensitivity test was run. This entailed conducting two noise and vibration measurements, one with an artificially introduced engine fault. Using Car 1, noise and vibration were recorded with the engine idling in normal condition. Then a measurement was made with one injector electrically isolated (thus no fuel could be injected). The results of the two measurements were compared. The sound pressure level and vibration over a range of frequencies was considerably higher in the test with the injector disabled. Frequency spectrograms of the average noise and vibration recorded during the measurements are shown in Figure 3.

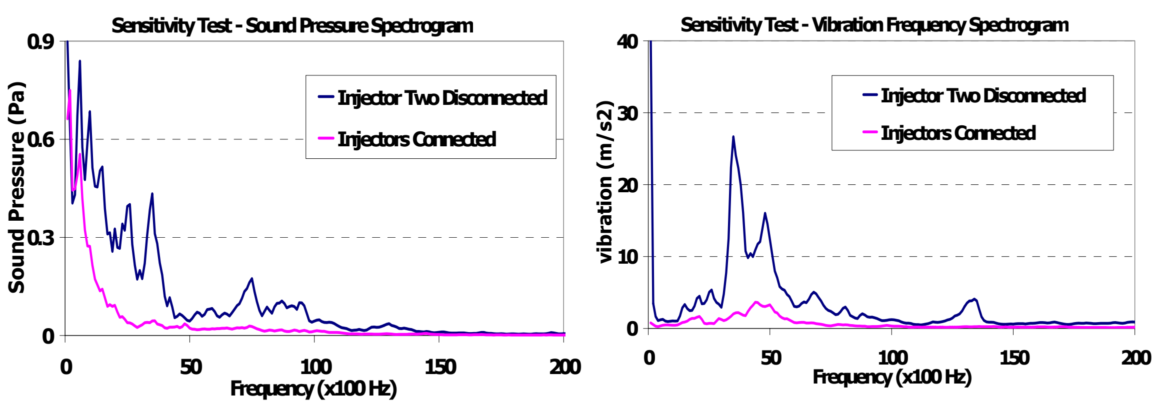


Figure 3: Frequency spectrograms of average sound pressure and vibration recorded with and without one cylinder disabled.

4.6. Test Conditions

Three testing temperatures were used, these represent cooler US temperatures which should increase the likelihood of seeing any operability problems from the vehicle/fuel matrix. The original proposal from CRC specified a lower testing temperature of -20°C; however the lower temperature was limited by the CFPPs (Cold Filter Plugging Points) of the test fuels used.

Identifier	T1	T2	T3
Temperature (^{0}C)	-10	0	+10

Table 3: Temperature Set Points

Humidity and barometric pressure were not controlled, but were recorded during testing.

4.7. Test Plan

4.7.1. Test Matrix Design

The test programme involved testing 4 cars with 8 fuels at 3 temperatures. A single test was carried out for each combination of car, fuel and temperature.
The test sequence was constructed using the principles of statistical experimental design under the constraints that (i) only one test could be conducted per car per day, (ii) only two cars could be tested on any one day and (iii) tests on the same day had to be at the same temperature. The test plan is given in Appendix 5 and the actual test roll out is shown in Table 4. The cars were tested in pairs with the complete set of tests on cars 1 and 2 being performed first followed by the tests on cars 3 and 4. The eight tests at a particular temperature in each vehicle were conducted on successive working days and a different randomised order was used for each car and each temperature. This minimised the risk of fuel effects being biased by any systematic trends in performance over time.
There were some minor departures from the planned test sequence due to the requirement for repeat tests.

		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
Block 1	C1	F1	F7	F2	F8	F4	F6	F5	F3
T2	C2	F3	F6	F7	F1	F4	F5	F8	F2
Block 2	C1	F5	F8	F3	F6	F2	F1	F4	F7
T3	C2	F8	F3	F2	F4	F1	F7	F6	F5
Block 3	C1	F6	F8	F2	F3	F7	F4	F1	F5
T1	C2	F5	F4	F3	F8	F6	F2	F7	F1
Block 4	C3	F5	F2	F7	F6	F3	F1	F4	F8
T3	C4	F8	F6	F2	F5	F3	F1	F4	F7
Block 5	C3	F4	F3	F8	F1	F7	F6	F5	F2
T1	C4	F2	F6	F1	F3	F4	F8	F7	F5
Block 6	C3	F1	F2	F8	F4	F5	F6	F7	F3
T2	C4	F7	F3	F4	F2	F1	F8	F5	F6

Table 4: Actual Test Matrix

Key: T = temperature set point, T1 is lowest, T3 is highest

C = car, C1 is car 1
F = fuel, F1 has lowest cetane number, F8 has highest cetane number

4.7.2. Test Protocol

Testing comprised the following activities:

Preparation
1. Disconnect previous fuel, connect next test fuel
2. Flush fuel system with 5 litres of new fuel
3. Run engine for 10 minutes with new fuel
4. Remove battery, charge until full charge is indicated
5. Condition car, fuel and battery at testing temperature for minimum 12 hours before test.
6. Calibrate microphone (if first test of day)
7. Set span and zero of smoke opacimeter
8. Prepare OROS analyser and test cell logging systems for measurement

Testing
1. Simultaneously start drive trace and carry out starting routine as defined in CEC-M-11-T-91, Cold Weather Performance Test Procedure for Diesel Vehicles. Log start up events in accordance with M11.
2. Thirty seconds after start of crank, commence the first drive cycle of CEC-M-08-T-83, Cold Weather Driveability Test Procedure for cold driveability performance, logging driveability demerits accordingly.
3. Repeat drive cycles up to a maximum of twelve, or until two consecutive de-merit free cycles are driven, (minimum 3 cycles).

4.8. Statistical Analysis Methodology

The test programme was constructed using the principles of statistical experimental design, as described in Section 4.7.1.
In most performance tests, the variability in the results is itself variable with the degree of scatter increasing as the measured value increases. Variability levels also tend to vary from vehicle to vehicle. Residual standard deviation versus mean plots show that most of the performance measures studied in this report behave in this way (see Appendix 3).
To avoid regression lines and fleet averages being dominated by small numbers of high-result yielding vehicles and/or fuels, each measurement was transformed to stabilise variability levels. Fleet averages were then computed on the transformed scale and subsequently transformed back to the original scale as below:

Measurement x	Transformed value $y = f(x)$	Back-transformation $x = f^{-1}(y)$
Average idle quality (B = 0) Time to 2000 rpm (B = 0.33) Vibration (B = 0) Driveability demerits (B = 1)	$\log(x + B)$	$\exp(y) - B$
Smoke opacity (%) (0-10s, 0-120s, 0-327s, 90-327s)	$\log(\frac{x}{100 - x})$ $(0 < x < 100)$	$100 \times \frac{\exp(y)}{1 + \exp(y)}$

Table 5: Explanation of statistical analysis methodology

Thus, for example, fleet-average demerits were calculated as

$$DD_{fleet} = \left[(DD_{veh\,1} + 1) \times (DD_{veh\,2} + 1) \times (DD_{veh\,3} + 1) \times (DD_{veh\,4} + 1)\right]^{1/4} - 1$$

and fleet-average smoke opacity as

$$SO_{fleet} = 100 \times \frac{z}{1+z} \quad \text{where}$$

$$z = \left[\frac{SO_{veh\,1}}{100 - SO_{veh\,1}} \times \frac{SO_{veh\,2}}{100 - SO_{veh\,2}} \times \frac{SO_{veh\,3}}{100 - SO_{veh\,3}} \times \frac{SO_{veh\,4}}{100 - SO_{veh\,4}} \right]^{1/4}$$

(See Appendix 3 for more detail)

No transformation was deemed necessary for noise.

Regression models were fitted to the untransformed data on a fleet-average basis using iteratively re-weighted least squares (IRLS). This technique takes into account the differing levels of variability (see Appendix 3).

The data were examined for possible outliers by examining studentized residuals (residuals divided by their standard errors) in regression models, fitted by IRLS, assuming each untransformed performance measure x to be linearly related to cetane number; i.e.,

$$x = a + b \times \text{CN}$$

The time to 2000 rpm for Car 3 on fuel 4 at –10C was rejected as subsequent investigations revealed a non-conformance with the test procedure. The 0-120s and 0–327s smoke opacity values from Car 1 on fuel 5 at +10C were also rejected as the trace suggested that some particulate matter may have been deposited on the lens of the smoke meter. In each case, the rejected value was replaced by an estimated value obtained by fitting a regression line through the remaining seven points for that vehicle × temperature combination. On the other side of the coin, some test data generated on fuel 1, (car 1, -10C), with high studentized residuals were retained as these were deemed indicative of a genuine non-linear response to cetane.

Trends in the data were sought by testing the significance of the *Test number* term in the regression model

$$x = a + b \times \text{CN} + c \times \textit{Test number}$$

which was fitted by IRLS. Some small variations in time were seen, but no corrections were applied as the randomisation of the fuel testing order in the experimental design made this unnecessary (see Section 4.7).

4.9. Rationale for Noise and Vibration Measurement and Analysis Techniques

4.9.1. Noise Measurement Considerations[4,5]

The human ear is not uniformly sensitive at all frequencies, as such a number of weighting scales have been developed which aim to adjust sound pressure level at a given frequency to simulate different sensitivities. The sound pressure level data are processed using the A-weighting scale. This weighting scale was chosen because in subjective tests, A-weighted noise correlates most closely with the response of the human ear.

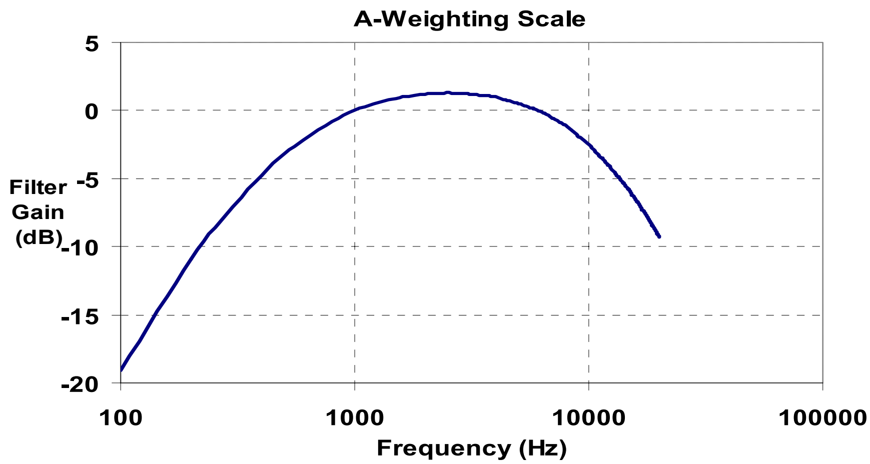


Figure 4: The A-Weighting Scale

Each discrete frequency at which sound has been measured was first considered, (20Hz – 20kHz), this then gives an idea of which frequencies see the most sensitivity to cetane number. It would be expected that the greatest sensitivity would be between 1 and 3 kHz, as combustion noise is usually generated in this band. Values for sound are all RMS, (Root Mean Square), as this is directly related to the amount of energy in the sound being measured.
The background noise from the test facility plant was in excess of 10dB lower than the total noise at all frequencies above 100Hz, therefore no correction is required. Below 100Hz, the background noise exceeded the engine noise; therefore sound measured in this frequency range is discarded.

4.9.2. Vibration Measurement Considerations[6]

Vibration was recorded in the Root Mean Square (RMS) form, as RMS values are accepted as the best measure of amplitude. The data were appraised via a frequency spectrogram in order to identify sensitive frequencies. The vibration at frequencies below 100 Hz was found to be largely due to the facility plant. Appreciable displacement of vibration can only be measured effectively at lower frequencies, therefore it is disregarded for use in this application. As the vibration acceleration is best suited to measurements made at higher frequencies, this method of evaluation of the data was also disregarded.
Combustion vibration reputedly occurs in the region of 1-3kHz. Vibration velocity measured at frequencies of this order is generally accepted as a good measure of a vibration's severity, hence the data was converted to this form prior to data analysis.
The accelerometer was secured by a permanent magnet. As the resonant frequency with this method is reputed as being in the region of 7kHz, (although there is no obvious sign of resonance occurring from the data), this should be considered when evaluating any data generated at frequencies above 6kHz.

5. Results and Data Analysis – Part 1, Cold Start-ability Measurements

5.1. Time to Start

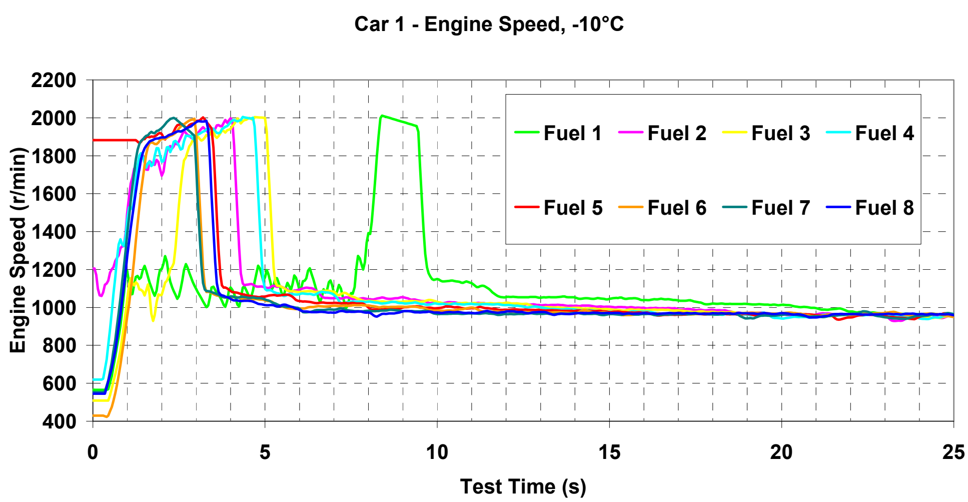
Time to start was evaluated using three methods that are described in the following sub-sections.

5.1.1. Engine Speed

Engine speed was recorded from the pulse generated by the car's own cam or crankshaft sensor output. An engine speed value would be first registered when two pulses were seen; i.e., the measuring unit (OROS analyser) calculates the engine speed from the interval between each two consecutive pulses.

In every test, the time from start of cranking to when the engine began to auto rotate was very short. In all tests, by the time the analyser had registered a speed signal, the engine speed had already exceeded cranking speed, making the time to start impossible to determine using this method.

Figure 5: Engine speed traces recorded during the tests at –10°C using Car 1.



As can be seen from Figure 5, even when vehicle performance is impaired, this materialises through reluctance to accelerate to 2000r/min, time to start is not effected.

5.1.2. Battery Voltage

As with the engine speed signal, little can be gained from appraisal of the battery voltage data, as start up occurred almost instantaneously.

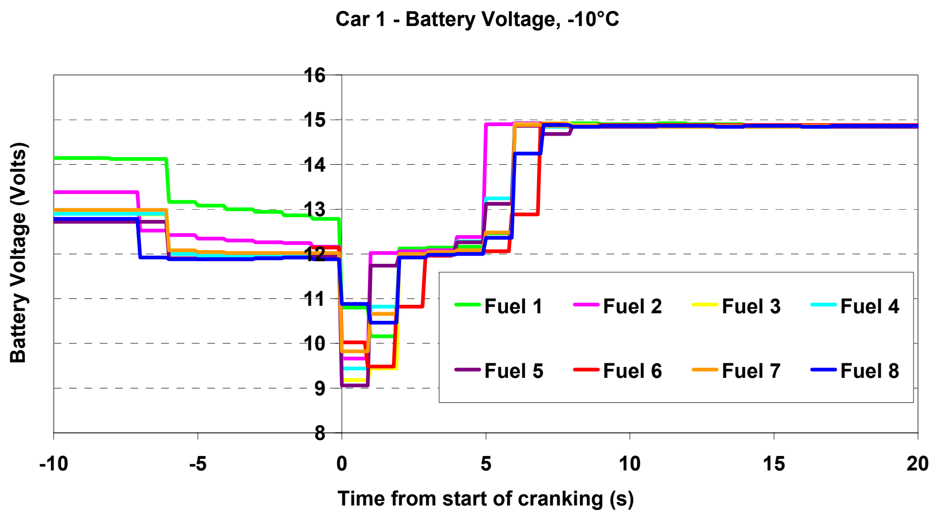


Figure 6: Battery Voltage recorded during tests at –10°C using Car 1

5.1.3. Stopwatch

Due to the fast start up event, little information can be gleaned from the stop watch data. When sufficient rounding of the start up time is taken into account to allow for human error, all start up events for any vehicle become the same. (Start up time was rounded to the nearest 0.5 seconds, allowing for variation in human reaction time.)

5.2. Time for Engine Speed Rise

Time for engine speed rise is the time elapsed between start of cranking and the point at which 2000 r/min is attained. Officially an extra 10 seconds engine running time is added after this point, but as no stalls were recorded this adds no value. Where time is indicated in the result charts (Figure 7) as being zero, the engine speed had reached or exceeded 2000r/min before speed logging started.

5.2.1. Time for Engine Speed Rise Categorised by Vehicle

Key to Figure 7:

• **10°C Natural**	• **10°C With additive**
◆ **0°C Natural**	◆ **0°C With additive**
▲ **-10°C Natural**	▲ **-10°C With additive**

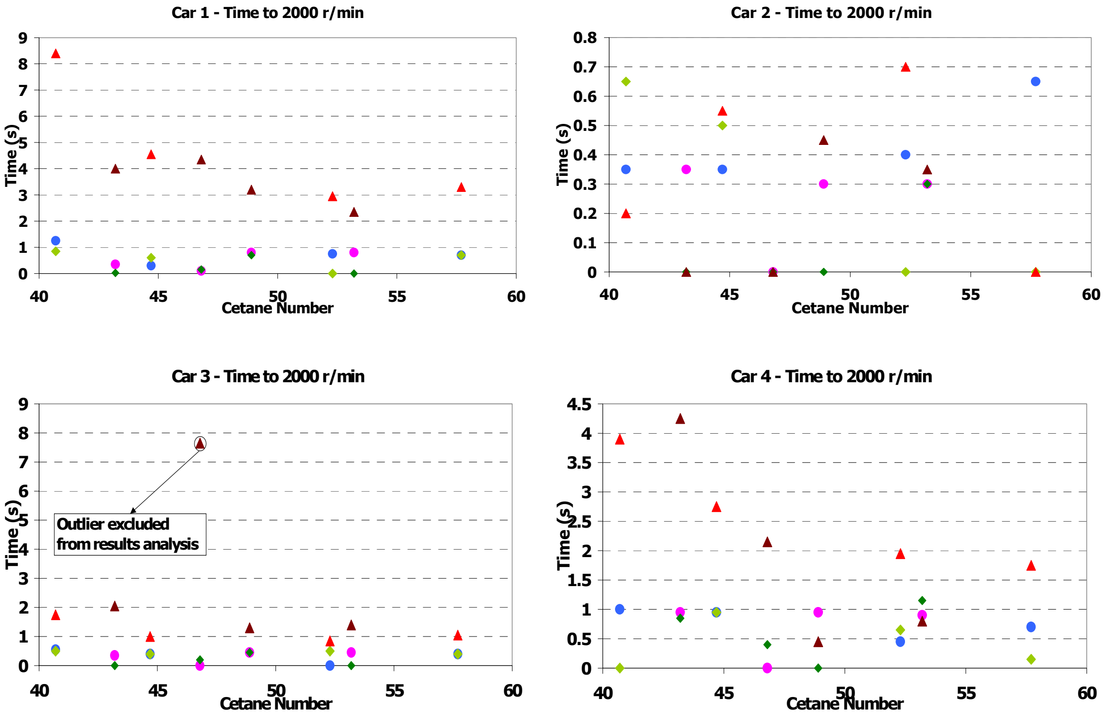
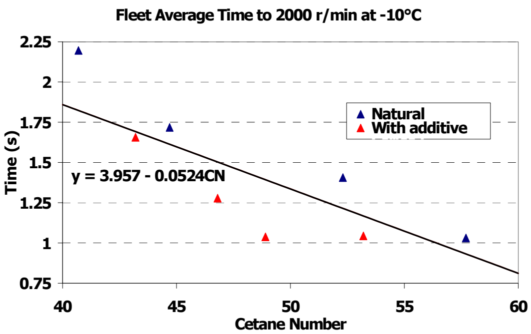


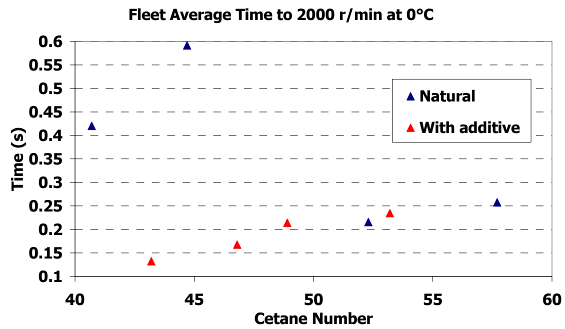
Figure 7: Time for engine speed rise categorised by vehicle

Figure 7 depicts the time for engine speed rise in all tests run on each individual vehicle. Time to 2,000 r/min varied greatly dependant on vehicle, maximum time for Car 2 being only 0.7 seconds, whilst Car 1 took up to 8.4 seconds in one test.
In each of Car 1, Car 3 and Car 4 time to 2000r/min tended to be longer at the colder test temperatures; whereas in Car 2 data there is no such trend. This could be attributed to the fact that Car 2 accelerated almost instantaneously to 2000r/min. Given this, it is feasible that the errors in the measurement would exceed any differences due to temperature sensitivity, thus making it difficult to identify any correlation between time to 2000r/min and temperature.
A similar pattern is shown in the vehicles' relative response to cetane number. At the –10°C testing condition each of Car 1, Car 3 and Car 4 exhibit correlations between increasing time to 2000 and decreasing cetane number that are not statistically significant. The correlation is lost in the tests conducted at 0 and +10°C.
Note: the result generated with Car 3 at –10°C with fuel 4 has been identified as an outlier, during this test, a vehicle EMS function caused a delay to occur between throttle demand and response.

5.2.2. Time for Engine Speed Rise Categorised by Testing Temperature

Evaluation of the fleet average data is best categorised by testing temperature. The geometric fleet average is used, (offset by 0.33 seconds, see 4.8), unlike the arithmetic average, this gives an average which is not skewed by any particularly sensitive test responses. Thus is more likely to reflect a realistic fleet average than the arithmetic method.





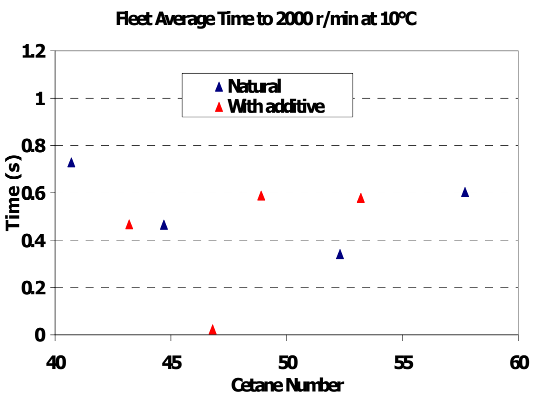


Figure 8: Fleet average time for engine speed rise categorised by testing temperature.

Greater sensitivity to cetane tends to be found at lower temperatures, as would be expected. However closer inspection of the data shows that at the warmer testing temperatures there is considerable spread in the data, which reflects the inconsistencies in the responses of the various vehicles. The trend in the data at –10°C is statistically significant at the 95% confidence level.

6. Results and Data Analysis – Part 2, Noise

6.1. Selecting and Analysing Data

6.1.1. Time Period

Differences in the noise perceivable between tests were appraised by recording sound pressure with a microphone fitted under the hood. Sound was recorded over the audible spectrum at 200 discrete frequencies spanning the range. Recording started at start of cranking (start of motor operation) and continued for a nominal period of 25 seconds. The overall noise levels recorded during that period were influenced greatly by the exact engine speed to which the engine was revved. Because the driver could not precisely control the engine speed, the period over which the engine speed exceeds idle is excluded from analysis. A further constraint on selecting the noise data for analysis was that in tests with Car 4, it was observed that the vehicle idle speed increased in response to the electrical load being applied 20 seconds after start up. Therefore, to ensure that the data considered was comparable between all vehicles and tests, sound data considered for analysis in this section is restricted to the period spanning 10 to 20 seconds after start of test.

6.1.2. Frequency Analysis

Some background noise emanates from the plant integral to the test installation. When a background noise check was carried out it became evident that the majority of sound registered in frequencies below 100Hz was attributable to pollution from plant noise. Given this, sound data collected below 100Hz is discounted.

Combustion noise is reputed to occur mainly in the frequency range 1- 3 kHz, however data were available for the entire audible frequency spectrum (20Hz – 20kHz); therefore, frequency spectrograms were assembled, in order to identify the most sensitive frequency ranges for this work. The spectrograms generated from data collected during the tests at –10°C are shown below in Figure 9.

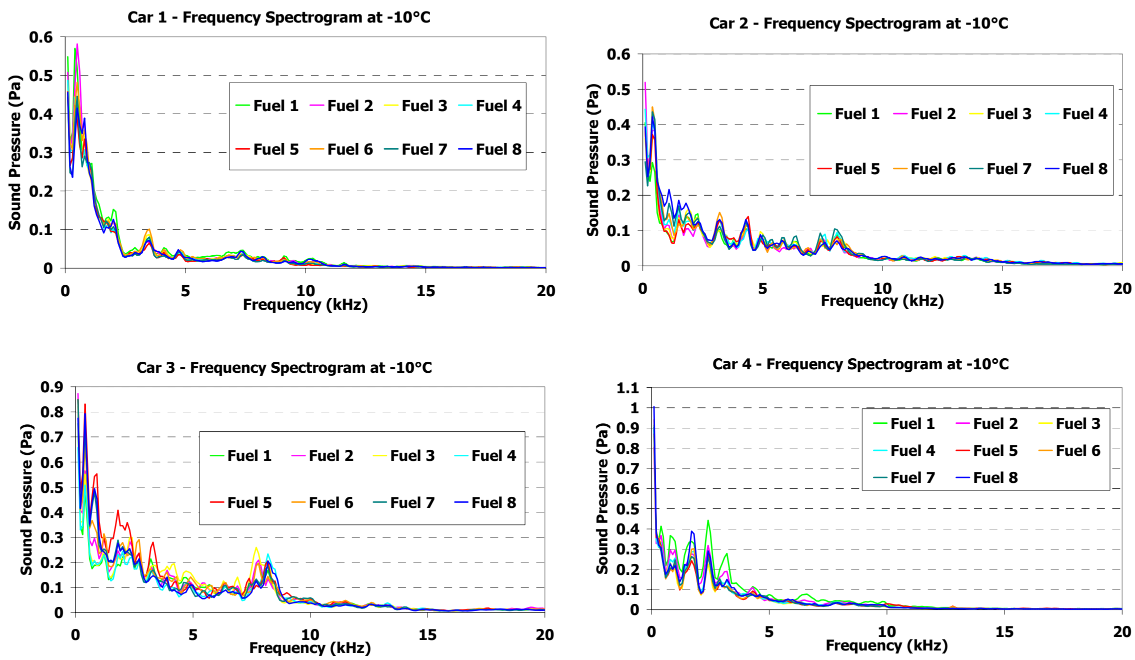


Figure 9: Frequency Spectrograms for sound pressure data collected during tests at –10°C

In general, Cars 2 and 3 show highest sound levels between 100Hz and 9kHz, whereas Car 1 and Car 4 vehicles emit the highest noise emissions below 4kHz. As there is no common frequency range for which all vehicles are more sensitive, the most suitable approach for data comparison is to consider data generated over frequency ranges that all vehicles are sensitive in. This is defined as:

- Lower limit set due to exclusion of plant background noise – 100Hz
- Upper limit set by range of sensitivity of vehicles with narrowest sensitivity band – 4kHz

Note: it is also conceivable that the higher sound pressures present in the data for Car 2 and Car 3 are inherently due to the engine design. These engines have cam driven electronic unit injectors, whereas Car 1 and Car 4 vehicles have common rail fuel injection systems. Noise over the frequency range 100Hz – 20kHz is considered in section 6.4.

6.1.3. Frequency Weighting

The sensitivity of the human ear to changes in sound pressure is dependant on the frequency of the sound. Of the weighting scales available, the A – weighted sound level has been shown to correlate most closely with subjective responses; therefore this frequency weighting is applied to the data, (see 4.9.1).

