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ENVIRONMENTAL SCIENCE FOR THE EUROPEAN REFINING INDUSTRY

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Phase 1: Effect of Fuel Octane on the Performance of Two Euro 4 Gasoline Passenger Cars

Environmental science for the European refining industry

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Phase 1: Effect of Fuel Octane on the Performance of Two Euro 4 Gasoline Passenger Cars

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ABSTRACT

This report details work that was carried out to study the response of modern gasoline passenger cars on octane. The objective of this phase 1 of the study was to investigate the effect of RON and MON on the power and acceleration performance of two Euro 4 gasoline vehicles under full throttle acceleration conditions. Fifteen fuels covering RON levels 95 to 103 and sensitivities (RON minus MON) up to 15 were blended and tested. Both pure hydrocarbon and blends containing ethanol or ETBE were included so that any specific effects of oxygenates could be identified. Three additional fuels, covering RON as low as 86, were blended using primary reference fuels. The results confirm the findings of previous studies on older vehicles by other workers that MON is not a good predictor of vehicle acceleration performance in more modern vehicles and in fact high MON levels increase acceleration time under full throttle conditions. In addition, it was found that during wide open throttle conditions efficiency deteriorated on the lowest octane (RON) fuels tested as expected as the engine adapts to knock. It was also observed that efficiency increased up to higher octane levels than would be expected for both vehicles.

KEYWORDS

Octane, RON, MON, acceleration, efficiency

INTERNET

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

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SUMMARY

The performance aspect of gasoline combustion has traditionally been measured using Research Octane Number (RON) and Motor Octane Number (MON) which describe antiknock performance under different conditions. Recent literature suggests that MON is less important than RON in modern cars and a relaxation in the MON specification could improve vehicle performance, while also helping refiners in the production of gasoline. At the same time, for the same octane number change, increasing RON appears to provide more benefit to engine power and acceleration than reducing MON. It has also been suggested that there could be fuel efficiency benefits (on a tank to wheels basis) for specially adapted engines, for example, operating at higher compression ratio, on very high RON (100+). Other workers have advocated the use of an octane index (OI) which incorporates both RON and MON to give an indication of octane quality.

The objective of the first phase of this study was to investigate the effect of RON and MON on the power and acceleration performance of two Euro 4 gasoline vehicles under full throttle acceleration conditions. Fifteen fuels covering RON levels 95 to 103 and sensitivities (RON minus MON) up to 15 were blended and tested. Both pure hydrocarbon and blends containing ethanol or ETBE were included so that any specific effects of oxygenates could be identified. Three additional fuels, covering RON as low as 86, were blended using primary reference fuels. The results confirm the findings of previous studies on older vehicles that MON is not a good predictor of vehicle acceleration performance and in fact high MON levels increase acceleration time under full throttle conditions. Both vehicles were tolerant of fuels in the 95-98 RON range, but reductions in performance were seen on lower octane fuels.

In addition, exhaust emission tests were performed on hot NEDC cycles and during the vehicle acceleration tests. These results, together with fuel data, allowed the vehicle energy consumption to be calculated. It was found that fuel octane had no effect on the efficiency of the vehicle on the NEDC cycle, suggesting that either knock does not occur under these lighter load conditions or that adaptations to knock are not severe enough to impact on engine efficiency. Under more extreme full throttle acceleration conditions efficiency deteriorated on the lowest octane fuels tested as expected as the engine adapts to knock. It was also observed that efficiency increased up to higher octane levels than were expected for both vehicles.

1. INTRODUCTION

General Background & Objectives

Gasoline combustion has traditionally been measured using Research Octane Number (RON) and Motor Octane Number (MON) which describe antiknock performance under different conditions. All European gasoline cars must be capable of running on the 95RON 'Eurosuper' petrol grade, however some vehicles are calibrated to be able to take advantage of higher octane fuels available in the market, typically by advancing spark timing or increasing boost pressure which allows more power and perhaps also better fuel consumption. In the future vehicles may be made available which have increased or variable compression ratio which can fully take advantage of higher octane but these are not commercially available at present.

Historically, increasing both RON and MON have been considered beneficial, however a large body of more recent literature suggests that while increasing RON still gives benefits in modern production cars, MON is less important and in fact lowering MON at the same RON level could improve vehicle performance. Reducing the MON specification in the EN228 fuel specification could also help refiners with gasoline production, since MON is sometimes a limiting parameter in meeting fuel specifications.

OEMs are interested in discussing higher octane levels in the market. Today's minimum RON or even increasing RON can be achieved either by increasing the octane of the blend stock for oxygenate blending (BOB) or by increasing the oxygenate concentration. Most oxygenates allowed by the current EN228 petrol specification, such as ethanol and ethers, have high octane numbers. In addition to its potential effect on octane number, ethanol can also affect the combustion process through its high latent heat so a test programme should attempt to separate these two effects. In addition, the energy content of ethers is significantly higher than that of ethanol and the overall fuel consumption depends on octane number but also on how much energy is contained in the fuel itself.

Higher amounts of ethanol and ethers may be used in the future. This could be a point of discussion within the next 5+ years for petrol containing more than 3.7% m/m oxygen (so-called 'E10+') although it is unlikely that such fuels will be a market reality in this decade. Having a sound database of the effects of RON, MON, and octane sensitivity on vehicle performance (power, acceleration, fuel consumption, and emissions) will be important in any discussions within CEN when it comes to setting future standards.

The specific objective of this study was to improve our understanding of the effects of RON and MON on modern gasoline cars by extending the existing database of full-throttle acceleration tests to cover newer cars than have been studied in previous work. The study used Euro 4 vehicles that had already been evaluated by Concawe in the Millbrook test programme on petrol volatility. It is considered a scoping study, and the experience gained will be used to improve the test protocol which could then be used to evaluate more advanced gasoline vehicles.

In these tests, vehicle performance under full throttle acceleration was the main criterion for evaluating octane effects, but in addition tests were included to evaluate

- The effects of knock under part load conditions, since relief of light load knock could improve vehicle fuel efficiency.
- Emissions and fuel consumption measurements on the hot NEDC cycle and during the acceleration tests.

Technical Background

Octane number is a measure of a fuel's resistance to auto-ignition. Gasoline spark-ignited engines need a high octane fuel to avoid knock in contrast to diesel engines which rely on auto-ignition and so require a low octane (or high cetane number) fuel. The octane number of a fuel is measured in a special test engine known as a CFR engine which is a single cylinder test engine with variable compression ratio dating from 1928 and although the test has been progressively improved over the years, the basic engine configuration and test conditions remain the same. Tests in the early 1930s demonstrated that the knocking behaviour of fuels in vehicles of that era did not correlate with the measured Research Octane Number, therefore a new, more severe, Motor Octane Number was developed. Both methods are still in use today:

- Research Octane Number (RON) is measured at a speed of 600rpm with a specified intake air temperature of 52°C and is traditionally associated with mild to moderate driving conditions.
- Motor Octane Number (MON) was introduced to simulate more severe higher load conditions and uses a higher engine speed of 900rpm and a governed charge temperature of 149°C. The MON of a fuel is typically about 10 numbers lower than its RON, because of the more severe test conditions, although the difference between RON and MON varies with fuel composition.

A fuel's octane number is determined by comparing its performance in the engine with a blend of pure compounds: iso-octane, defined to be 100 octane and n-heptane, defined to have zero octane number. Although the engine test conditions, especially the engine speed, seem far from typical of today's engines, octane number has proved a valuable measure of fuel quality up to the present and the octane requirement of even the most advanced vehicles can be described as a function of RON and MON. Fuel specifications usually set minimum requirements for both RON and MON. In most parts of the world, RON is the primary measure of gasoline octane at the point of sale. In the USA, Canada and some other countries, a different system is used where the octane measure displayed at the point of sale is the Anti-Knock Index, defined as (RON+MON)/2.

How an individual road vehicle responds to octane number depends on the details of its engine design and calibration. The 'octane requirement' of a vehicle has traditionally been determined by testing under acceleration or steady speed full load conditions, either on the road or on a chassis dynamometer. By running on a series of specially blended test fuels of progressively changing octane number, the lowest octane number that will run in the vehicle without knock can be determined. In the past, large numbers of vehicles were tested in co-operative industry programmes in Europe and the USA to build up a picture of the road vehicle fleet, so that the octane number of fuels sold could be matched to the needs of the vehicle fleet. More recently, the octane numbers are determined purely by the fuel specification and vehicles are developed to operate on them. However, a growing body of vehicle test data shows that the traditional expectation that RON correlates with mild operating conditions and MON with more severe driving no longer holds [1,2,4,5,8, 9,10,11,12,13,14,15,16,17].

The Anti-Knock Index used in the USA and other countries is a specific case which predates a more general relationship between vehicle octane requirement, RON and MON which can be expressed as:

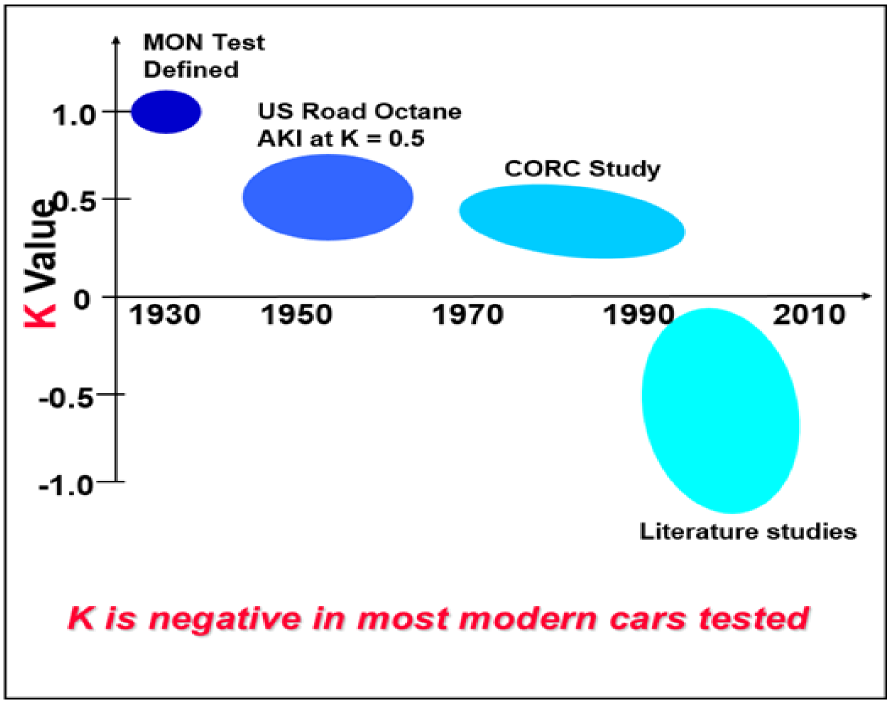
$$\text{Octane Index} = (1-K).\text{RON} + K.\text{MON}$$
$$= \text{RON} - K.S$$

where S is the sensitivity of the fuel, defined as (RON-MON)

With K set to 0.5, the octane index becomes the same as the Anti-Knock Index, (RON+MON)/2.

Vehicles encounter their knock limits primarily under high-load conditions. If an older vehicle were to operate on a fuel with insufficient octane for its needs, knock would occur. Knock is uncontrolled auto-ignition of part of the fuel-air mixture in the combustion chamber (the end gas) and if this becomes severe, the resultant pressure waves can lead to engine damage. As attention has moved from controlling exhaust emissions to increasing energy efficiency engines have become more sophisticated. Multiple strategies are available to improve spark ignition engine fuel economy including higher compression ratios, direct injection and downsizing through turbocharging. As a result, engines run at higher cylinder temperatures and pressures with more potential for knock. Modern cars have knock sensors that detect the onset of mild knock. When knock is detected the engine management system (EMS) takes corrective action, initially by retarding ignition timing and at higher engine speeds a level of over-fuelling may also be applied to lower the exhaust temperature. These actions protect the engine from damaging knock, but may result in reduced power and acceleration performance which can be measured to determine a vehicle's octane requirement. A large body of test evidence is now available showing that this vehicle evolution has changed the way in which vehicles respond to RON and MON (**Figure 1**).

Figure 1. The way in which vehicles respond to RON and MON has changed



While the value of K=0.5 remained a good estimate up to the early 1990s, vehicles produced more recently have k factors that are much lower and usually negative and while there are differences between vehicles a large body of data suggests that this is a general trend [2,4,5,9,10,11,12]. More recent studies [15, 16, 17] confirm that this trend also holds for the boosted, downsized engines representative of future production.

In other studies [13,14,17] it is shown that response to octane varies to some degree for different performance metrics and at different operating conditions, but that the general trend towards negative K-values is preserved.

The implication of a negative K-factor is that RON is more beneficial to engine operation than MON and in fact that increasing MON may actually be detrimental to engine performance. The reasons why the MON test does not correlate with vehicle performance are briefly addressed in the discussion section.

It is now generally recognised that minimising energy consumption and CO_2 emissions in transportation needs consideration of both fuel production and vehicle efficiency, combining these factors into a 'well-to-wheels' approach. For the future, higher octane fuels could be used by engine designers to improve fuel efficiency using higher compression ratios, boost pressures, and other techniques [3,6,7]. This needs to be balanced against the additional energy needed in the refinery to produce higher octane. For this reason, the optimum octane number for future fuels will come under discussion and the correct balance between RON and MON is clearly part of this process. However, such consideration of future vehicle possibilities cannot be addressed by testing vehicles in the market. The purpose of this study was rather to extend the existing database of full-throttle acceleration tests that have already been published to cover newer cars meeting Euro 4 emission limits. The effects of knock under part load conditions were also investigated since it was considered that relief of light load knock could improve vehicle fuel efficiency. Regulated emission measurements were also made and used to calculate carbon balance fuel consumption during the hot NEDC cycles and the acceleration tests.

2. TEST PROGRAMME

2.1. GENERAL CONSIDERATIONS

To obtain reliable data to determine fuel effects, it is important that sufficient and appropriate vehicle conditioning is performed, so that the 'experience' of the vehicle on each fuel is the same. This is particularly important and challenging for modern vehicles where the engine control system adapts to the fuel being used. A conditioning procedure was therefore used after each fuel change to allow the vehicle to 'learn' and stabilise its performance on the new test fuel, taking into account advice received from vehicle manufacturers and the test laboratory.

In addition, in any prolonged test programme, care needs to be taken that effects due to the fuel are not confounded with changes during the test period arising from ambient conditions or vehicle condition. Effects of ambient conditions were addressed by applying correction factors as appropriate to the measured acceleration times using SAE or other correction factors. To address long term drift, the test programme was designed to include duplicate 'long term' repeat tests on each fuel, separated in time, with the order of the test fuels randomised. As an additional safeguard, the data were validated to identify any outlier or suspect tests before analysis began.

