Concawe
Environmental Science
for European Refining

Report

Report no. 7/19

Phase 2: Effect of Fuel Octane on the Performance of Four Euro 5 and Euro 6 Gasoline Passenger Cars

ISBN 978-2-87567-104-2

9 782875 671042 >

Phase 2: Effect of Fuel Octane on the Performance of Four Euro 5 and Euro 6 Gasoline Passenger Cars

Prepared for FEMG by Concawe FE/STF-20 members:

C. A. Bontoft
C. Callu
M. D. Cardenas Almena
J. H. Farenback-Brateman
H. Hovius
A. Kolbeck
K. Lehto
S. Mason
W. Mirabella
E.M. Rebesco
B. Taylor
P. Van de Heijning
J. Williams (Chair)

Concawe:
H. D. Hamje (Science Executive)
D. J. Rickeard (Consultant)
P.J. Zemroch (Consultant)
P. Ziman (Consultant)

Brussels
August 2019

ABSTRACT

Research Octane Number (RON) and Motor Octane Number (MON) are used to describe gasoline combustion antiknock performance under different conditions. Recent literature suggests that MON is less important than RON in modern cars due to a move towards negative k-values which are a factor in the relationship between RON and MON and that 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. Some workers have advocated the use of an octane index (OI) which incorporates both parameters instead of either RON or MON to give an indication of octane quality. Previous Concawe work investigated the effect of RON and MON on the power and acceleration performance of two Euro 4 gasoline passenger cars during an especially-designed acceleration test cycle. In phase 1 of this programme which has been previously reported, a large number of fuels blended with and without oxygenates and ranging from around 95 to 103 RON and sensitivities (RON minus MON) up to around 15 were tested. The results were vehicle dependent but in general, showed that sensitivity and octane index appear to be better predictors for improved acceleration times versus either RON or MON alone. In the current study a wider range of newer vehicles (Euro 5+) have been screened on a more limited fuel set and several chosen for further evaluation on the full fuel set. Improvements in fuel efficiency were observed during this testing and additional testing using standardized test cycles was carried out on one vehicle.

KEYWORDS

Octane, RON, MON, acceleration, efficiency

INTERNET

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

CONTENTS

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 due to a move towards negative k-values which are a factor in the relationship between RON and MON and that 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 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.

A first phase of this study was carried out 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 confirmed 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. 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 without adaption to take advantage of the higher octane fuels.

In the current study a wider range of newer vehicles (Euro 5+) have been screened on a more limited fuel set and several chosen for further evaluation on the full fuel set. Improvements in fuel efficiency were also observed during this testing and additional testing using standardized test cycles was carried out on one vehicle showing again indications of efficiency improvement

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 95 RON 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. To achieve a certain oxygen level more ether is needed compared to ethanol.

Higher octane fuels which may contain higher amounts of ethanol and/or ethers may be used in the future. This could be a point of discussion within the next 5+ years for petrol. 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 previous (Phase 1) study used Euro 4 vehicles that had already been evaluated by Concawe in the Millbrook test programme on petrol volatility. It was considered a scoping study, and the experience gained was 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.

In the current (phase 2) study the focus was on full throttle tests only and the NEDC was only used as part of the fuel learn cycle. Emissions and fuel consumption measurements were carried out on WLTC and US06 cycles which were the most transient cycles available. At this point the RDE cycle was not fully developed so was not used.

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.[21]
- 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.[22]

A fuel's octane number is determined by comparing and extrapolating its performance in the engine with blends 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 which assumes a positive k-value of 0.5 as discussed below.

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].