6.1.4. Data Conversion

The raw RMS sound pressure data collected during this work has the units Pascals, (Pa). This must then be converted to decibels weighted using the A scale (dBA). For this the following applies:

Decibels are calculated as:

dB = 10 x log (Power / Ref)

where:

'Power' is the magnitude of a power related product or unit (e.g. watts, volts x amps, pressure x velocity, pressure^2)

'Ref' is a reference quantity, usually defined in International Standards (e.g. 20μPa for sound pressure, 1nm/s for vibration velocity)

By consideration of the above expression, it can be seen that decibels can also be calculated as:

dB = 20 x log (Value / Ref)

where:

Value is a scalar quantity (e.g. Pa) whose squared value is proportional to a power unit

Therefore, to convert a raw sound level value ‘**x**’Pa into ‘**x**’dBA:

$$\mathbf{x}\ \mathrm{dB(A)} = \frac{20\log[\,(\mathbf{x}\ \mathrm{Pa})^2\ \mathrm{AWF}]}{\mathrm{ref}^2}$$

where:

AWF = A weighting factor applicable at the given frequency

ref = reference quantity for sound pressure (20μPa)

6.2. Noise Levels Categorised by Vehicle (10-20 seconds)

As stated in 6.1, the noise data considered is that collected at frequency ranges between 100Hz and 4kHz. This has been converted to decibels and weighted using the A scale. Figure 10 shows the average values for noise collected for each vehicle at all temperatures.

Key to Figure 10

● **10°C Natural**	● **10°C With additive**
◆ **0°C Natural**	◆ **0°C With additive**
▲ **-10°C Natural**	▲ **-10°C With additive**

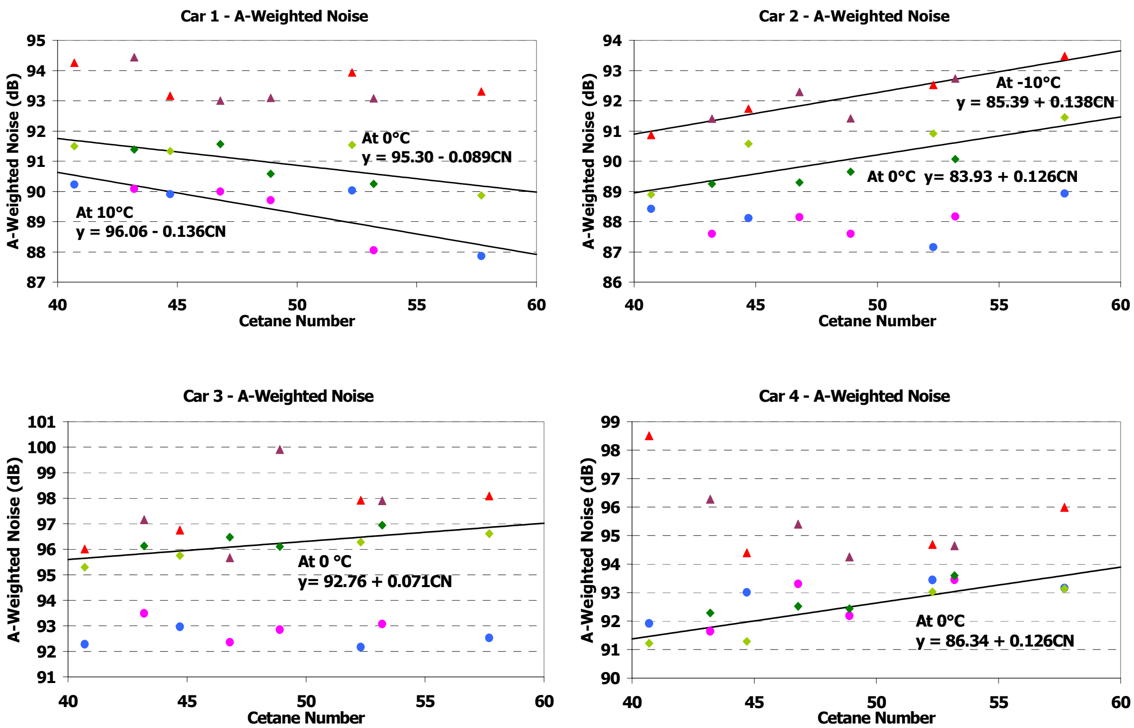


Figure 10: Average noise levels at all temperatures categorised by vehicle

6.2.1. Impact of Temperature

It can be seen from the data that the sound levels increase with decreasing temperature. This is common for all four vehicles.

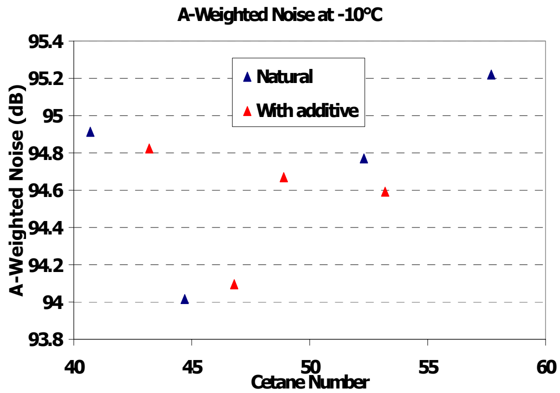
6.2.2. Impact of Cetane Number

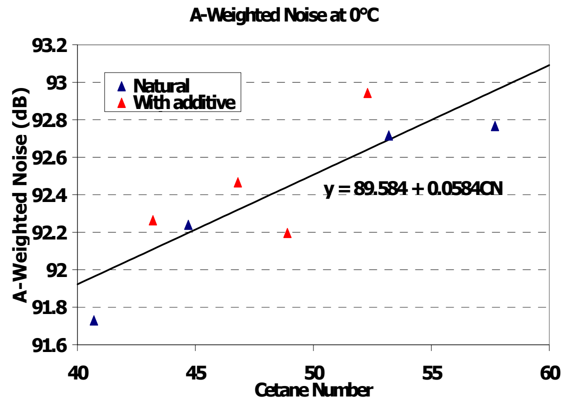
The impact of cetane number is less consistent between vehicles and indeed between sets of tests run at different temperatures with a common vehicle. Thus, these are summarised by vehicle:

- Car 1 – increasing cetane yields a corresponding reduction in noise at 0°C and 10°C, the trends in the data are statistically significant at the 95% confidence level. There is no trend in the data at -10°C.
- Car 2 - increasing cetane yields increases in noise at 0°C and at -10°C, which are statistically significant at the 95% and 99% confidence levels respectively. There is no trend in the data at 10°C.
- Car 3 – increasing cetane gives an increase in noise at –10°C and 0°C, Only the trend at 0°C is statistically significant, (at the 95% confidence level.) There is no trend in the data at 10°C.
- Car 4 – increasing cetane gives a reduction in noise at –10°C, but leads to an increase in noise at 0 and +10°C. Only the trend at 0°C is statistically significant, (at the 99% confidence level.)

6.3. Fleet Average Sound Levels, (10 – 20 seconds)

Fleet average sound levels are grouped by tests run on all vehicles at the same temperature.





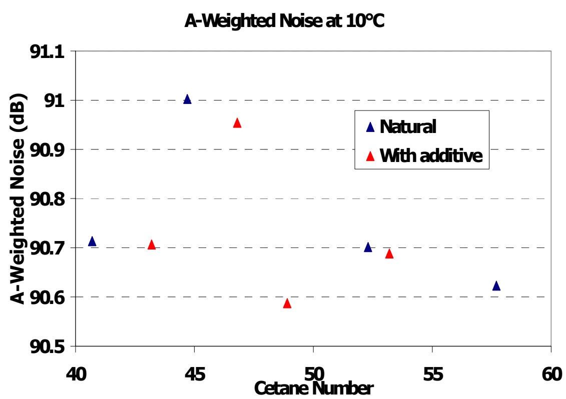


Figure 11: Fleet average noise levels categorised by testing temperature

Although it is clear that testing temperature impacts on noise levels, there is no overall correlation between increasing cetane and decreasing noise. Considering the individual plots, the increase in noise with increasing cetane is statistically significant at 0°C at the 99% confidence level. The trend in the data at -10°C is not statistically significant, But there is a weak trend for noise to increase with increasing cetane. At +10°C there is a weak trend for noise to decrease with higher cetane, again this is not statistically significant.

6.4. Noise Levels Recorded Over 0-25 Seconds

This section considers sound pressure data collected over the entire testing duration, (0-25 seconds), and over the entire usable frequency range (100Hz – 20kHz). No statistical analysis has been undertaken with these data.

6.4.1. Results Categorised by Vehicle

Key to figure 12

• **10°C Natural**	• **10°C With additive**
◆ **0°C Natural**	◆ **0°C With additive**
▲ **-10°C Natural**	▲ **-10°C With additive**

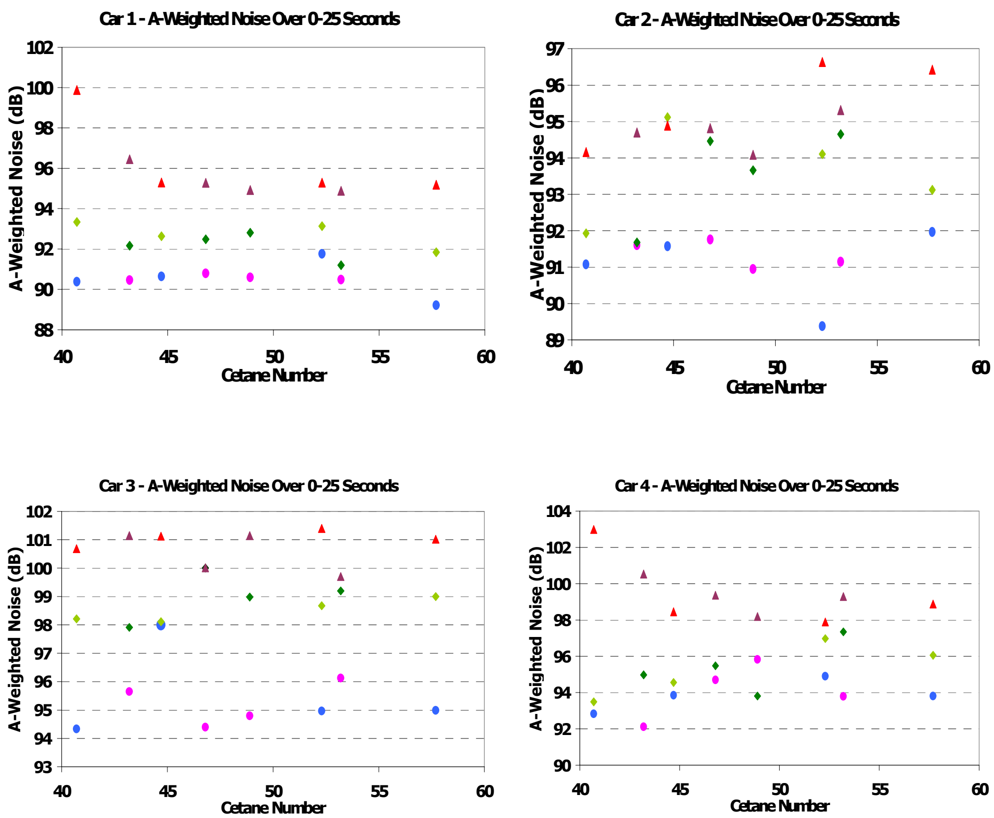


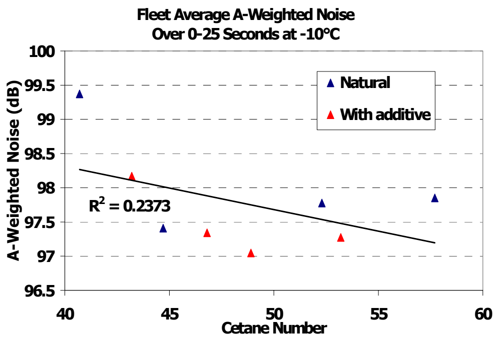
Figure 12: A-Weighted Noise Over 0-25 Seconds

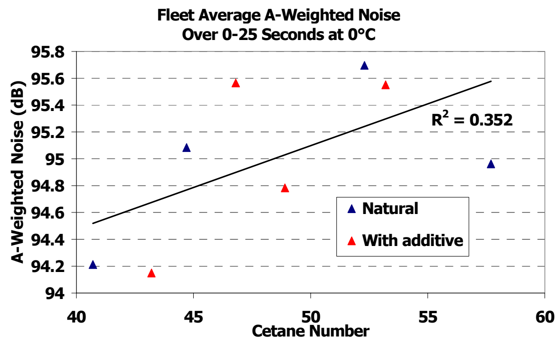
It can be seen that with each car sound level drops with an increase in temperature. The following trends, all at the -10°C testing temperature are evident in the data:

- A weak trend is apparent in the data using Car 2 linking increasing noise with increasing cetane.
- A weak trend is apparent in the data using Car 4 linking decreasing noise with increasing cetane.

No trends appear to be present in the data collected at the warmer testing temperatures.

6.4.2. Fleet Averages





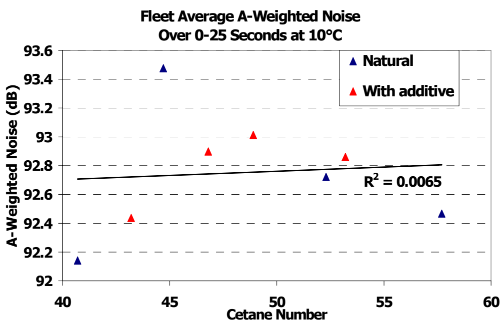


Figure 13: Fleet Average A-Weighted Noise

There are no trends apparent in the fleet average data at any testing temperature.

7. Results and Data Analysis – Part 3, Vibration

7.1. Selecting and Analysing Data

7.1.1. Time Interval

Vibration was measured using an accelerometer magnetically attached to the engine block. Data was logged over 200 discrete frequencies spanning 0 – 20 kHz. Recording started at start of cranking and continued for a nominal period of 25 seconds. The overall vibration levels recorded during that period were influenced greatly by the engine speed to which the engine was revved, and as the driver could not precisely control that, the period over which the engine speed exceeds idle is excluded from analysis. A further constraint on selecting the vibration data for analysis was that in tests with Car 4, it was observed that the vehicle idle speed increased in response to the electrical load being applied 20 seconds after start up (this also applied for the noise data). Therefore, to ensure that data considered was comparable between all vehicles, the period from 10 to 20 seconds after start of test was considered for vibration analysis for all tests.

7.1.2. Frequency Analysis

Combustion noise and vibration is reputed to occur mainly in the frequency range 1- 3 kHz, however all of the data available (spanning 0 – 20kHz) was examined using frequency spectrograms. This was done to determine the most sensitive frequency ranges for this work. The spectrograms generated from data collected during the tests at –10°C are shown below in Figure 14.

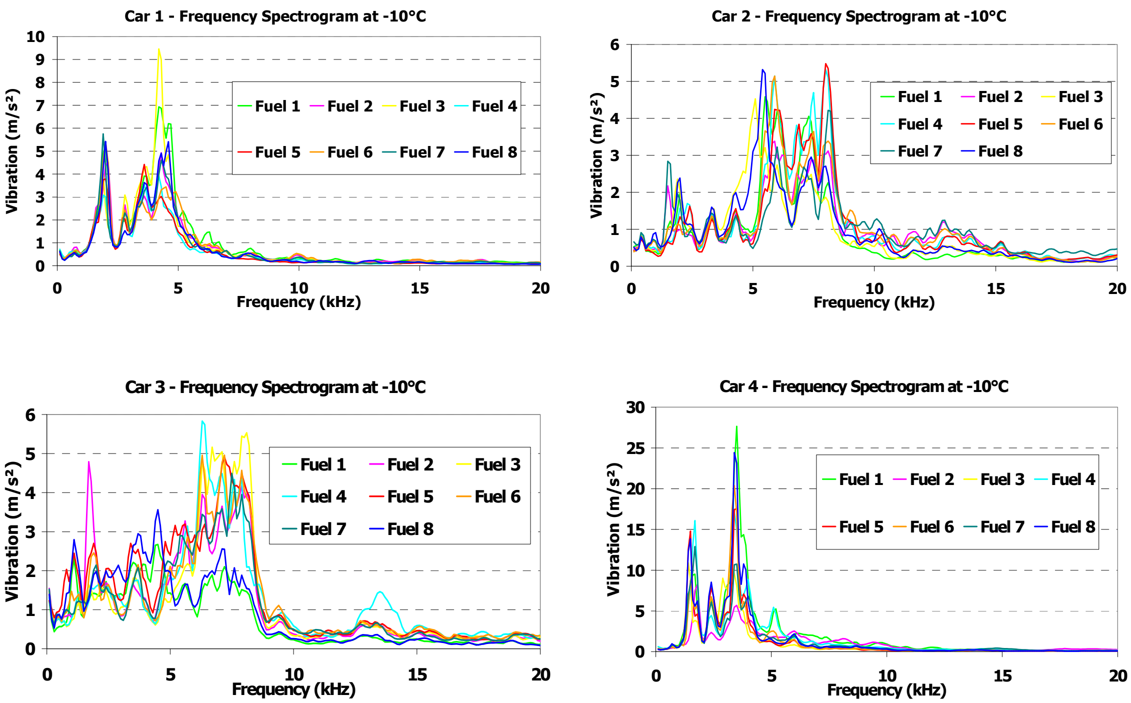


Figure 14: Frequency spectrograms of vibration data collected during tests run at –10°C

As for the noise frequency analyses there are differences in the ranges at which the largest vibrations occur dependent on vehicle. Both Car 2 and 3 exhibit greatest vibration levels over frequency ranges of 20Hz – 10 kHz, whereas Car 1 and Car 4 show most vibration between 1 and 6 kHz. A further consideration in selecting a suitable frequency range is in avoiding the resonant frequency of the accelerometer. Resonance in permanent magnet mounted accelerometers can occur at frequencies as low as 7 kHz, however there is no evidence of resonance in the data.

In order to draw a fair comparison between data from the different vehicles, cover the frequencies at which combustion tends to occur and avoid possible resonance, the frequency range considered for the analysis of the vibration data is 1 – 6kHz.

7.1.3. Data Conversion

The vibration data collected during testing was RMS vibration acceleration (m/s^2). Vibration can be appraised by either displacement, acceleration or velocity components. Acceleration measurements of vibration tend to weight in bias of higher frequency vibrations, whereas appreciable displacement vibration only tends to occur at very low frequencies in mechanical systems.

Common practice is to use vibration velocity to assess a vibration's severity, as a given velocity vibration corresponds to the energy level. The most suitable unit for assessing vibration velocity in this instance is mm/s, therefore to convert the raw data from m/s^2, the following expression is used: -

$$vV = 1 \times 10^3 (vA / 2\pi f)$$

Dimensionally, the equation balances as: -

$$L/T = \frac{L \times T}{T^2}$$

where:
vV = vibration velocity (mm/s)
vA = vibration acceleration (m/s^2)
f = vibration frequency (Hz)
L = length dimension
T = time dimension

The vibration is then in the unit mm/s. This value is squared to convert to the equivalent energy level. The square root of the sum of the vibration data over the frequency range is then the value representative of the vibration across the frequency range in the subject measurement and is used to assess the data: -

Thus, the vibration value for a given test = $\sqrt{(\mathrm{sum}(vV^2))}$

7.2. Vibration Categorised by Vehicle, (10 – 20 seconds)

Key to figure 15

● **10°C Natural**	● **10°C With additive**
◆ **0°C Natural**	◆ **0°C With additive**
▲ **-10°C Natural**	▲ **-10°C With additive**

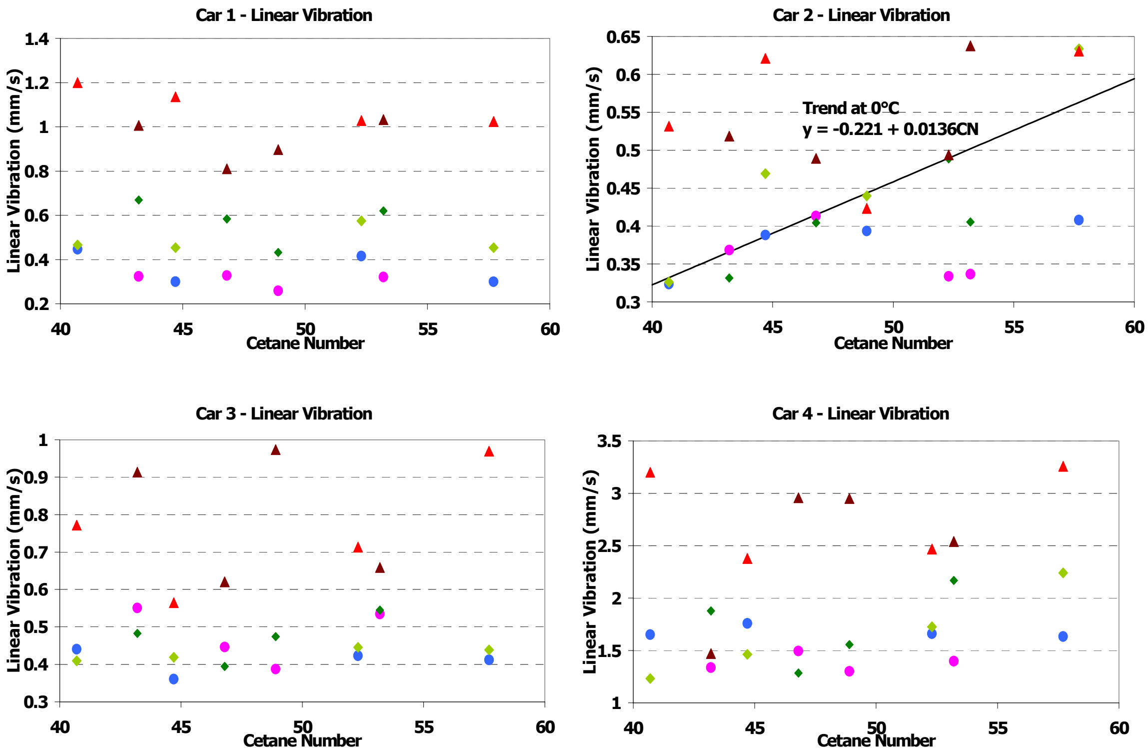


Figure 15: Vibration velocity categorised by vehicle

7.2.1. Impact of Temperature

It can be seen from the data that the vibration levels are highest for all vehicles during tests run at –10°C. There is less distinction between vibration measured at 0°C and +10°C, with only Car 1 exhibiting clearly higher vibration at 0°C than at +10°C.

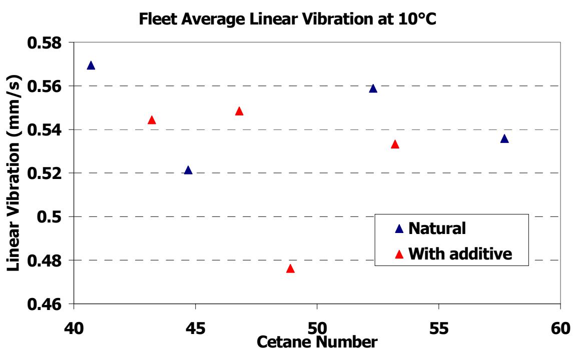
7.2.2. Impact of Cetane Number

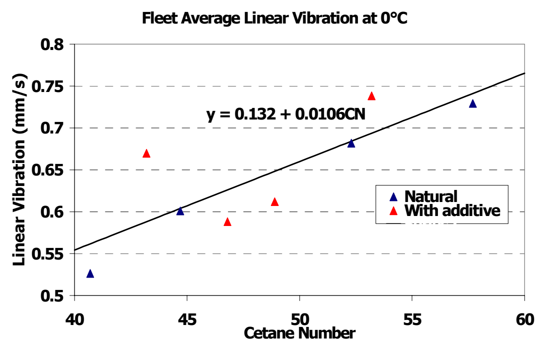
Impact of cetane number on vibration is described separately for each vehicle, trends are not statistically significant unless stated as such:

- Car 1 – At –10°C vibration tends to lessen with increasing cetane number. At 0°C and +10°C vibration levels are not noticeably affected by changes in cetane number.
- Car 2 - increasing cetane tends to yield a corresponding increase in vibration, for tests run at –10°C and 0°C. At +10°C, vibration is not noticeably affected by changes in cetane number. Only the trend at 0°C is statistically significant, (at the 95% confidence level.)
- Car 3 – increasing cetane gives an increase in vibration at –10°C. At the two higher test temperatures vibration is not noticeably affected by changes in cetane number.
- Car 4 – despite exhibiting higher absolute vibration, the pattern in vibration response to cetane is similar to that seen in Car 2. Vibration increases with increasing cetane at the lower testing temperatures, but is not noticeably affected at +10°C.

7.3. Fleet Average Vibration, (10 – 20 seconds)

As for the noise data, fleet average vibration is grouped by testing temperature. In this case the geometric mean is used. The geometric mean gives the 4 cars similar levels of influence whereas the arithmetic mean is dominated by car 4 which exhibits vibration levels 3-4 times higher than the other vehicles.





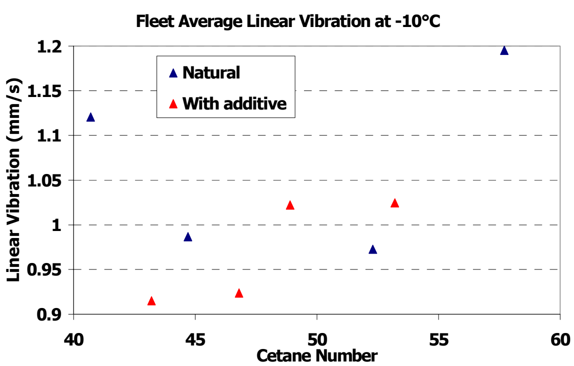


Figure 16: Fleet average vibration grouped by testing temperature

The charts show that the trends in vibration mirror those seen in noise. The only statistically significant relationship is between increasing vibration and increasing cetane at 0°C. The trend is significant at a confidence level of 95%.

7.4. Vibration Data in the Period 0-25 Seconds

This section considers vibration data collected over the entire testing duration, (0-25 seconds), and over the entire usable frequency range (100Hz – 20kHz). No statistical analysis has been undertaken with these data.

7.4.1. Results Categorised by Vehicle

Key to figure 17

● **10°C Natural**	● **10°C With additive**
◆ **0°C Natural**	◆ **0°C With additive**
▲ **-10°C Natural**	▲ **-10°C With additive**

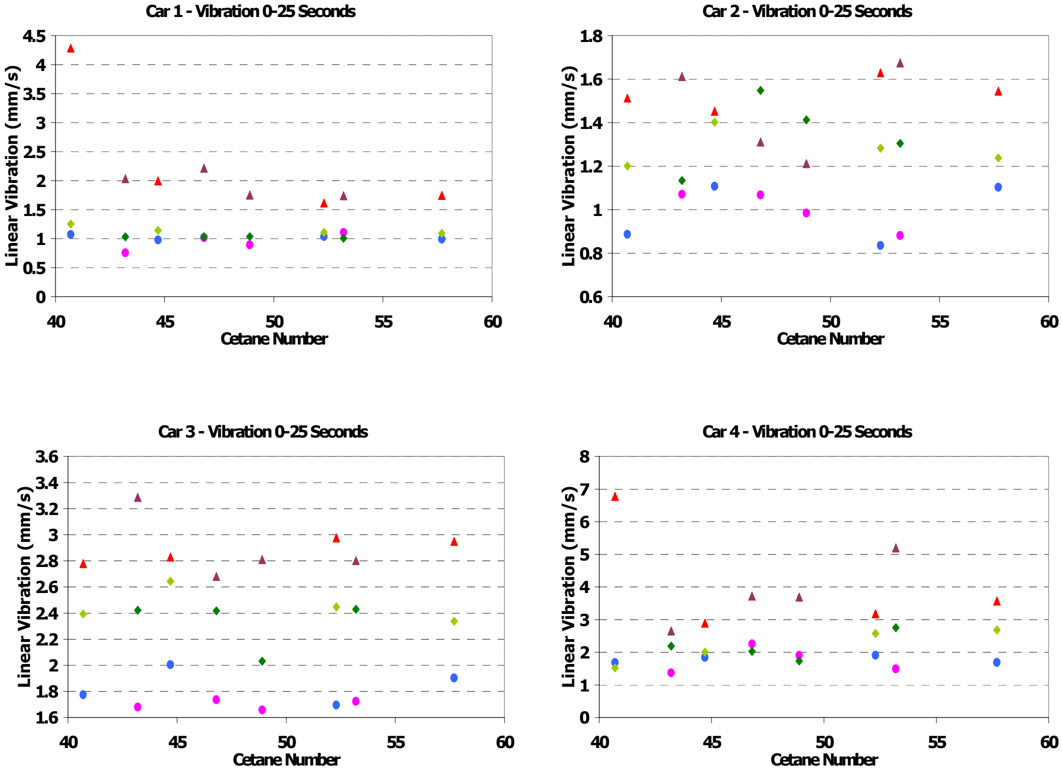
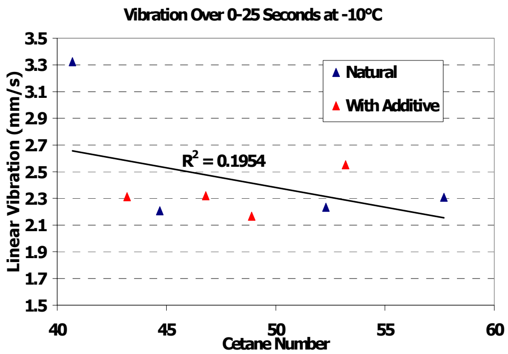
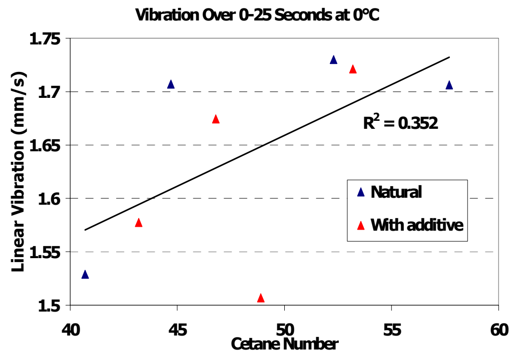


Figure 17: Vibration velocity categorised by vehicle over 0-25 seconds

There is little correlation evident between cetane number and vibration in any of the datasets. Vibration tends to be lower at higher testing temperatures.