2.2. VEHICLE SELECTION

This phase of the Concawe programme focused on effects in the current vehicle fleet, recognising that future discussions may consider the potential for adapted vehicles to be more efficient if higher octane (above 98RON) fuels were available in the market. Two vehicles were tested, both meeting Euro 4 emission limits.

- Vehicle 1 was an Upper Medium class passenger car with a 2.5 litre Direct Injection naturally aspirated engine and optimised for 98RON fuel.
- The second was a Small passenger car with a 1.24 litre naturally aspirated engine and Port Fuel Injection and designed for 95RON fuel.
- Both vehicles had manual transmissions and Three-Way Catalysts. In addition, Vehicle 1 was equipped with a lean NOx trap.
- Both vehicles were equipped with knock-sensors. In the case of Vehicle 2 the primary purpose of this is to protect the engine, whereas that in Vehicle 1 it additionally allows improved performance on fuels with RON higher than the minimum EU specification of 95.

Table 1. Vehicle Data

Vehicle No.	**1**	**2**
Vehicle Class	Upper Medium	Small
Emission Standard (homologation)	Euro 4	Euro 4
Engine Displacement (litres)	2.5	1.24
Max. Power (kW)	140	60
Inertia Class (kg)	1590	1020
Cylinders	6	4
Valves	24	16
Aspiration	Natural	Natural
Combustion Type	Homogeneous stoichiometric/lean	Homogeneous stoichiometric
Injection System	DI	PFI
After-treatment device	TWC + lean NOx trap	TWC
Drive	RWD	FWD
Transmission	Manual 6-speed	Manual 5-speed
E10 Compatible?	Yes	Yes
Registration Date	2007	2009
Mileage at start of test (miles)	23,354	8,890

2.2.1. Test Vehicle Preparation

The vehicles were carefully checked and conditioned before the start of the test programme to ensure that they were in good condition. Both vehicles had completed at least 8,000km on the fuel recommended by the manufacturer to ensure that the catalyst was adequately aged and the engine combustion chamber deposits had stabilised. The condition of the vehicle battery was also checked to ensure that the EMS did not experience power failure during the programme. If the battery had to be disconnected while work was being performed on the vehicle, it was done only before Step 2.

The engine oil and filter were changed in addition to the air filter. The oil was aged by driving a minimum of 500km on the road or mileage accumulation dynamometer. The fuels used for mileage accumulation contained a commercial detergent additive package. The engine oil was changed to a reference oil of the grade recommended by the vehicle manufacturer and appropriate for normal vehicle service.

Before starting the test programme, the emissions performance of the test vehicles was measured and confirmed to meet the emissions limits for which each vehicle was certified, using the NEDC test procedure and based on true, and not simulated, road-load data. The CEC RF-02-08 reference fuel was used for this evaluation. At least three repeat tests were run to ensure that the vehicle was stabilised. An initial evaluation was carried out to check the effects of fuel variations on acceleration and to explore the most useful ways of extending the test conditions to part load.

The setting of the engine and of the vehicle's controls were checked and adjusted if necessary, with any changes recorded before testing. No further adjustments were permitted during the test programme.

The tyre pressures were checked and set to the manufacturer's recommendations for use on the road.

The variation in DVPE in the fuel matrix were sufficiently small so as not to significantly influence the operation of the evaporative emissions control system. The carbon canister/evaporative emissions system were therefore retained connected and functioning throughout the test programme.

The appropriate coast down characteristics for the vehicle were determined on a test track and the dynamometer set to the appropriate inertia class for the vehicle. Periodic checks were carried out throughout the programme to ensure consistent dynamometer performance. Variations in vehicle run down characteristics (carried out at the same condition) were corrected and recorded. However, every effort was made to avoid changes to dynamometer settings in the middle of a block of test fuels.

The test equipment was in accordance with the appropriate regulations. All calibrations were conducted prior to the test programme according to the provisions of and the test laboratory's internal quality assurance system. Recalibration was avoided as far as possible during the test programme and any necessary changes recorded.

2.3. TEST FUELS, BLENDING AND HANDLING

2.3.1. Test Fuels

The objective of the fuel matrix was to explore octane parameters of interest in the current and future European context. RON and MON were varied independently as far as possible. EU efforts to reduce energy consumption and CO_2 emissions have resulted in increased use of biofuels in road fuels. For gasoline, the available biofuels are principally ethanol (EtOH) and Ethyl-Tertiary-Butyl-Ether (ETBE), both of which have high values of RON and MON. In addition, ethanol can also affect the combustion process through its high latent heat. Oxygenate fuel blends were therefore included in the matrix, but in order that RON and MON effects could be distinguished from other possible effects of oxygenates, a series of pure hydrocarbon fuels was included as well.

To ensure the fuels were as representative as possible, they were blended using refinery-typical components. Differences in octane between the fuels needed to be big enough to detect performance changes, without running out of the calibration range of the engine. Nominal RON levels of 95 and 98, typical of the European market were therefore selected for this study, with higher levels allowed for the fuels containing oxygenates.

All European vehicles must be capable of operating on EN228 95RON fuel, so there was some risk that knocking may not be detected on some or all of the test fuels. Lowering the RON below 95 would not be representative of today's fuels[1], however, for negative k-factors a higher severity fuel can be made by lowering the sensitivity at 95RON, i.e. by increasing MON. Other fuel parameters were held constant as far as possible, especially the distillation curve. The objective for the core matrix was to blend fuels at 95 and 99 RON, with sensitivities of 10 and 15. In the end it proved difficult to blend the 95RON/80MON fuels and the octane of these fuels turned out

[1] However, 91RON Regular grade is still sold in Germany

higher than the target. To further extend the sensitivity range a low sensitivity fuel (Fuel 1) was also included.

Finally, to cover the possibility that no differences between the full-boiling range test fuels might be seen (because they all have sufficient octane for good vehicle performance), three Primary Reference Fuels were added to the matrix, with octane numbers of 95, 91 and 86. By definition, these PRF fuels have zero sensitivity. As a safeguard against any detrimental effects, these lower octane fuels were tested at the end of the fuel sequence.

Because octane sensitivity equals 'RON minus MON', it is not an independent variable, but can be calculated from the RON and MON values. In the same way, the specified oxygen contents are simply the consequence of the oxygenate volumes specified.

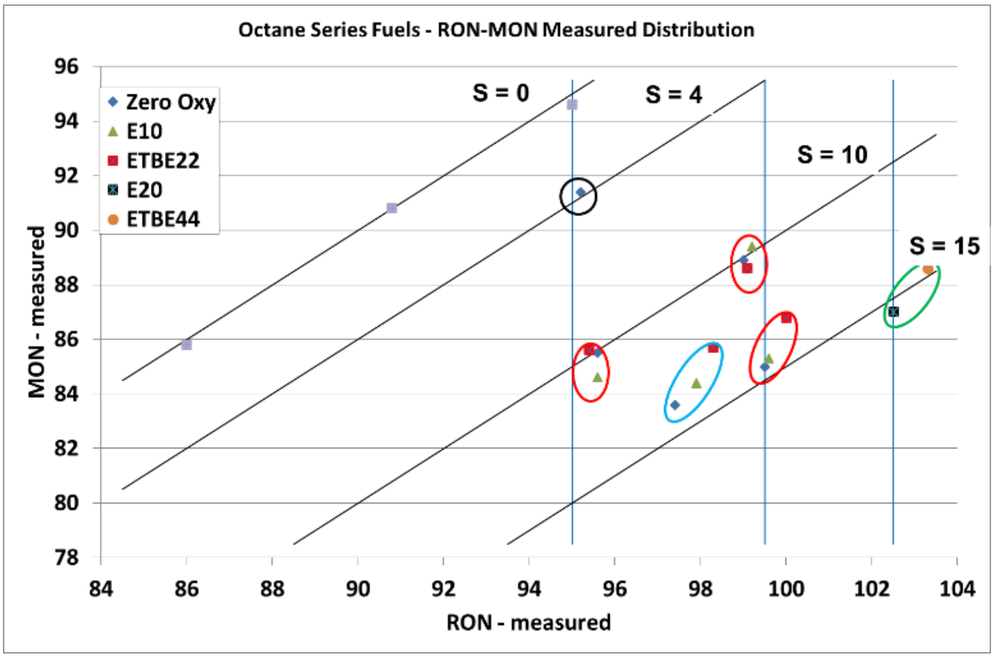
The high latent heat of ethanol is believed to influence octane measurements in the CFR engine. For this reason, fuels having the same CFR octane number may behave differently in a modern engine depending on whether the fuel contains ethanol. Pure hydrocarbon fuels were therefore included in the fuel matrix even though they are not typical of European fuels so that the effects of ethanol on octane are not confounded with the oxygen content and latent heat effects of ethanol.

All other fuel properties, particularly distillation were kept as constant as possible and a full set of inspections run as shown in **Appendix 1**. Key parameters of the fuels are shown in **Table 2** and **Figure 2**.

Table 2. Test Fuel Matrix - main parameters

		EtOH	ETBE	Oxygen	RON	MON	Sensitivity
		vol %	vol %	% m/m	measured	measured	RON-MON
Fuel 1	E0 ETBE0	0	0	0	95.2	91.4	4
Fuel 2	E0 ETBE0	0	0	0	95.6	85.5	10
Fuel 3	E0 ETBE0	0	0	0	97.4	83.6	14
Fuel 4	E0 ETBE0	0	0	0	99.0	88.9	10
Fuel 5	E0 ETBE0	0	0	0	99.5	85.0	15
Fuel 6	E10 ETBE0	10.0	0	3.63	95.6	84.6	11
Fuel 7	E10 ETBE0	9.4	0	3.46	97.9	84.4	14
Fuel 8	E10 ETBE0	9.3	0	3.49	99.2	89.4	10
Fuel 9	E10 ETBE0	10.2	0	3.70	99.6	85.3	14
Fuel 10	E0 ETBE22	0	22.4	3.78	95.4	85.6	10
Fuel 11	E0 ETBE22	0	23.3	3.77	98.3	85.7	13
Fuel 12	E0 ETBE22	0	23.1	3.88	99.1	88.6	11
Fuel 13	E0 ETBE22	0	22.9	3.84	100.0	86.8	13
Fuel 14	E20 ETBE0	19.2	0	6.84	102.5	87.0	16
Fuel 15	E0 ETBE44	0	40.2	7.58	103.3	88.6	15
Fuel 16	PRF86	0	0	PRF	86.0	85.8	0
Fuel 17	PRF91	0	0	PRF	90.8	90.8	0
Fuel 18	PRF95	0	0	PRF	95.0	94.6	0

Figure 2. RON, MON and Sensitivity of the 18 Fuels



Note: the fuels highlighted in blue were targeted at 95 RON/80 RON but those targets were not met

2.3.2. Fuel Handling

All the fuels were stored in secure storage compartments meeting both safety requirements and storage requirements provided by Concawe to avoid loss of light ends and ensure the fuels remained consistent throughout the test programme.

A fuel changeover rig (**Figure 3**) was used which allowed running on two fuels at any one time and then switching between them without turning the vehicle off. During the switch over, the spill return fuel went into a separate barrel so that there was no cross contamination. This approach helped make fuel changes quicker and also enabled the examination of instantaneous effects.

Figure 3. Fuel Changeover Rig

2.3.3. Test Design

All the acceleration tests were performed on a chassis dynamometer. Two separate tests were performed on each fuel in each vehicle to allow statistical evaluation of fuel effects and the fuels were tested in a randomized order as shown in **Table 3**. The tests on the two lower octane PRF fuels (fuels 16 and 17) were run close to the end of the series: as tests 31, 33, 35 and 36, so that any adverse effects on the engine would not impact the results from the other fuels. In practice, both vehicles operated without problems on all the fuels apart from some performance loss at lower octane.

Table 3. Order of Fuel Testing

Test No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Fuel No.	14	2	11	7	1	18	10	4	12	9	15	3	8	6	5	13	10	9
Test No.	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
Fuel No.	13	8	11	5	7	6	2	3	18	1	4	12	17	15	16	14	17	16

Note: For Vehicle 2, tests 33 & 34 were reversed.

3. TEST METHODOLOGY

3.1. TEST PROCEDURE

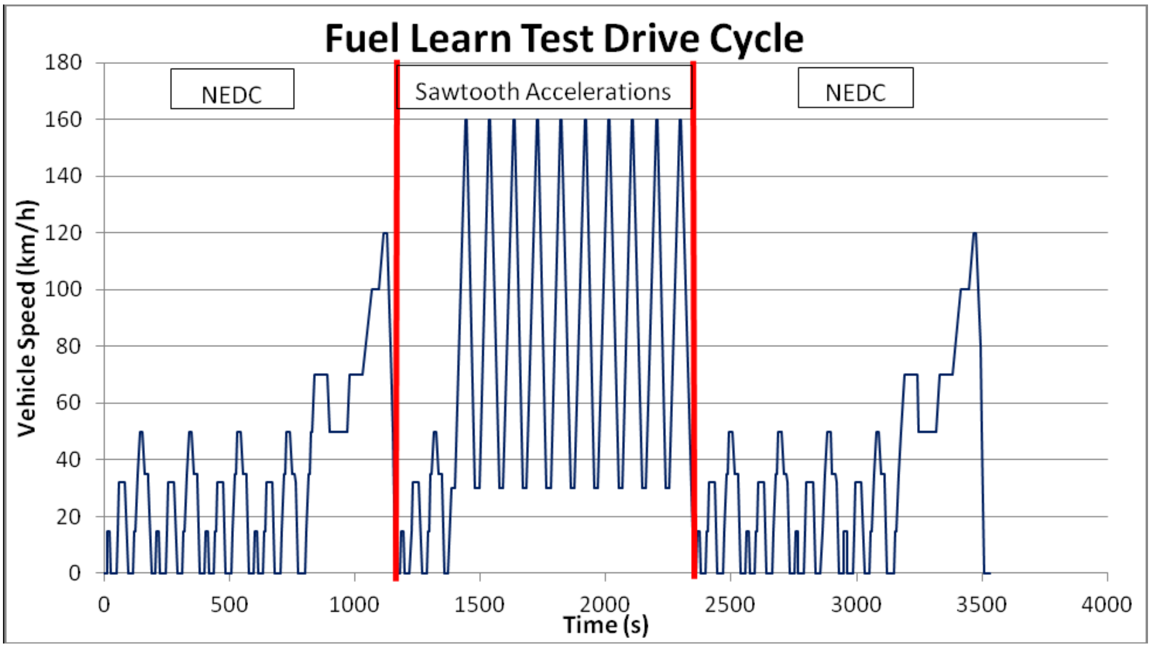
The test procedure was separated into three elements:

- A fuel learning procedure,
- An NEDC (New European Drive Cycle) plus steady states and
- A set of Sawtooth Accelerations.