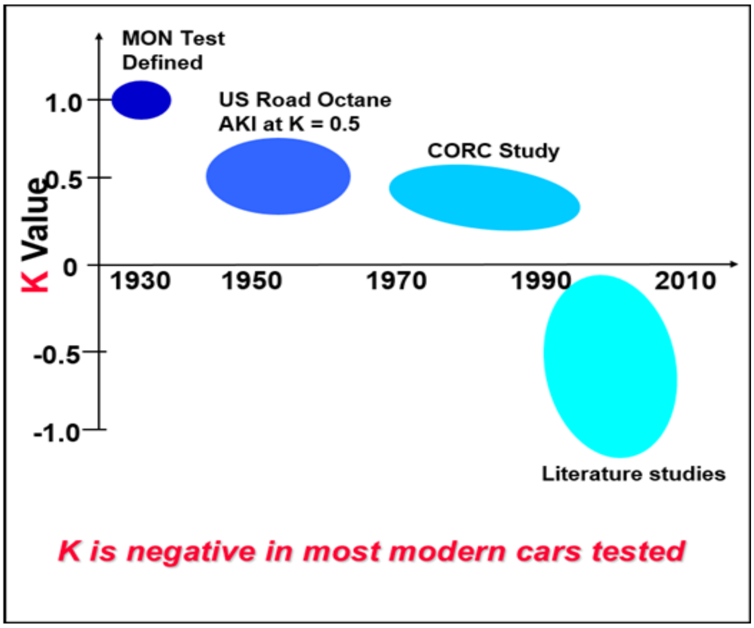
The Anti-Knock Index used in the USA and other countries is a specific case which predates a more general relationship between vehicle octane requirement, RON and MON which can be expressed as:

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

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. Concawe carried out a study the first phase of which was reported during 2016 and the subject of several papers [18], [19] and a Concawe report published in 2017 [20]. 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. 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.

In the current study a wider range of newer vehicles (Euro 5+) have been screened on a more limited fuel set and several chosen for further evaluation on the full fuel set. Improvements in fuel efficiency were also observed during this testing and additional testing using standardized test cycles was carried out on one vehicle showing again indications of efficiency improvement. Aspects of this work have been published in an SAE paper [23].

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. Four vehicles were tested, one meeting Euro 5 emission limits and three homologated for Euro 6 limits. All of the vehicles were direct injected, turbo-charged, equipped with three way catalysts and were chosen as they were common vehicles on the European market from different manufacturers.

In order to screen the vehicles for sensitivity to octane the vehicles were tested using two fuels of RON 96 and RON 100 (described as fuels 21 and 22) respectively. As a result of this, two vehicles (vehicles 1 and 3) were selected for further testing using the full range of fuels. One of these vehicles was then tested using standardized test cycles to understand the fuel economy performance.

Table 1 Vehicle Data

Vehicle No.	**1**	**2**	**3**	**4**
Emission Standard (homologation)	Euro 5	Euro 6	Euro 6	Euro 6
Engine Displacement (litres)	1.0	1.4	1.0	1.2
Max. Power (kW)	92kW	110kW	85kW	95kW
Inertia Class (kg)	1900	1800	1163	1094
Cylinders	3	4	3	3
Valves	12	16	12	12
Aspiration	Turbo-charged	Turbo-charged	Turbo-charged	Turbo-charged
Combustion Type	Spark Ignition	Spark Ignition	Spark Ignition	Spark Ignition
Injection System	DI	DI	DI	DI
After-treatment device	Catalytic Converter	Catalytic Converter	Catalytic Converter	Catalytic Converter
Drive	FWD	FWD	FWD	FWD
Transmission	Manual 6-speed	Manual 6-speed	Manual 6-speed	Manual 6-speed
E10 Compatible?	YES	YES	YES	YES
Registration Date	2014	2014	2015	2014
Mileage at start of test (miles)	6571	3278	2047	6480

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. Vehicles had completed at least 2,000km 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 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**.