7.0.1. Fleet Average Vibration





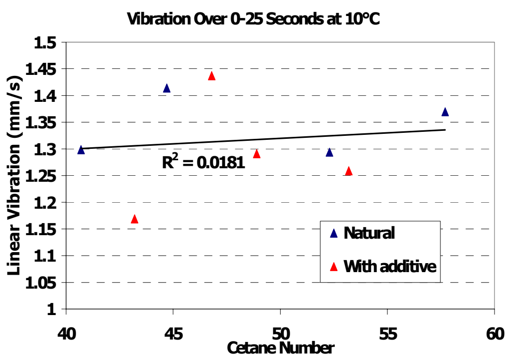


Figure 18: Fleet Average vibration over 0-25 seconds

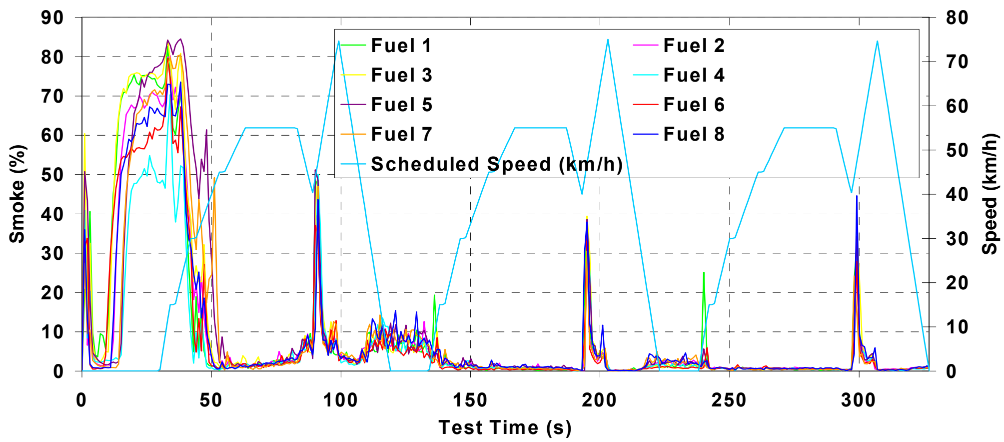
There are no trends apparent in the fleet average data at any testing temperature.

8. Results and Data Analysis – Part 4, Smoke

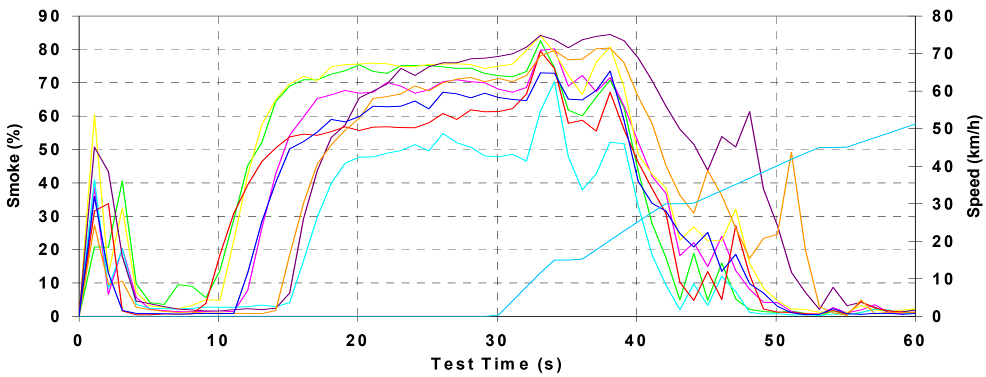
8.1. Data Analysis

Smoke opacity was sampled constantly through each test. In order to determine suitable methods of analysis, plots of the smoke data were examined. Examples of these are displayed in Figure 19.

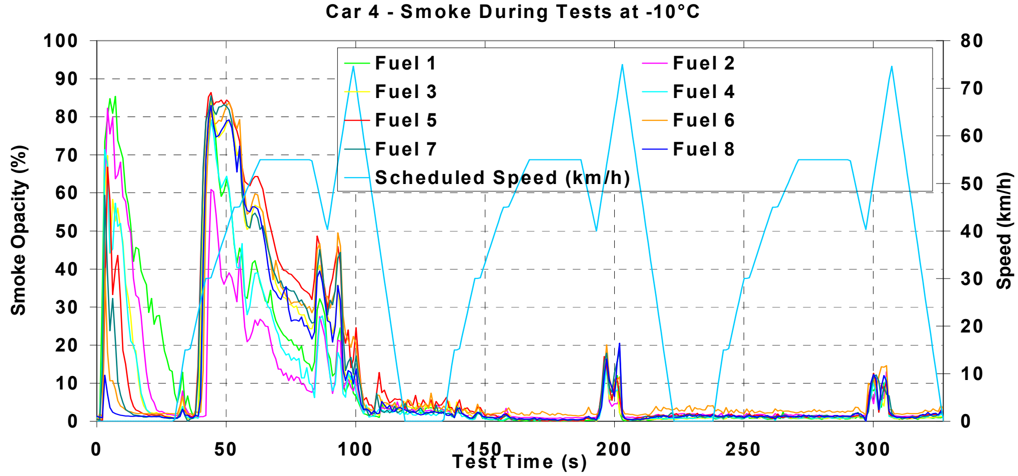
Car 2 - Smoke Data During Tests at -10°C



Car 2 - Smoke Data During Tests at -10°C Between 0-60 Seconds



Car 4 - Smoke During Tests at -10°C



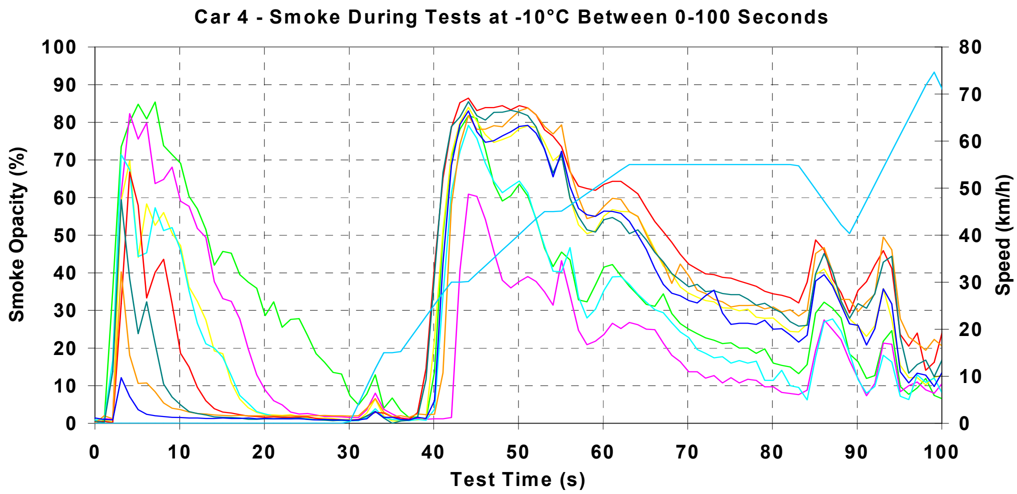


Figure 19: Smoke traces for tests run at –10°C using Car 2 and Car 4 vehicles

For each vehicle, peaks in smoke tended to occur on revving directly after start up, whilst driving up through the gears on the first drive cycle, and during the 4th gear acceleration of each cycle. As the smoke meter measures opacity, partially burnt and un-burnt fuel plus water vapour are registered. It is inevitable that some water vapour is present in the exhaust gas, especially soon after start up. As the engine runs, the amount of water vapour would diminish, a factor which would improve measurement reliability, but the amount of un-burnt or partially burnt fuel would also decrease, thus reducing the chance of detecting fuel based differences. The amount of incompletely burnt fuel is a measure of combustion quality and is therefore an indicator of the impact of cetane number on the performance of the engine. Hence, smoke was appraised in the following ways:

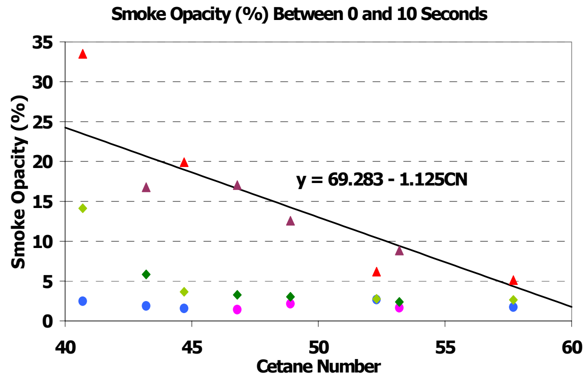
- 0-10 seconds of test, capturing the start up and revving emissions, but also the largest amount of water vapour. The fact that the engines were revved to different speeds is a variable that will affect the reliability of this measure.
- 0-120 seconds, the time until the end of the first cycle, containing the emissions from the coldest cycle, but with 12 times more data than the first measure, which should improve reliability.
- 0-327 seconds, covering the first 3 drive cycles. This was the minimum number of cycles that were driven in any of the tests. Although the vehicle engines would have been warming by the end of this period, the size of the data sample would benefit the reliability of the data.
- 90-327 seconds, to exclude the first part of the sampled data in an attempt to reduce the impact of water vapour on the results.
- Peak smoke, the maximum smoke value recorded through the test, typically either just after start up or during the accelerative part of the first cycle, (see Figure 19). This would give a measure of smoke correlating well with a subjective perception of the vehicle emissions, i.e. the smoke emissions most likely to be noticed by the observer.

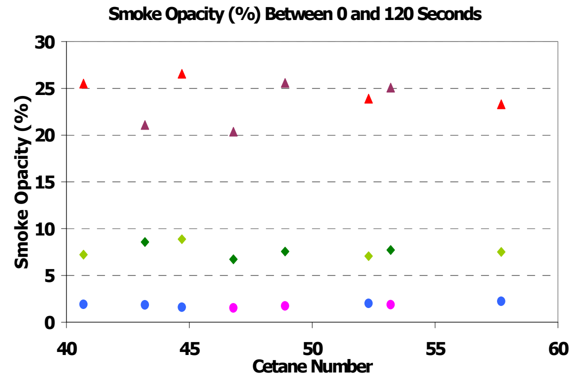
8.2. Fleet Average Data

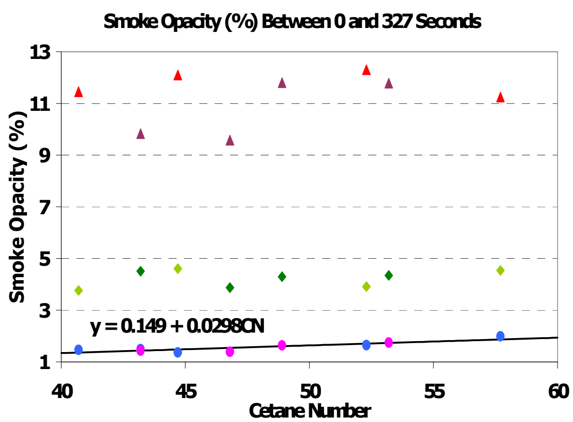
Figure 20 shows the trends in the geometric fleet average of the smoke measures given in Section 8.1:

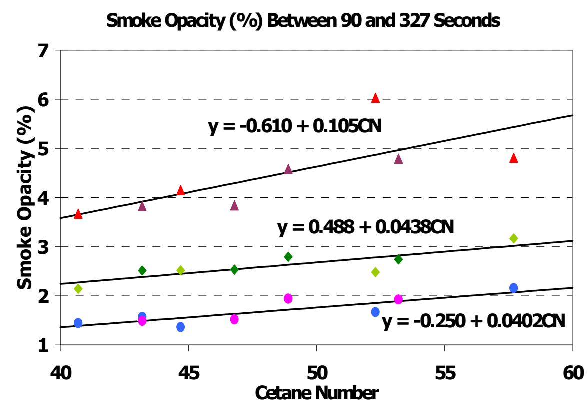
Key to figure 20

10°C Natural	**10°C With additive**
0°C Natural	**0°C With additive**
-10°C Natural	**-10°C With additive**









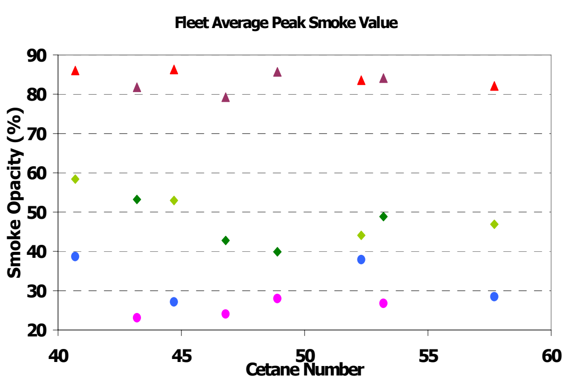


Figure 20: Fleet average values of smoke opacity for all ranges evaluated.

For all ranges, smoke levels measured at –10°C were higher than at 0°C and these in turn were higher than those at +10°C. This is to be expected, as there will be an increasingly larger amount of saturated water vapour in the exhaust gases as temperature decreases. The question is whether cetane number has also affected the values. This is considered in the text below.

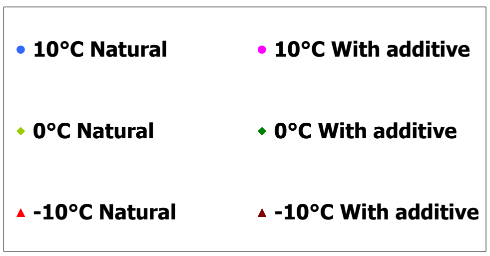
- 0-10 seconds: the fleet average shows smoke in this period to correlate strongly with cetane number. The impact of cetane was greater at lower temperatures; the trend at -10°C is significant at the 99% confidence level.
- 0-120 seconds: the data shows the fleet average values to be insensitive to cetane over this period, with the correlations seen in the earlier period (0-10 seconds) being lost.

- 0-327 seconds and 90-327 seconds: during these periods the correlation between smoke and cetane seen in the initial part of the test is reversed with smoke tending to increase with increasing cetane, albeit by a small amount. For 0-327 seconds the trend at 10°C is significant at the 99% confidence level. For 90-327 seconds the trend at -10°C is significant at the 95% confidence level and the trends at 0°C and 10°C are significant at the 99% confidence level.
- Peak smoke: this was insensitive to cetane at -10°C and +10°C, but a weak trend exists at 0°C linking increasing cetane and decreasing smoke.

8.3. Smoke Results by Vehicle

As there only appears to be an inverse cetane/smoke relationship in the running period soon after start up, it is only this data that is considered for the individual vehicles. Charts of this data are shown in Figure 21.

Key to figure 21



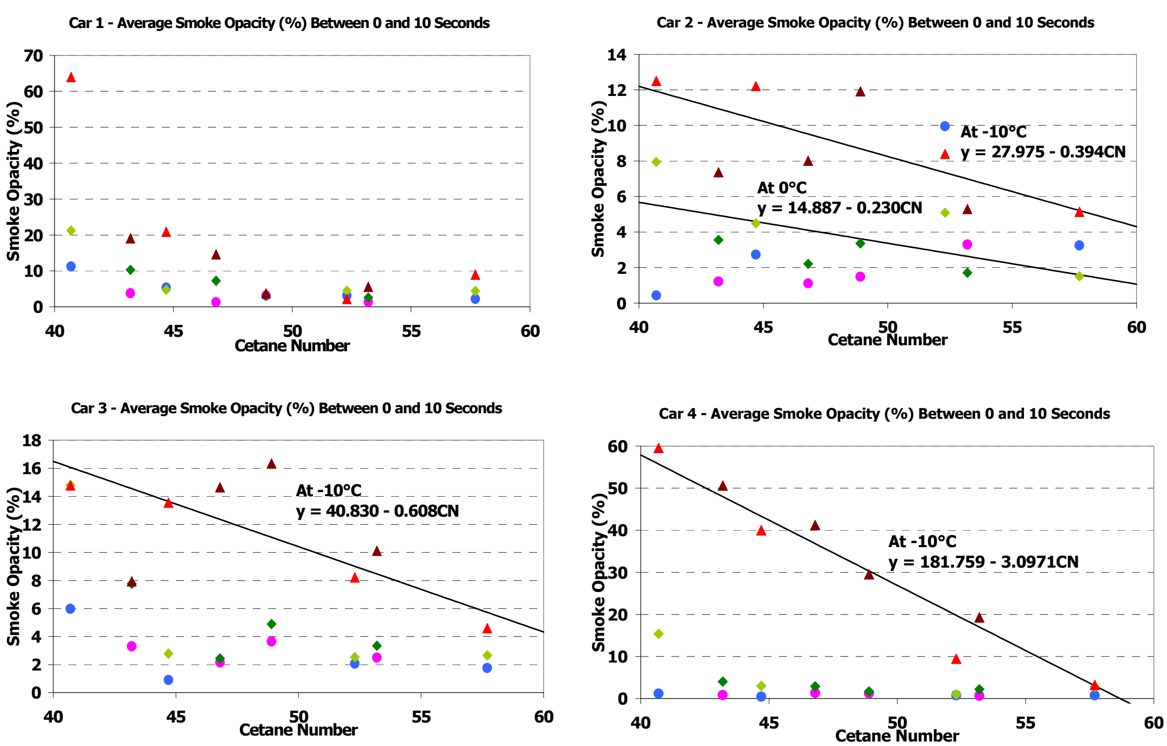


Figure 21: Average smoke opacity between 0 and 10 seconds, all vehicles

As can be seen from the traces, the absolute levels of smoke differ greatly dependant on vehicle, therefore means are calculated on a transformed scale as described in section 4.8. Apparent outliers are:

- Fuel 1, Car 1 -10°C – this test saw Car 1 misfiring immediately after start up, a condition which would lead to high amounts of un-burnt and partially burnt fuel being present in the exhaust gases. Therefore, the result is a valid reflection of the impact of the cetane number on vehicle performance in this vehicle and so is included in the data analysis.
- Fuel 6, Car 2 at +10°C – there are no trends in the other variables recorded during this test to corroborate the high smoke levels. However, the smoke trace shows consistency in the overall trend with the other tests, it is simply higher in places. There is no zero error pre and post test, therefore the result cannot be legitimately excluded from analysis.

All of the vehicles show some sensitivity to cetane. The trends in the data are not statistically significant unless stated as such:

- Car 1 – no statistically significant trends but higher smoke levels are generally found with lower cetane fuels at all temperatures.
- Car 2 – trends in the data at -10°C and 0°C linking lower smoke with higher cetane are statistically significant with 95% confidence. There is no trend in the data at 10°C.
- Car 3 – at -10°C there is a trend in the data linking lower smoke with higher cetane that is statistically significant at the 95% level. At 10°C and 0°C the highest smoke readings occur with lower cetane fuel, but there are no statistically significant trends in the data.
- Car 4 – at -10°C there is a trend linking higher smoke with lower cetane that is statistically significant at the 99.9% confidence level. There are no trends in the data at the other testing temperatures.

9. Results and Data Analysis – Part 5, Measured Idle Quality

9.1. Defining the Measurement

Idle quality is a measure of combustion quality at idle. Misfiring will cause fluctuations in idle speed as less energy from a misfiring cylinder is converted into rotational motion of the crankshaft. This parameter is subjectively assessed as part of the CEC-M11-T-91 requirements (see chapter 10).

As engine speed was logged for the first 25 seconds of testing it is possible to make an appraisal of idle quality from this data. The first dataset sampled for this appraisal, which is comparable for all vehicles, was that recorded between 10 and 20 seconds after start of test. This period coincides with that at which noise and vibration is sampled, and as for those measures is defined by the period which falls between the engine revving stage (for time to 2000r/min step), and the point at which the electrical load is applied in the vehicles (after 20 seconds of engine operation). Statistical analysis was carried out on this dataset.

Impact of the application of electrical load cannot be detected from the engine speed traces in three of the cars, but in some tests with car 4, there is an increment in engine speed that occurs after electrical loading. To facilitate an assessment of fuel impact on idle quality during this period the following protocol is invoked: -

Car	Protocol
1	Consider all data recorded from 20-25 seconds
2	Consider all data recorded from 20-25 seconds
3	Consider all data recorded from 20-25 seconds
4	If an increase in engine speed occurs, consider data before and after, but not during change in speed. If an increase in engine speed does not occur, consider all data recorded from 20-25 seconds

Table 6: Protocol for assessment of idle speed data from 20-25 seconds

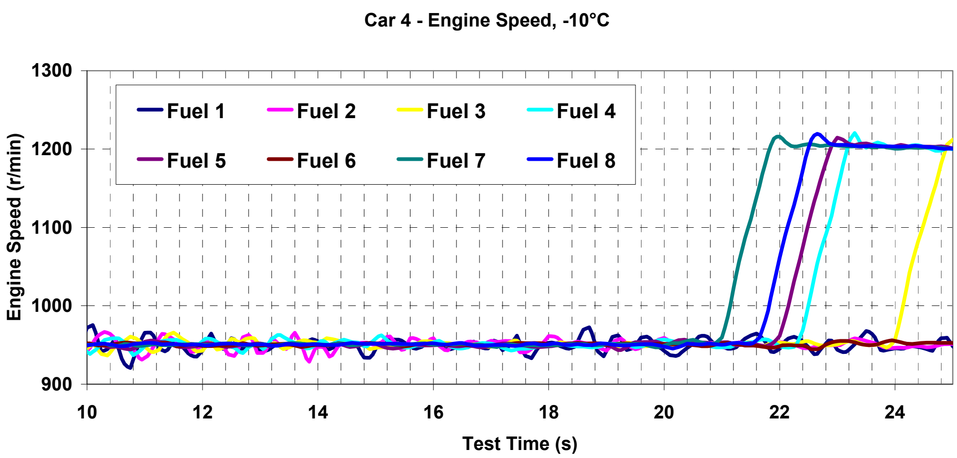
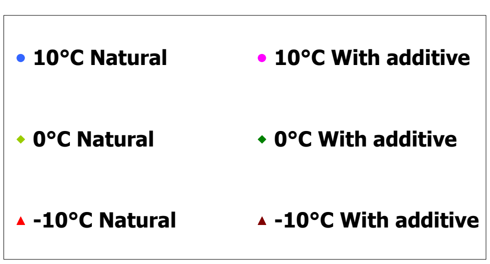


Figure 22: Example of engine speed traces, Car 1: showing engine speed reaction to electrical load application in some tests.

It was anticipated that any trends in measured idle quality would concur with trends in smoke, noise, vibration and perceived idle quality, therefore reinforcing any conclusions drawn from evidence in the other measures.
For this exercise, idle quality is defined as the standard deviation of the engine speed during the sample time.

9.2. Measured Idle Quality Results by Vehicle, 10 – 20 seconds

Key to figure 23



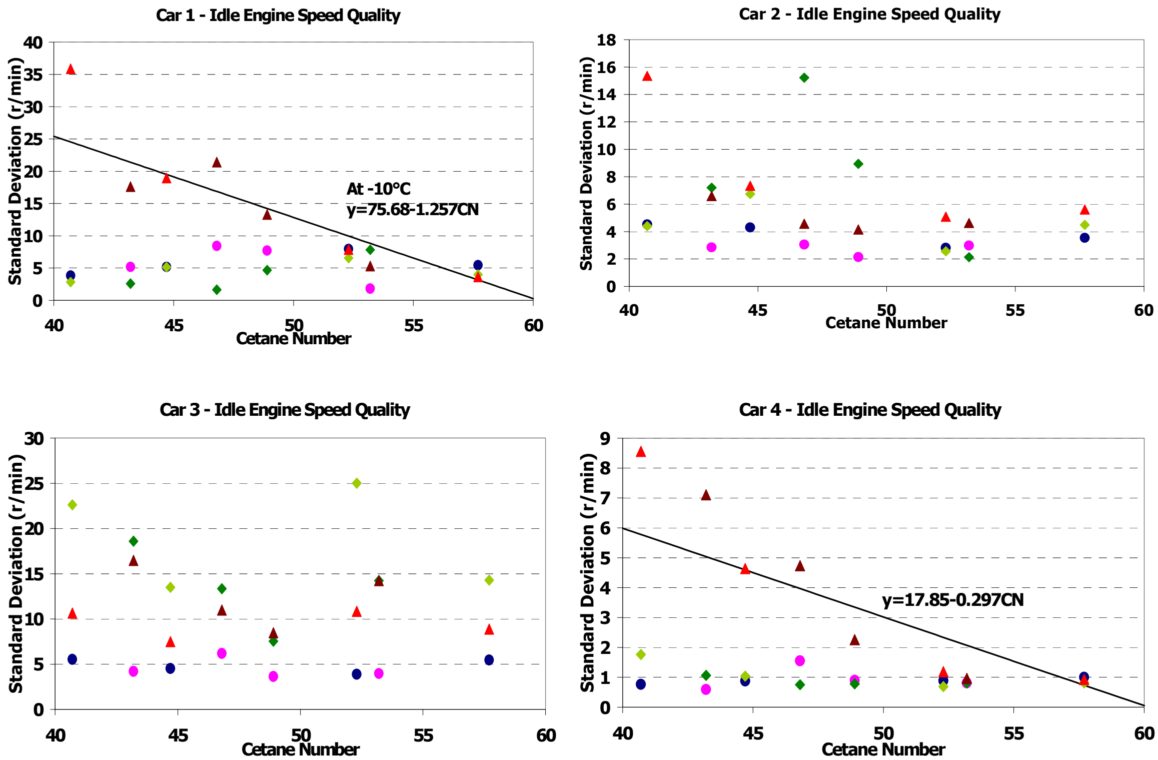
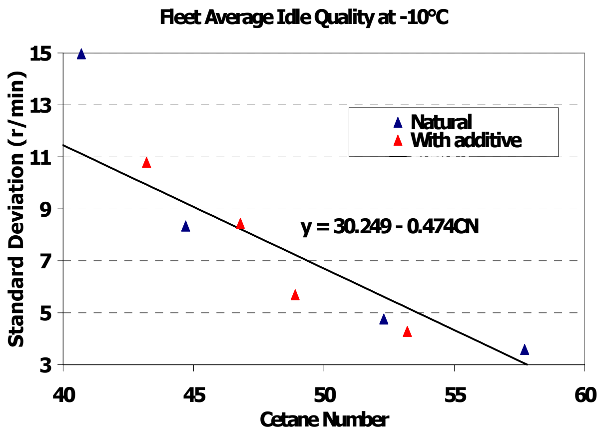


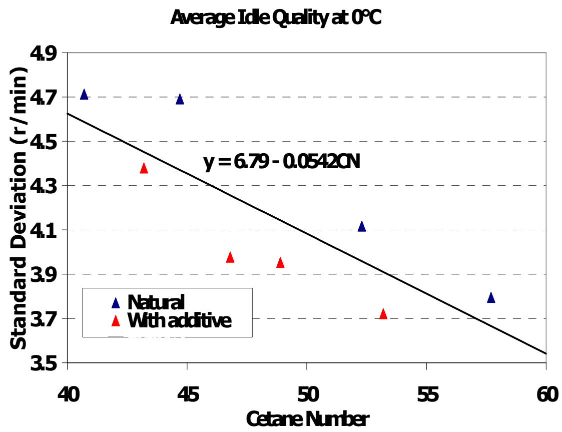
Figure 23: Measured idle speed quality by vehicle, 10-20 seconds

Car 1 and Car 3 suffer a higher level of variation in the engine idle speed than Car 2 and Car 4. Fuel effects are appraised below:

- Car 1 – a strong correlation between improving idle quality and increasing cetane exists at -10°C, which is statistically significant at the 99% confidence level. No impact of cetane on idle quality is evident in the data collected at the warmer temperatures.
- Car 2 – there is little correlation in the data linking cetane and idle quality.
- Car 3 – no correlation between cetane and idle quality is observed.
- Car 4 – a strong correlation exists in the data at -10°C, linking improving idle quality with increasing cetane. This is significant at the 99% confidence level. No impact of cetane on idle quality is evident in the data collected at the warmer temperatures.