3.1.1. Fuel Learn Cycle

The Fuel Learn Cycle was made up of two NEDCs and one Sawtooth Acceleration sequence as shown in **Figure 4**. The NI (National Instruments) system was used to create a drive cycle that was followed on a tablet screen. No emissions data were recorded from the learning cycle. Data were recorded from NI logger and a VBox data acquisition systems measuring data from various thermocouples. CAN (controller area network) data and lambda (normalized air fuel ratio) data were also collected.

Figure 4: Fuel Learn Drive Cycle



3.1.2. NEDC and Steady State Test Cycle

Following the Fuel Learning Cycle the vehicle then immediately commenced the main phase of the test, with one hot-start NEDC cycle followed immediately by steady state tests with the dynamometer adjusted to 85% and 100% of full load at 2000rpm and 4500rpm engine speed.

The New European Drive Cycle (NEDC), over which the exhaust emissions and fuel consumption of light duty vehicles is evaluated, consists of two phases, Urban (ECE) and Extra-Urban (EUDC) and is performed on a chassis dynamometer at an ambient temperature of 20°C to 30°C and from a 'cold' start i.e. the engine has not run for several hours. The urban cycle consists of a series of accelerations, steady speeds, decelerations and idling with a maximum speed of 31mph (50 km/h), average speed 12 mph (19 km/h). The distance covered is 2.5 miles (4km). The extra-urban cycle is conducted immediately following the urban cycle and consists of roughly half-steady speed driving and the remainder accelerations, decelerations and some idling. Maximum speed is 75 mph (120 km/h), average speed is 39 mph (63 km/h) and the distance covered is 4.3 miles (7km). In the tests reported here the regulated NEDC cycle was driven with the engine already warm from the preceding operation, so the results are not strictly comparable with the regulated emission limits.

The NEDC cycle was followed by a series of steady speed tests at engine speeds of 2000 and 4500 rpm. These were performed both at full load and at 85% load to represent the part-throttle condition. The figure of 85% load was chosen following a series of trial runs, because it was found unlikely that knock would occur at lower loads. Because of the different vehicle characteristics and gearing, the actual road speed to achieve the required test conditions was different for each vehicle as shown in **Figures 5(a)** and **5(b).**

Figure 5(a). Vehicle 1 – NEDC Drive Cycle

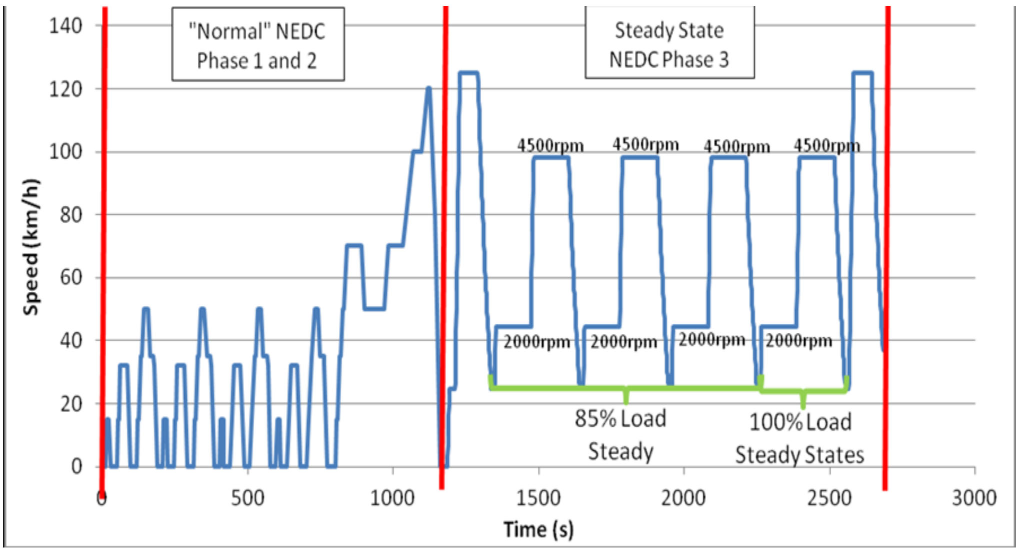
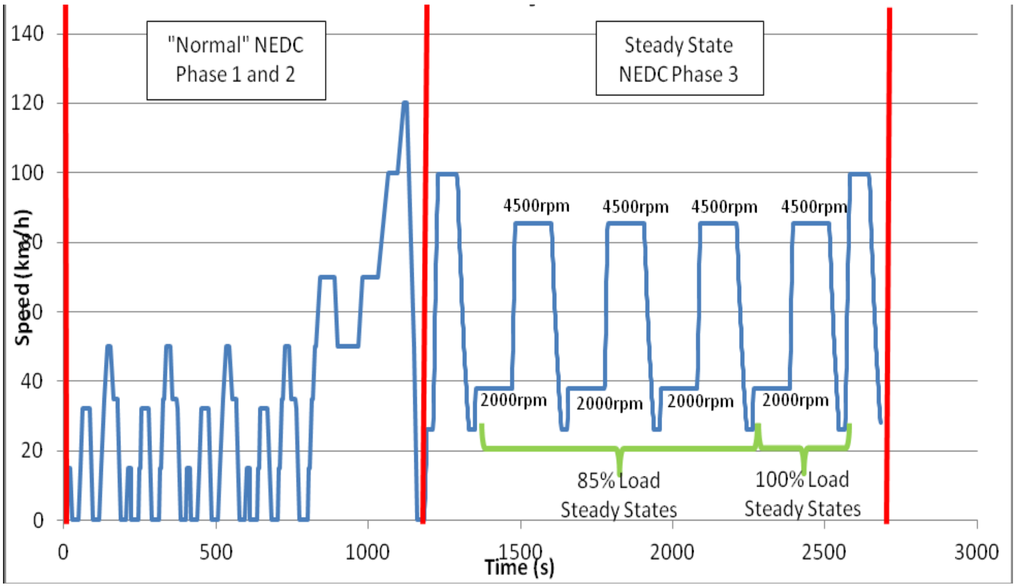


Figure 5(b). Vehicle 2 – NEDC Drive Cycle

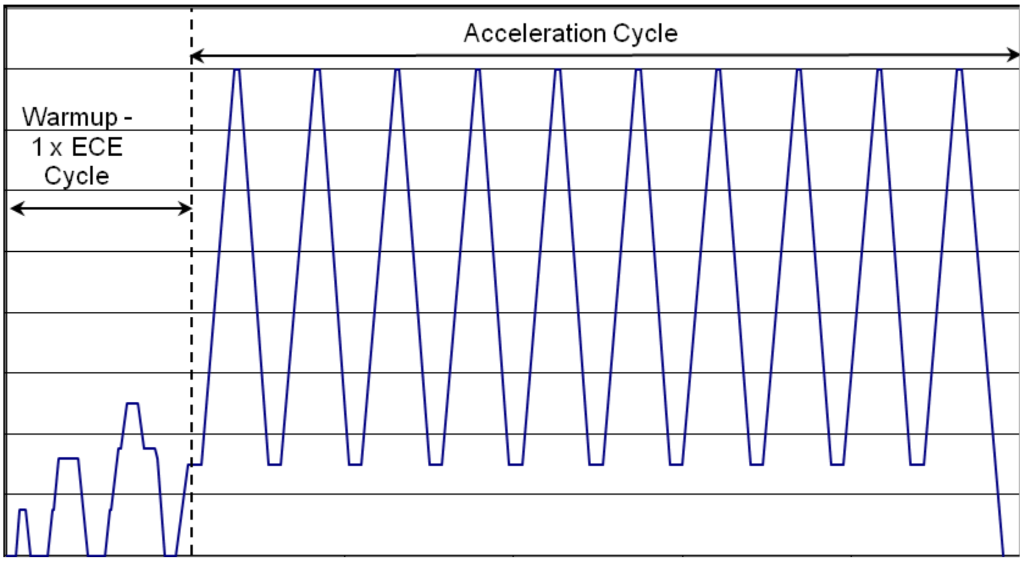


Emissions measurements were taken over this part of the test. Although measurements were made during the steady state phase of the test, it was found that conditions did not fully stabilise and the results were difficult to interpret. The full throttle sawtooth accelerations were found to be the most useful in studying octane effects on performance.

3.1.3. Sawtooth Acceleration Test Cycle

The sawtooth acceleration test measured full-throttle acceleration time and was devised specifically for this programme. The vehicle was already warm and stabilised from the preceding events. One ECE cycle was driven as a conditioning run and a 30km/h cruise in 3rd gear held for ten seconds. The throttle was then fully opened accelerating the vehicle at the maximum rate in 3rd gear up to top engine speed before the vehicle was slowed to 30km/h and the acceleration repeated a further 9 times. A graph of this drive cycle is shown in **Figure 6**. Vehicle 1 achieved in excess of 140 km/h during these tests, while Vehicle 2 achieved in excess of 120 km/h.

Figure 6. Sawtooth WOT Acceleration Cycle



3.2. DATA MEASUREMENT

3.2.1. Sawtooth Accelerations

Both test vehicles were naturally aspirated so it was expected that the response of the Electronic Control unit (ECU) to knock would be to retard the ignition timing and to potentially apply over-fuelling for component protection at higher engine speeds. It was decided against directly monitoring the knock sensor in case this affected the control system. Instead, spark retard was monitored from the ECU via the OBD connector. Vehicle speed was monitored at intervals of 0.1 second and this provided the primary acceleration performance data. Power and torque at specified engine rpm values were also calculated from the speed trace, however these derived parameters were found to be more variable than the directly measured speed-time data and so were not used in the analysis.

In addition, extensive engine data were recorded second by second including temperatures at the air intake, fuel rail, oil sump and exhaust ahead of the catalyst. Air-fuel ratio was measured by Universal Exhaust Gas Oxygen Analyser (UEGO) sensors: two sensors were used on Vehicle 1 (one placed in each exhaust branch) while only a single sensor was required for Vehicle 2. Engine parameters including mass air flow and ignition timing were also monitored and were used as an aid to understanding any observed changes in acceleration performance.

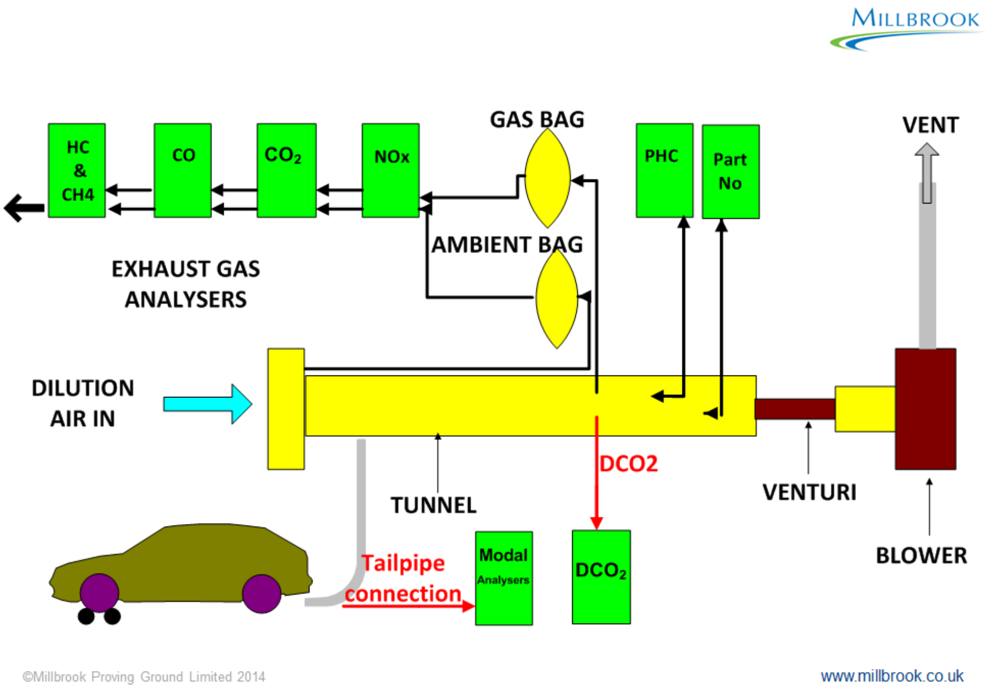
Emission measurements were taken and fuel consumption calculated using the carbon balance method as outlined in EC directive 70/220 amended to the latest rule. Actual fuel property data were used in the calculation of fuel consumption to allow for the effect of differences between the fuels of H/C ratio and density.

3.2.2. Hot NEDC Emissions

Because the NEDC cycles were run after the fuel learning cycle the engine was already warm, so the results are not directly comparable with the certified cold NEDC emission results. Mass emissions were determined by sampling the vehicle tailpipe emissions using industry standard constant volume sampling (CVS) technology as shown in **Figure 7**. Integrated bag sampled emissions were collected for each phase of the test and corrected for ambient contaminants. Emissions collected and detection methods were as follows:-

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

Figure 7. Emission Test Equipment



3.2.3. Fuel Consumption

Fuel consumption was calculated using the carbon balance method as outlined in EC directive 70/220 amended to the latest rule. In all tests, second by second measurements were taken to allow analysis of vehicle operation in greater detail at various points in the test. Actual fuel property data were used in the calculation so that differences in fuel H/C ratio properly reflected in the fuel consumption calculation.

4. TEST RESULTS AND DISCUSSION

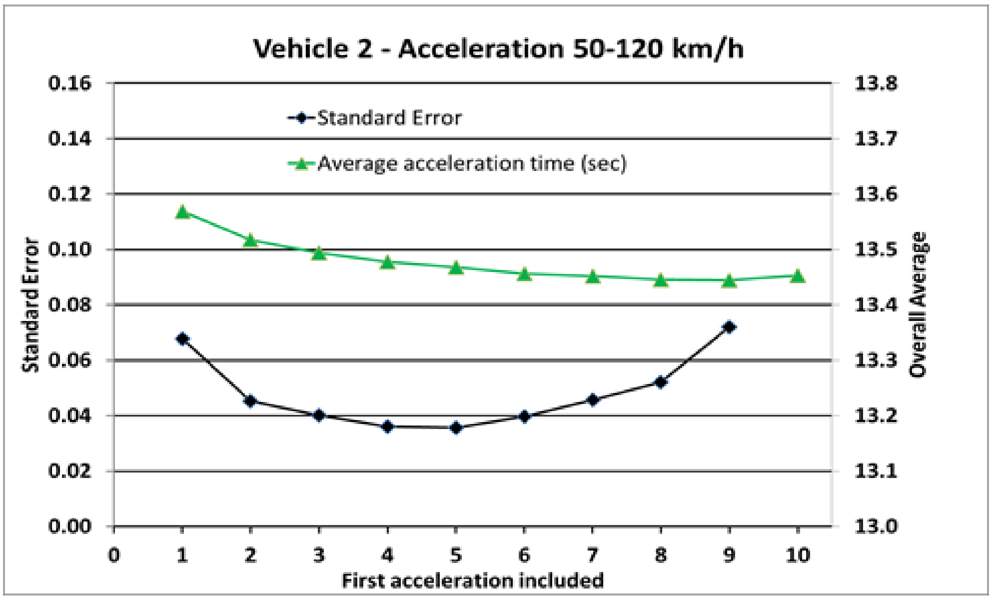
4.1. DATA HANDLING AND ANALYSIS

The measurements of power and torque during the steady state conditions were found to be very variable and were not analysed in detail. The variability appears to be influenced primarily by the short duration of the cruise period which meant that throttle variations at the start and end of the cruise limited the period of steady-state operation.