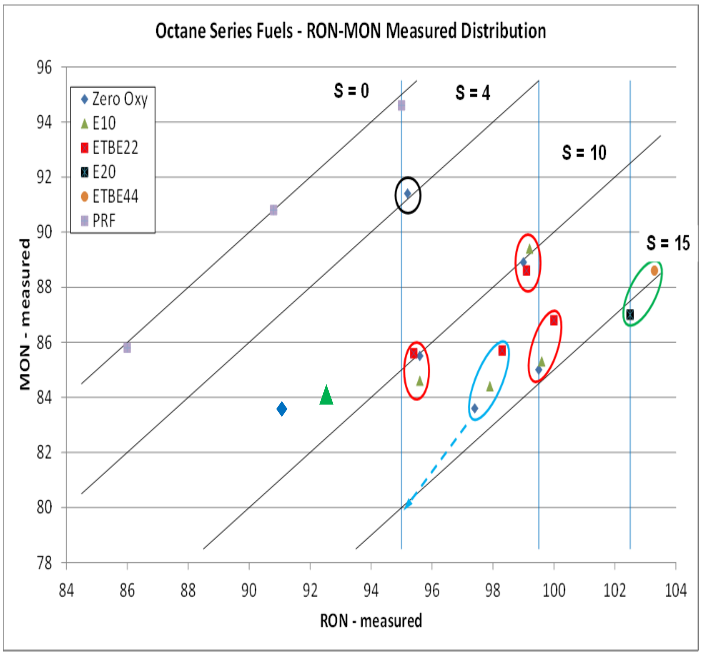
---

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

Table 2 Test Fuel Matrix - main parameters

		ETOH	ETBE	Oxygen	RON	MON	Sens
		vol%	vol%	%m/m			
Fuel 1	E0ETBE0	0	0	0	95.2	91.4	4
Fuel 2	E0ETBE0	0	0	0	95.6	85.5	10
Fuel 3	E0ETBE0	0	0	0	97.4	83.6	14
Fuel 4	E0ETBE0	0	0	0	99.0	88.9	10
Fuel 5	E0ETBE0	0	0	0	99.5	85.0	15
Fuel 6	E10ETBE0	10.0	0	3.63	95.6	84.6	11
Fuel 7	E10ETBE0	9.4	0	3.46	97.9	84.4	14
Fuel 8	E10ETBE0	9.3	0	3.49	99.2	89.4	10
Fuel 9	E10ETBE0	10.2	0	3.70	99.6	85.3	14
Fuel 10	E0ETBE22	0	22.4	3.78	95.4	85.6	10
Fuel 11	E0ETBE22	0	23.3	3.77	98.3	85.7	13
Fuel 12	E0ETBE22	0	23.1	3.88	99.1	88.6	11
Fuel 13	E0ETBE22	0	22.9	3.84	100.0	86.8	13
Fuel 14	E20ETBE0	19.2	0	6.84	102.5	87.0	16
Fuel 15	E0ETBE40	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	95.6	0
Fuel 19	E0ETBE0	0	0	0	91.2	83.3	8
Fuel 20	E10ETBE0	9.5	0	3.50	92.6	84.0	9
Fuel 21	RON95	9.5	0	3.66	95.9	86.2	10
Fuel 22	RON100	0	0	2.40	100.1	88.2	12

Figure 2 RON, MON and Sensitivity of Fuel 1- 20



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.	Fuel No.	Test No.	Fuel No.
1	Fuel 6	21	Fuel 13
2	Fuel 13	22	Fuel 19
3	Fuel 2	23	Fuel 7
4	Fuel 1	24	Fuel 18
5	Fuel 9	25	Fuel 20
6	Fuel 10	26	Fuel 10
7	Fuel 11	27	Fuel 8
8	Fuel 7	28	Fuel 14
9	Fuel 20	29	Fuel 6
10	Fuel 4	30	Fuel 3
11	Fuel 8	31	Fuel 5
12	Fuel 12	32	Fuel 17
13	Fuel 15	33	Fuel 2
14	Fuel 19	34	Fuel 12
15	Fuel 5	35	Fuel 16
16	Fuel 3	36	Fuel 1
17	Fuel 14	37	Fuel 4
18	Fuel 18	38	Fuel 11
19	Fuel 15	39	Fuel 17
20	Fuel 9	40	Fuel 16

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

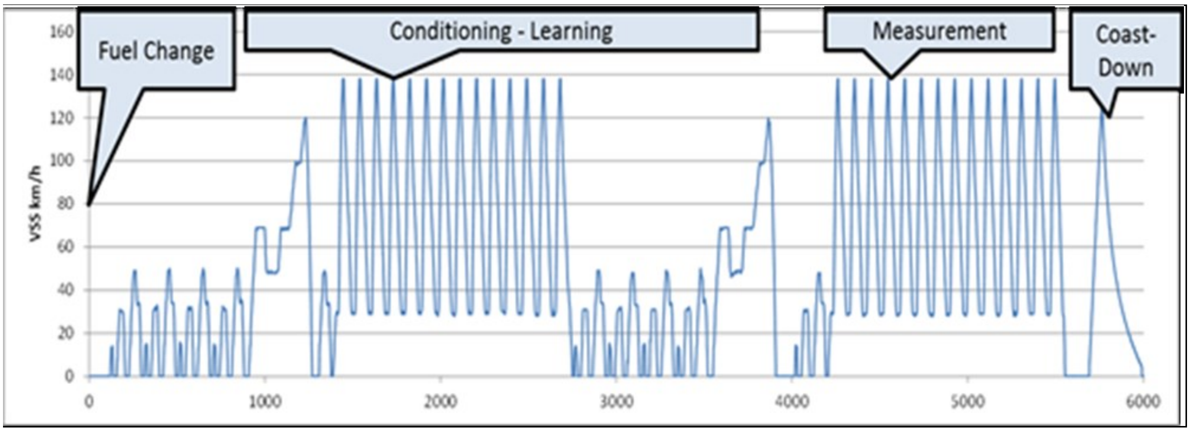
3. TEST METHODOLOGY

3.1. TEST PROCEDURE FOR ACCELERATION TESTING

The test procedure was separated into three elements and is shown in figure 4:

- A fuel learning procedure,
- A set of sawtooth accelerations,
- Coastdown

Figure 4 Test Procedure



3.1.1. Fuel Learn Cycle

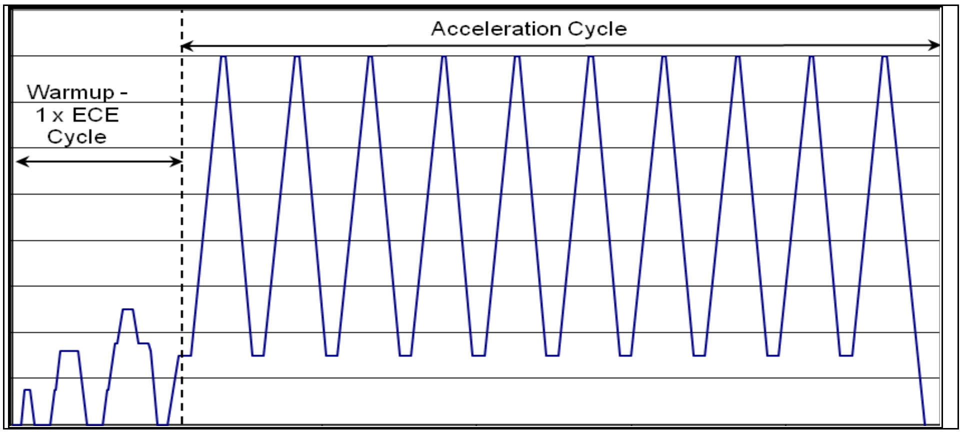
The Fuel Learn Cycle was made up of two NEDCs with one Sawtooth Acceleration sequence in between as shown in **Figure 4**. The NI (National Instruments) system was used to create a drive cycle that was followed on a tablet screen. No emissions data were recorded from the learning cycle. Data were recorded 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.

In the previous work the fuel learn cycle was followed by an NEDC and a steady state test cycle. These were not found to be particularly useful so were not carried out during phase 2.

3.1.2. 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 detailed graph of this drive cycle is shown in **Figure 5**. Vehicle 1 achieved in excess of 140 km/h during these tests, while Vehicle 2 achieved in excess of 120 km/h.

Figure 5 Sawtooth Wide Open Throttle Acceleration Cycle



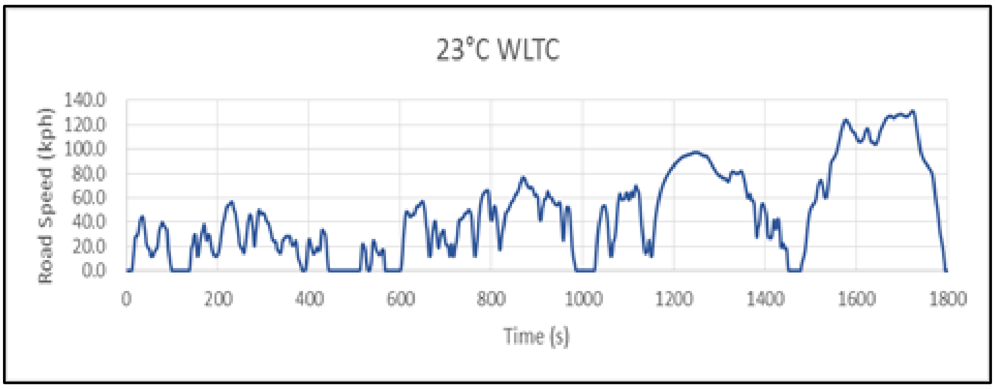
3.2. TEST CYCLES FOR FUEL ECONOMY TESTS

Whilst it is clear to see that fuel octane can improve performance and efficiency during full load acceleration events, the more pertinent question would be the impact of fuel octane on vehicle efficiency under a representative, transient drive-cycle. It was therefore decided to carry out focused fuel economy testing using standardized test cycles on the chassis dynamometer. A cold Worldwide harmonized Light duty Test Cycle (WLTC) was carried out followed immediately by a hot US06 test, the WLTC being representative of a near-future type approval test, the US06 being a higher-load cycle more representative of motorway driving.