9.3. Fleet Average Idle Quality, 10 – 20 Seconds





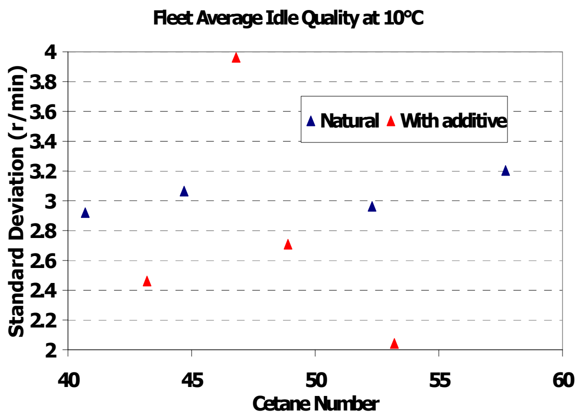
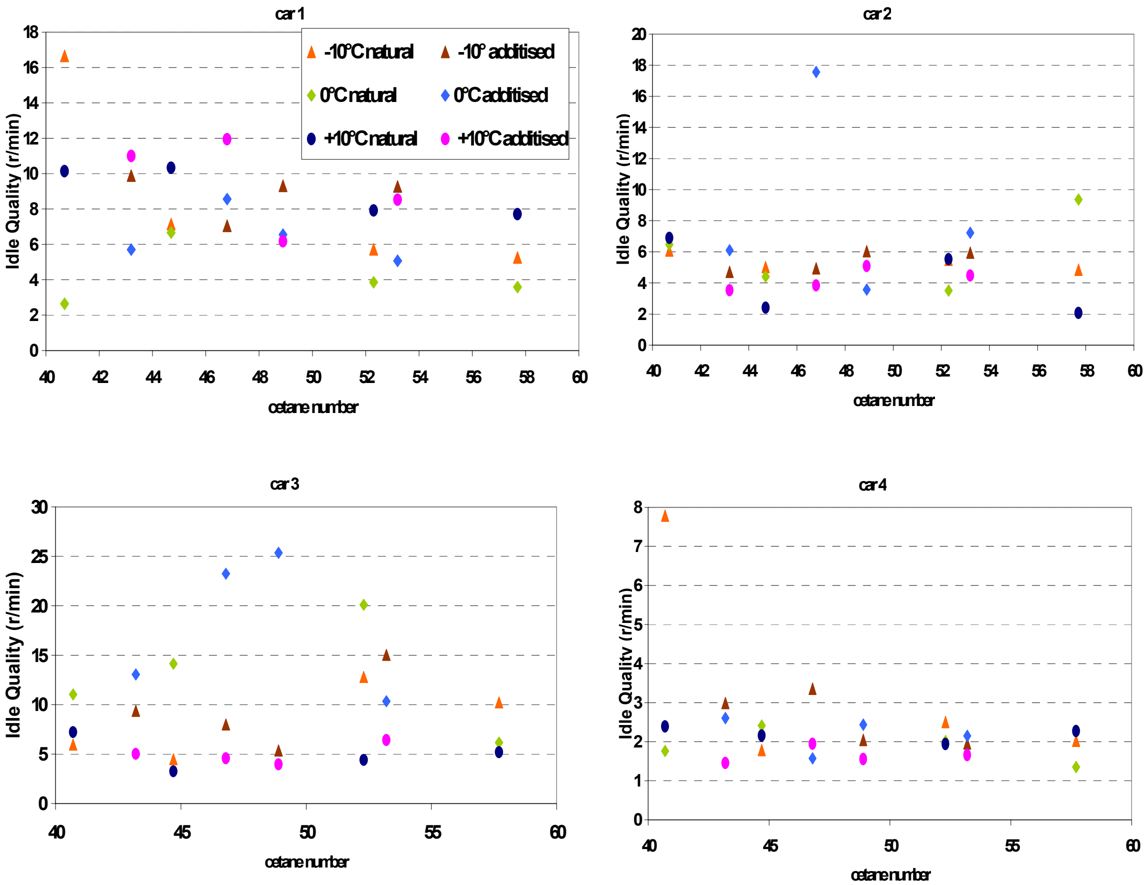


Figure 24: Fleet average measured idle quality plots at each test temperature.

The fleet average is calculated using the geometric mean. Plots of the data at each temperature show sensitivity of idle quality to cetane at the lower test temperatures. The trend linking increasing cetane and improving idle quality is statistically significant at -10°C and 0°C at the 99% confidence level. There is no idle quality sensitivity to cetane detectable at +10°C.

9.4. Idle Quality by Vehicle, 20 – 25 Seconds



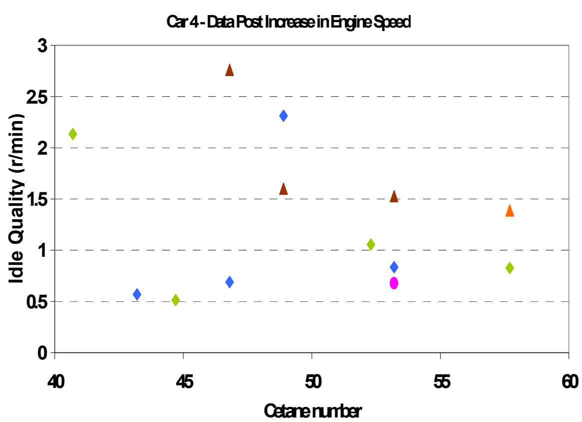


Figure 25: Idle speed quality by vehicle, 20-25 seconds

No idle quality sensitivity to cetane number is detectable for any of the datasets appraised. The lack of correlation is as anticipated, as the application of electrical load confounds any cetane effect.

No fleet average appraisal of this data range is attempted as vehicle reaction to the application of electrical load and the timing of the application by the operator are additional variables in this period of the test.

10. Results and Data Analysis – Part 6, Cold Driveability Ratings

Idle quality and driveability demerits were logged in accordance with CEC-M08-T-83. Total (weighted) demerits are examined plus the idle quality demerits are examined separately in order to establish whether these correlate with the measured idle quality described in the previous chapter.

10.1. Total Weighted Demerits

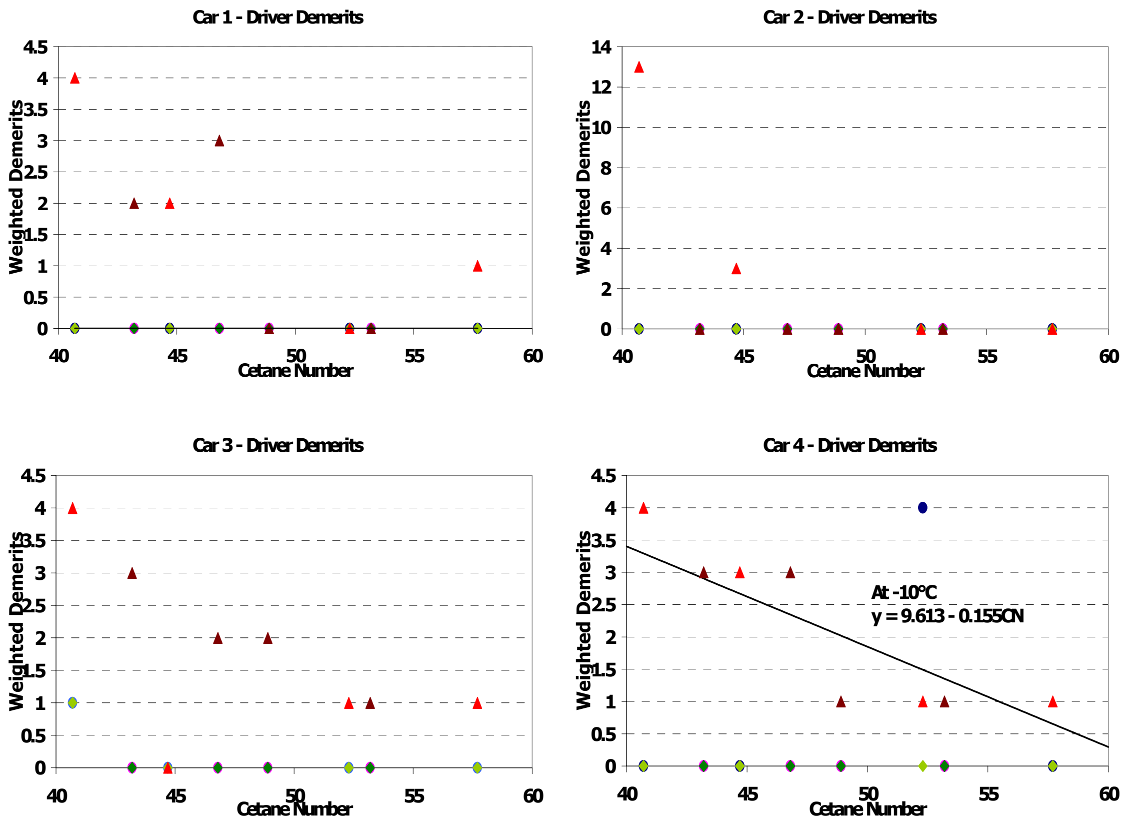
Weightings are applied to the demerits identified. These are shown in Table 7. Figure 26 shows weighted driveability demerits catalogued by vehicle.

Demerit	Weighting
Idle quality	1
Hesitation	4
Stumble	4

Table 7: Driveability demerit weightings

Key to figure 26:

10°C Natural	**10°C With additive**
0°C Natural	**0°C With additive**
-10°C Natural	**-10°C With additive**



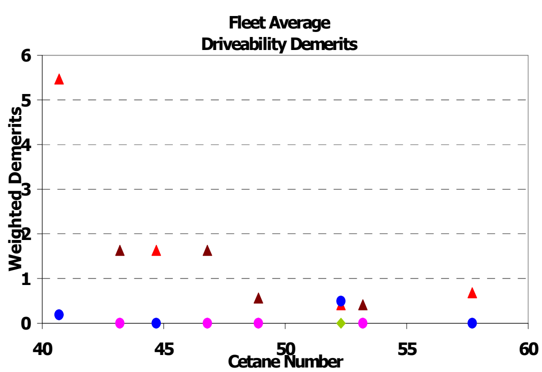
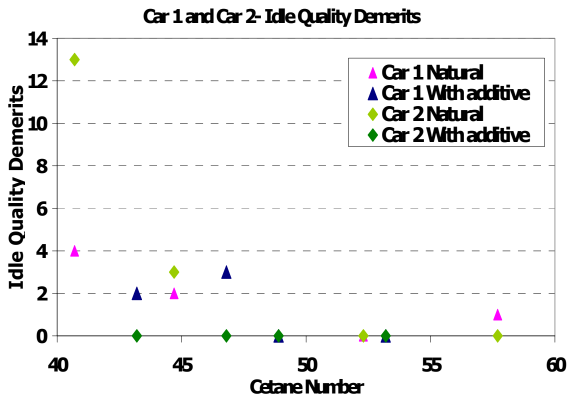


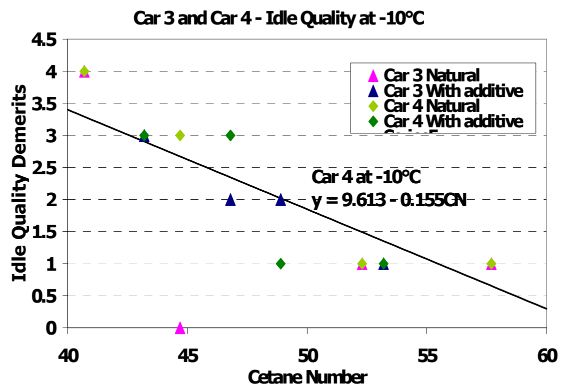
Figure 26: Driveability demerits grouped by vehicle and fleet average demerits.

The general level of driveability demerits was very low. Idle quality demerits formed the majority of instances recorded, these tending to be at -10°C and more numerous with lower cetane number fuels. So few demerits were recorded at 0°C and 10°C that it is impossible to link these to fuel quality, rather than normal vehicle variability. Only the trend at -10°C for Car 4 is statistically significant, (at the 99% confidence level).

10.2. Idle Quality Demerits

Idle quality demerits are considered separately to assess how they correlate with the measured idle quality. Only logs taken at -10°C are considered here as so few demerits were recorded at the warmer temperatures that it would be impossible to identify any patterns.





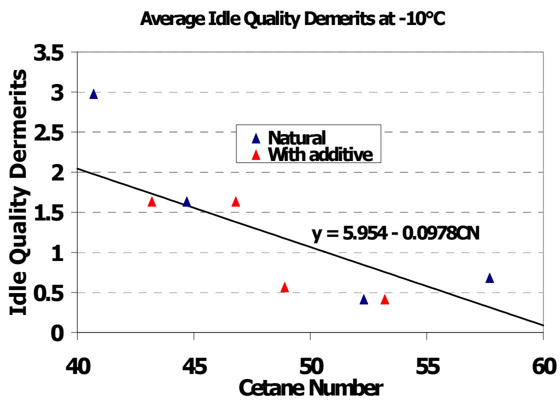


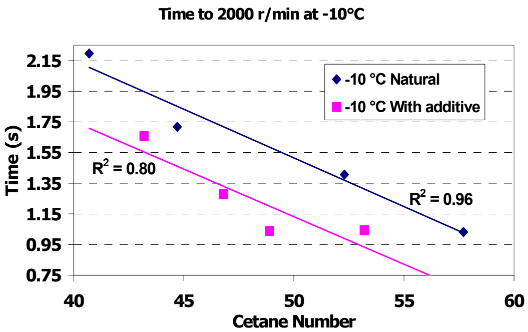
Figure 27: Idle quality demerits at -10°C

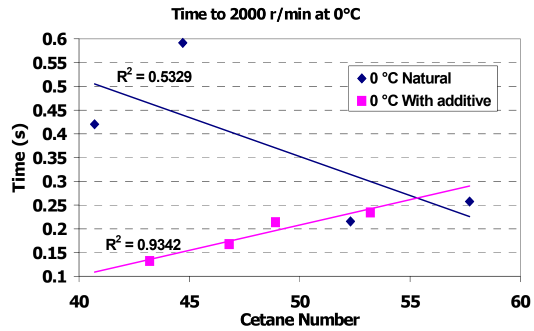
Cars 1, 2 and 3 tend to suffer most idle quality demerits with lower cetane fuel, but there are no statistically significant trends in the data. The trend for Car 4 at -10°C is identical to the total weighted demerits, as Car 4 only experienced idle quality demerits at this temperature, (statistically significant at the 99% confidence level). The fleet average trend at -10°C is statistically significant at the 95% confidence level.

11. Impact of Natural vs Additised Cetane

All trend lines fitted to the data in this section were linear models of the form y=mx+c (m = slope, c = y intercept at x=0). Trend line equations were not shown on charts to avoid overcrowding of the data.
Time to start was not considered due to the reasons set out in the sections specifically addressing the measurable and in the Executive Summary.
Note: the equations of linear trend lines of best fit, (and the corresponding R^2 values) for all data considered in this chapter are listed in Appendix 9.

11.1. Time for Engine Speed Rise





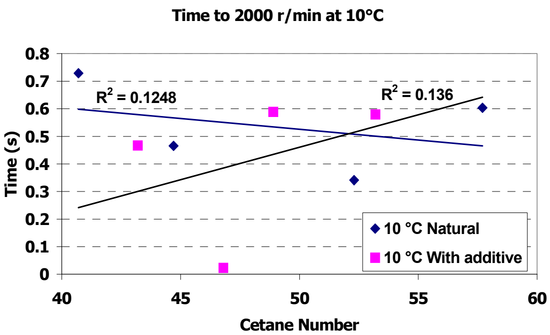
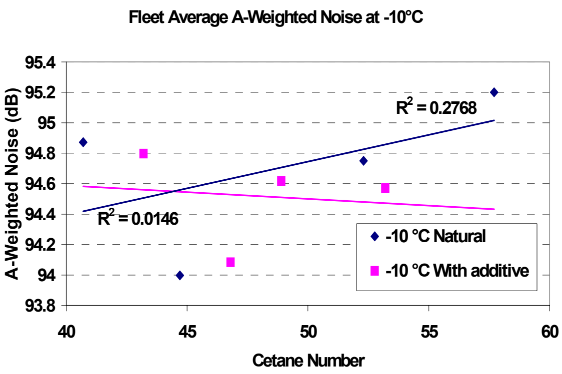


Figure 28: Time for engine speed rise

It is apparent from the data that: -

- In tests at -10°C there is a consistent time advantage for fuels of additised cetane quality of approximately 0.4 seconds.
- At 0°C, tests with additised fuel have quicker acceleration times than those with natural cetane fuel at lower cetane numbers, the advantage is lost at higher cetane numbers.
- At 10°C there are no trends in either dataset and so comparisons cannot be drawn.

11.2. Sound Levels



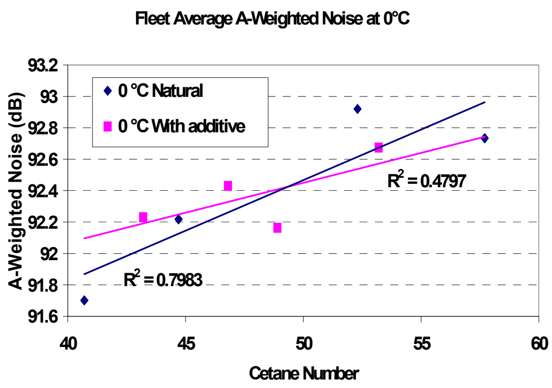
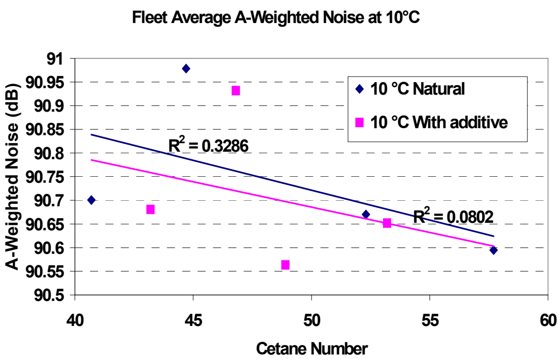
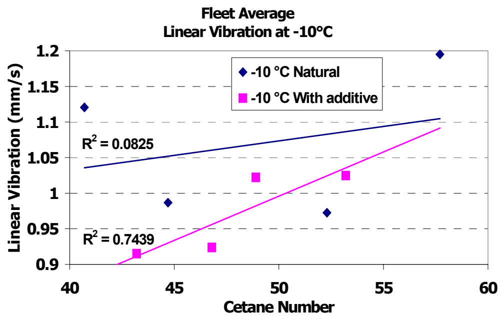


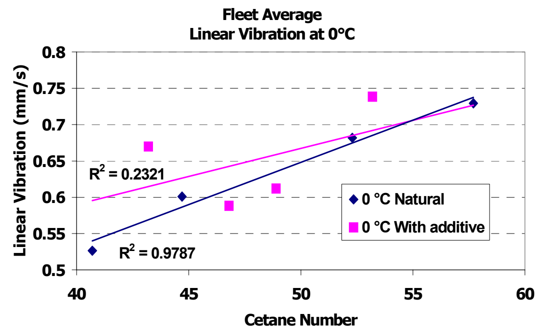
Figure 29: Fleet average A-Weighted Noise Levels grouped by temperature.



The data shows no substantial differences in the trends between fuels of natural and additised cetane quality.

11.3. Vibration





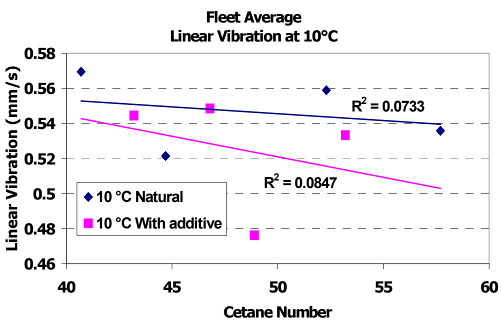
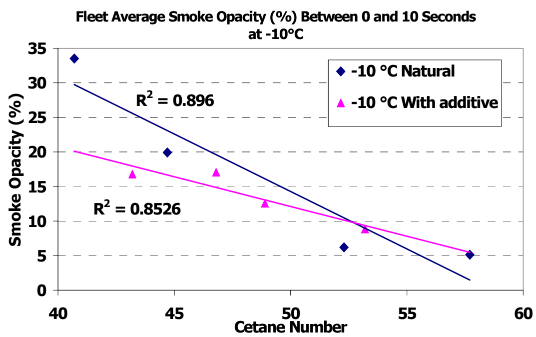


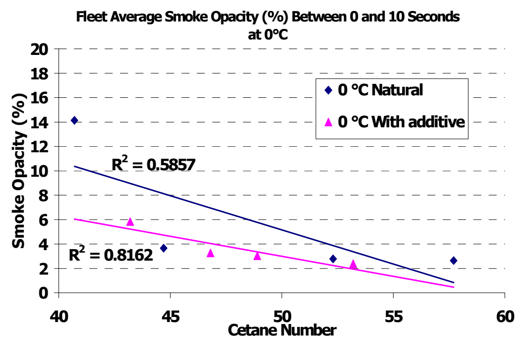
Figure 30: Fleet average linear vibration grouped by testing temperature.

The data shows little difference between data generated with fuels of natural and additised cetane quality.

11.4. Smoke

Smoke data showed no conclusive evidence of any difference in trends in smoke between fuels of natural and additised cetane quality. Smoke in the first 10 seconds after start up is shown here. The trend line and R^2 values for the other ranges examined can be found in Appendix 9.





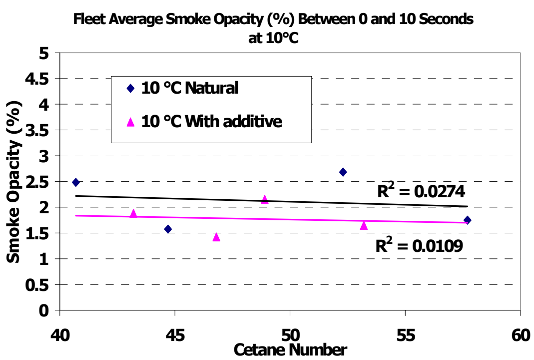
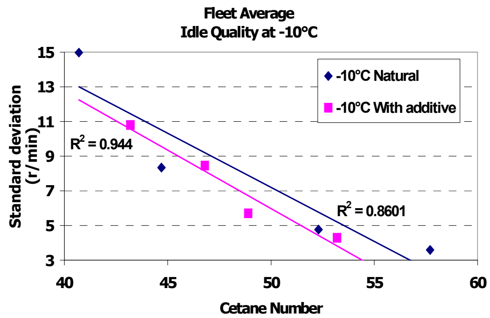
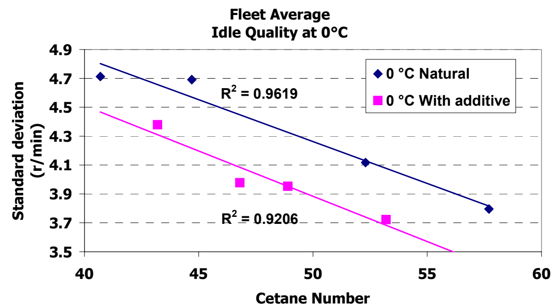


Figure 31: Smoke Opacity between 0 and 10 seconds

11.5. Measured Idle Quality





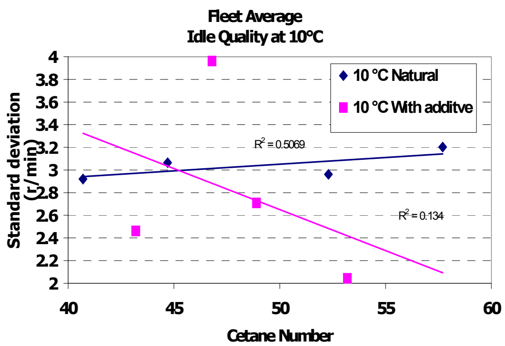
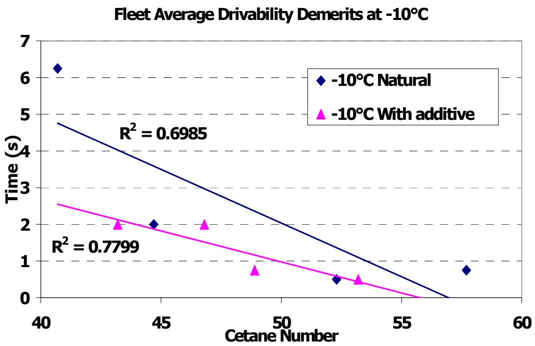


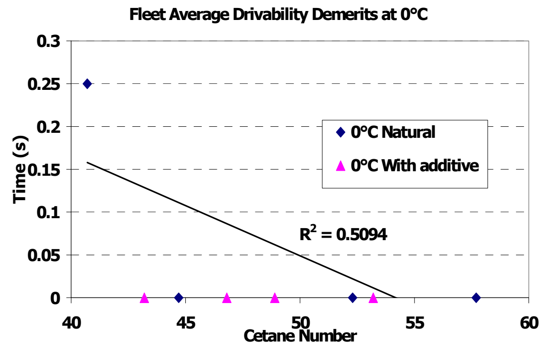
Figure 32: Measured Idle Quality between 10 and 20 seconds.

The charts show that fuels of natural cetane quality tend to give a higher standard deviation in idle speed at the –10°C and 0°C test temperatures. The difference increases as cetane number increases. At +10°C fuels of natural cetane quality tend to exhibit slightly poorer idle quality as cetane increases. There is no trend in the data with additised cetane at this temperature.

11.6. Subjective Driveability Ratings

11.6.1. Driveability Demerits





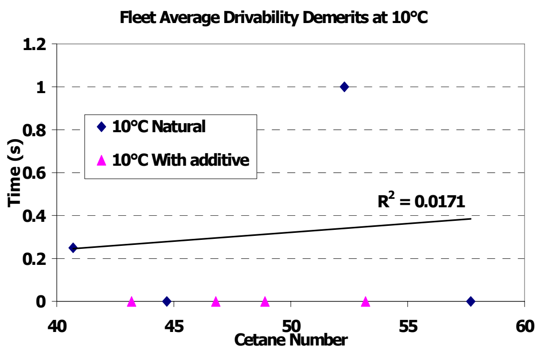


Figure 33: Fleet Average Driveability Demerits

Fuels of additised cetane quality tend to give less driveability demerits at -10°C. It can be seen that at 0°C and 10°C that natural cetane fuels produced a small number of demerits whilst fuels of additised cetane produced none.

11.6.2. Idle Quality Demerits

Only logs at -10°C have been evaluated here for the reasons set out in Section 10.2.

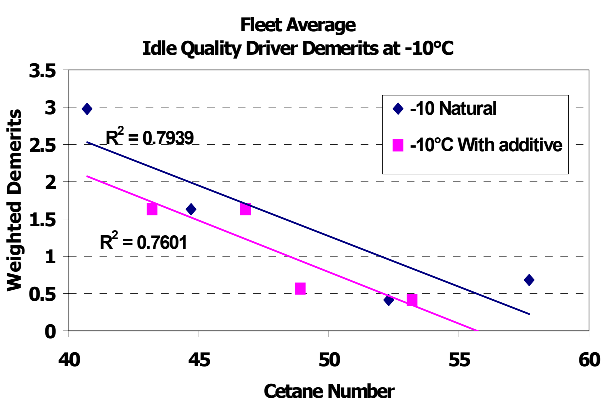


Figure 34: Idle Quality demerits

Both fuel sets produce fewer idle quality demerits as cetane increases. Fuels of additised cetane quality tend to produce fewer idle quality demerits at a given cetane number than fuels of natural cetane quality.

12. Impact of Fuel Properties Other Than Cetane Number

The fuels used in the study have a considerable spread in viscosity and differing boiling ranges. As the purpose of the report was to assess the effect of cetane number on vehicle performance, the effects of viscosity and boiling range on the data are considered to see if they have impacted on the results.
A fuel of higher viscosity will tend to vaporise less readily, thus leading to poorer air fuel mixing, later and possible incomplete combustion. Fuel with a higher boiling range will ignite and completely combust later than that with a lower boiling range. In both cases, this could then lead to an increase in smoke, noise, vibration and be detrimental to idle quality.
If viscosity and distillation impacted on the results in addition to cetane number, it would be expected that trends corresponding to viscosity and distillation would be present in datasets as well as trends corresponding to cetane number.

To assess this, smoke, noise, vibration and idle quality data, (which showed a statistical correlation with cetane number), were evaluated for the effects of viscosity and boiling range. Due to the small data ranges available, strong conclusions cannot be drawn and results should be taken as an indicator. Some evidence of the impact of viscosity and distillation is discussed in section 13.10.