For this reason, the full throttle sawtooth accelerations were used to investigate fuel effects on vehicle performance on the different test fuels. Analysis was based on the acceleration time from 50km/h to 120km/h, which speed range could be achieved by both vehicles. As a first step, this was calculated for each of the 10 repeat accelerations, and variations during each test studied. It was found that the vehicle accelerated more slowly in the earlier runs and did not equilibrate until the fifth or sixth run. **Figure 8** shows (as green triangles) the mean acceleration time for Vehicle 2 as the first runs are progressively left out of the average.

At position 1 all 10 individual runs are included in the average, at position 5 runs 5-10 are included. The black diamonds show the standard error of the data at each position on the chart, i.e. the standard deviation of those accelerations included, with the results averaged over all 36 test runs. When all the test runs are included the SE is relatively high, because the time varies between runs. As the first few more variable acceleration times are left out the SE reduces, but increases towards the end of the series where few points are included in the average. The Standard Error was minimised when the first four accelerations were ignored and the mean taken for runs 5-10 and this was used as the metric to study fuel effects.

Figure 8. Accelerations 5-10 were averaged and accelerations 1-4 were discarded



The improvement in acceleration time through the ten sawtooth accelerations may be a result of engine temperature stabilisation during the series: the oil temperature was lower for the first few runs than for the rest of the series. To remove this variability from the data, accelerations 5 to 10 were averages for each test. The average 50km/h to 120km/h acceleration times calculated in this way were then studied for outliers and trends. Lambda data for one test (which was repeated) was rejected because of a problem with the data logger. There was some evidence of a time trend with acceleration performance continuing to improve throughout the programme for Vehicle 1 and deteriorate for Vehicle 2, albeit with some fluctuations in pattern.

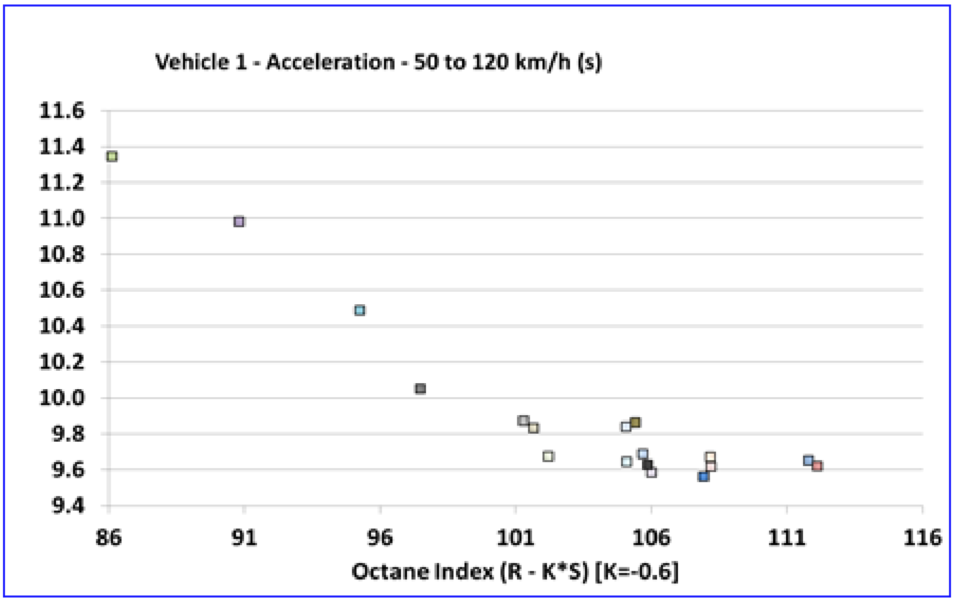
In the light of these trends, the variations in acceleration times between the pair of tests on each fuel were examined to see if there was any impact of ambient conditions. In the case of vehicle 1, the SAE J1349 power correction was applied. This reduced the variability in average acceleration times for each fuel, but had little impact on the patterns of responses to the different fuels as a randomized block design had been used with the repeats on each fuel spread across the two halves of the test period. In the case of the Vehicle 2, there was only a trend with humidity, and this was used to correct the data which made a modest improvement in variability. Bar charts of uncorrected and corrected averages are shown in Appendix 2, and the corrected results tabulated in Appendix 3.

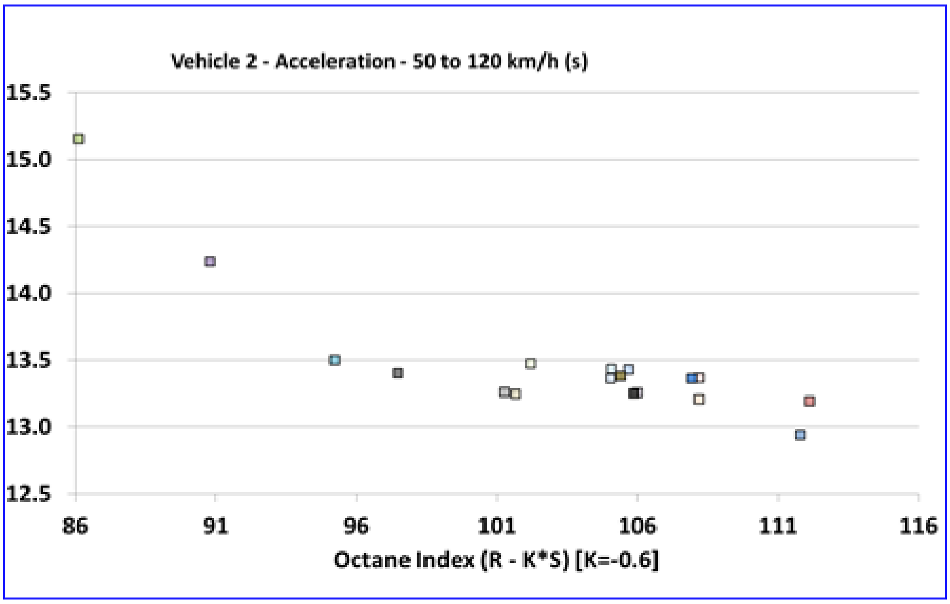
For the NEDC tests, there was also one repeated test for the Vehicle 1 (on fuel 13). For the first test, the NEDC followed the sawtooth rather than preceded it, so to preserve the balance of the results this test was excluded.

4.2. VEHICLE WOT ACCELERATION PERFORMANCE

Differences in acceleration time were seen for the different test fuels. For the fuels with 95RON and above, these were small, but bigger changes were seen for the PRF fuels at 91RON and 86RON. This is not surprising, because the vehicles were designed for RON levels of 98 (Vehicle 1) or 95 (Vehicle 2) so we would expect the vehicles' control systems to compensate for knock at lower octane numbers. The acceleration times were plotted against octane index and the value of k adjusted to give the best fit. At K=0.5, equivalent to the traditional AKI of (RON+MON)/2, the correlation was very poor. A slightly improved correlation was seen at K=0 (which is equivalent to plotting the data against RON only), however the correlation was much improved for negative K-values of -0.6 or even more negative. In these cases the fuels aligned along a single trend line and similar trends were seen in both vehicles. Plots for K=-0.6 are shown in **Figure 9**, and for other K-values are plotted in **Appendix 4.**

Figure 9. Vehicle acceleration correlates well with octane index having negative K-values



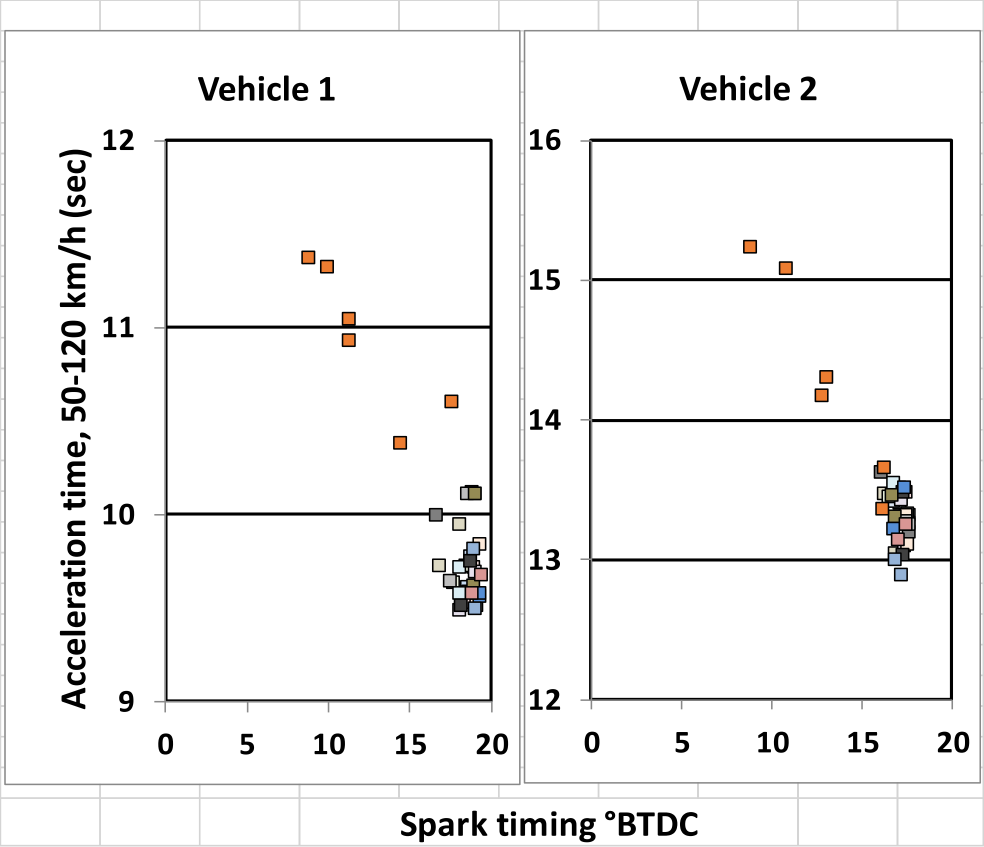


The best value of K to describe the data cannot be determined with great accuracy. In fact, good correlations are seen for a wide range of for very negative K-values. However, we can say that for Vehicle 1, the correlation deteriorates when k is more positive than minus 0.6 and for Vehicle 2, the correlation deteriorates when k is more positive than minus 0.3.

The results therefore show that vehicle performance can still be related to fuel octane number as measured by RON and MON, but that the relationship has changed from traditionally expected. What this means in practice is that these vehicles respond to higher RON, but that increasing MON, can actually reduce vehicle performance. A negative K-value also means that the Octane Index is higher than the RON of the fuel.

To understand in more detail how the vehicles were affected by fuel changes, and whether other factors in addition to octane were involved, the acceleration times were plotted against key vehicle parameters. For both vehicles, there was a strong correlation between acceleration time and spark timing, confirming that the knock sensor retarded the spark timing in response to knock. However, the correlation is only clear when the very low octane fuels are included (**Figure 10**).

Figure 10. WOT Acceleration time correlated with spark timing



There is still some variation in acceleration time within the group of fuels with RON of 95 or above. For Vehicle 2 (calibrated for 95RON) there is no remaining trend with spark timing, however for Vehicle 1 (calibrated for 98RON) there seems to be some remaining variation in spark timing.

Additional regressions were carried out to check for any other fuel effects on performance. The presence of ethanol or ETBE in the fuel had no effect on acceleration time outside the contribution of these oxygenates to the fuel octane number. Starting with the basic correlation between acceleration performance and spark timing, adding exhaust gas temperature as a variable slightly improved the correlation. However, increased exhaust gas temperature was associated with the lower octane fuels running with retarded spark timing. It is considered that the increased exhaust temperature is caused by the retarded spark timing rather than a fundamental difference in the way these fuel combust. Engine power can also be affected by air-fuel ratio, or lambda. Both vehicles controlled lambda within a fairly narrow range (which was narrower for Vehicle 1 than for Vehicle 2) and there was no evidence of a systematic variation across the fuels. Finally, the volumetric heat content of the test fuels varied over a significant range, so the amount of fuel energy entering the engine on each test was estimated from the mass air flow and the stoichiometric AFR of each fuel. Again, no significant effect was found, indicating that the engines were able to fully adjust for the variations in fuel energy content. As a result of these checks we can be confident that the changes in acceleration time seen between the fuels can be fully explained in terms of the octane numbers of the fuels and the response of the test vehicles to retard spark timing in response to lower octane.