The analysed data was split into 4 sets. Each set corresponds to fuels sharing the same boiling range and viscosity as outlined in the table below:

Set	Cetane Number/Identifier	Final Boiling Point	Viscosity
1	40.7	348.6	1.686
	43.2		
	46.8/ **B**		
2	44.7/ **A**	352.6	1.925
	48.9		
	53.2		
3	52.3	355.6	2.204
4	57.7/ **C**	360.7	3.523

Table 8: Fuel Sets arranged by similar Viscosity and Boiling Range

In assessing the data, fuels with the 3 highlighted cetane values were specifically considered, due to the differences in viscosity and boiling range. The fuel from set 2, (fuel A) has a lower cetane number than that of set 1, (fuel B) but also has favourable viscosity and boiling range values. The position of these fuels is highlighted on the charts by a circle around each corresponding point.
Therefore, if the differences in viscosity and boiling range, (as well as cetane), are impacting performance, the fuel from set 1 (fuel B) should show a better response in the data sets considered than would be expected from its cetane number alone.
The points are referred to as A, B and C in order of ascending cetane (lowest A, highest C).
Viscosity and boiling range also increase in accordance to set number (1 lowest, 4 highest).
The effect that would be expected to be seen if viscosity and boiling range were influencing performance (as well as cetane) is illustrated in Figure 35.

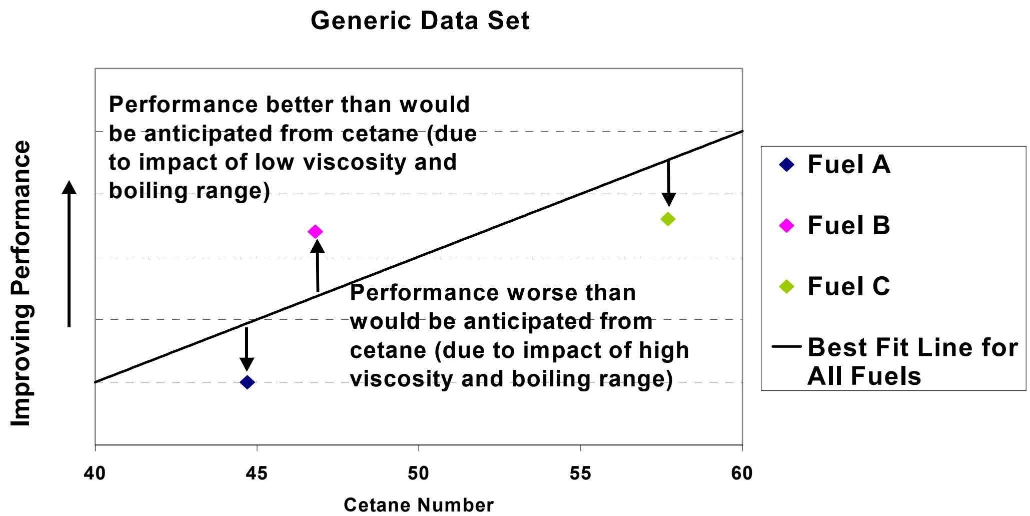


Figure 35: Trend expected in values for fuels A, B and C if viscosity and boiling range impact performance.

12.1. Smoke

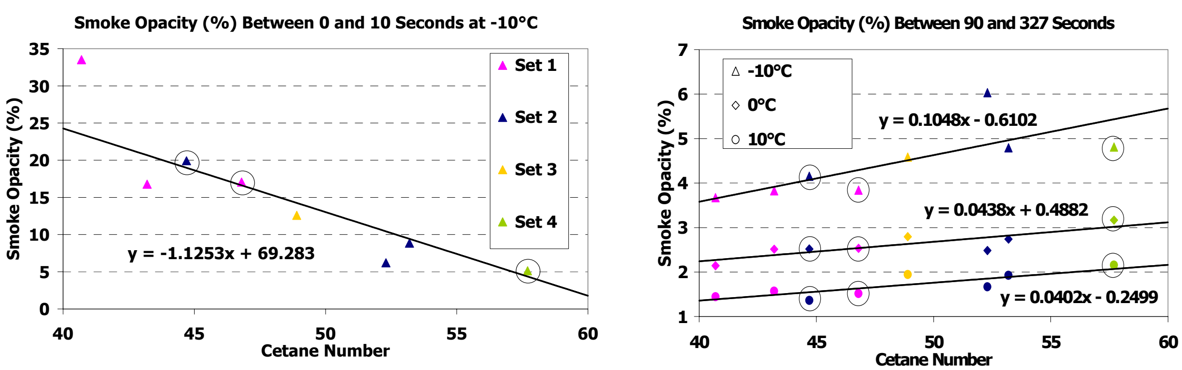


Figure 36: Fleet Average Smoke Opacity Between 0 and 10 Seconds and Between 90 and 327 Seconds

Between 0 and 10 seconds the three points considered lie along the trend line, indicating no impact of viscosity and boiling range, only cetane. Between 90 and 327 seconds fuel B and fuel C produce a lower result than would be expected from their cetane numbers at -10°C, so no conclusion can be drawn. The data considered are very close to the best fit line at 0°C and 10°C.

12.2. Noise

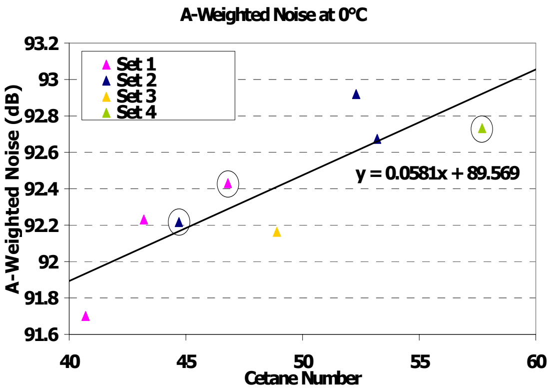


Figure 37: Fleet Average A-Weighted Noise at 0°C.

The data indicate higher noise than expected for fuel B and lower than expected noise for fuel C, thus little evidence for a dependency on viscosity and boiling range.

12.3. Vibration

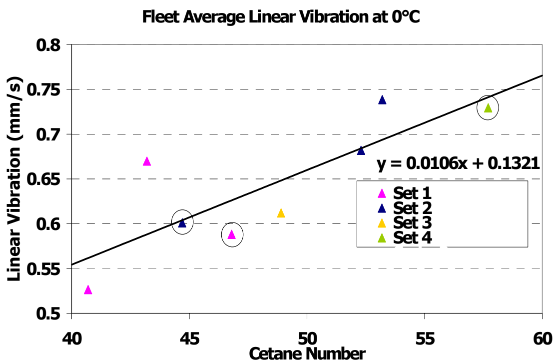
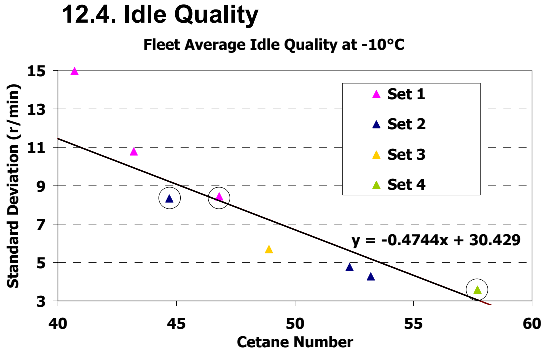


Figure 38: Fleet Average Vibration Velocity at 0°C

The data indicate lower than expected vibration from fuel B, a possible viscosity/boiling range effect. However when fuel 2 of set 1 is also considered, which gives much higher vibration than would be expected from its cetane, this becomes unlikely.

12.4. Idle Quality



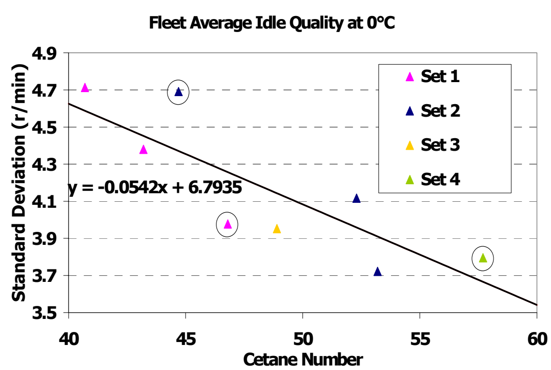


Figure 39: Fleet Average Idle Quality

Little impact of viscosity and boiling range at -10°C can be seen. Data at 0°C shows a better response for fuel B, indicating a possible viscosity/distillation affect.

13. Discussion

13.1. Time to Start

Cetane number and temperature are known to impact on the time to start of older technology diesel vehicles, but this is not the case with the modern technology vehicles considered here. Improvements in start assist systems and fuel atomisation and mixture preparation have been necessary to enable contemporary vehicles to meet increasingly stringent emissions standards. The conformity of production tests applicable include the cold start phase of operation, this yields the greatest amount of incompletely burnt fuel produced in the vehicles' normal drive cycle. Given that the longest time to start in this test programme was in the order of 1 second, it was not feasible to capture any meaningful differences in start up time. It would certainly be difficult for the driver to detect any perceivable differences in start up time.
It may be possible to cause some perceivable differences in start up time by further reducing fuel cetane number or testing temperature.

13.2. Time for Engine Speed Rise

The time for the engine speed to rise to 2000r/min was affected by temperature and cetane number in some of the tests. Car 1, Car 3 and Car 4 all took longer to reach 2000r/min in tests at –10°C, whilst there was little difference in times generated during equivalent tests at the warmer temperatures. Car 1 and Car 4 also exhibited sensitivity to cetane number at –10°C and there was a marginal effect on Car 3 times.
Car 2 seemed insensitive to either temperature or cetane changes (within the ranges tested). In all tests using Car 2 the time recorded to reach 2000r/min was less than 0.8 seconds.
The geometric fleet average results show that there is a statistically significant impact of cetane at –10°C, at the 95% confidence level, which is lost at the warmer temperatures.

13.3. Sound Measurements

Similar responses to temperature were seen in sound recorded from all vehicles. In each case sound pressure levels (SPLs) were higher at the –10°C testing condition. In tests with Car 1, Car 2 and Car 3, SPLs were higher at 0°C than at +10°C. This is as expected, as at colder temperatures, the engine running temperature is further removed from its optimum. This will impact on mechanical noise worsened by the lubricant, (which will be at higher than ideal viscosity), as well as impacting on combustion noise.

As shown in the results, there is not only vehicle to vehicle variation in magnitude, but also in the direction of the response to increasing cetane.
Higher cetane number reduces the ignition delay of the fuel/air mixture; as the mixture starts to burn earlier, the rate of cylinder pressure rise due to combustion is reduced, which in turn reduces audible combustion noise. The response of Car 2 to increasing cetane is therefore counter intuitive.

It is not clear why the vehicle responds in this way, but it is conceivable that it may be a function of the fuel injection strategy particular to this vehicle.

The fleet average SPLs from data collected between 10 and 20 seconds show a tendency for louder running with higher cetane at –10°C, which is not statistically significant. At 0°C there is a trend in the same direction which is statistically significant at the 99% confidence level. Conventional theory would suggest that increasing cetane would reduce the noise emissions. There is no real trend in the data collected at +10°C. The response to cetane is greatly dependent on vehicle type, and as such, a true market representation of average vehicle response would only be gained by screening a much larger selection of vehicle types.
Trends in the data examined over the entire testing recording period, (0-25 seconds), and including the complete usable frequency range, (100Hz – 20kHz), are either similar or less evident than in the smaller data range. No new or improved trends can be seen.

13.4. Vibration

The fleet average vibration data at 0°C collected between 10 and 20 seconds contain a trend linking higher cetane to increased vibration which is significant with 95% confidence. This trend is consistent with that seen in the fleet average sound data at this test temperature. No trends were apparent in the data recorded at the other test temperatures.
A larger cross section of market vehicle types would have to be tested to determine with certainty whether vibration tends to worsen with increasing cetane, and indeed whether this effect is only seen over a limited temperature range.
Trends in the data examined over the entire testing recording period, (0-25 seconds), and including the complete usable frequency range, (100Hz – 20kHz), are either similar or less evident than in the smaller data range. No new or improved trends can be seen.

13.5. Smoke

The most marked relationship in the fleet average smoke data occurred during the period immediately following start up (0-10 seconds test time). Despite the chance of inconsistencies in water vapour skewing the results, it seems that this is not the case. Indeed at –10°C, a trend linking increasing cetane and reduction in smoke is statistically significant at the 99% confidence level. The trend is still evident, but not statistically significant at 0°C, and is lost at +10°C.
As the test time increases, the smoke/cetane relationship changes. For the period up to the end of the first drive cycle (0-120 seconds), smoke is consistent irrespective of cetane number. When the entire test duration is considered, (0-327 seconds), there is a tendency for increasing smoke to accompany higher cetane levels. When only the latter part of the tests are considered (90-327 seconds, after the peak smoke has subsided), smoke increases with cetane. The trends being statistically significant at 95%, 99% and 99% for tests run at -10 °C, 0°C and +10°C, respectively.

In terms of the emissions response, there is some evidence that higher cetane can be detrimental to smoke emissions. In regulated emission measurements, EPEFE (the experimental part of the first European Auto/Oil programme) found that increasing cetane led to increased PM emissions. This effect was fairly consistent across the whole cycle (cold start and warm phases). For the fleet as a whole, an increase in cetane from 50 to 58 gave a 5.2% increase in PM over the full cycle and a 7.8% increase over the cold-start (+20°C ECE) phase. Out of eighteen vehicles in the fleet, only four vehicles showed a benefit of increased cetane number in reducing PM emissions. In the EPEFE fuel set, there was only one comparison of natural cetane (51 vs 58), and in this case the viscosity also increased from

2.2 to 2.8 cSt. There were also three fuels where 2-EHN was used (at levels up to 2800 mg/kg).
Tests using a larger fleet would be required to gain a true appreciation of the market average smoke/cetane relationship.

13.6. Measured Idle Quality

In general, there was more variation in idle speed at lower temperature. The only trends identifiable in the data linking improving idle quality with increasing cetane number were collected over the 10 – 20 second period of the test at -10°C using Car 1 and Car 4 and at 0°C using Car 3 and Car 4.
These trends carried through to make the relationships at these temperatures statistically significant for the fleet average values at the 99% confidence level.
No idle quality sensitivity to cetane number was detectable over the 20 –25 second period of the test. The lack of correlation is as anticipated, as the application of electrical load confounds any cetane effect.

13.7. Subjective Performance Ratings

The general level of subjective performance demerits was very low. Of those recorded, the majority were idle quality demerits logged during tests run at -10°C. Car 3 and Car 4 recorded higher instances of demerits than Car 2 or Car 1. It is only possible to identify a correlation between cetane number and demerit ratings for tests at -10°C, where increasing cetane resulted in decreasing demerits, which is statistically significant at the 95% confidence level.

13.8. Correlations in Datasets of Different Variables

In order to check the overall impact of cetane (and temperature) on the performance of the vehicles tested, the results can be tabulated for ease of comparison. Confidence level is only shown if it exceeds 95%; if the confidence level exceeds 99%, then this is indicated. If there is a comment but no confidence interval, then some trend is apparent from the dataset, but is not statistically significant.

Variable	Beneficial or Detrimental trend in fleet average with increasing cetane number? (confidence level)		
	-10°C	0°C	+10°C
Time to 2000 r/min	Beneficial (99%)	none	none
Measured Idle quality (10-20 seconds)	Beneficial (99%)	Beneficial (99%)	none
Smoke 0-10 seconds	Beneficial (99%)	none	none
Smoke 90-327 seconds	Detrimental (95%)	Detrimental (99%)	Detrimental (99%)
Sound pressure level (10-20s, 100Hz - 4 kHz)	none	Detrimental (99%)	none
Vibration (10 – 20s, 1 – 6 kHz)	none	Detrimental (95%)	none
Driveability demerits (total)	none	none	none
Idle quality demerits	Beneficial (95%)	none	none

Table 9: Comparison of trends in measured variables with increasing cetane number

Care must be taken not to compare variables measured in different parts of the tests. Comparisons can be drawn between:

- 0-10 seconds – time to 2000r/min and smoke 0-10 seconds. The results of these variables correlate well and suggest that increased cetane is beneficial immediately after start up.
- 10-20 seconds – SPL, vibration, measured idle quality and idle quality demerits. There are two conflicting trends here. Vibration and SPL severity increase as cetane number increases (at 0°C). Whereas subjective and measured idle quality tend to improve with increasing cetane. Assuming that these conflicting trends are real effects, there is no clear advantage or disadvantage for higher cetane in an idle period soon after cold start up.
- Post 20 seconds – measures here, which underwent statistical analysis, were smoke and driveability. Higher cetane fuels tend to produce more smoke after the initial start up and idle period. The majority of driveability demerits were due to idle quality demerits logged in the first idle period; hence, there is not enough data to identify a cetane/demerit correlation after this point. Therefore, the overall result based on the parameters measured is that higher cetane is detrimental to vehicle performance after the initial start up and idle period.

13.9. Comparison with Results of Previous Work[7]

A test programme executed in the early 1990s at Shell Global Solutions' UK laboratory, CIP considered the influence of cetane boost on cold start-ability and operability. This work used 6 trios of contemporary light-duty diesel vehicles, four IDI types and two DI types in tests conducted at –5°C. EHN was added at a concentration of 300ppmw to create a test fuel with cetane boosted by approximately 2 numbers. The testing concluded the following:

- Time to start – values ranging from 0.9 to 9 seconds were recorded. An improvement was seen for tests run on the higher cetane fuel.
- No improvement in cold start smoke or cold acceleration smoke was evident for the higher cetane fuel.
- Cold acceleration vehicle performance was improved with the use of the higher cetane fuel.
- Cold start noise and vibration increased with the higher cetane fuel.

Although the test methods, test temperatures and range of cetane number differs between the previous and current work, some comparisons between general traits in technology sensitivities can be drawn. These are considered in Table 7, below.

Performance measure	1992 Technology response to cetane increase	2003 Technology response to cetane increase
Time to auto-rotate	Improved	Not measurable
Responsiveness	Improved	Improved
Start up smoke	No response	Improved
Cold operability smoke	No response	Deteriorated
Cold idle noise	Deteriorated	Deteriorated
Cold idle vibration	Deteriorated	Deteriorated

Table 10: Responses to cetane number found in a Shell study a decade ago versus the responses found in the current programme.

It must be remembered that the cetane range tested during the earlier programme was much smaller than that used in the current work, testing a wider range may have allowed relationships between cetane and the measured parameters to be identified, and indeed could show responses to reverse over the larger range. However the following general trends are apparent:

- Both older and new technology vehicles exhibit higher sound and vibration levels with higher cetane.
- Both older and new technology vehicles show better cold responsiveness with higher cetane fuel.
- Starting time was reduced with increased cetane in the older vehicles, the newer models are insensitive to cetane.
- Start up smoke is reduced in the modern vehicle tests with higher cetane, but is unaffected in the older technology tests.
- Cold operability smoke worsened with higher cetane in modern vehicles but was unaffected in the older vehicles.

13.10. Impact of Fuel Properties

Since there is a link between volatility and viscosity, it is always difficult to separate these two possible influences. Thus, in this case, with increasing natural cetane, there is an increase in viscosity and an increase in the proportion of the higher boiling point components (i.e., reduced volatility). There have been studies of the effect of T90 or T95 on regulated emissions (e.g., EPEFE), but we are not aware of any studies concerning cold-start performance. In EPEFE, increasing T95 (which was also accompanied by increases in viscosity (2.0 to 3.8 cSt), but the effects were attributed to T95) resulted in increased PM emissions in both the cold-start phase (ECE) and the high-speed final phase (EUDC). A 45°C increase in T95 (325°C to 370°C) gave an 8.7% increase in PM in the cold-start phase (ECE). If linear, the 14°C change in T95 in the current fuel set might result in a 2% to 3% PM change.

Fuel viscosity can have an effect on spray characteristics such as the spray angle and the droplet size. Both these factors are likely to affect the fuel air mixing characteristics. According to J.B. Heywood (Internal Combustion Engine Fundamentals) the atomisation of the liquid jet is characterised by the divergence of the jet spray after an undisturbed length downstream of the nozzle. Under typical diesel injection conditions, the fuel jet usually forms a cone-shaped spray at or close to the nozzle exit. The spray jet divergence angle increases with decreasing fuel viscosity, and below a certain viscosity level, the divergence will begin at the nozzle exit. The gas/liquid density for the fuel and the hole geometry will also affect the jet divergence. The droplet size appears to be dependent on various fuel properties, including the liquid density, viscosity and surface tensions. Increases in surface tension and viscosity tend to increase the Sauter mean diameter, although the response is a function of the injection pressure, with higher pressures tending to reduce the influence of the fuel properties. Based on this information, the higher cetane fuels, having higher viscosity, may exhibit reduced spray divergence angles and larger droplet size, both of which could impair the fuel air mixing process.

The issues pertinent to the current work are: -

1. whether the differences in viscosity and distillation across the fuels used were large enough to influence the test results and
2. whether the fact that some fuels have cetane number attained via the addition of EHN has impacted the results for some reason other than because of the viscosity and distillation differences.

13.10.1. Apparent Impact of Viscosity and Boiling Range

In some of the plots in the section concerned with the impact of fuel properties other than cetane, (Chapter 12), some possible impact due to viscosity and distillation can be seen. There is no impact in the smoke data examined, the data correlate well with cetane number. In the noise data generated at 0°C, the fuel with a lower viscosity and distillation gives more noise than would be expected by its cetane value, this is opposite to the expected trend. The trends in the other data are as would be expected if viscosity and distillation have an effect, these are in vibration and measured idle quality at 0°C. In most of the datasets examined (where a good correlation existed between cetane and the variable), no affect of viscosity and distillation could be seen. Overall the data indicate that there is no impact from the viscosity and distillation, or that this effect is not consistent in the various datasets.

13.10.2. Impact of Natural vs Additised Cetane

The plots of the test measures showing separate series for fuels of natural and additised cetane quality show no clear benefits for either sub set of fuel except in two datasets:

- In the time to 2000r/min data at –10°C there is a clear benefit for fuels of additised cetane.
- In the measured idle quality data recorded at 0°C there is a clear benefit for fuels of additised cetane.

This effect is seen in only these two datasets (from 19 examined) and so could be coincidental. The expected effect, if any, would be that the fuel sets with natural cetane would give better performance for a given cetane number due to advantages in viscosity and distillation.

14. Conclusions

- **Cetane Number Sensitivity**

Based on the findings of this work, it is observed that modern vehicles equipped with solenoid controlled, high pressure DI fuel systems are less sensitive to changes in cetane number than older technology vehicles.

- **Time to Start**

Given the speed with which the modern vehicles' engines started during this work, it was not possible to determine the vehicle response to cetane number using this measure with the fuel and temperature ranges used. It may be possible to measure an appreciable response to cetane using these vehicles at lower testing temperatures.

- **Time for Engine Speed Rise**

The time for the engine speed to rise to 2000r/min was affected by temperature and cetane number in some tests. The impact of cetane number is vehicle model dependent. The geometric fleet average results show that there is a statistically significant reduction in time taken for engine speed rise in response to increasing cetane at –10°C. There is no effect at the warmer temperatures.

- **Sound Measurements**

Similar responses to temperature were seen in sound pressure levels recorded from all vehicles, with higher sound pressure levels occurring at lower temperatures. The only statistically significant correlation between cetane and fleet average SPLs show a trend linking higher cetane and increasing noise at 0°C. It was observed that the response to cetane is dependent on vehicle type, and as such, a true market representation of average vehicle response would only be gained by screening a much larger selection of vehicle types.
Trends in the data examined over the entire testing recording period (0-25 seconds) and including the complete usable frequency range (100Hz – 20kHz) are either similar or less evident than in the period of the test between 10 and 20 seconds.

- **Vibration**

The only statistically significant trend in the fleet average vibration data links higher cetane to higher vibration at 0°C. A larger cross section of market vehicle types would have to be tested to determine with certainty whether vibration increasing with rising cetane is a typical response, and indeed whether this effect is only seen over a limited temperature range.
Trends in the data examined over the entire testing recording period (0-25 seconds) and including the complete usable frequency range (100Hz – 20kHz) are either similar or less evident than in the period of the test between 10 and 20 seconds.

- **Smoke**

Lowering cetane number increases cold start smoke. This correlation is stronger at lower temperatures. Variations in water vapour present in the exhaust gas at this stage of the test do not have a significant impact on result reliability.
As the test time increases, the smoke/cetane relationship changes. Smoke values from a partially warmed engine are more likely to be higher with higher cetane number fuels.

- **Measured Idle Quality**

More variation in idle speed occurs at lower temperatures. Not all vehicles have idle quality sensitive to cetane. The fleet average values for this work show that increasing cetane leads to improving idle quality at lower temperatures, over the 10 – 20 second period of the test. There are no clear trends in the data collected after 20 seconds.

- **Subjective Performance Ratings**

The modern vehicles tested suffered few driveability faults during the tests; these were only significant at the coldest testing temperature. More driveability faults occurred with lower cetane fuels.

- **Impact of Fuel Variables other Than Cetane Number**

From the appraisal of the data that has been made, it is concluded that there is no clear influence of any fuel property other than cetane number evident.

- **Impact of Natural versus Additised Cetane Quality**

A substantial difference in only two data subsets was seen between fuels of natural and additised cetane. In both cases, fuels of additised cetane quality outperformed fuels of natural cetane quality. As this trend is only seen in a proportionately small amount of data, and is counter intuitive, it is concluded that this is a coincidental occurrence.

- **Perceivable Vehicle Response to Cetane Number and Temperature Variations**

In summary of the findings of this work, it would be difficult for the operator or bystander to identify any differences in the performance of the vehicles tested when subjected to the variations in fuel cetane number and temperature applied during this work. None of the vehicles were rendered inoperable by the use of the fuels and temperature ranges employed.

15. Further Work

- Further work with more vehicles, at lower temperatures, possibly including -20°C, would be necessary to identify the temperature and cetane number ranges that would constitute the limits of acceptable operation for modern light duty diesel vehicles. Engine damage could occur if cetane number was dropped much below 40.
- Tests with in-cylinder pressure data would be necessary to determine the reasons for the counter intuitive impact on vibration and noise emissions with increasing cetane.
- Sufficient information to determine the limit of operability for the vehicles could be gained from tests focussing on engine speed traces, smoke and perceived driveability performance.
- Further work would be required to ascertain the limits of perceptible changes in vibration and smoke opacity in order to qualify the findings of this report in terms of human perception.

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Appendices

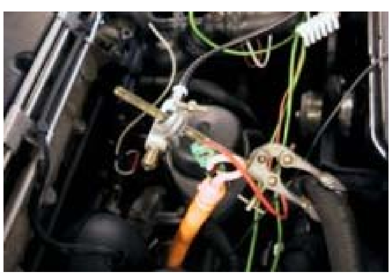
Appendix 1: Properties of Test Fuels

CRC Project AVFL-

Measured Fuel Properties. (Fuels with 2-EHN should have same properties as base fuel, except for Cetane Number.)
Base fuels for 2-EHN blends are repeated for clarity. Fuel set contains 8 fuels in total.

	Natural Cetane Blends					2-EHN Boost from 40 CN				2-EHN Boost from 45 CN		
Code	DBR 0216	DBR 0222	DBR 0221	DBR 0218		DBR 0216	DBR 0219	DBR 0220		DBR 0222	DBR 0223	DBR 0224
Description	40 CN Base	45 CN	50 CN	55 CN Base		40 CN Base	40 CN + 2-EHN	40 CN + 2-EHN		45 CN	45 CN + 2-EHN	45 CN + 2-EHN
2-EHN mg/kg	-	-	-	-		-	2522	4780		-	2005	4545
Density 15C kg/m3	836.4	835.4	834.6	833.8		836.4	836.6	836.8		835.4	835.6	836.0
Cetane No	40.7	44.7	52.3	57.7		40.7	43.2	46.8		44.7	48.9	53.2
CFPP	-26	-18	-17	-15		-26				-18		
IBP	162.8	164.3	170	174.1		162.8				164.3		
90% Rec	305	313.7	319.5	323.1		305				313.7		
95% Rec	327.9	334.8	339.1	341.7		327.9				334.8		
FBP	348.6	352.6	355.6	360.7		348.6				352.6		
Viscosity cS 40C	1.686	1.925	2.204	3.532		1.686				1.925		
Sulphur	38	36	36	36		38	37	36		36	37	36
Aromatics - Mono	28	26.2	24.1	21.8		28	28	28		26.2	26.1	26
- Di	1.8	1.9	2	2		1.8	1.8	1.8		1.9	2	1.9
- Tri+	0.4	0.3	0.3	0.4		0.4	0.3	0.3		0.3	0.3	0.3
- Total	30.2	28.4	26.4	24.2		30.2	30.1	30.1		28.4	28.4	28.2
C/H Ratio	1:1.8			1:1.9		1:1.8						
Cal Value Gross	11015			10940		11015						
Cal Value Net	10345			10255		10345						

Appendix 2: Images of Accelerometer and Microphone Positioning


Car 2 microphone position


Car 1 microphone position


Car 4 microphone position


Car 3 microphone position


Car 1 accelerometer position


Car 2 accelerometer position


Car 4 accelerometer position


Car 3 accelerometer position

Appendix 3: Statistical Data Analysis

This Appendix provides additional information on the statistical design and data analyses discussed in Sections 4.7 and 4.8.

Statistical Significance

Throughout the report the standard convention of quoting significance at one of three confidence levels, viz. 95% (i.e., $P < 5\%$), 99% ($P < 1\%$) or 99.9% ($P < 0.1\%$) as appropriate. Effects are deemed to be "not significant" if they are not significant at 95%, (i.e., $P < 5\%$).

Residual standard deviation vs. mean plots

In most performance tests, the variability in the results is itself variable with the degree of scatter increasing as the measured value increases. Variability levels also tend to vary from vehicle to vehicle.

Standard deviation vs mean plots are used to study relationships between variability levels and measured results and hence find suitable variance stabilising transformations (see, for example, standard ISO 4259[9]). In the absence of repeats in the present programme, standard deviations were calculated by fitting linear regression models of the form

$$x = a + b \times \text{CN},$$

by ordinary least squares, relating each untransformed measurement x to cetane number for each vehicle × temperature combination. The residual standard deviation (i.e., the residual mean square error) for each of the 12 vehicle × temperature fuel combinations was then plotted against the corresponding mean value across the eight fuels.

Figure 30 shows examples of residual standard deviation vs. mean plots so produced. No dependency is seen between S.D. and mean for *Average Idle Speed* and therefore no transformation is necessary. The S.D. is directly proportional to the mean for *Idle Quality* which suggests a simple logarithmic transform (ISO 4259[9], Annex E).

A fairly linear dependency is also seen for *Time to 2000 r/min*. However it is not possible to take logarithms as there are measurements equal to zero in the data. The variability is slightly larger than zero when the acceleration time is zero. A transformation of the form

$$y = \log(x + B)$$

can be used in such circumstances where the offset B is gauged from the S.D. vs mean plot by assuming the relationship takes the form

$$\text{S.D.} = k \times (\text{fitted value} + B)$$

Zeros appear in the data as logging does not start until some 0.25-0.5s after the engine is switched on. This and Figure 30 suggest 0.33(s) as a suitable value for the offset B.

The residual S.D. vs mean plot for *Smoke Opacity – 0-120s* shows a different pattern with the S.D. beginning to flatten out once the mean reaches 20%. This behaviour is common for data measured on a percentage or otherwise bounded scale. The S.D. is roughly

$$\text{S.D.} = k \times \frac{\textit{fitted value}}{100} \times \left(1 - \frac{\textit{fitted value}}{100}\right)$$

and the logistic transformation

$$y = \log\left(\frac{x}{100 - x}\right)$$

is appropriate.

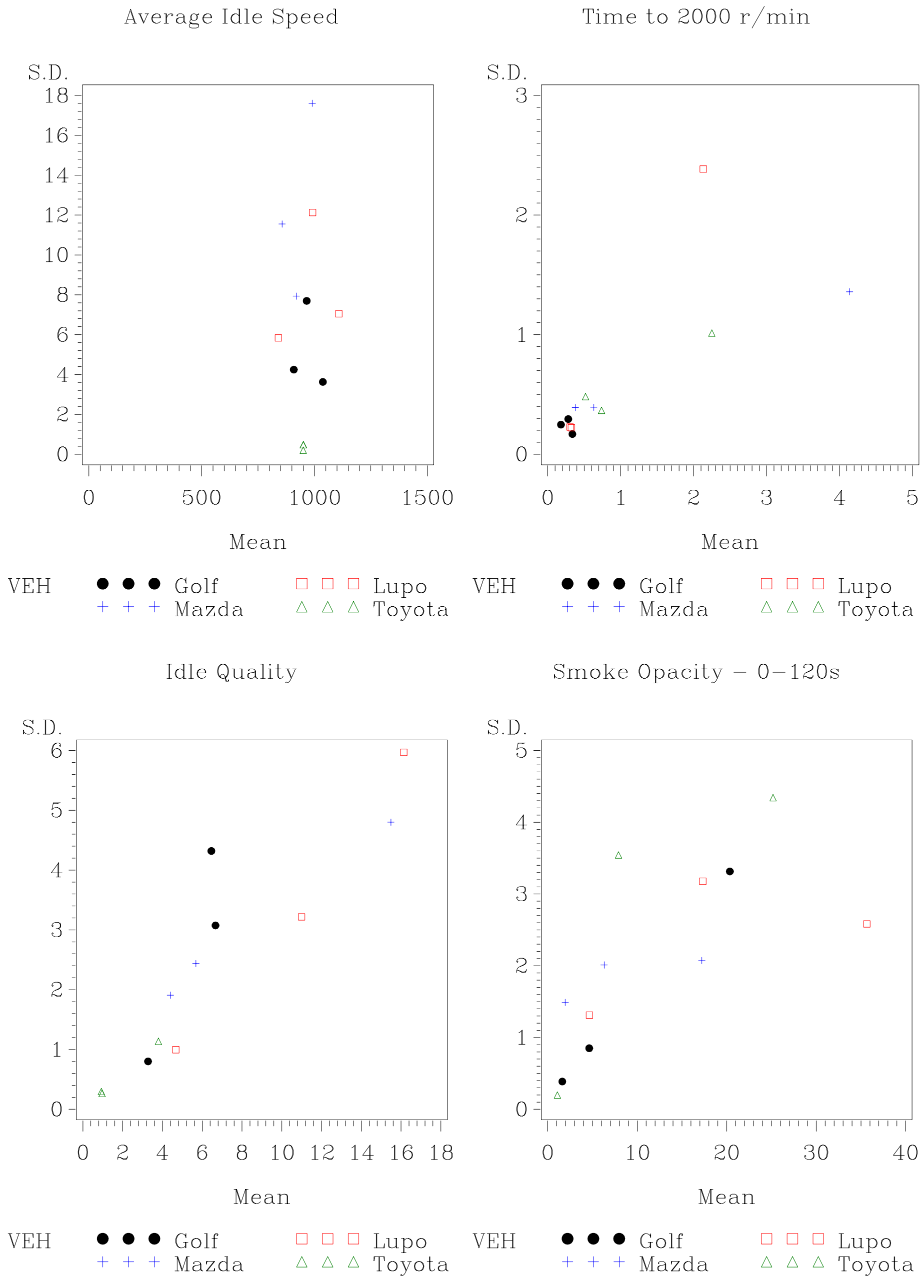


Figure 30. Residual standard deviation vs mean plots

Iteratively Re-weighted Least Squares

Linear models, e.g.

$$\log(DD + 1) = a + b \times CN$$

can be fitted using conventional linear regression techniques to data transformed to stabilise variability. However such models are non-linear when converted back to the original DD (demerit) scale, e.g.

$$DD = \exp(a + b.CN) - 1,$$

and non-linear models are not always appropriate.
Iteratively re-weighted least squares can be used to fit linear regression models, e.g.

$$DD = a + b \times CN$$

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

$$\text{weight} = \frac{1}{(\text{fitted value} + 1)^2}$$

The fitted values and weights are then recomputed and a subsequent weighted regression analysis is conducted. This process is continued until the regression coefficients have converged.
The same process can be used when the logistic transform is deemed apposite. The appropriate weight is then

$$\text{weight} = \frac{1}{\left(\frac{\text{mean}}{100} \times \left(1 - \frac{\text{mean}}{100}\right)\right)^2}$$

Outliers

In the absence of repeat tests, a model-based approach was used to examine the data for possible outliers. Regression models were fitted by IRLS assuming again that each untransformed performance measure x was linearly related to cetane number, i.e.

$$x = a + b \times \text{CN}$$

The studentized residuals (residuals divided by their standard errors) were then examined and compared with the 5% and 1% critical values in Table XXXVII of reference 8. Investigations were made into tests yielding studentized residuals above the critical values while recognising that high residuals could be a consequence of an inappropriate choice of model. Therefore, results were not rejected unless there was clear evidence of an abnormality in the execution of the test that was not fuel related.

Appendix 4: Parameters Measured and Metrics Evaluated

Parameters Measured via Dynamometer Control System	Metrics Evaluated
Force	Noise
Rolls Speed	Vibration
Coolant Temperature	Engine Speed
Oil Sump Temperature	Driveability
Air Filter In Temperature	Engine Idle Quality
Air Filter Out Temperature	Cold Start-ability
Fuel Filter In Temperature	
Fuel Filter Out Temperature	
Return Fuel Temperature	
Test Time	
Scheduled Speed	
Actual Speed	
Phase distance	
Bag distance	
Cell Pressure	
Cell Temperature	
Relative Humidity	
Smoke Opacity	
Fuel In Pressure	
Fuel Out Pressure	
Boost Pressure	
Battery Voltage	

Note - Noise, Vibration and Engine Speed were only recorded for the first 25 seconds.

Appendix 5: Proposed Test Matrix

		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
Block 1	C1	F1	F5	F2	F8	F7	F3	F4	F6
T2	C2	F3	F8	F2	F6	F1	F4	F7	F5
Block 2	C1	F4	F7	F3	F6	F1	F5	F2	F8
T3	C2	F3	F6	F1	F5	F8	F2	F4	F7
Block 3	C1	F8	F4	F7	F1	F3	F6	F2	F5
T1	C2	F7	F2	F3	F8	F4	F1	F5	F6
Block 4	C3	F2	F3	F8	F4	F6	F7	F1	F5
T3	C4	F5	F1	F6	F2	F7	F8	F3	F4
Block 5	C3	F6	F7	F4	F3	F5	F2	F8	F1
T1	C4	F3	F6	F1	F7	F2	F4	F8	F5
Block 6	C3	F8	F1	F3	F5	F2	F7	F4	F6
T2	C4	F1	F8	F4	F2	F6	F3	F5	F7

Key: T = temperature set point, T1 is lowest, T3 is highest
C = car, C1 is car 1
F = fuel, F1 has lowest cetane number, F8 has highest cetane number

Appendix 6: Table References

Table 1: Test Vehicles
Table 2: Fuel Details
Table 3: Temperature Set Points
Table 4: Actual Test Matrix
Table 5: Explanation of Statistical Methodology
Table 6: Protocol for assessment of idle speed data from 20 – 25 seconds
Table 7: Driveability Demerit Weightings
Table 8: Fuel Sets arranged by similar Viscosity and Boiling Range
Table 9: Trends with Cetane Numbers
Table 10: Responses to cetane number found in a Shell study a decade ago versus the responses found in the current programme

Appendix 7: List of Abbreviations

CRC: Coordinating Research Council
CIP: Cheshire Innovation Park
SPLs: Sound Pressure Levels
CEC: Coordinating European Council
EHN: 2-ethylhexyl nitrate
RMS: Root Mean Square
IDI: Indirect Injection
DI: Direct Injection

Appendix 8: Overview of CEC Test Procedures Used

CEC M-11-T-91 COLD WEATHER PERFORMANCE TEST PROCEDURE FOR DIESEL VEHICLES

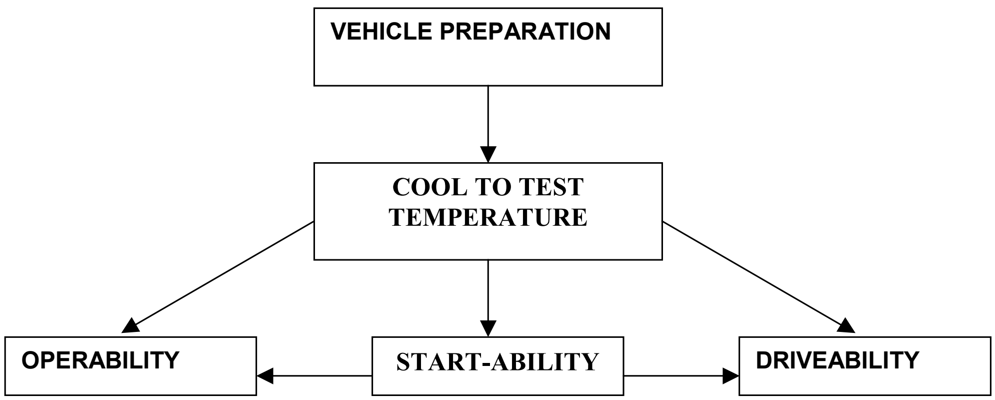
***Note**: Only the Start-ability section of this test procedure was used in the test programme*

PURPOSE AND SCOPE

The test procedure aims to determine the performance of a diesel vehicle/fuel combination at a low temperature by assessing vehicle behaviours.

SUMMARY

The two procedures may be performed independently or in combination as illustrated below.



The procedures may be applied to any diesel vehicle/fuel combination.

DEFINITIONS

Start-ability: The ability to start the vehicle using normal starting procedures.

Operability: Operability and vehicle driveability under fuel waxing conditions

Driveability: Vehicle driveability, including assessment of noise and smoke emissions, during the warm up phase following a cold start. This assessment is conducted at temperatures above that at which waxing will influence vehicle performance.

START-ABILITY TEST

The test method may be applied either to an engine on a stand, or to one installed in a vehicle. A set cool-down regime is followed prior to: -

(a) Use the starting procedure recommended by the vehicle or engine constructor. Use all recommended starting aids (e.g. block heaters at very low temperatures, glo plugs, ether sprays, etc). If a recommendation does not exist the following procedure is suggested:

- Place the gear lever in neutral. (In position “N” for vehicle equipped with automatic transmission.)
- Operate the starting aid(s).
- Declutch.
- Fully depress the acceleration pedal.

(b) Start a timing device and turn the key to operate the starter motor in sequences of 30 seconds cranking, unless otherwise stated by the manufacturer. If possible record cranking speed as this may explain a poor result if too low.

(c) In case of non-start, release the key, stop the stopwatch and wait 1 minute between each sequence. (If the vehicle manufacturer advises longer than 30 seconds cranking the waiting period between successive attempts should be extended, e.g. 1 minute cranking, 2 minutes wait, etc.)

(d) Repeat the above action (a) to (c) until a start has been achieved with a maximum of 3 attempts.

(e) Keep the starter motor operating after the initial firings until the engine can auto rotate.
Release the accelerator pedal when the engine speed reaches a suitable level, for example:

- 2000 rpm for passenger cars.
- 1000 rpm for trucks.

For vehicles equipped with automatic fast idle, release the accelerator completely and note idle speed. For other vehicles, regulate the idle speed at 1000 revs/min, by means of the hand accelerator, if fitted, or by the foot pedal, after noting the idle speed.
If the engine stalls during the first ten seconds of idling speed in auto-rotation, restart the engine. If the engine again stalls, terminate the cold start test. Report the result as “Stall at start” and commence a new test.

METHOD OF EVALUATION

The starting performance is evaluated by means of the parameters noted below as measured during the test.

(a) *Time to start:*
Define as being the total time of action on the starter to obtain engine auto-rotation for at least ten seconds without starter.

(b) *Time for engine speed rise:*
Defined as being the total time of operation of the starter motor and of the time of auto-rotation of the engine just to the point where the engine accelerates, to the speed defined in (e), followed by an operation time for at least ten seconds without stalling.

(c) *Number of attempts to start*

(d) *Number of stalls*

(e) *Time of stalls after first auto-rotation.*

(f) *Idle speed.*

CEC M-08-T-83 COLD WEATHER DRIVEABILITY TEST PROCEDURE

Note: *Only the driveability section of this procedure was used in the test programme*

PURPOSE AND SCOPE

A test procedure to determine start-ability and driveability in road going vehicles.

SUMMARY

The test procedure entails: -

- Vehicle preparation
- Conditioning at the test temperature
- Testing start-ability
- Testing driveability
- Evaluation of vehicle performance over the test

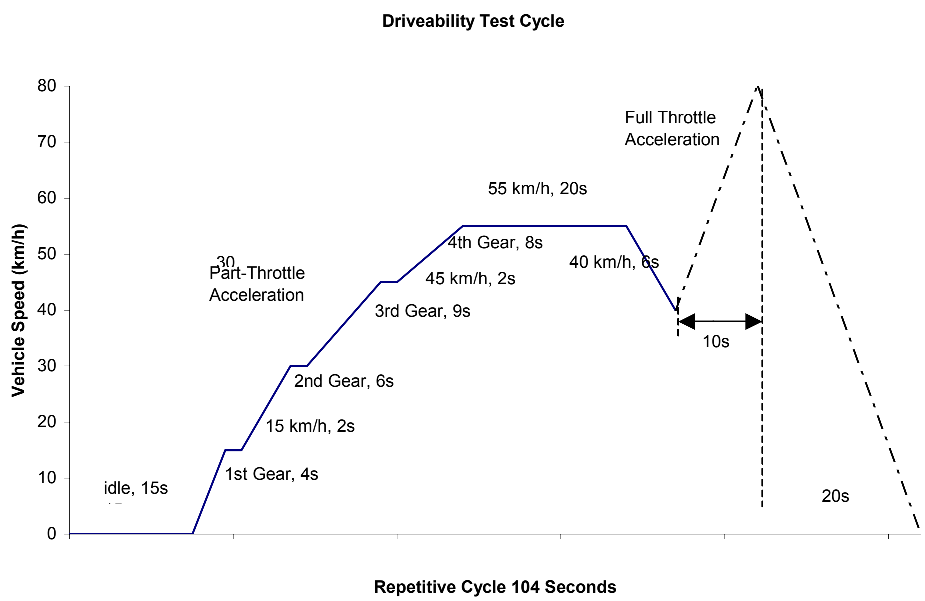
DEFINITIONS

Start-ability:	The ability to start the vehicle using normal starting procedures.
Driveability:	Vehicle driveability, during the warm up phase following a cold start. This assessment is conducted at temperatures above that at which waxing will influence vehicle performance.

TEST PROCEDURE

Note: *Start-ability assessment was conducted under CEC M-11-T-91*

1. Start engine
2. after 20 seconds idling unaided by the starter, deploy electrical load
3. Commence drive cycle after 30 seconds
4. Drive 12 cycles (or until the vehicle is clear of malfunctions with choke off)
5. Rate driveability malfunctions during the test cycles



EVALUATION:

Malfunctions to be rated as follows:

- Driving stall - a stall that occurs when the vehicle is driven under load.
- Idle stall - a stall that occurs during deceleration to idle or at idle
- Idle quality - evaluation of the variation in idle speed from the reference setting as measured on a continuous basis
- Hesitation - a momentary lack of initial response in acceleration
- Stumble - a short, sharp reduction in acceleration
- Surge - a continued condition of short fluctuations in power, which are cyclic and can occur at any speed and/or load. In this test procedure, surge is rated only during the cruise section of the test cycle.

Appendix 9: Natural vs Additised Cetane Trend line Tables

9.1 Fleet Average Time for Engine Speed Rise

Temperature	Intercept		Slope		R^2 Value	
	Natural	Additised	Natural	Additised	Natural	Additised
-10°C	4.69	4.24	-0.064	-0.06	0.96	0.80
0°C	1.174	-0.3249	-0.0164	0.0107	0.53	0.93
10°C	0.9156	-0.7175	-0.0078	0.0236	0.125	0.136

9.2 Fleet Average Noise Levels

	Natural	Additised	Natural	Additised	Natural	Additised
-10°C	93.058	94.95	0.0342	-0.0084	0.2591	0.0125
0°C	89.259	90.543	0.0647	0.0389	0.8057	0.4822
10°C	91.334	91.195	-0.0117	-0.0096	0.2882	0.0662

9.3 Fleet Average Linear Vibration

Temperature	Intercept		Slope		R^2 Value	
	Natural	Additised	Natural	Additised	Natural	Additised
-10°C	0.8706	0.3746	0.8706	0.0124	0.0825	0.7439
0°C	0.0664	0.2813	0.0116	0.0077	0.9787	0.2321
10°C	0.5843	0.6379	-0.0008	-0.0023	0.0733	0.0847

9.4 Smoke

9.4.1 Fleet Average Smoke Opacity (%) Between 0 and 10 Seconds

Temperature	Intercept		Slope		R^2 Value	
	Natural	Additised	Natural	Additised	Natural	Additised
-10°C	97.427	55.2	-1.663	-0.8617	0.896	0.8526
0°C	33.177	19.413	-0.5603	-0.3285	0.5857	0.8162
10°C	2.6981	2.1532	-0.0118	-0.0078	0.0274	0.0109

9.4.2 Fleet Average Smoke Opacity (%) Between 0 and 120 Seconds

Temperature	Intercept		Slope		R^2 Value	
	Natural	Additised	Natural	Additised	Natural	Additised
-10°C	33.099	-0.4178	-0.1696	0.4882	0.7503	0.5741
0°C	9.0159	10.435	-0.0276	-0.0583	0.0647	0.1032
10°C	0.6618	1.338	0.026	0.0084	0.5698	0.0486

9.4.3 Fleet Average Smoke Opacity (%) between 90 and 327 Seconds

Temperature	Intercept		Slope		R^2 Value	
	Natural	Additised	Natural	Additised	Natural	Additised
-10°C	0.116	-0.9114	0.0932	0.1077	0.4819	0.81
0°C	0.1321	1.3651	0.0501	0.0267	0.79	0.6062
10°C	-0.4264	-0.3105	0.0427	0.0427	0.8299	0.6187

9.4.4 Fleet Average Smoke Opacity (%) Between 0 and 327 Seconds

Temperature	Intercept		Slope		R^2 Value	
	Natural	Additised	Natural	Additised	Natural	Additised
-10°C	12.222	-0.3818	-0.0091	0.2318	0.0188	0.6402
0°C	3.1216	4.484	0.0222	-0.0047	0.1551	0.0053
10°C	0.0166	0.1409	0.0328	0.0297	0.8294	0.6289

9.4.5 Peak Fleet Average Smoke Opacity (%) Between 0 and 10 Seconds

Temperature	Intercept		Slope		R^2 Value	
	Natural	Additised	Natural	Additised	Natural	Additised
-10°C	96.955	65.673	-0.255	0.3547	0.9279	0.2775
0°C	86.742	65.806	-0.7401	-0.4084	0.7759	0.0809
10°C	45.806	5.1988	-0.2607	0.4277	0.1064	0.599

9.5 Fleet Average Idle Quality

Temperature	Intercept		Slope		R^2 Value	
	Natural	Additised	Natural	Additised	Natural	Additised
-10°C	38.363	39.681	-0.6233	-0.6741	0.8601	0.944
0°C	7.1627	7.0218	-0.058	-0.0628	0.9619	0.9206
10°C	2.4634	6.2705	0.0118	-0.0724	0.5069	0.134

9.6 Cold Driveability Demerits

9.6.1 Fleet Average Driveability Demerits

Temperature	Intercept		Slope		R^2 Value	
	Natural	Additised	Natural	Additised	Natural	Additised
-10°C	16.669	9.4406	-0.2926	-0.1692	0.6985	0.7799
0°C	0.6349	y=0	-0.0117	y=0	0.5094	NA
10°C	-0.0844	y=0	0.0081	y=0	0.0171	NA

9.6.2 Fleet Average Idle Quality Demerits

Temperature	Intercept		Slope		R^2 Value	
	Natural	Additised	Natural	Additised	Natural	Additised
-10°C	8.0477	7.7024	-0.1355	-0.1383	0.794	0.7601

Appendix 10: Data Summary

10.1 Idle Quality and Time For Engine Speed Rise

Car 1 Engine Speed, Block 1 Data Analysis at 0°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
Average Idle	926.97	919.20	927.82	920.02	907.50	930.04	912.60	912.37
Idle Quality	2.82	2.59	5.14	1.64	4.67	6.53	7.82	3.98
Time to 2000 r/min	0.85	0.03	0.60	0.15	0.70	0.00	0.00	0.70

Car 1 Engine Speed, Block 2 Data Analysis at 10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
Average Idle	875.47	847.79	860.09	843.74	848.62	852.81	867.97	855.42
Idle Quality	3.81	5.17	5.18	8.43	7.70	7.92	1.81	5.44
Time to 2000 r/min	1.25	0.35	0.30	0.10	0.80	0.75	0.80	0.70

Car 1 Engine Speed, Block 3 Data Analysis -10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
Average Idle	1053.76	1001.35	994.86	985.34	977.95	973.38	964.05	970.66
Idle Quality	35.85	17.60	18.96	21.40	13.29	7.87	5.31	3.61
Time to 2000 r/min	8.40	4.00	4.55	4.35	3.20	2.95	2.35	3.30

Car 2 Data Analysis, Block 1 at 0°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
Average Idle	972.15	964.77	969.57	964.09	957.59	959.45	958.89	977.71
Idle Quality	4.39	7.20	6.74	15.23	8.94	2.56	2.13	4.48
Time to 2000 r/min	0.65	0.00	0.50	0.00	0.00	0.00	0.30	0.00

Car 2 Engine Speed, Block 2 Data Analysis at 10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
Average Idle	906.41	907.58	918.55	908.43	906.51	908.07	906.80	906.23
Idle Quality	4.52	2.85	4.30	3.05	2.14	2.82	2.99	3.54
Time to 2000 r/min	0.35	0.35	0.35	0.00	0.30	0.40	0.30	0.65

Car 2 Engine Speed, Block 3 Data Analysis at -10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
Average Idle	1039.55	1036.16	1040.55	1034.29	1030.75	1038.49	1039.99	1038.61
Idle Quality	15.36	6.59	7.34	4.57	4.15	5.08	4.63	5.61
Time to 2000 r/min	0.20	0.00	0.55	0.00	0.45	0.70	0.35	0.00

Car 3 Engine Speed, Block 4 Data Analysis at 10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
Average Idle	848.34	848.17	836.77	846.60	833.86	834.11	833.67	841.27
Idle Quality	5.52	4.20	4.52	6.19	3.64	3.88	3.96	5.47
Time to 2000 r/min	0.55	0.35	0.40	0.00	0.45	0.00	0.45	0.40

Car 3 Engine Speed, Block 5 Data Analysis at -10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
Average Idle	1104.73	1117.18	1100.73	1108.40	1113.69	1114.24	1099.06	1108.39
Idle Quality	10.65	16.46	7.49	10.99	8.46	10.84	14.23	8.87
Time to 2000 r/min	1.75	2.05	1.00	7.65	1.30	0.85	1.40	1.05

Car 3 Engine Speed, Block 6 Data Analysis at 0°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
Average Idle	992.92	989.60	977.71	998.76	989.76	1003.91	1005.33	974.58
Idle Quality	22.61	18.59	13.49	13.34	7.53	25.01	14.22	14.29
Time to 2000 r/min	0.50	0.00	0.40	0.20	0.45	0.50	0.00	0.40

Car 4 Engine Speed, Block 4 Data Analysis at 10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
Average Idle	950.27	950.34	950.27	949.80	950.15	950.25	950.43	950.13
Idle Quality	0.76	0.59	0.88	1.55	0.90	0.89	0.81	1.00
Time to 2000 r/min	1.00	0.95	0.95	0.00	0.95	0.45	0.90	0.70

Car 4 Engine Speed, Block 5 Data Analysis at -10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
Average Idle	949.60	950.77	950.74	950.52	949.70	950.70	950.43	950.68
Idle Quality	8.56	7.11	4.64	4.73	2.26	1.19	0.96	0.93
Time to 2000 r/min	3.90	4.25	2.75	2.15	0.45	1.95	0.80	1.75

Car 4 Engine Speed, Block 6 Data Analysis at 0°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
Average Idle	952.06	950.94	950.88	950.31	950.58	950.73	950.41	950.81
Idle Quality	1.76	1.06	1.04	0.75	0.78	0.69	0.81	0.81
Time to 2000 r/min	0.00	0.85	0.95	0.40	0.00	0.65	1.15	0.15