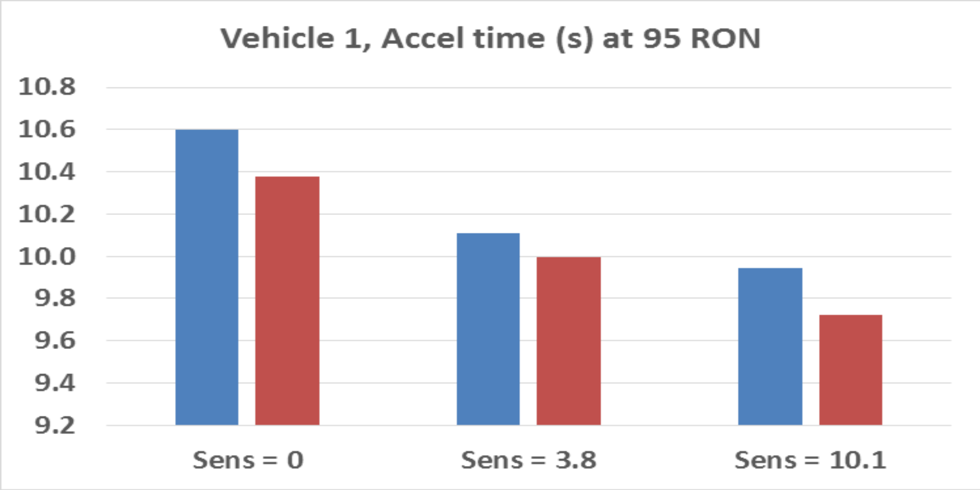
4.2.1. Acceleration Time - Discussion

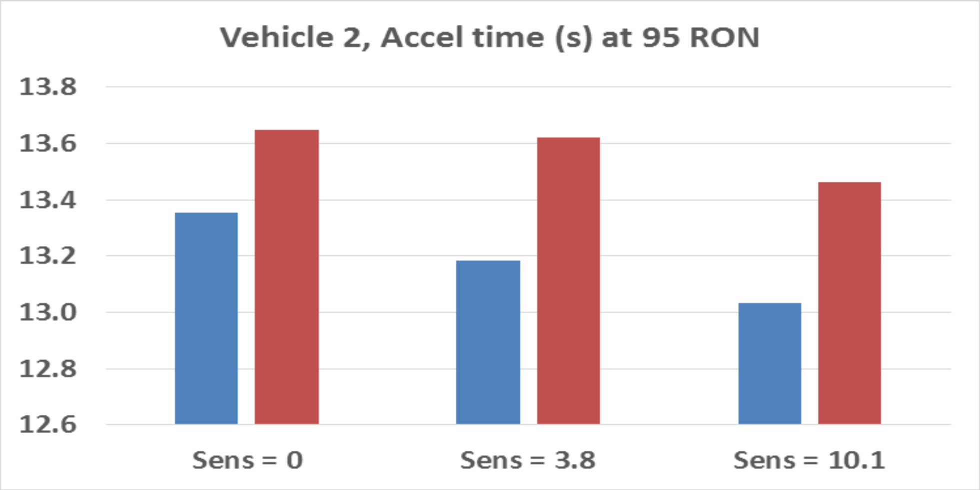
A negative K-value means that the operating conditions in the vehicle's engine no longer lie between those of the RON and MON tests, but that the knock resistance of the vehicle is higher than that predicted by the RON of the fuel. What this means in practice is that these vehicles respond to higher RON, but that increasing MON, can actually reduce vehicle performance. In the foregoing discussion, the K-factor has been determined by visual inspection of the data. This is not a precise method and a wide range of values fit the data

In [17] a more analytical method of determining the K-value is shown based on regression of performance data against RON and MON. The RON and MON coefficient in the equation can then be used to calculate K. The majority of the fuels in **Figure 10** form a matrix with RON and MON varied independently and were analysed separately as a 'non-extreme' fuel set. The 3 PRF fuels (16, 17 and 18) marked in red on the diagram and the low sensitivity Fuel 1 were excluded from the analysis. Within the analysed fuel set, variations in acceleration time were small, however significant effects on acceleration time were found for RON and MON in Vehicle 1, giving a K-value of -1.75 and for RON in Vehicle 2, implying a K-value of 0.

The variability of the test data means that comparison of individual results must be undertaken with care, however the effect of a negative K-value can be illustrated by comparing fuels 18, 1 and 2 (two different runs) which are all pure hydrocarbon fuels at 95RON, but have sensitivities of 0, 3.8 and 10.1 respectively (**Figure 11**).

Figure 11. Acceleration time reduces with high sensitivity at constant RON





As shown in **Figure 11**, acceleration time in Vehicle 1, with a strongly negative K-factor was clearly lower for the fuel with high sensitivity and hence lower MON. The effect was also seen, but less clearly marked, in Vehicle 2, which had a less negative K-factor.

The MON test was originally introduced to protect vehicles from knock, and in the standard CFR engine fuels with high MON perform better that those with lower MON. These differences in response between the CFR engine and modern production vehicles are therefore probably related to engine design features and test conditions.

In the RON test, the CFR engine operates at a speed of 600rpm with a specified intake air temperature. The temperature of the fuel-air mixture charge admitted to the engine is therefore a function of fuel composition, and may vary depending on the air-fuel ratio and the latent heat of the fuel. The MON test uses a higher engine speed of 900rpm and regulates the charge temperature (post fuel addition) to a much higher temperature of 149°C irrespective of fuel composition. In simple terms we can consider that the RON engine measures the impact of both evaporative cooling tendency of a fuel as well as its reactivity, whereas the MON test relates principally to the reactivity or chemical resistance of a fuel to knock.

Unlike early engines, where intake systems were heated to improve fuel vaporisation and mixture formation (MON-like), the modern engine takes full advantage of the evaporative cooling of a fuel in order to avoid knock (RON-like). Not only does this help explain the shift in engine-correlation from MON in the 1930s to RON nowadays, but suggests that appetite of the DI engine, where a fuel's cooling tendency is applied directly in-cylinder, would be even beyond RON and behave like a PRF with an octane number higher than the RON of the test fuel. A further factor in explaining these effects is that octane is determined by comparison with purely paraffinic PRF reference fuels. Whereas for most fuels, reaction rate is expected to increase with temperature, in certain temperature ranges the reaction rate of PRFs can be insensitive or even decrease as temperature rises.

The fact that the K-factor is generally negative for modern vehicles is an indicator that the conditions in the RON and MON tests no longer reflect those in modern engines. These factors have led a number of researchers to consider that the MON test is no longer suitable to describe the performance of modern vehicles and have investigated improvements to the RON method [1,2,4,5,8].

4.3. EXHAUST EMISSION AND FUEL CONSUMPTION RESULTS

The fuel matrix used in this study was designed to study the effects of octane and oxygenate variations on performance and variables usually associated with fuel effects on emissions such as volatility and aromatics content were not varied in a systematic manner. Emissions measurements were included in the study to test whether vehicle knock affected emissions and as an additional tool to understand the effects of lower octane fuels on vehicle performance. Emission measurements were taken during the NEDC cycle and also during the sawtooth accelerations at full throttle.

The emission results by fuel are shown in Appendix 5, where the individual data for HC, CO, NOx and energy consumption are plotted by fuel. Gaseous emission figures are reported in g/km, however it should be noted that he NEDC results were obtained using a hot start, so the results are not directly comparable with the regulated cold start NEDC figures. Results are also shown for the WOT acceleration tests, averaged over the 50-120km/h accelerations. WOT acceleration is not a condition where emission measurements are normally performed, however these measurements provide additional information on how the engine is responding to changes in fuel octane.

Comparison of fuel consumption measurements in litres/100km is of limited usefulness in comparing test fuel performance, because the fuels vary in their densities and Lower Heating Values. Similarly, tailpipe CO_2 emissions depend on the C/H ratio of the test fuel as well as the engine efficiency. While these variables can be important in real world vehicle operation, for this study a more useful metric is the energy consumption of the vehicle, which is a direct reflection of its efficiency. Energy consumption has been calculated in MJ/100km, from exhaust emission data (to calculate volumetric fuel consumption), and the individual density and LHV figures for each test fuel. The results are shown in Appendix 6.

The hot NEDC exhaust emission test results showed considerable variability between repeats on each test fuel. This is perhaps related to the daily test routine which prioritized vehicle performance measurement. There is also some evidence that variability is higher for hot NEDC tests than for the regulated cold start NEDC.

Although the hot NEDC emissions are not directly comparable with the regulated cold-start NEDC limits, the overall performance of the two vehicles can be gauged from the following table where results on all the test fuels have been averaged. HC and NOx are broadly in line with the regulated limits, while CO emissions are higher.

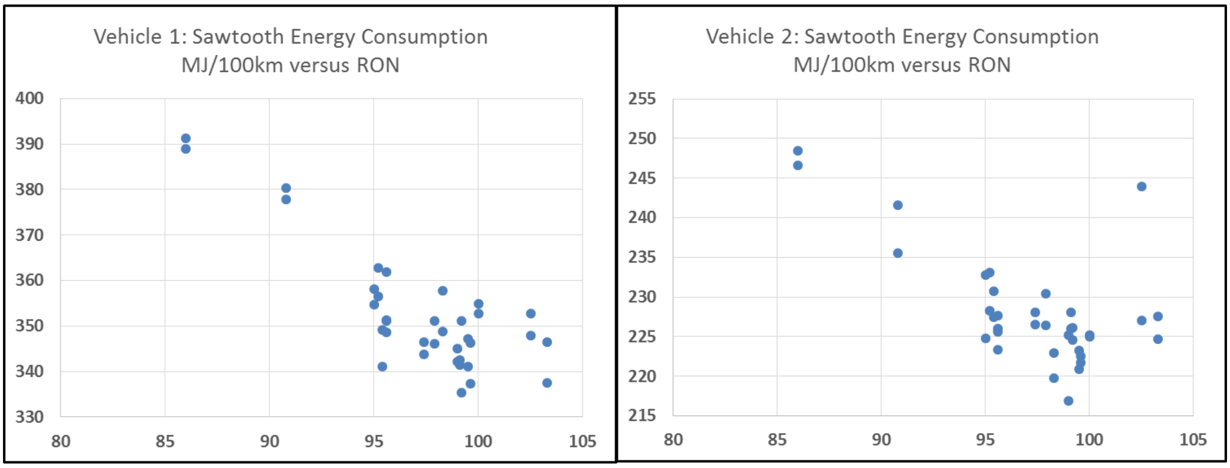
Table 4. Comparison of NEDC hot starts with regulated limits

	HC	CO	NOx	HC+NOx
Euro 4 Regulated limit		0.5	0.25	0.30
Vehicle 1 hot start	0.10	0.86	0.25	0.35
Vehicle 2 hot start	0.03	0.12	0.02	0.05

HC emissions in the Sawtooth acceleration test were about the same as the NEDC for Vehicle 1, but 10 times higher for Vehicle 2. CO emissions were much higher in the acceleration tests than in the hot NEDC - 10 times higher for Vehicle 1 and 100 times higher for Vehicle 2. Conversely, NOx emissions for Vehicle 1 were 20 times lower in the acceleration tests. Vehicle 2 retained very low NOx emissions in both tests.

Vehicle energy consumption was about 40% higher on the acceleration test than the NEDC for Vehicle 1 and about 20% higher for Vehicle 2. This is not unexpected, because engine efficiency generally increases as full power is approached in many vehicles. There is some evidence of higher consumption on the lower octane fuels and the data are plotted against RON in **Figure 12**.

Figure 12. Vehicle energy consumption increases as RON decreases at WOT

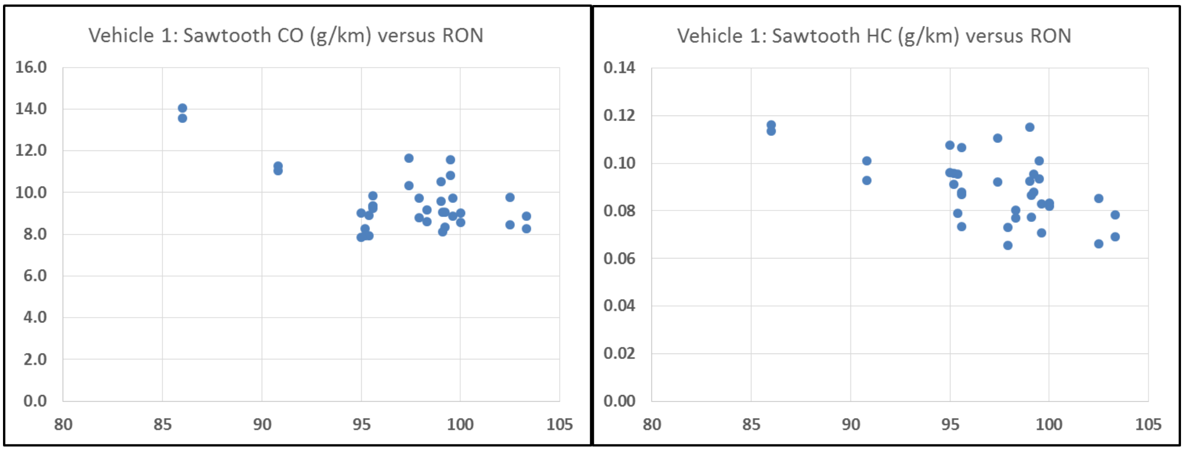


There is a clear increase in energy consumption as fuel octane decreases. This is not surprising for those fuels below 95 or 98 RON where the engine may be adapting to reduce knock. However, in spite of some scatter in the data, the trend appears to continue to at least 98RON and perhaps even higher in the case of Vehicle 2. The effects of lower octane are therefore twofold:

- There is a loss of acceleration performance (see **Figure 9**)
- And, this lower performance is delivered with increased fuel consumption

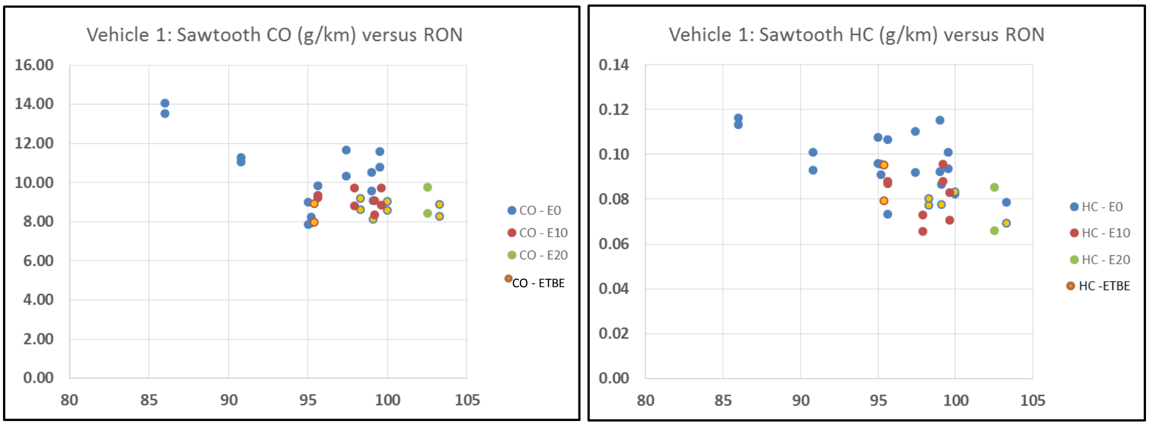
In Vehicle 1, at least part of the deterioration in efficiency at lower octane is due to incomplete combustion as shown by the CO and HC emissions in **Figure 13**. There was no clear trend in Vehicle 2.

Figure 13. CO and HC emissions increase at lower RON in the acceleration test



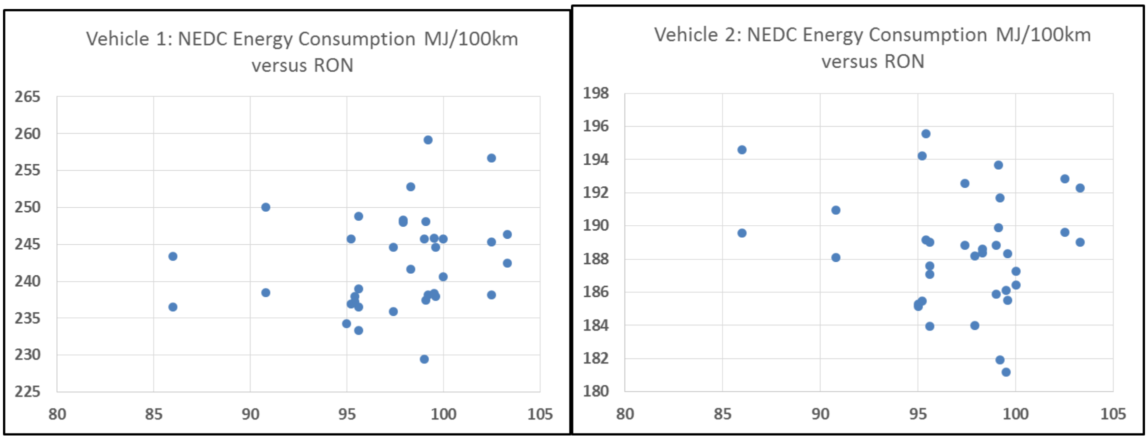
The plots suggest a trend for slightly lower CO and HC emissions in the presence of ethanol and ETBE indicating more complete combustion likely to be due to local leaning out due the incorporation of oxygen. This can be seen in **Figure 14**.

Figure 14. CO and HC emissions increase at lower RON in the acceleration test



WOT acceleration is an extreme condition and energy consumption is of greatest interest under more normal driving conditions. **Figure 15** shows energy consumption versus RON in the hot NEDC test. No effect of RON is seen in either vehicle, even at the lowest RON values tested. This suggests that either that knock does not occur under these lighter load conditions or that adaptations to knock are not severe enough to impact on engine efficiency.

Figure 15. Vehicle energy consumption is insensitive to RON in the hot NEDC



Visual inspection of the NEDC data shows little evidence of fuel effects although inspection of the WOT acceleration emissions data suggested that there may be some effects as indicated above. Statistical analysis was, therefore, carried out on the WOT acceleration data to investigate further and showed some significant effects. The primary analysis used fuels 2-13 (i.e. excluding the most extreme fuels) since these provide a balanced matrix for the octane and oxygenate variables:

- For Vehicle 1, the analysis confirmed that HC and CO emissions were reduced in the presence of ethanol and ETBE, but there were no fuel effects on NOx

- For Vehicle 2, there were no significant fuel effects on HC, CO or NOx emissions. Where the most extreme fuels were included in the analysis there were some effects of Sensitivity on CO and NOx and of ETBE on NOx, however these results should be treated with caution, because including the extreme fuels unbalances the matrix.

5. CONCLUSIONS

Full Throttle Acceleration Results

Tests on two Euro 4 passenger cars have evaluated vehicle performance under full throttle acceleration conditions on a wide range of fuels including ethanol and ETBE blends.

The vehicles were designed and optimised for fuels with RON of 95 and 98. Below these octane levels the engines' control system retarded spark timing to protect against knock, leading to increases in acceleration time.

Vehicle performance was more influenced by RON than MON and in fact increasing MON was found to be detrimental to performance, in line with the findings of other literature studies.

The best agreement between performance and fuel octane number was found using an Octane Index [(1-K).RON + K.MON] with a K-value of minus 0.6 or even more negative. However, a wide range of K-values fitted the data and care should be exercised in using the reported K-values.

The presence of ethanol or ETBE in the fuel blends had no effect on acceleration time other than their contribution to fuel octane number.

The reason why these modern engines respond to RON rather than MON is believed to be because the MON test measures chemical resistance to knock, whereas the RON test also includes the evaporative cooling tendency of the fuel, which is increasingly important in modern engines.

Emissions & Fuel Consumption Results

Emissions were measured over a hot NEDC cycle and also during the full throttle acceleration test. Although these tests are not directly comparable with the regulated cold-start NEDC test, they give insights into how vehicle performance varies as fuel octane number changes.

Octane number showed no effect on exhaust emissions in the hot NEDC test. For vehicle 1, the presence of ethanol and ETBE in the fuel appeared to reduce HC and CO emissions in the WOT acceleration test, but a similar effect was not seen in Vehicle 2.

Vehicle energy consumption (MJ/100km) increased with reducing octane number in the WOT acceleration tests. This indicates that in addition to performance being impaired at low octane, the engine is operating in a less efficient regime. Both vehicles showed reductions in energy consumption up to quite high levels of octane number in the WOT acceleration tests.

However in the part load hot NEDC cycle which is more representative of normal driving conditions, no effect of octane on vehicle energy consumption was observed.

Effectiveness of the test procedure

The full throttle acceleration tests were found to be the most effective measurements to evaluate the effects of octane number on vehicle performance.

To evaluate part load conditions, steady-state measurements of power and torque were undertaken, however the results were found to be unreliable because the cruise conditions were maintained for too short a time for stable results to be achieved. It was found that knock effects were unlikely to be experienced in these vehicles at loads less than 85% of full power. It is recommended that these measurements be excluded from future test programmes.

Test Vehicles and Fuels

The test fuel matrix was effective in separating RON, Sensitivity, EtOH and ETBE content in a full factorial matrix at two levels, with additional fuels extending the range of oxygenate content and PRFs extending to lower octane numbers.

Since the test vehicles were designed to run on fuels of 95/98RON the extent of fuel effects seen was limited except for the lower octane PRF fuels. For future work, efforts should be made to identify test vehicles that are more sensitive to octane effects, or to extend the fuel matrix to lower octane numbers.

The vehicles tested were Euro 4 models from 2007 & 2009 production. Vehicles produced to the latest emission levels including turbocharged and down-sized engines should be included in future studies.

6. GLOSSARY

A/F	Air / Fuel
AKI	Anti-Knock Index defined as (RON+MON)/2
AFR	Air-Fuel Ratio
CFR	Cooperative Fuel Research Engine - used in the standard RON and MON tests
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CR	Compression Ratio
ECE	City cycle, First part of the NEDC
ECU	Electronic Control Unit, a component of the EMS
EMS	Engine Management System
ETBE	Ethyl Tertiary Butyl Ether
EtOH	Ethanol
EUDC	Extra-Urban Driving Cycle. Second part of the NEDC
GDI	Gasoline Direct Injection
HC	Hydrocarbon
k	Factor used in Octane Index describing the relative importance of RON and MON
lambda	Normalised AFR (relative to shoichiometric AFR)
LCV	Lower Calorific Value (same as LHV)
LHV	Lower Heating Value (same as LCV)
MJ	Megajoule
NEDC	New European Driving Cycle
NMHC	Non-Methane Hydrocarbon
MON	Motor Octane Number
NEDC	New Emissions Driving Cycle, the legislative test cycle for emissions and fuel consumption measurement in Europe
NOx	Oxides of Nitrogen
OI	Octane Index defined as (1-K).RON + K.MON

PRF Primary Reference Fuels used in RON/MON determination. Blends of iso-octane and n-heptane.

RON Research Octane Number

S Fuel Sensitivity, defined as RON-MON

UEGO Universal Exhaust Gas Oxygen sensor. Measures AFR or lambda.

7. ACKNOWLEDGEMENTS

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15. Davies, T. et al (2011) Fuel effects in a boosted DISI engine. SAE Technical Paper 2011-01-1985. Warrendale PA: Society of Automotive Engineers

16. Amer, A. et al (2012) Fuel effects on knock in a highly boosted direct injection spark ignition engine. SAE Int. J. Fuels Lubr. 5(3):1048-1065, 2012, SAE Paper 2012-01-1634. Warrendale PA: Society of Automotive Engineers

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APPENDIX 1 - TEST FUEL INSPECTION DATA

(a) Fuels 1-9

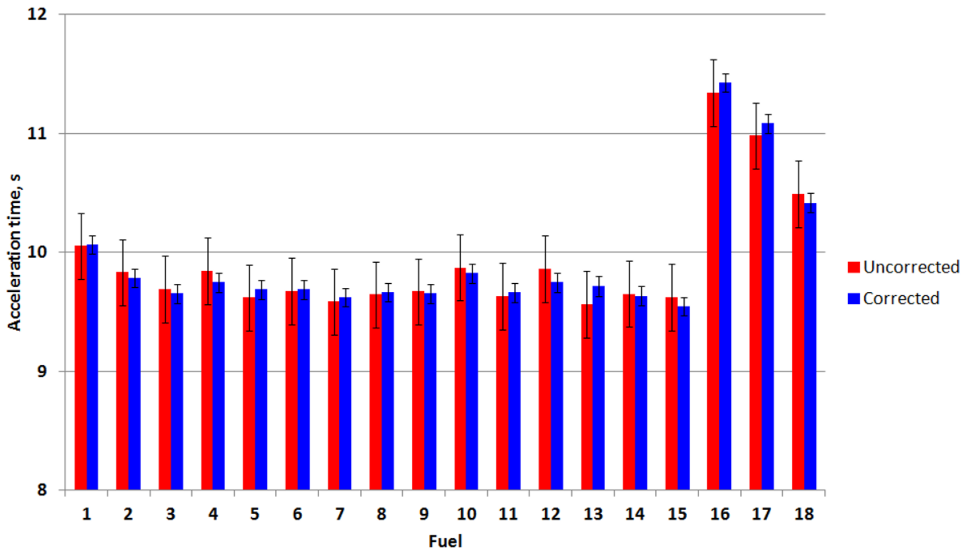
			Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8	Fuel 9
			E0 ETBE0	E0 ETBE0	E0 ETBE0	E0 ETBE0	E0 ETBE0	E10 ETBE0	E10 ETBE0	E10 ETBE0	E10 ETBE0
			95-93	95-85	95-80	99-89	99-84	95-85	95-80	99-89	99-84
Parameter	Method	Unit	CAF-W12/944	CAF-W12/852	CAF-W13/053	CAF-W12/853	CAF-W12/901	CAF-W12/854	CAF-W13/061	CAF-W12/881	CAF-W12/902
Density	EN ISO 12185	kg/L	0.6937	0.7443	0.7642	0.7429	0.7669	0.7547	0.7453	0.7311	0.7565
RON - measured	EN ISO 5164		95.2	95.6	97.4	99.0	99.5	95.6	97.9	99.2	99.6
MON - measured	EN ISO 5163		91.4	85.5	83.6	88.9	85.0	84.6	84.4	89.4	85.3
Sensitivity - measured			3.8	10.1	13.8	10.1	14.5	11.0	13.5	9.8	14.3
Sensitivity - target			0-3	10	15	10	15	10	15	10	15
FIA											
Aromatics	ASTM D1319	% v/v	1.8	30.7	29.3	29.7	35.1	26.0	24.6	20.5	25.6
Olefins	ASTM D1319	% v/v	0.3	10.0	16.7	6.4	16.9	14.2	21.2	0.3	14.9
Saturates	ASTM D1319	% v/v	97.9	59.3	54.0	63.9	48.0	49.8	44.8	69.9	49.3
Ethanol	ASTM D6730 mod	% v/v	<0.1	<0.1	<0.1	<0.1	<0.1	10.0	9.4	9.3	10.2
ETBE	ASTM D6730 mod	% v/v	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Distillation											
E70	ASTM D86	% v/v	22.6	28.3	28.6	29.1	31.0	42.0	48.3	50.9	50.2
E100	ASTM D86	% v/v	68.5	57.1	57.4	54.7	57.1	55.2	60.9	66.9	64.4
E150	ASTM D86	% v/v	96.3	89.3	93.0	92.8	94.7	87.6	94.7	95.1	95.1
IBP	ASTM D86	degC	30.5	29.6	35.1	27.8	35.4	37.9	32.4	32.3	34.8
T10	ASTM D86	degC	58.2	54.1	57.0	50.2	56.2	55.9	51.2	51.0	51.4
T20	ASTM D86	degC	67.7	62.9	64.3	60.5	62.9	60.5	55.6	55.2	55.5
T30	ASTM D86	degC	76.7	71.7	70.9	71.1	69.3	63.9	60.1	59.7	58.9
T40	ASTM D86	degC	85.4	81.2	79.5	83.6	77.8	67.8	64.5	64.1	62.7
T50	ASTM D86	degC	92.1	92.1	91.1	95.5	90.1	90.2	73.7	68.7	69.7
T60	ASTM D86	degC	95.7	103.4	102.7	103.9	103.5	107.6	99.2	94.7	93.5
T70	ASTM D86	degC	99.8	114.0	109.8	109.7	110.3	120.7	106.7	102.1	104.4
T80	ASTM D86	degC	103.9	126.2	115.6	115.9	114.2	135.0	110.7	108.4	109.5
T90	ASTM D86	degC	111.6	152.6	132.2	132.4	124.2	156.1	119.5	120.8	116.7
T95	ASTM D86	degC									
FBP	ASTM D86	degC	176.9	195.3	194.9	191.3	193.0	199.2	196.3	185.9	191.8
Residue	ASTM D86	% v/v	0.9	1.1	1.0	1.0	1.0	1.0	1.0	1.0	0.9
Appearance	Visual		C&B	C&B	C&B	C&B	C&B	C&B	C&B	C&B	C&B
DVPE @37.8C	EN 13016-1	kPa	55	61.5	55.1	69.6	56.1	55.2	67.1	62.3	65.7
Benzene	ASTM D6730 mod	% v/v	<0.1	0.2	<0.1	<0.1	0.1	0.5	0.1	<0.1	<0.1
Oxidation Stability	EN ISO 7356	min	>360	>360	>360	>360	>360	>360	>360	>360	>360
Existent Gum(unwashed)	EN ISO 6246	mg/100mL	2	1	3	1	1	4	4	4	3
Existent Gum(washed)	EN ISO 6246	mg/100mL	<1	<1	1	<1	1	2	2	2	2
Cu Corrosion	EN ISO 2160		1a	1a	1a	1a	1a	1a	1a	1a	1a
Sulphur	EN ISO 20846	mg/kg	1.6	0.4	<0.1	0.6	0.6	0.4	<0.1	0.7	0.5
Lead	EN 237	mg/L	<2.5	<1	<1	<1	<1	<1	<1	<1	<1
Oxygen	ASTM D6730 mod	% m/m	0.00	0.00	0.00	0.00	0.00	3.63	3.46	3.49	3.70
Oxygenates total	ASTM D6730 mod	% v/v	<0.1	<0.1	<0.1	<0.1	<.1	10.0	9.4	9.3	10.2
Carbon	ASTM D5291		84.77	87.17	87.70	87.51	87.84	83.69	84.00	82.23	83.74
Hydrogen	ASTM D5291		15.23	12.83	12.30	12.49	12.16	12.68	12.54	13.28	12.56
Oxygen	ASTM D6370 mod		0.00	0.00	0.00	0.00	0.00	3.63	3.46	3.49	3.70
Net Calorific Value	IP 12	MJ/kg	44.54	43.46	43.19	43.04	42.72	41.63	41.66	40.67	41.08
Net Calorific Value (vol)	calc	MJ/litre	30.90	32.35	33.01	31.97	32.76	31.42	31.05	29.73	31.08
Gross Calorific Value	IP 12	MJ/kg	47.77	46.18	45.80	45.69	45.30	44.32	44.32	43.49	43.74
Stoichiometric AFR	calc	m/m	14.94	14.40	14.28	14.32	14.24	13.79	13.78	13.97	13.75
H:C Molar Ratio			2.14	1.75	1.67	1.70	1.65	1.81	1.78	1.92	1.79
O:C Molar Ratio			0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.03	0.03
N:C Molar Ratio			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(b) Fuels 10-18