Appendix 10.2 Noise and Vibration

							Noise	Vibration
Test Number	Date	Time	Car	Fuel Number	Cetane number	Temperature	A-wtd	Linear
		Hours				°C	dB(A)	mm/s
1	11-Nov-03	12:07	Car 1	Fuel 1	40.7	0°C	91.57509	0.990632
5	13-Nov-03	09:58	Car 1	Fuel 2	43.2	0°C	91.51364	0.947774
14	24-Nov-03	15:38	Car 1	Fuel 3	44.7	0°C	91.44689	1.034426
8	19-Nov-03	11:02	Car 1	Fuel 4	46.8	0°C	91.67524	0.993778
11	21-Nov-03	10:30	Car 1	Fuel 5	48.9	0°C	90.82686	0.75654
10	20-Nov-03	15:25	Car 1	Fuel 6	52.3	0°C	91.67123	0.857042
4	12-Nov-03	15:32	Car 1	Fuel 7	53.2	0°C	90.51826	0.918842
7	14-Nov-03	15:22	Car 1	Fuel 8	57.7	0°C	90.05998	0.91091
22	08-Dec-03	15:14	Car 1	Fuel 1	40.7	10°C	90.38122	1.07111
20	05-Dec-03	10:10	Car 1	Fuel 2	43.2	10°C	90.21147	0.715442
17	02-Dec-03	11:05	Car 1	Fuel 3	44.7	10°C	90.04206	0.932471
23	09-Dec-03	10:44	Car 1	Fuel 4	46.8	10°C	90.12489	0.937494
15	27-Nov-03	11:01	Car 1	Fuel 5	48.9	10°C	89.83344	0.867269
19	04-Dec-03	16:53	Car 1	Fuel 6	52.3	10°C	90.15665	0.796712
26	10-Dec-03	14:57	Car 1	Fuel 7	53.2	10°C	88.23722	0.978698
16	28-Nov-03	15:17	Car 1	Fuel 8	57.7	10°C	88.01723	0.812901
45	20-Jan-04	10:27	Car 1	Fuel 1	40.7	-10°C	94.4986	1.676955
37	14-Jan-04	11:04	Car 1	Fuel 2	43.2	-10°C	94.59841	1.492075
40	15-Jan-04	15:11	Car 1	Fuel 3	44.7	-10°C	93.37229	1.64392
44	19-Jan-04	15:07	Car 1	Fuel 4	46.8	-10°C	93.20744	1.511932
48	21-Jan-04	15:05	Car 1	Fuel 5	48.9	-10°C	93.25489	1.273573
33	08-Jan-04	10:58	Car 1	Fuel 6	52.3	-10°C	94.12223	1.402289
41	16-Jan-04	10:48	Car 1	Fuel 7	53.2	-10°C	93.23425	1.513124
36	13-Jan-04	14:55	Car 1	Fuel 8	57.7	-10°C	93.48872	1.454653
9	19-Nov-03	15:18	Car 2	Fuel 1	40.7	0°C	90.08824	1.021545
28	20-Dec-03	11:19	Car 2	Fuel 2	43.2	0°C	90.45508	1.02632
2	11-Nov-03	14:03	Car 2	Fuel 3	44.7	0°C	92.25987	1.048428
12	21-Nov-03	13:53	Car 2	Fuel 4	46.8	0°C	90.77248	0.839113
13	24-Nov-03	11:10	Car 2	Fuel 5	48.9	0°C	91.05457	0.911086
3	12-Nov-03	10:37	Car 2	Fuel 6	52.3	0°C	92.20423	1.069133
6	14-Nov-03	10:12	Car 2	Fuel 7	53.2	0°C	91.76252	1.021046
27	18-Dec-03	09:54	Car 2	Fuel 8	57.7	0°C	92.70573	1.208636
29	23-Dec-03	14:43	Car 2	Fuel 1	40.7	10°C	90.08106	0.805116
24	09-Dec-03	15:29	Car 2	Fuel 2	43.2	10°C	88.67496	0.712239
21	08-Dec-03	10:33	Car 2	Fuel 3	44.7	10°C	89.09387	0.846087
25	10-Dec-03	10:49	Car 2	Fuel 4	46.8	10°C	89.29639	0.805573
32	07-Jan-04	14:43	Car 2	Fuel 5	48.9	10°C	89.20232	0.796084
31	05-Jan-04	16:06	Car 2	Fuel 6	52.3	10°C	88.40467	0.755327
30	24-Dec-03	10:57	Car 2	Fuel 7	53.2	10°C	89.80412	0.768049
18	04-Dec-03	11:00	Car 2	Fuel 8	57.7	10°C	89.89028	0.924462
47	21-Jan-04	10:46	Car 2	Fuel 1	40.7	-10°C	92.31966	1.242175
43	19-Jan-04	11:43	Car 2	Fuel 2	43.2	-10°C	92.58766	1.141154
38	14-Jan-04	15:13	Car 2	Fuel 3	44.7	-10°C	93.11687	1.206468
35	13-Jan-04	10:32	Car 2	Fuel 4	46.8	-10°C	93.43072	1.115784
34	09-Jan-04	15:06	Car 2	Fuel 5	48.9	-10°C	92.82766	1.062106
42	16-Jan-04	14:59	Car 2	Fuel 6	52.3	-10°C	93.56555	1.08101
46	20-Jan-04	14:39	Car 2	Fuel 7	53.2	-10°C	93.91672	1.469919
39	15-Jan-04	14:39	Car 2	Fuel 8	57.7	-10°C	94.36312	1.227838

							Noise	Vibration
Test Number	*Date*	*Time*	*Car*	*Fuel Number*	*Cetane number*	*Temperature*	*A-wtd*	*Linear*
		Hours				*°C*	*dB(A)*	*mm/s*
82	25-Feb-04	15:31	Car 3	Fuel 1	40.7	0°C	96.54928	2.167895
83	26-Feb-04	11:28	Car 3	Fuel 2	43.2	0°C	97.03958	2.348253
96	09-Mar-04	13:10	Car 3	Fuel 3	44.7	0°C	96.4941	2.120921
87	01-Mar-04	10:26	Car 3	Fuel 4	46.8	0°C	97.75875	2.165039
90	03-Mar-04	15:13	Car 3	Fuel 5	48.9	0°C	97.05109	1.868631
93	05-Mar-04	14:27	Car 3	Fuel 6	52.3	0°C	97.02505	2.2558
94	08-Mar-04	10:45	Car 3	Fuel 7	53.2	0°C	97.71915	2.304842
86	27-Feb-04	14:54	Car 3	Fuel 8	57.7	0°C	97.46975	2.225682
59	09-Feb-04	14:48	Car 3	Fuel 1	40.7	10°C	92.90595	1.692097
51	28-Jan-04	14:22	Car 3	Fuel 2	43.2	10°C	94.12375	1.517929
57	03-Feb-04	15:34	Car 3	Fuel 3	44.7	10°C	93.8292	1.693607
60	10-Feb-04	09:05	Car 3	Fuel 4	46.8	10°C	92.82803	1.616081
49	27-Jan-04	10:54	Car 3	Fuel 5	48.9	10°C	93.20431	1.519263
54	02-Feb-04	09:19	Car 3	Fuel 6	52.3	10°C	92.67339	1.451427
52	29-Jan-04	09:13	Car 3	Fuel 7	53.2	10°C	93.82342	1.537406
63	11-Feb-04	11:17	Car 3	Fuel 8	57.7	10°C	92.94117	1.794748
71	17-Feb-04	09:50	Car 3	Fuel 1	40.7	-10°C	97.42679	2.242199
79	23-Feb-04	10:53	Car 3	Fuel 2	43.2	-10°C	98.2575	2.837899
67	13-Feb-04	10:51	Car 3	Fuel 3	44.7	-10°C	98.44691	2.551703
66	12-Feb-04	15:16	Car 3	Fuel 4	46.8	-10°C	96.98085	2.395947
78	20-Feb-04	14:06	Car 3	Fuel 5	48.9	-10°C	100.4815	2.563317
75	19-Feb-04	11:06	Car 3	Fuel 6	52.3	-10°C	98.84228	2.652045
74	18-Feb-04	15:34	Car 3	Fuel 7	53.2	-10°C	98.67031	2.716419
70	16-Feb-04	14:55	Car 3	Fuel 8	57.7	-10°C	98.75806	2.598066
89	03-Mar-04	11:04	Car 4	Fuel 1	40.7	0°C	91.66341	1.312646
88	01-Mar-04	14:57	Car 4	Fuel 2	43.2	0°C	92.63936	1.943189
84	26-Feb-04	16:27	Car 4	Fuel 3	44.7	0°C	91.64647	1.533576
85	27-Feb-04	11:07	Car 4	Fuel 4	46.8	0°C	92.75934	1.356233
92	05-Mar-04	11:17	Car 4	Fuel 5	48.9	0°C	92.79916	1.633076
95	08-Mar-04	17:05	Car 4	Fuel 6	52.3	0°C	93.31303	1.797049
81	25-Feb-04	11:22	Car 4	Fuel 7	53.2	0°C	93.85588	2.247943
91	04-Mar-04	15:19	Car 4	Fuel 8	57.7	0°C	93.49511	2.309156
61	10-Feb-04	13:32	Car 4	Fuel 1	40.7	10°C	92.17222	1.720772
55	02-Feb-04	13:42	Car 4	Fuel 2	43.2	10°C	91.84372	1.43624
58	09-Feb-04	10:19	Car 4	Fuel 3	44.7	10°C	93.20423	1.833073
62	11-Feb-04	08:45	Car 4	Fuel 4	46.8	10°C	93.50891	1.578157
56	03-Feb-04	10:30	Car 4	Fuel 5	48.9	10°C	92.33558	1.388606
53	29-Jan-04	13:34	Car 4	Fuel 6	52.3	10°C	93.61591	1.736941
64	11-Feb-04	16:16	Car 4	Fuel 7	53.2	10°C	93.65532	1.508807
50	28-Jan-04	10:40	Car 4	Fuel 8	57.7	10°C	93.32914	1.710618
69	16-Feb-04	10:02	Car 4	Fuel 1	40.7	-10°C	98.78564	3.28127
65	12-Feb-04	10:59	Car 4	Fuel 2	43.2	-10°C	96.57495	1.575178
72	17-Feb-04	14:35	Car 4	Fuel 3	44.7	-10°C	94.71703	2.455425
73	18-Feb-04	10:01	Car 4	Fuel 4	46.8	-10°C	95.67316	3.168334
80	23-Feb-04	14:52	Car 4	Fuel 5	48.9	-10°C	94.62389	3.029445
68	13-Feb-04	15:20	Car 4	Fuel 6	52.3	-10°C	95.02136	2.581129
77	20-Feb-04	10:19	Car 4	Fuel 7	53.2	-10°C	94.97185	2.614219
76	19-Feb-04	15:06	Car 4	Fuel 8	57.7	-10°C	96.25688	3.320214

Appendix 10.3 Smoke

Car 1 Smoke, Block 1 Data Analysis at 0°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
0 - 10 Seconds	21.23636364	10.26363636	4.745454545	7.227272727	3.063636364	4.490909091	2.590909091	4.381818182
0 -120 Seconds	6.747107438	6.566115702	5.689256198	10.55702479	3.961983471	6.301652893	6.202479339	4.374380165
0 - 327 Seconds	3.14847561	3.062804878	2.840853659	4.667682927	2.230182927	3.238414634	3.128963415	2.541768293
90 - 327 Seconds	1.335714286	1.246218487	1.429831933	1.678991597	1.408823529	1.72605042	1.616386555	1.729831933
Peak	75.1	57.4	47.3	58.9	28.2	37.8	38.6	24.6

Car 1 Smoke, Block 2 Data Analysis at 10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
0 - 10 Seconds	11.20909091	3.763636364	5.354545455	1.281818182	3.136363636	3.081818182	1.318181818	2.181818182
0 - 120 Seconds	2.17107438	1.172727273	1.385123967	0.79338843	5.205785124	1.587603306	1.389256198	1.95785124
0 - 327 Seconds	1.538719512	1.060670732	1.310060976	0.969512195	2.894512195	1.522256098	1.491158537	2.016463415
90 - 327 Seconds	1.306722689	1.182773109	1.403781513	1.192857143	2.259663866	1.743277311	1.768907563	2.446218487
Peak	56.8	22.1	31.1	17.8	29.5	22.6	23.5	33.2

Car 1 Smoked, Block 3 Data Analysis at -10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
0- 10 Seconds	63.96363636	19.07272727	20.86363636	14.60909091	3.727272727	2.172727273	5.581818182	8.954545455
0 - 120 Seconds	18.89586777	15.33966942	20.21322314	15.98181818	15.02644628	18.00578512	15.78099174	18.4677686
0 - 327 Seconds	7.971341463	6.718292683	8.500304878	7.219207317	6.742378049	9.561280488	7.285365854	8.47195122
90 - 327 Seconds	2.014285714	2.103361345	2.224369748	2.370588235	2.225630252	5.233193277	2.734033613	3.116806723
Peak	88.7	77.9	88.1	82.8	83.5	82.8	81.1	84.5

Car 2 Smoke, Block 1 Data Analysis at 0°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
0 - 10 Seconds	7.945454545	3.554545455	4.490909091	2.209090909	3.363636364	5.090909091	1.709090909	1.509090909
0 - 120 Seconds	7.285950413	6.300826446	4.4	5.038016529	4.756198347	3.170247934	2.619008264	3.490082645
0 - 327 Seconds	3.446036585	3.164939024	2.544512195	2.786890244	2.607621951	1.946036585	1.817073171	2.762195122
90 - 327 Seconds	1.580672269	1.701680672	1.802941176	1.893277311	1.657142857	1.46512605	1.679831933	2.387394958
Peak	54.3	54.7	42.1	41.8	41.3	37	44.6	45.1

Car 2 Smoke, Block 2 Data Analysis at 10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
0 - 10 Seconds	0.436363636	1.218181818	2.727272727	1.109090909	1.490909091	9.954545455	3.3	3.245454545
0 - 120 Seconds	1.028099174	2.04214876	1.679338843	1.314049587	1.453719008	2.22231405	1.650413223	1.637190083
0 - 327 Seconds	1.162804878	1.690853659	1.603658537	1.376219512	1.583231707	1.775	1.666158537	1.551219512
90 - 327 Seconds	1.460084034	1.789495798	1.781932773	1.639915966	1.923529412	1.774369748	1.901680672	1.740336134
Peak	48.5	39.1	40.4	37.6	42.6	90.5	40.5	38.4

Car 2 Smoke, Block 3 Data Analysis at -10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
0 -10 Seconds	12.5	7.363636364	12.20909091	8.009090909	11.91818182	8.4	5.290909091	5.136363636
0 - 120 Seconds	21.76033058	20.45950413	23.83966942	14.12396694	23.84380165	18.88347107	20.89834711	18.96859504
0 - 327 Seconds	9.394817073	8.772560976	10.11310976	6.352743902	10.22408537	7.90152439	8.952439024	8.591463415
90 - 327 Seconds	3.017226891	2.790336134	3.056722689	2.739495798	3.144957983	2.313445378	2.830252101	3.236134454
Peak	82.6	80.2	84.2	70.3	84.5	79.5	80.4	73.5

Car 3 Smoke, Block 4 Data Analysis at 10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
0-10 Seconds	5.972727273	3.3	0.9	2.154545455	3.654545455	2.063636364	2.5	1.754545455
0 - 120 Seconds	6.603305785	5.018181818	3.239669421	3.961157025	3.029752066	4.96446281	4.733057851	5.744628099
0 - 327 Seconds	3.531707317	3.017378049	2.056402439	2.441463415	2.18902439	3.06097561	3.441158537	3.663719512
90 - 327 Seconds	2.618907563	2.593697479	1.335714286	1.997058824	1.886554622	2.262184874	3.031092437	3.04789916
Peak	28	13.5	11.6	12.6	14.4	14.5	13.6	18.3

Car 3 Smoke, Block 5 Data Analysis at -10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
0 - 10 Seconds	14.77272727	7.936363636	13.54545455	14.63636364	16.33636364	8.218181818	10.10909091	4.590909091
0 - 120 Seconds	35.13801653	31.71570248	35.6446281	34.40330579	36.39090909	35.23801653	41.40247934	35.38677686
0 - 327 Seconds	19.66158537	18.38567073	21.1875	20.40884146	21.19359756	24.5195122	24.99512195	21.7929878
90 - 327 Seconds	13.35504202	13.26218487	15.68067227	15.58235294	15.37941176	20.91218487	18.99579832	16.77941176
Peak	87.4	86.7	88.9	84.7	88.4	88.2	89.4	87.4

Car 3 Smoke, Block 6 Data Analysis at 0°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
0 - 10 Seconds	14.79090909	7.763636364	2.781818182	2.436363636	4.890909091	2.536363636	3.345454545	2.654545455
0 - 120 Seconds	19.09173554	13.55702479	21.08595041	12.93553719	18.37190083	17.66942149	15.75619835	20.12892562
0 - 327 Seconds	10.45640244	8.95945122	12.59573171	8.193902439	12.26128049	11.52439024	10.08932927	11.42256098
90 - 327 Seconds	7.198319328	7.442436975	9.468067227	6.804201681	10.34537815	10.24747899	8.173529412	8.124369748
Peak	69.8	60.2	65.6	51.1	52.7	65.2	54.6	69.6

Car 4 Smoke, Block 4 Data Analysis at 10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
0 - 10 Seconds	1.181818182	0.818181818	0.454545455	1.336363636	1.245454545	0.772727273	0.672727273	0.745454545
0 - 120 Seconds	0.852066116	0.941322314	0.852892562	1.27107438	1.376859504	0.898347107	1.107438017	1.309090909
0 - 327 Seconds	0.716158537	0.91554878	0.811890244	1.145426829	1.456402439	0.890243902	1.079573171	1.359756098
90 - 327 Seconds	0.862605042	1.099579832	1.031092437	1.360504202	1.740756303	1.102521008	1.342857143	1.658823529
Peak	21.5	17.8	25.6	28.3	25.5	24.1	29.6	24

Car 4 Smoke, Block 5 Data Analysis at -10°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
0 - 10 Seconds	59.54545455	50.59090909	39.98181818	41.22727273	29.52727273	9.472727273	19.27272727	3.218181818
0 - 120 Seconds	28.15123967	19.03884298	28.01652893	20.63553719	30.63140496	25.87355372	26.42727273	22.67520661
0 - 327 Seconds	11.31128049	8.313414634	11.32743902	8.52347561	12.67195122	11.62896341	11.00640244	9.619817073
90 - 327 Seconds	2.099579832	2.589915966	2.578571429	1.979411765	3.81302521	4.678151261	3.233613445	2.917647059
Peak	85.4	82.3	84	79.2	86.4	83.8	85.5	83

Car 4 Smoke, Block 6 Data Analysis at 0°C

Fuel	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
Cetane Number	40.7	43.2	44.7	46.8	48.9	52.3	53.2	57.7
0 - 10 Seconds	15.4	4.018181818	3.009090909	2.9	1.690909091	1.009090909	2.190909091	2.763636364
0 -120 Seconds	2.658677686	9.415702479	10.8107438	2.809090909	8.768595041	6.585123967	12.7768595	9.461157025
0 - 327 Seconds	1.702134146	4.667073171	4.721036585	2.06554878	4.543597561	3.081097561	5.983841463	5.087195122
90 - 327 Seconds	1.342016807	2.454201681	1.572268908	1.859243697	2.399579832	1.390336134	2.459243697	2.923109244
Peak	34.4	40.6	56.9	19.3	37.4	36.3	57.7	48.3

Appendix 10.4 Driveability Demerits

Test Details							CRC Demerits			
Test Number	Date	Time	Temperature	Car	Fuel Number	Cetane number	Idle Quality	Stumble	Hesitation	Total Demerits
1	11-Nov-03	12:07	0°C	Car 1	Fuel 1	40.7				0
5	13-Nov-03	09:58	0°C	Car 1	Fuel 2	43.2				0
14	24-Nov-03	15:38	0°C	Car 1	Fuel 3	44.7				0
8	19-Nov-03	11:02	0°C	Car 1	Fuel 4	46.8				0
11	21-Nov-03	10:30	0°C	Car 1	Fuel 5	48.9				0
10	20-Nov-03	15:25	0°C	Car 1	Fuel 6	52.3				0
4	12-Nov-03	15:32	0°C	Car 1	Fuel 7	53.2				0
7	14-Nov-03	15:22	0°C	Car 1	Fuel 8	57.7				0
22	08-Dec-03	15:14	10°C	Car 1	Fuel 1	40.7				0
20	05-Dec-03	10:10	10°C	Car 1	Fuel 2	43.2				0
17	02-Dec-03	11:05	10°C	Car 1	Fuel 3	44.7				0
23	09-Dec-03	10:44	10°C	Car 1	Fuel 4	46.8				0
15	27-Nov-03	11:01	10°C	Car 1	Fuel 5	48.9				0
19	04-Dec-03	16:53	10°C	Car 1	Fuel 6	52.3				0
26	10-Dec-03	14:57	10°C	Car 1	Fuel 7	53.2				0
16	28-Nov-03	15:17	10°C	Car 1	Fuel 8	57.7				0
45	20-Jan-04	10:27	-10°C	Car 1	Fuel 1	40.7	4			4
37	14-Jan-04	11:04	-10°C	Car 1	Fuel 2	43.2	2			2
40	15-Jan-04	15:11	-10°C	Car 1	Fuel 3	44.7	2			2
44	19-Jan-04	15:07	-10°C	Car 1	Fuel 4	46.8	3			3
48	21-Jan-04	15:05	-10°C	Car 1	Fuel 5	48.9				0
33	09-Jan-04	10:35	-10°C	Car 1	Fuel 6	52.3				0
41	16-Jan-04	10:48	-10°C	Car 1	Fuel 7	53.2				0
36	13-Jan-04	14:55	-10°C	Car 1	Fuel 8	57.7	1			1
9	19-Nov-03	15:18	0°C	Car 2	Fuel 1	40.7				0
28	20-Dec-03	11:19	0°C	Car 2	Fuel 2	43.2				0
2	11-Nov-03	14:03	0°C	Car 2	Fuel 3	44.7				0
12	21-Nov-03	13:53	0°C	Car 2	Fuel 4	46.8				0
13	24-Nov-03	11:10	0°C	Car 2	Fuel 5	48.9				0
3	12-Nov-03	10:37	0°C	Car 2	Fuel 6	52.3				0
6	14-Nov-03	10:12	0°C	Car 2	Fuel 7	53.2				0
27	18-Dec-03	09:54	0°C	Car 2	Fuel 8	57.7				0
29	23-Dec-03	14:43	10°C	Car 2	Fuel 1	40.7				0
24	09-Dec-03	15:29	10°C	Car 2	Fuel 2	43.2				0
21	08-Dec-03	10:33	10°C	Car 2	Fuel 3	44.7				0
25	10-Dec-03	10:49	10°C	Car 2	Fuel 4	46.8				0
32	07-Jan-04	14:43	10°C	Car 2	Fuel 5	48.9				0
31	05-Jan-04	16:06	10°C	Car 2	Fuel 6	52.3				0
30	24-Dec-03	10:57	10°C	Car 2	Fuel 7	53.2				0
18	04-Dec-03	11:00	10°C	Car 2	Fuel 8	57.7				0
47	21-Jan-04	10:46	-10°C	Car 2	Fuel 1	40.7	1	12		13
43	19-Jan-04	11:43	-10°C	Car 2	Fuel 2	43.2				0
38	14-Jan-04	15:13	-10°C	Car 2	Fuel 3	44.7	3			3
35	13-Jan-04	10:32	-10°C	Car 2	Fuel 4	46.8				0
34	09-Jan-04	15:06	-10°C	Car 2	Fuel 5	48.9				0
42	16-Jan-04	14:59	-10°C	Car 2	Fuel 6	52.3				0
46	20-Jan-04	14:39	-10°C	Car 2	Fuel 7	53.2				0
39	15-Jan-04	14:39	-10°C	Car 2	Fuel 8	57.7				0

Test Details							CRC Demerits			
Test Number	Date	Time	Temperature	Car	Fuel Number	Cetane number	Idle Quality	Stumble	Hesitation	Total Demerits
82	25-Feb-04	15:31	0°C	Car 3	Fuel 1	40.7	1			1
83	26-Feb-04	11:28	0°C	Car 3	Fuel 2	43.2				0
96	09-Mar-04	13:10	0°C	Car 3	Fuel 3	44.7				0
87	01-Mar-04	10:26	0°C	Car 3	Fuel 4	46.8				0
90	03-Mar-04	15:13	0°C	Car 3	Fuel 5	48.9				0
93	05-Mar-04	14:27	0°C	Car 3	Fuel 6	52.3				0
94	08-Mar-04	10:45	0°C	Car 3	Fuel 7	53.2				0
86	27-Feb-04	14:54	0°C	Car 3	Fuel 8	57.7				0
59	09-Feb-04	14:48	10°C	Car 3	Fuel 1	40.7	1			1
51	28-Jan-04	14:22	10°C	Car 3	Fuel 2	43.2				0
57	03-Feb-04	15:34	10°C	Car 3	Fuel 3	44.7				0
60	10-Feb-04	09:05	10°C	Car 3	Fuel 4	46.8				0
49	27-Jan-04	10:54	10°C	Car 3	Fuel 5	48.9				0
54	02-Feb-04	09:19	10°C	Car 3	Fuel 6	52.3				0
52	29-Jan-04	09:13	10°C	Car 3	Fuel 7	53.2				0
63	11-Feb-04	11:17	10°C	Car 3	Fuel 8	57.7				0
71	17-Feb-04	09:50	-10°C	Car 3	Fuel 1	40.7	4			4
79	23-Feb-04	10:53	-10°C	Car 3	Fuel 2	43.2	3			3
67	13-Feb-04	10:51	-10°C	Car 3	Fuel 3	44.7				0
66	12-Feb-04	15:16	-10°C	Car 3	Fuel 4	46.8	2			2
78	20-Feb-04	14:06	-10°C	Car 3	Fuel 5	48.9	2			2
75	19-Feb-04	11:06	-10°C	Car 3	Fuel 6	52.3	1			1
74	18-Feb-04	15:34	-10°C	Car 3	Fuel 7	53.2	1			1
70	16-Feb-04	14:55	-10°C	Car 3	Fuel 8	57.7	1			1
89	03-Mar-04	11:04	0°C	Car 4	Fuel 1	40.7				0
88	01-Mar-04	14:57	0°C	Car 4	Fuel 2	43.2				0
84	26-Feb-04	16:27	0°C	Car 4	Fuel 3	44.7				0
85	27-Feb-04	11:07	0°C	Car 4	Fuel 4	46.8				0
92	05-Mar-04	11:17	0°C	Car 4	Fuel 5	48.9				0
95	08-Mar-04	17:05	0°C	Car 4	Fuel 6	52.3				0
81	25-Feb-04	11:22	0°C	Car 4	Fuel 7	53.2				0
91	04-Mar-04	15:19	0°C	Car 4	Fuel 8	57.7				0
61	10-Feb-04	13:32	10°C	Car 4	Fuel 1	40.7				0
55	02-Feb-04	13:42	10°C	Car 4	Fuel 2	43.2				0
58	09-Feb-04	10:19	10°C	Car 4	Fuel 3	44.7				0
62	11-Feb-04	08:45	10°C	Car 4	Fuel 4	46.8				0
56	03-Feb-04	10:30	10°C	Car 4	Fuel 5	48.9				0
53	29-Jan-04	13:34	10°C	Car 4	Fuel 6	52.3			4	4
64	11-Feb-04	16:16	10°C	Car 4	Fuel 7	53.2				0
50	28-Jan-04	10:40	10°C	Car 4	Fuel 8	57.7				0
69	16-Feb-04	10:02	-10°C	Car 4	Fuel 1	40.7	4			4
65	12-Feb-04	10:59	-10°C	Car 4	Fuel 2	43.2	3			3
72	17-Feb-04	14:35	-10°C	Car 4	Fuel 3	44.7	3			3
73	18-Feb-04	10:01	-10°C	Car 4	Fuel 4	46.8	3			3
80	23-Feb-04	14:52	-10°C	Car 4	Fuel 5	48.9	1			1
68	13-Feb-04	15:20	-10°C	Car 4	Fuel 6	52.3	1			1
77	20-Feb-04	10:19	-10°C	Car 4	Fuel 7	53.2	1			1
76	19-Feb-04	15:06	-10°C	Car 4	Fuel 8	57.7	1			1

Appendix 10.5 Fleet Means and Regressions

			Idle Quality	Idle Quality	Idle Quality	Time to 2000 rpm	Time to 2000 rpm	Time to 2000 rpm
Temperature	Fuel Number	Cetane Number	log(x)	Back-transformed mean	Arithmetic mean	log(x+0.33)	Back-transformed mean	Arithmetic mean
-10	1	40.7	2.7058	14.9663	17.6029	0.92661	2.19594	3.5625
-10	2	43.2	2.37894	10.7934	11.9401	0.68643	1.6566	2.575
-10	3	44.7	2.12078	8.3376	9.6057	0.71686	1.71798	2.2125
-10	4	46.8	2.13381	8.447	10.425	0.47514	1.27823	1.97914
-10	5	48.9	1.73986	5.6966	7.0395	0.31324	1.03785	1.35
-10	6	52.3	1.56098	4.7635	6.2439	0.55177	1.40633	1.6125
-10	7	53.2	1.45469	4.2831	6.2829	0.31762	1.04386	1.225
-10	8	57.7	1.27805	3.5896	4.7526	0.30876	1.03173	1.525
0	1	40.7	1.55031	4.7129	7.8965	-0.28742	0.4202	0.5
0	2	43.2	1.47694	4.3795	7.3604	-0.77186	0.13215	0.21875
0	3	44.7	1.54569	4.6912	6.6007	-0.08169	0.59156	0.6125
0	4	46.8	1.38063	3.9774	7.7404	-0.69806	0.16755	0.1875
0	5	48.9	1.37442	3.9528	5.4791	-0.60906	0.21386	0.2875
0	6	52.3	1.41514	4.1171	8.6961	-0.60596	0.21555	0.2875
0	7	53.2	1.31423	3.7219	6.2472	-0.57183	0.23449	0.3625
0	8	57.7	1.33379	3.7954	5.8906	-0.53195	0.25746	0.3125
10	1	40.7	1.0718	2.9206	3.6558	0.05728	0.72895	0.7875
10	2	43.2	0.90068	2.4613	3.2037	-0.22753	0.4665	0.5
10	3	44.7	1.11999	3.0648	3.7177	-0.22889	0.46542	0.5
10	4	46.8	1.37679	3.9621	4.8035	-1.04249	0.02258	0.025
10	5	48.9	0.99645	2.7087	3.5936	-0.08535	0.58819	0.625
10	6	52.3	1.086	2.9624	3.878	-0.39872	0.34118	0.4
10	7	53.2	0.71426	2.0427	2.3931	-0.09532	0.57909	0.6125
10	8	57.7	1.16407	3.2029	3.862	-0.06895	0.60337	0.6125