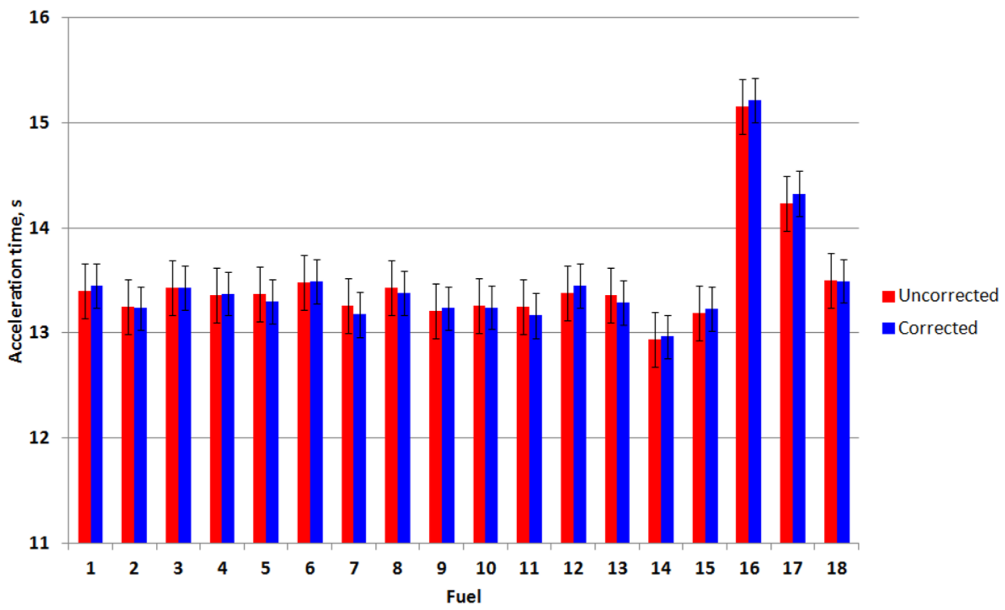
			Fuel 10 E0 ETBE22 95-85	Fuel 11 E0 ETBE22 95-80	Fuel 12 E0 ETBE22 99-89	Fuel 13 E0 ETBE22 99-84	Fuel 14 E20 ETBE0 102-87	Fuel 15 E0 ETBE44 102-87	Fuel 16 PRF86	Fuel 17 PRF91	Fuel 18 PRF95
Parameter	Method	Unit	CAF-W12/903	CAF-W13/056	CAF-W12/882	CAF-W12/942	CAF-W12/930	CAF-W12/931	CAF-W12/855	CAF-W12/856	CAF-W12/857
Density	EN ISO 12185	kg/L	0.7395	0.7446	0.7389	0.7475	0.7687	0.7536	0.6956	0.6960	0.6965
RON - measured	EN ISO 5164		95.4	98.3	99.1	100.0	102.5	103.3	86.0	90.8	95.0
MON - measured	EN ISO 5163		85.6	85.7	88.6	86.8	87.0	88.6	85.8	90.8	94.6
Sensitivity - measured			9.8	12.6	10.5	13.2	15.5	14.7	0.2	0.0	0.4
Sensitivity - target			10	15	10	15	15	15	0	0	0
FIA											
Aromatics	ASTM D1319	% v/v	18.3	11.7	18.8	10.6	27.8	10.7	0.2	0.2	0.3
Olefins	ASTM D1319	% v/v	12.3	22.7	9.2	18.7	12.6	12.4	0.2	0.2	0.2
Saturates	ASTM D1319	% v/v	47.0	42.3	48.9	47.8	40.4	29.9	99.6	99.6	99.5
Ethanol	ASTM D6730 mod	% v/v	1.1	0.5	1.0	1.2	19.2	1.3	<0.1	<0.1	<0.1
ETBE	ASTM D6730 mod	% v/v	21.3	22.8	22.1	21.7	<0.1	45.6	<0.1	<0.1	<0.1
Distillation											
E70	ASTM D86	% v/v	21.0	35.4	24.8	27.9	38.6	27.3	0.0	0.0	0.0
E100	ASTM D86	% v/v	65.1	71.5	63.7	66.4	63.9	79.8	97.6	97.9	97.6
E150	ASTM D86	% v/v	92.5	90.7	93.4	87.5	95.0	95.0	99.1	99.3	99.1
IBP	ASTM D86	degC	32.4	37.7	28.3	37.1	32.0	43.7	95.2	95.1	94.9
T10	ASTM D86	degC	61.3	57.3	55.3	59.6	53.5	63.4	97.2	97.3	97.3
T20	ASTM D86	degC	69.4	62.8	65.7	65.8	60.3	67.5	97.5	97.5	97.6
T30	ASTM D86	degC	75.8	67.4	74.7	71.0	65.9	70.9	97.6	97.7	97.7
T40	ASTM D86	degC	81.6	72.2	82.6	76.9	70.5	74.4	97.7	97.7	97.8
T50	ASTM D86	degC	87.6	77.9	89.7	84.1	73.4	78.1	97.7	97.8	97.8
T60	ASTM D86	degC	95.1	86.0	97.0	93.5	79.1	82.6	97.8	97.8	97.9
T70	ASTM D86	degC	106.3	97.7	106.2	106.3	112.7	89.0	97.9	97.9	98.0
T80	ASTM D86	degC	122.5	113.1	118.5	121.6	118.3	100.2	97.9	98.0	98.1
T90	ASTM D86	degC	143.2	145.3	138.0	163.1	131.2	116.5	98.2	98.3	98.3
T95	ASTM D86	degC									
FBP	ASTM D86	degC	184.8	196.7	188.4	196.4	178.4	186.2	104.9	104.5	106.7
Residue	ASTM D86	% v/v	1.0	1.1	1.0	1.1	1.0	1	0.9	0.7	0.9
Appearance	Visual		C&B	C&B	C&B	C&B	C&B	C&B	C&B	C&B	C&B
DVPE @37.8C	EN 13016-1	kPa	53.7	56.1	64.7	53.9	64.2	44.7	21.8	13.3	13.8
Benzene	ASTM D6730 mod	% v/v	0.4	<0.1	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Oxidation Stability	EN ISO 7356	min	>360	>360	>360	>360	>360	>360	>360	>360	>360
Existent Gum(unwashed)	EN ISO 6246	mg/100mL	<1	<1	1	1	<1	2	<1	<1	<1
Existent Gum(washed)	EN ISO 6246	mg/100mL	<1	<1	1	<1	<1	1	<1	<1	<1
Cu Corrosion	EN ISO 2160		1a	1a	1a	1a	1a	1a	1a	1a	1a
Sulphur	EN ISO 20846	mg/kg	0.2	<0.1	0.5	0.7	0.3	0.2	0.1	0.1	<0.1
Lead	EN 237	mg/L	<1	<1	<1	<1	<2.5	<2.5	<2.5	<1	<2.5
Oxygen	ASTM D6730 mod	% m/m	3.78	3.77	3.88	3.84	6.84	7.58	0.00	0.00	0.00
Oxygenates total	ASTM D6730 mod	% v/v	22.4	23.3	23.1	22.9	19.2	47.0	<0.1	<0.1	<0.1
Carbon	ASTM D5291		83.30	82.88	83.10	82.70	81.04	79.76	84.66	84.63	84.63
Hydrogen	ASTM D5291		12.92	13.35	12.98	13.46	12.11	12.66	15.34	15.37	15.37
Oxygen	ASTM D6370 mod		3.78	3.77	3.88	3.84	6.84	7.58	0.00	0.00	0.00
Net Calorific Value	IP 12	MJ/kg	41.96	41.90	41.82	41.91	39.66	40.20	44.56	44.65	44.03
Net Calorific Value (vol)	calc	MJ/litre	31.03	31.20	30.90	31.33	30.49	30.29	31.00	31.08	30.67
Gross Calorific Value	IP 12	MJ/kg	44.70	44.74	44.58	44.77	42.23	42.89	47.81	47.91	47.29
Stoichiometric AFR	calc	m/m	13.82	13.92	13.82	13.93	13.15	13.16	14.97	14.97	14.97
H:C Molar Ratio			1.85	1.92	1.86	1.94	1.78	1.89	2.16	2.16	2.16
O:C Molar Ratio			0.03	0.03	0.04	0.03	0.06	0.07	0.00	0.00	0.00
N:C Molar Ratio			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

APPENDIX 2 - ACCELERATION RESULTS BEFORE AND AFTER CORRECTION

Vehicle 1 - Acceleration from 50 to 120 km/h - Correction based on SAE J1349 factor



Vehicle 2 - Acceleration from 50 to 120 km/h - Relative humidity correction



APPENDIX 3 - TABULATED WOT ACCELERATION TIMES 50-120KM/H AFTER CORRECTION

Average acceleration times from 50 to 120 km/h (seconds)

Fuel	Vehicle 1	Vehicle 2
	Corrected	Corrected
1	10.06	13.45
2	9.79	13.24
3	9.65	13.43
4	9.75	13.37
5	9.69	13.30
6	9.69	13.49
7	9.62	13.17
8	9.66	13.38
9	9.65	13.23
10	9.82	13.24
11	9.66	13.17
12	9.75	13.45
13	9.72	13.29
14	9.63	12.97
15	9.55	13.23
16	11.43	15.21
17	11.08	14.32
18	10.42	13.49

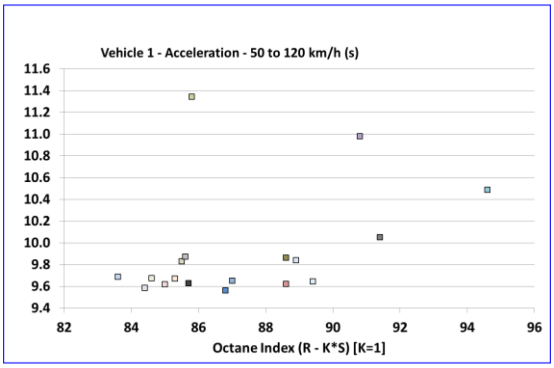
The Vehicle 1 values have been corrected using the SAE J1349 correction factor, based on ambient temperature & pressure and relative humidity as a covariate

The Vehicle 2 values have been corrected using relative humidity as a covariate

APPENDIX 4 - WOT ACCELERATION TIME VERSUS OCTANE INDEX FOR VARIOUS VALUES OF K

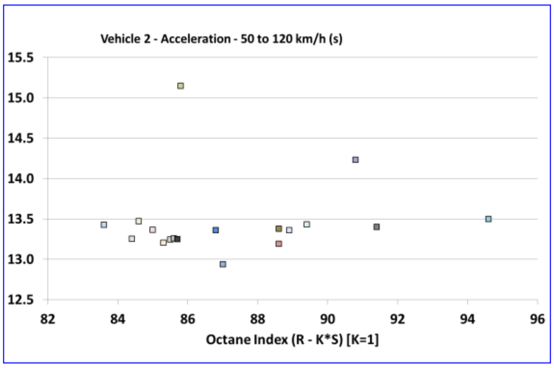
Vehicle 1

k=1 - equivalent to plotting against MON

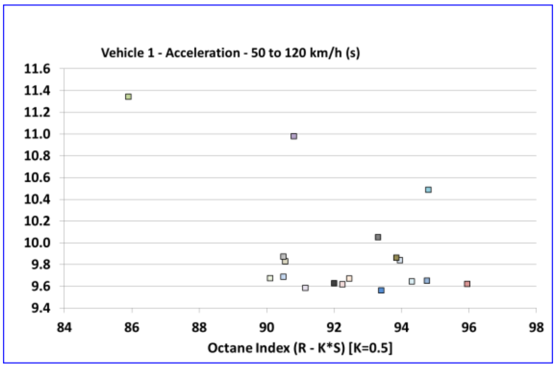


Vehicle 2

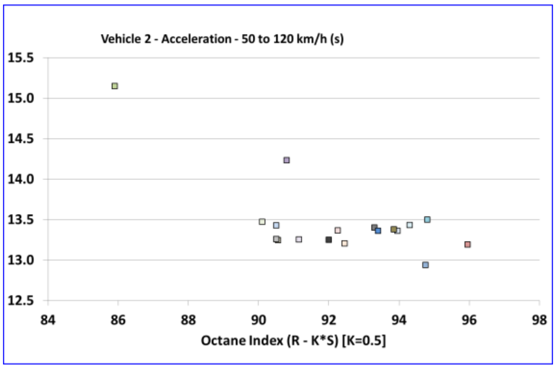
k=1 - equivalent to plotting against MON



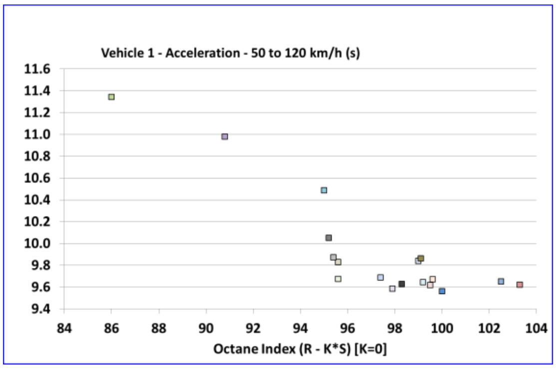
k=0.5 - representative of AKI, (RON+MON)/2



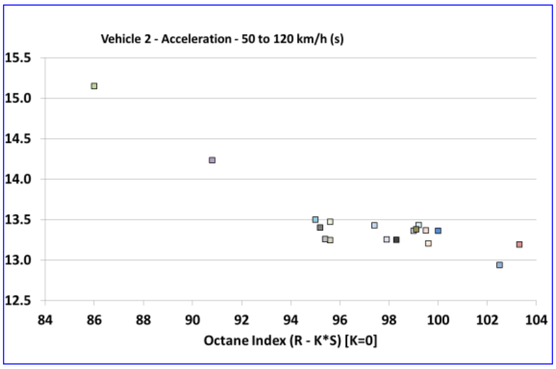
k=0.5 - representative of AKI, (RON+MON)/2



k=0 - equivalent to plotting against RON

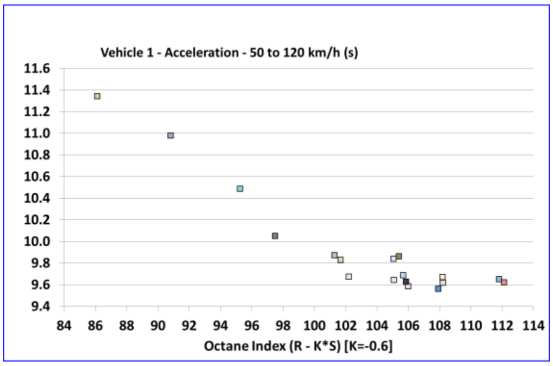


k=0 - equivalent to plotting against RON



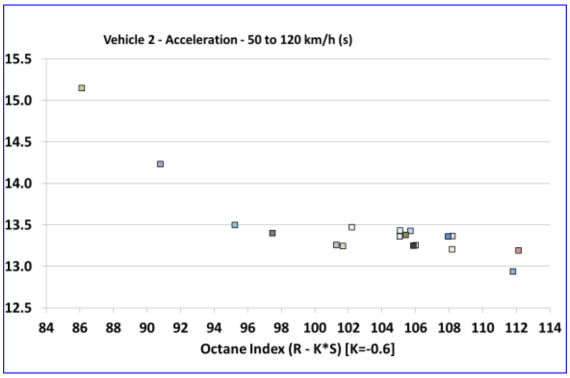
Vehicle 1

k is negative (-0.6), meaning high MON is detrimental

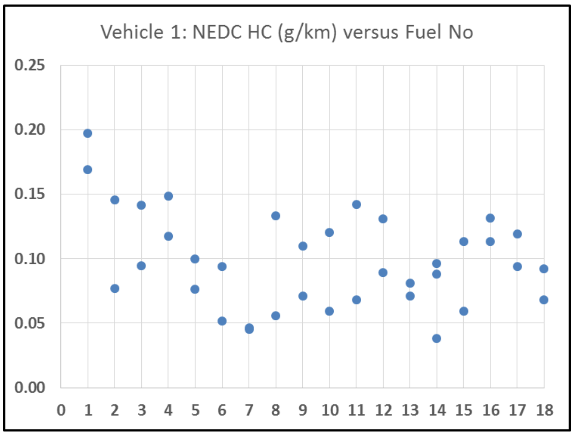


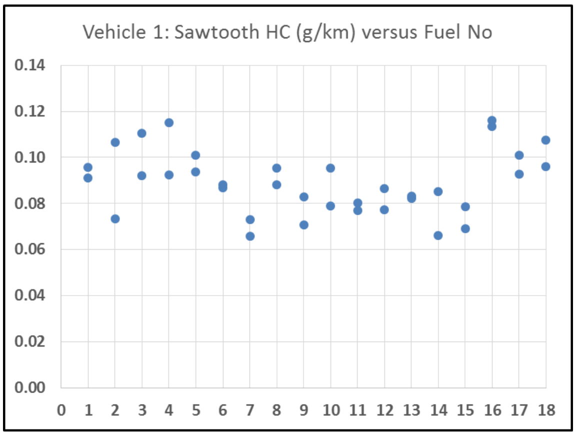
Vehicle 2

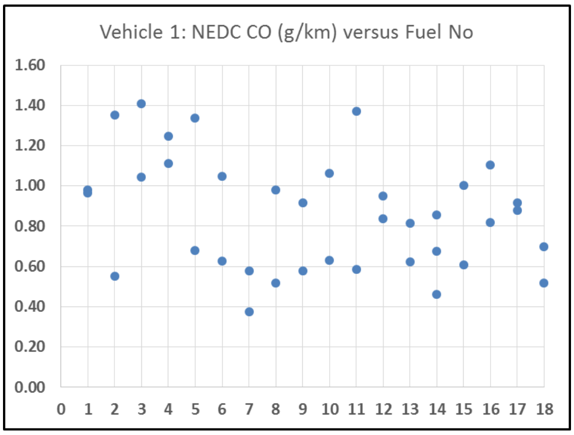
k is negative (-0.6), meaning high MON is detrimental

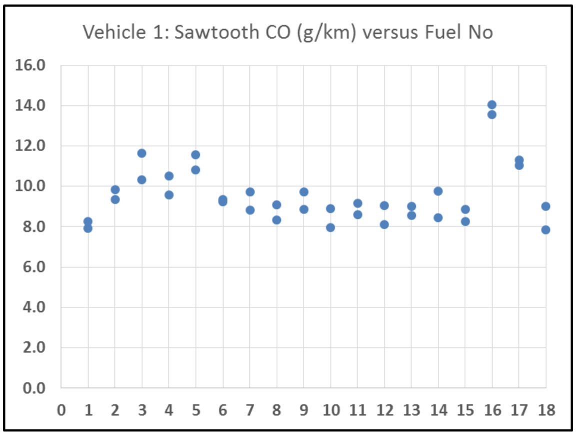


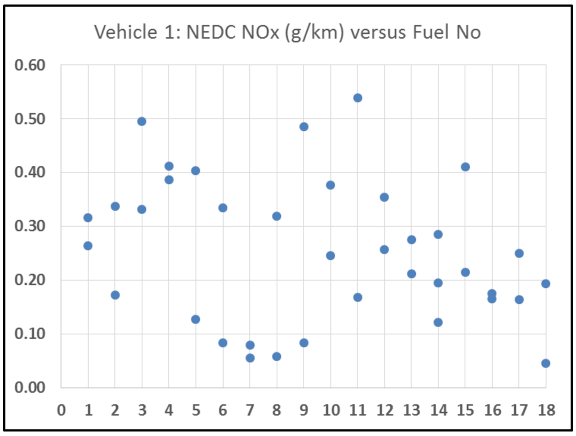
APPENDIX 5 - EXHAUST EMISSION RESULTS

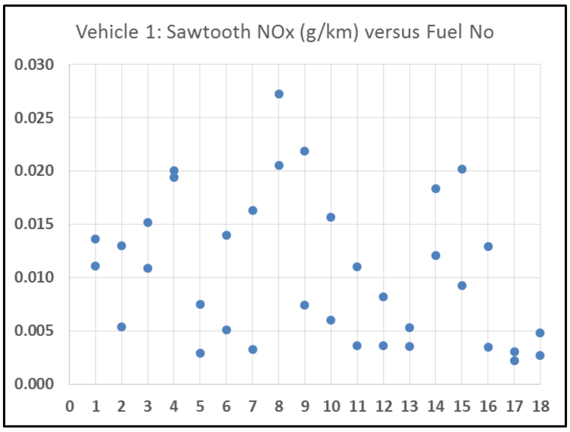


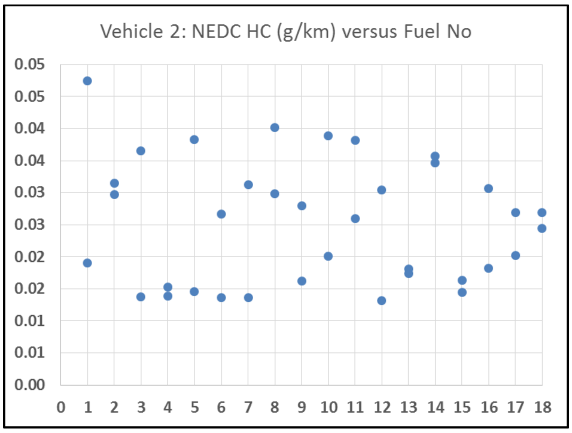


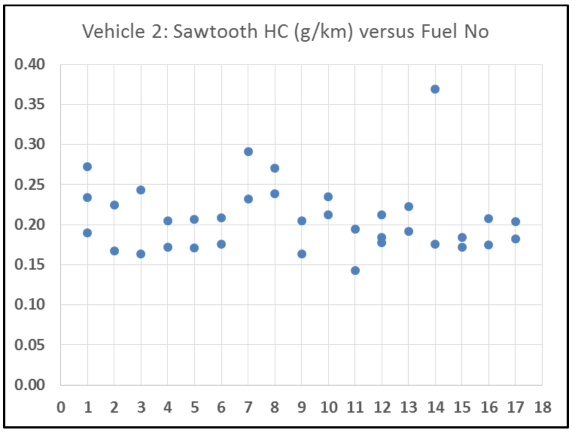


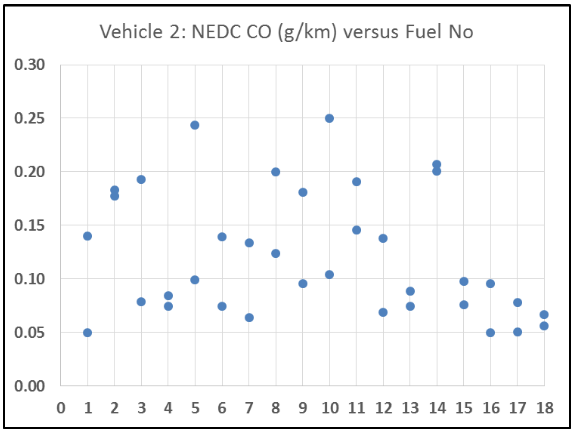


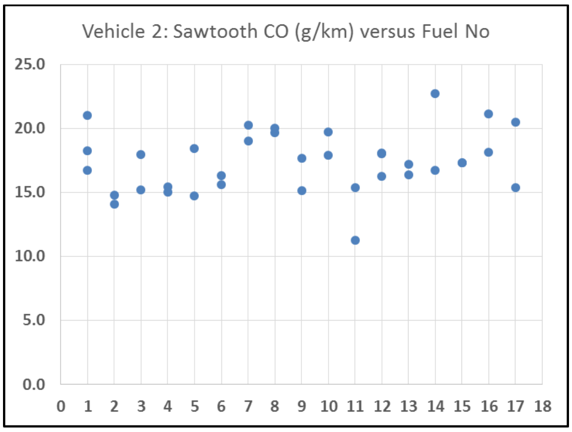


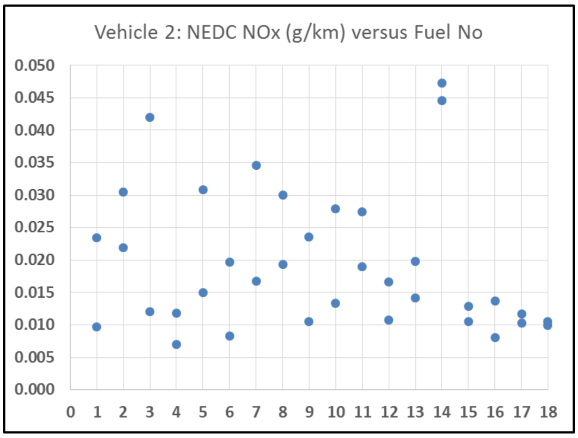


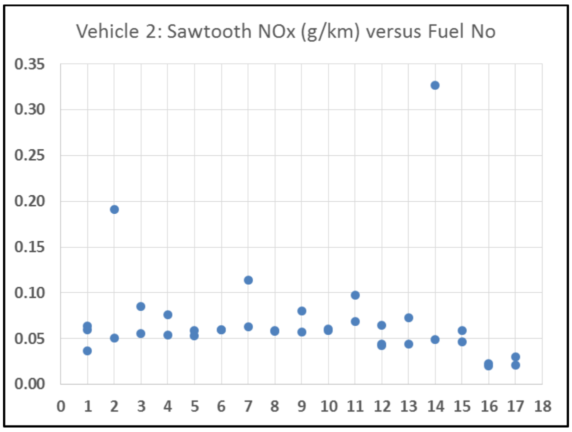

Vehicle 2: NEDC HC (g/km) versus Fuel No


Vehicle 2: Sawtooth HC (g/km) versus Fuel No

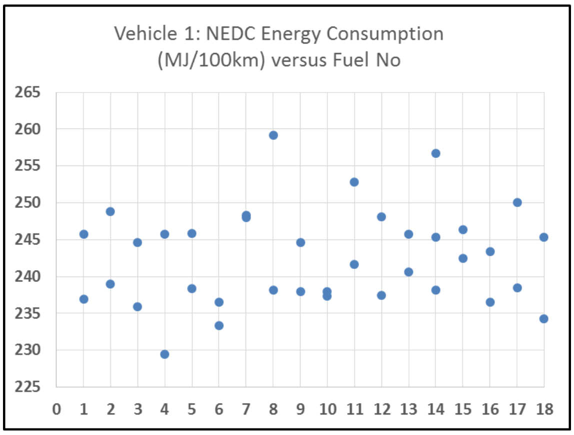

Vehicle 2: NEDC CO (g/km) versus Fuel No

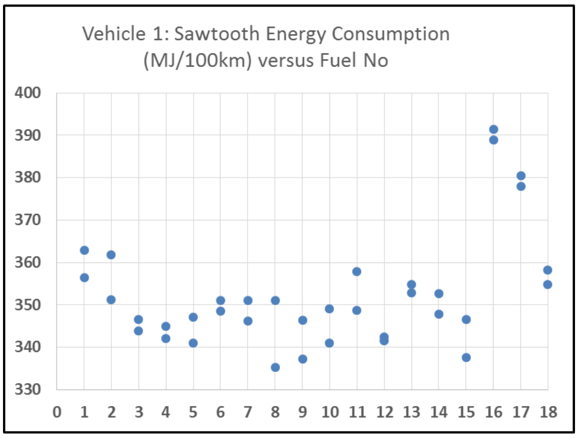

Vehicle 2: Sawtooth CO (g/km) versus Fuel No

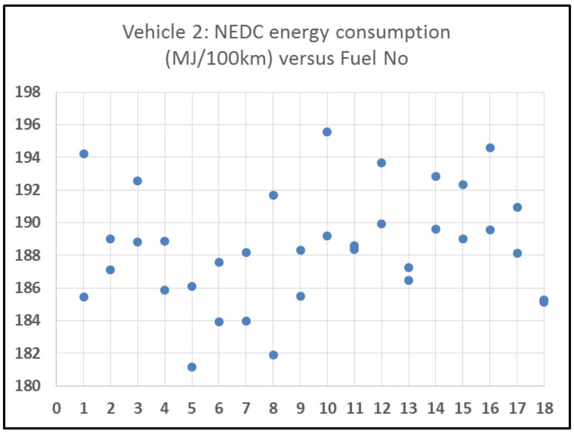

Vehicle 2: NEDC NOx (g/km) versus Fuel No

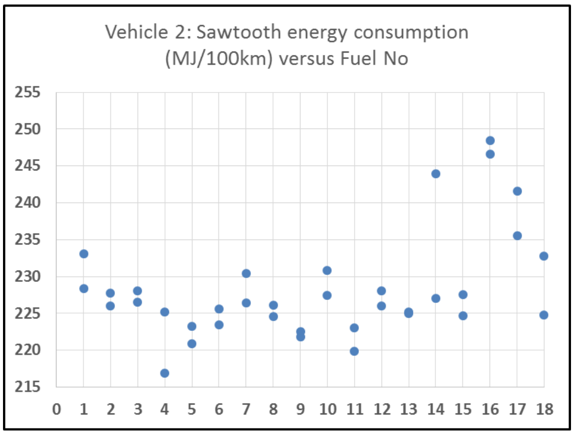

Vehicle 2: Sawtooth NOx (g/km) versus Fuel No

APPENDIX 6 - ENERGY CONSUMPTION RESULTS









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