			Noise	Vibration	Vibration	Vibration	Demerits	Demerits	Demerits
Temperature	Fuel Number	Cetane Number	Arithmetic mean	log(x)	Back-transformed mean	Arithmetic mean	log(x+1)	Back-transformed mean	Arithmetic mean
-10	1	40.7	94.9131	0.1139	1.12064	1.42634	1.86684	5.46784	6.25
-10	2	43.2	94.8232	-0.08881	0.91502	0.97727	0.9678	1.63215	2
-10	3	44.7	94.0155	-0.01339	0.9867	1.17515	0.9678	1.63215	2
-10	4	46.8	94.0954	-0.07939	0.92368	1.21959	0.9678	1.63215	2
-10	5	48.9	94.6697	0.0219	1.02214	1.31112	0.44794	0.56508	0.75
-10	6	52.3	94.7703	-0.02778	0.9726	1.17619	0.34657	0.41421	0.5
-10	7	53.2	94.5917	0.0243	1.0246	1.21751	0.34657	0.41421	0.5
-10	8	57.7	95.2202	0.17834	1.19524	1.47073	0.51986	0.68179	0.75
0	1	40.7	91.7295	-0.64167	0.52641	0.60867	0.17329	0.18921	0.25
0	2	43.2	92.2641	-0.40076	0.66981	0.84045	0	0	0
0	3	44.7	92.2399	-0.50917	0.601	0.70114	0	0	0
0	4	46.8	92.4663	-0.53067	0.58821	0.66695	0	0	0
0	5	48.9	92.1963	-0.491	0.61201	0.72564	0	0	0
0	6	52.3	92.9433	-0.38293	0.68186	0.809	0	0	0
0	7	53.2	92.7168	-0.30337	0.73833	0.93484	0	0	0
0	8	57.7	92.7668	-0.31566	0.72931	0.94195	0	0	0
10	1	40.7	90.7136	-0.56304	0.56948	0.71572	0.17329	0.18921	0.25
10	2	43.2	90.7067	-0.608	0.54444	0.64501	0	0	0
10	3	44.7	91.0026	-0.65117	0.52143	0.70189	0	0	0
10	4	46.8	90.9544	-0.60057	0.5485	0.67072	0	0	0
10	5	48.9	90.5875	-0.74187	0.47622	0.58539	0	0	0
10	6	52.3	90.7017	-0.58178	0.5589	0.70844	0.40236	0.49535	1
10	7	53.2	90.6884	-0.62869	0.53329	0.6477	0	0	0
10	8	57.7	90.6231	-0.6239	0.53585	0.68855	0	0	0

Temperature	Fuel Number	Cetane Number	Smoke Opacity (0-10) log(x/(1-x)	Smoke Opacity (0-10) Back-transformed mean	Smoke Opacity (0-10) Arithmetic mean	Smoke Opacity (0-120) log(x/(1-x)	Smoke Opacity (0-120) Back-transformed mean	Smoke Opacity (0-120) Arithmetic mean
-10	1	40.7	-0.68453	33.5252	37.6955	-1.07161	25.5098	25.9864
-10	2	43.2	-1.6012	16.7814	21.2409	-1.32009	21.0802	21.6384
-10	3	44.7	-1.39143	19.9179	21.65	-1.01724	26.5565	26.9285
-10	4	46.8	-1.58117	17.0629	19.6205	-1.36426	20.355	21.2862
-10	5	48.9	-1.93876	12.5784	15.3773	-1.06741	25.5896	26.4731
-10	6	52.3	-2.71668	6.1996	7.0659	-1.15867	23.8908	24.5002
-10	7	53.2	-2.33265	8.8455	10.0636	-1.09423	25.0823	26.1273
-10	8	57.7	-2.91826	5.1258	5.475	-1.19146	23.2998	23.8746
0	1	40.7	-1.80379	14.139	14.8432	-2.55356	7.2188	8.9459
0	2	43.2	-2.77931	5.8452	6.4	-2.36781	8.5661	8.9599
0	3	44.7	-3.27084	3.6585	3.7568	-2.32914	8.8738	10.4965
0	4	46.8	-3.38589	3.2739	3.6932	-2.63094	6.7174	7.8349
0	5	48.9	-3.46072	3.0451	3.2523	-2.50464	7.5533	8.9647
0	6	52.3	-3.55434	2.7805	3.2818	-2.57739	7.0608	8.4316
0	7	53.2	-3.71028	2.3886	2.4591	-2.48233	7.7106	9.3386
0	8	57.7	-3.60599	2.6442	2.8273	-2.51031	7.5139	9.3636
10	1	40.7	-3.67056	2.483	4.7	-3.94528	1.8979	2.6636
10	2	43.2	-3.95307	1.8834	2.275	-3.97534	1.8427	2.2936
10	3	44.7	-4.13424	1.5762	2.3591	-4.12194	1.5954	1.7893
10	4	46.8	-4.23801	1.4231	1.4705	-4.17205	1.5186	1.8349
10	5	48.9	-3.81653	2.153	2.3818	-4.03511	1.7376	1.8393
10	6	52.3	-3.59143	2.682	3.9682	-3.89159	2.0004	2.4182
10	7	53.2	-4.08793	1.6497	1.9477	-3.961	1.8688	2.22
10	8	57.7	-4.02865	1.7487	1.9818	-3.78241	2.2261	2.6622

Temperature	Fuel Number	Cetane Number	Smoke Opacity (0-327) log(x/(1-x)	Smoke Opacity (0-327) Back-transformed mean	Smoke Opacity (0-327) Arithmetic mean	Smoke Opacity (90-327) log(x/(1-x)	Smoke Opacity (90-327) Back-transformed mean	Smoke Opacity (90-327) Arithmetic mean
-10	1	40.7	-2.04488	11.4571	12.0848	-3.26672	3.67306	5.12153
-10	2	43.2	-2.21586	9.8335	10.5475	-3.22409	3.82692	5.18645
-10	3	44.7	-1.98308	12.099	12.7821	-3.13849	4.1547	5.88508
-10	4	46.8	-2.24458	9.5818	10.6261	-3.21992	3.8423	5.66796
-10	5	48.9	-2.01077	11.8076	12.708	-3.03576	4.58361	6.14076
-10	6	52.3	-1.9638	12.3056	13.4028	-2.746	6.03129	8.28424
-10	7	53.2	-2.01302	11.7843	13.0598	-2.98919	4.79168	6.94842
-10	8	57.7	-2.06561	11.2485	12.1191	-2.98518	4.81	6.5125
0	1	40.7	-3.24069	3.7663	4.6883	-3.82194	2.14167	2.86418
0	2	43.2	-3.05276	4.5098	4.9636	-3.65801	2.51356	3.21113
0	3	44.7	-3.02992	4.6092	5.6755	-3.65634	2.51767	3.56828
0	4	46.8	-3.21097	3.8755	4.4285	-3.6503	2.53254	3.05893
0	5	48.9	-3.10343	4.2966	5.4107	-3.54915	2.79456	3.95273
0	6	52.3	-3.20093	3.9131	4.9475	-3.67051	2.48312	3.70725
0	7	53.2	-3.09101	4.348	5.2548	-3.56941	2.74006	3.48225
0	8	57.7	-3.04555	4.541	5.4534	-3.41973	3.16845	3.79118
10	1	40.7	-4.21016	1.4627	1.7373	-4.22416	1.44264	1.56208
10	2	43.2	-4.18821	1.4947	1.6711	-4.1389	1.56903	1.66639
10	3	44.7	-4.27687	1.3696	1.4455	-4.28195	1.36274	1.38813
10	4	46.8	-4.26102	1.3912	1.4832	-4.17194	1.51881	1.54758
10	5	48.9	-4.09441	1.6392	1.6644	-3.92084	1.94391	1.95263
10	6	52.3	-4.08773	1.65	1.8121	-4.07702	1.66751	1.72059
10	7	53.2	-4.03013	1.7462	1.9195	-3.93063	1.92534	2.01113
10	8	57.7	-3.89687	1.9901	2.1478	-3.81537	2.15546	2.22332

Temp	Dependent	Parameter	Estimate	StdErr	tValue	Probt
-10	Time to 2000rpm	Intercept	3.95672718	0.77516743	5.1	0.0022
-10	Time to 2000rpm	CN	-0.052420506	0.01532405	-3.42	0.0141
0	Time to 2000rpm	Intercept	0.662153017	0.47745372	1.39	0.2148
0	Time to 2000rpm	CN	-0.007911492	0.00964648	-0.82	0.4435
10	Time to 2000rpm	Intercept	0.461627481	0.75499922	0.61	0.5633
10	Time to 2000rpm	CN	0.000263854	0.01549942	0.02	0.987

Temp	Dependent	Parameter	Estimate	StdErr	tValue	Probt
-10	Idle Quality	Intercept	30.42886216	4.48435855	6.79	0.0005
-10	Idle Quality	CN	-0.4744237	0.08407168	-5.64	0.0013
0	Idle Quality	Intercept	6.7934547	0.73262956	9.27	<.0001
0	Idle Quality	CN	-0.05420077	0.01480184	-3.66	0.0106
10	Idle Quality	Intercept	3.20060376	1.96069213	1.63	0.1537
10	Idle Quality	CN	-0.00588203	0.04014005	-0.15	0.8883

Temp	Dependent	Parameter	Estimate	StdErr	tValue	Probt
-10	Smoke 0 - 10s	Intercept	69.28270905	10.886052	6.36	0.0007
-10	Smoke 0 - 10s	CN	-1.1253066	0.201067	-5.6	0.0014
0	Smoke 0 - 10s	Intercept	18.11751775	7.251017	2.5	0.0466
0	Smoke 0 - 10s	CN	-0.28007386	0.136871	-2.05	0.0867
10	Smoke 0 - 10s	Intercept	2.3331035	1.558055	1.5	0.1849
10	Smoke 0 - 10s	CN	-0.0079118	0.031823	-0.25	0.8119

Temp	Dependent	Parameter	Estimate	StdErr	tValue	Probt
-10	Smoke 0 - 120s	Intercept	24.13098819	7.773765	3.1	0.021
-10	Smoke 0 - 120s	CN	-0.00434574	0.159503	-0.03	0.9791
0	Smoke 0 - 120s	Intercept	9.30116971	2.434691	3.82	0.0088
0	Smoke 0 - 120s	CN	-0.03405115	0.049722	-0.68	0.519
10	Smoke 0 - 120s	Intercept	0.85387181	0.645609	1.32	0.2341
10	Smoke 0 - 120s	CN	0.02026647	0.013417	1.51	0.1817

Temp	Dependent	Parameter	Estimate	StdErr	tValue	Probt
-10	Smoke 0 - 327s	Intercept	8.64630885	3.417158	2.53	0.0447
-10	Smoke 0 - 327s	CN	0.05405682	0.070469	0.77	0.4721
0	Smoke 0 - 327s	Intercept	3.48409345	1.13137	3.08	0.0217
0	Smoke 0 - 327s	CN	0.01544959	0.023312	0.66	0.5321
10	Smoke 0 - 327s	Intercept	0.14865168	0.351682	0.42	0.6873
10	Smoke 0 - 327s	CN	0.02980519	0.007373	4.04	0.0068

Temp	Dependent	Parameter	Estimate	StdErr	tValue	Probt
-10	Smoke 90 -327s	Intercept	-0.61017639	1.692507	-0.36	0.7308
-10	Smoke 90 -327s	CN	0.10479162	0.035645	2.94	0.026
0	Smoke 90 -327s	Intercept	0.48821428	0.550832	0.89	0.4096
0	Smoke 90 -327s	CN	0.04383501	0.01152	3.81	0.0089
10	Smoke 90 -327s	Intercept	-0.2499297	0.51204	-0.49	0.6428
10	Smoke 90 -327s	CN	0.04020853	0.010795	3.72	0.0098

Temp	Dependent	Parameter	Estimate	StdErr	tValue	Probt
-10	Noise	Intercept	93.39967659	1.32073346	70.72	<.0001
-10	Noise	CN	0.02555255	0.02710295	0.94	0.3822
0	Noise	Intercept	89.58449138	0.71067492	126.06	<.0001
0	Noise	CN	0.05844434	0.01458386	4.01	0.0071
10	Noise	Intercept	91.27960962	0.47526901	192.06	<.0001
10	Noise	CN	-0.01099069	0.00975306	-1.13	0.3028

Temp	Dependent	Parameter	Estimate	StdErr	tValue	Probt
-10	Vibration	Intercept	0.733991674	0.31043909	2.36	0.0559
-10	Vibration	CN	0.005904992	0.00641382	0.92	0.3927
0	Vibration	Intercept	0.132098037	0.15691028	0.84	0.4321
0	Vibration	CN	0.01055536	0.00328188	3.22	0.0182
10	Vibration	Intercept	0.581490101	0.09725941	5.98	0.001
10	Vibration	CN	-0.000938876	0.00199176	-0.47	0.654

Temp	Dependent	Parameter	Estimate	StdErr	tValue	Probt
-10	Driver Demerits	Intercept	7.969768923	3.1950412	2.49	0.0469
-10	Driver Demerits	CN	-0.133884158	0.0609497	-2.2	0.0704
0	Driver Demerits	Intercept	0.320183397	0.19058169	1.68	0.144
0	Driver Demerits	CN	-0.006128503	0.00389075	-1.58	0.1663
10	Driver Demerits	Intercept	-0.010882713	0.61804432	-0.02	0.9865
10	Driver Demerits	CN	0.001991279	0.01271031	0.16	0.8806

Temp	Dependent	Parameter	Estimate	StdErr	tValue	Probt
-10	Idle Quality Demerits	Intercept	5.954066151	1.69254874	3.52	0.0126
-10	Idle Quality Demerits	CN	-0.097756397	0.03279622	-2.98	0.0246
0	Idle Quality Demerits	Intercept	0.320183397	0.19058169	1.68	0.144
0	Idle Quality Demerits	CN	-0.00061285	0.00389075	-1.58	0.1663
10	Idle Quality Demerits	Intercept	0.320183397	0.19058169	1.68	0.144
10	Idle Quality Demerits	CN	-0.006128503	0.00389075	-1.58	0.1663

Appendix 10.6 Individual Car Regressions

CAR	TEMP	Dependent	Parameter	Estimate	StdErr	tValue	Probt
1	-10	Time to 2000rpm	Intercept	12.53273	3.94606	3.18	0.0192
1	-10	Time to 2000rpm	CN	-0.17418	0.076996	-2.26	0.0644
1	0	Time to 2000rpm	Intercept	0.719828	1.268109	0.57	0.5909
1	0	Time to 2000rpm	CN	-0.007065	0.025715	-0.27	0.7927
1	10	Time to 2000rpm	Intercept	0.506789	1.285771	0.39	0.7071
1	10	Time to 2000rpm	CN	0.002569	0.026468	0.1	0.9258
2	-10	Time to 2000rpm	Intercept	-0.04279	0.937217	-0.05	0.9651
2	-10	Time to 2000rpm	CN	0.006697	0.01948	0.34	0.7427
2	0	Time to 2000rpm	Intercept	1.113836	0.710825	1.57	0.1682
2	0	Time to 2000rpm	CN	-0.019303	0.013898	-1.39	0.2142
2	10	Time to 2000rpm	Intercept	-0.201961	0.544545	-0.37	0.7235
2	10	Time to 2000rpm	CN	0.011121	0.011393	0.98	0.3667
3	-10	Time to 2000rpm	Intercept	3.29943	1.163006	2.84	0.0364
3	-10	Time to 2000rpm	CN	-0.040232	0.022992	-1.75	0.1406
3	0	Time to 2000rpm	Intercept	0.276925	0.737199	0.38	0.7201
3	0	Time to 2000rpm	CN	0.000605	0.015145	0.04	0.9694
3	10	Time to 2000rpm	Intercept	0.57924	0.719123	0.81	0.4513
3	10	Time to 2000rpm	CN	-0.005252	0.014617	-0.36	0.7317
4	-10	Time to 2000rpm	Intercept	7.618204	3.321686	2.29	0.0616
4	-10	Time to 2000rpm	CN	-0.111657	0.064373	-1.73	0.1335
4	0	Time to 2000rpm	Intercept	0.287984	1.559803	0.18	0.8596
4	0	Time to 2000rpm	CN	0.004767	0.03222	0.15	0.8872
4	10	Time to 2000rpm	Intercept	1.333498	1.170252	1.14	0.2979
4	10	Time to 2000rpm	CN	-0.012312	0.023686	-0.52	0.6218

CAR	TEMP	Dependent	Parameter	Estimate	StdErr	tValue	Probt
1	-10	Idle Quality	Intercept	75.67696	11.47909	6.59	0.0006
1	-10	Idle Quality	CN	-1.256875	0.205893	-6.1	0.0009
1	0	Idle Quality	Intercept	-6.294849	5.451929	-1.15	0.2922
1	0	Idle Quality	CN	0.220998	0.118651	1.86	0.1118
1	10	Idle Quality	Intercept	4.605788	7.827032	0.59	0.5777
1	10	Idle Quality	CN	0.022205	0.161356	0.14	0.895
2	-10	Idle Quality	Intercept	18.93723	8.495136	2.23	0.0673
2	-10	Idle Quality	CN	-0.255153	0.165894	-1.54	0.175
2	0	Idle Quality	Intercept	21.40521	12.63719	1.69	0.1412
2	0	Idle Quality	CN	-0.308036	0.243573	-1.26	0.2529
2	10	Idle Quality	Intercept	5.282531	2.543158	2.08	0.0831
2	10	Idle Quality	CN	-0.041463	0.051403	-0.81	0.4507
3	-10	Idle Quality	Intercept	15.06775	10.24773	1.47	0.1919
3	-10	Idle Quality	CN	-0.084008	0.208395	-0.4	0.7008
3	0	Idle Quality	Intercept	24.05259	19.37002	1.24	0.2607
3	0	Idle Quality	CN	-0.163545	0.392716	-0.42	0.6916
3	10	Idle Quality	Intercept	5.689603	3.228777	1.76	0.1285
3	10	Idle Quality	CN	-0.020983	0.065907	-0.32	0.761
4	-10	Idle Quality	Intercept	17.85315	3.902507	4.57	0.0038
4	-10	Idle Quality	CN	-0.296666	0.069962	-4.24	0.0054
4	0	Idle Quality	Intercept	2.482807	0.773949	3.21	0.0184
4	0	Idle Quality	CN	-0.031507	0.015239	-2.07	0.0842
4	10	Idle Quality	Intercept	0.372045	0.98199	0.38	0.7178
4	10	Idle Quality	CN	0.011381	0.020443	0.56	0.5978

CAR	TEMP	Dependent	Parameter	Estimate	StdErr	tValue	Probt
1	-10	Vibration	Intercept	1.269347	0.406463	3.12	0.0205
1	-10	Vibration	CN	-0.005211	0.008291	-0.63	0.5528
1	0	Vibration	Intercept	0.575221	0.31566	1.82	0.1182
1	0	Vibration	CN	-0.000896	0.006465	-0.14	0.8943
1	10	Vibration	Intercept	0.486972	0.2052	2.37	0.0553
1	10	Vibration	CN	-0.003098	0.004165	-0.74	0.4851
2	-10	Vibration	Intercept	0.346198	0.257106	1.35	0.2268
2	-10	Vibration	CN	0.004067	0.005322	0.76	0.4737
2	0	Vibration	Intercept	-0.220995	0.186489	-1.19	0.2808
2	0	Vibration	CN	0.013588	0.003967	3.43	0.0141
2	10	Vibration	Intercept	0.306453	0.120681	2.54	0.0441
2	10	Vibration	CN	0.001326	0.002487	0.53	0.6131
3	-10	Vibration	Intercept	0.50301	0.549158	0.92	0.395
3	-10	Vibration	CN	0.005579	0.011365	0.49	0.6409
3	0	Vibration	Intercept	0.29857	0.156498	1.91	0.105
3	0	Vibration	CN	0.003151	0.003238	0.97	0.368
3	10	Vibration	Intercept	0.485458	0.232014	2.09	0.0813
3	10	Vibration	CN	-0.000847	0.004751	-0.18	0.8643
4	-10	Vibration	Intercept	1.328123	2.02429	0.66	0.5361

CAR	TEMP	Dependent	Parameter	Estimate	StdErr	tValue	Probt
1	-10	Driver Demerits	Intercept	7.319562	3.74162	1.96	0.0982
1	-10	Driver Demerits	CN	-0.121431	0.071854	-1.69	0.142
1	0	Driver Demerits	Intercept	0	0	.	.
1	0	Driver Demerits	CN	0	0	.	.
1	10	Driver Demerits	Intercept	0	0	.	.
1	10	Driver Demerits	CN	0	0	.	.
2	-10	Driver Demerits	Intercept	12.42457	8.192273	1.52	0.1802
2	-10	Driver Demerits	CN	-0.224659	0.152722	-1.47	0.1917
2	0	Driver Demerits	Intercept	0	0	.	.
2	0	Driver Demerits	CN	0	0	.	.
2	10	Driver Demerits	Intercept	0	0	.	.
2	10	Driver Demerits	CN	0	0	.	.
3	-10	Driver Demerits	Intercept	6.972347	2.957029	2.36	0.0564
3	-10	Driver Demerits	CN	-0.108156	0.05768	-1.88	0.1099
3	0	Driver Demerits	Intercept	1.465093	0.932989	1.57	0.1674
3	0	Driver Demerits	CN	-0.027817	0.01874	-1.48	0.1882
3	10	Driver Demerits	Intercept	1.465093	0.932989	1.57	0.1674
3	10	Driver Demerits	CN	-0.027817	0.01874	-1.48	0.1882
4	-10	Driver Demerits	Intercept	9.612748	2.050755	4.69	0.0034
4	-10	Driver Demerits	CN	-0.155284	0.039356	-3.95	0.0076
4	0	Driver Demerits	Intercept	0	0	.	.
4	0	Driver Demerits	CN	0	0	.	.
4	10	Driver Demerits	Intercept	-3.592453	3.809004	-0.94	0.382
4	10	Driver Demerits	CN	0.084513	0.082783	1.02	0.3467

CAR	TEMP	Dependent	Parameter	Estimate	StdErr	tValue	Probt
1	-10	Idle Quality Demerits	Intercept	7.319556	3.74162	1.96	0.0982
1	-10	Idle Quality Demerits	CN	-0.121431	0.071854	-1.69	0.142
1	0	Idle Quality Demerits	Intercept	0	0	.	.
1	0	Idle Quality Demerits	CN	0	0	.	.
1	10	Idle Quality Demerits	Intercept	0	0	.	.
1	10	Idle Quality Demerits	CN	0	0	.	.
2	-10	Idle Quality Demerits	Intercept	4.105552	2.879657	1.43	0.2038
2	-10	Idle Quality Demerits	CN	-0.074883	0.056166	-1.33	0.2308
2	0	Idle Quality Demerits	Intercept	0	0	.	.
2	0	Idle Quality Demerits	CN	0	0	.	.
2	10	Idle Quality Demerits	Intercept	0	0	.	.
2	10	Idle Quality Demerits	CN	0	0	.	.
3	-10	Idle Quality Demerits	Intercept	6.972347	2.957029	2.36	0.0564
3	-10	Idle Quality Demerits	CN	-0.108156	0.05768	-1.88	0.1099
3	0	Idle Quality Demerits	Intercept	1.465093	0.932989	1.57	0.1674
3	0	Idle Quality Demerits	CN	-0.027817	0.01874	-1.48	0.1882
3	10	Idle Quality Demerits	Intercept	1.465093	0.932989	1.57	0.1674
3	10	Idle Quality Demerits	CN	-0.027817	0.01874	-1.48	0.1882
4	-10	Idle Quality Demerits	Intercept	9.612748	2.050755	4.69	0.0034
4	-10	Idle Quality Demerits	CN	-0.155284	0.039356	-3.95	0.0076
4	0	Idle Quality Demerits	Intercept	0	0	.	.
4	0	Idle Quality Demerits	CN	0	0	.	.
4	10	Idle Quality Demerits	Intercept	0	0	.	.
4	10	Idle Quality Demerits	CN	0	0	.	.

CAR	TEMP	Dependent	Parameter	Estimate	StdErr	tValue	Probt	
1	*-10*	*Smoke 0 - 10 seconds*	*Intercept*	*94.52153*	*43.54691*	*2.17*	*0.073*	*Model converegence problems*
1	*-10*	*Smoke 0 - 10 seconds*	*CN*	*-1.6403*	*0.844328*	*-1.94*	*0.1001*	
1	0	Smoke 0 - 10 seconds	Intercept	27.78508	12.06481	2.3	0.0609	
1	0	Smoke 0 - 10 seconds	CN	-0.429414	0.228142	-1.88	0.1088	
1	10	Smoke 0 - 10 seconds	Intercept	15.04279	6.308154	2.38	0.0544	
1	10	Smoke 0 - 10 seconds	CN	-0.232476	0.11903	-1.95	0.0986	
2	-10	Smoke 0 - 10 seconds	Intercept	27.97491	6.867892	4.07	0.0066	
2	-10	Smoke 0 - 10 seconds	CN	-0.394489	0.133629	-2.95	0.0255	
2	0	Smoke 0 - 10 seconds	Intercept	14.88709	4.883214	3.05	0.0226	
2	0	Smoke 0 - 10 seconds	CN	-0.230387	0.092083	-2.5	0.0464	
2	10	Smoke 0 - 10 seconds	Intercept	-12.64877	5.865892	-2.16	0.0745	
2	10	Smoke 0 - 10 seconds	CN	0.322717	0.134378	2.4	0.0532	
3	-10	Smoke 0 - 10 seconds	Intercept	40.8302	10.31514	3.96	0.0075	
3	-10	Smoke 0 - 10 seconds	CN	-0.608452	0.198307	-3.07	0.022	
3	0	Smoke 0 - 10 seconds	Intercept	20.12486	7.985916	2.52	0.0453	
3	0	Smoke 0 - 10 seconds	CN	-0.312487	0.150485	-2.08	0.0831	
3	10	Smoke 0 - 10 seconds	Intercept	8.393692	3.719831	2.26	0.0649	
3	10	Smoke 0 - 10 seconds	CN	-0.116013	0.072417	-1.6	0.1603	
4	-10	Smoke 0 - 10 seconds	Intercept	181.7591	13.81698	13.15	<.0001	

CAR	TEMP	Dependent	Parameter	Estimate	StdErr	tValue	Probt
1	-10	Noise	Intercept	95.89006	1.788242	53.62	<.0001
1	-10	Noise	CN	-0.048559	0.036697	-1.32	0.2339
1	0	Noise	Intercept	95.30322	1.532333	62.19	<.0001
1	0	Noise	CN	-0.08873	0.031445	-2.82	0.0303
1	10	Noise	Intercept	96.06452	1.946703	49.35	<.0001
1	10	Noise	CN	-0.135805	0.039949	-3.4	0.0145
2	-10	Noise	Intercept	85.38798	1.177096	72.54	<.0001
2	-10	Noise	CN	0.137745	0.024155	5.7	0.0013
2	0	Noise	Intercept	83.93191	1.903004	44.1	<.0001
2	0	Noise	CN	0.125599	0.039052	3.22	0.0182
2	10	Noise	Intercept	87.14269	1.897132	45.93	<.0001
2	10	Noise	CN	0.018107	0.038931	0.47	0.6583
3	-10	Noise	Intercept	91.20566	3.941814	23.14	<.0001
3	-10	Noise	CN	0.128496	0.080891	1.59	0.1633
3	0	Noise	Intercept	92.75972	1.089494	85.14	<.0001
3	0	Noise	CN	0.07105	0.022358	3.18	0.0191
3	10	Noise	Intercept	93.38302	1.570688	59.45	<.0001
3	10	Noise	CN	-0.013772	0.032232	-0.43	0.6841
4	-10	Noise	Intercept	101.115	4.378353	23.09	<.0001
4	-10	Noise	CN	-0.115472	0.089849	-1.29	0.2461
4	0	Noise	Intercept	86.34311	1.566011	55.14	<.0001
4	0	Noise	CN	0.125858	0.032136	3.92	0.0078
4	10	Noise	Intercept	88.5282	1.867605	47.4	<.0001
4	10	Noise	CN	0.087507	0.038325	2.28	0.0625

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Cetane Number Effects on Light-Duty Diesel Performance