3.2.1. WLTC

The Worldwide harmonized Light duty Test Cycle (WLTC) contains a mix of far more realistic driving characteristics and a range of speeds than the NEDC which it has been developed to replace in vehicle homologation testing. Figure 6 shows the profile of the test cycle which takes around 30 minutes and covers 11km.

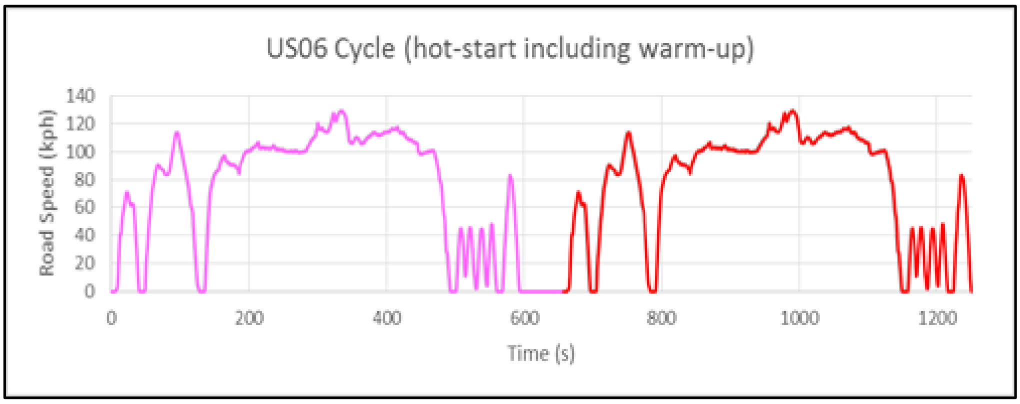
Figure 6 WLTC Test Cycle



3.2.2. US06

The US06 (Figure 7), which was developed to specifically highlight the impacts of high speed, rapid acceleration and speed variability on emissions. The US06 is a hot start cycle, driven in duplicate, with emissions sampled from the second test of the pair. The US06 test lasts ~10 minutes and covers ~13 km.

Figure 7 US06 Test Cycle



3.3. DATA MEASUREMENT

3.3.1. 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.

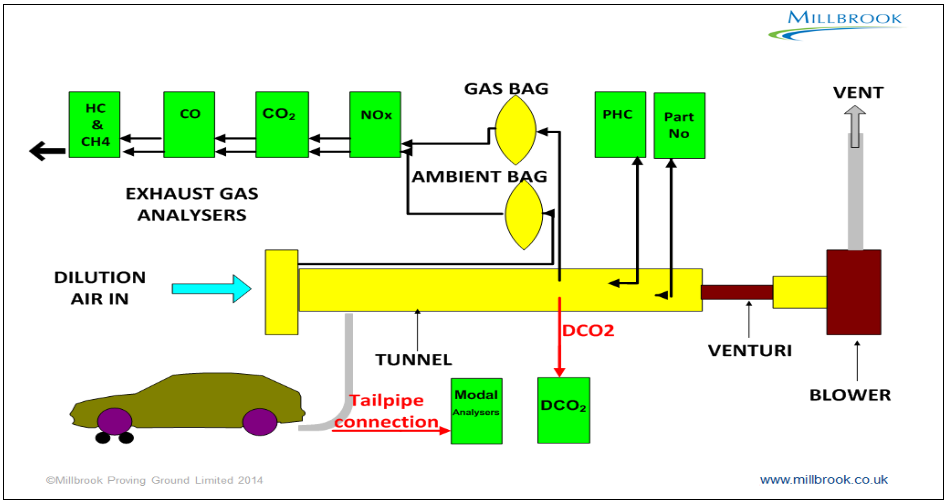
Emission measurements were taken and fuel consumption calculated using the carbon balance method as outlined in EC directive 70/220 amended to the latest rule. Actual fuel property data were used in the calculation of fuel consumption to allow for the effect of differences between the fuels of H/C ratio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

3.3.2. Emissions measurements

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 8**. 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 8 Emission Test Equipment



3.3.3. Fuel Consumption

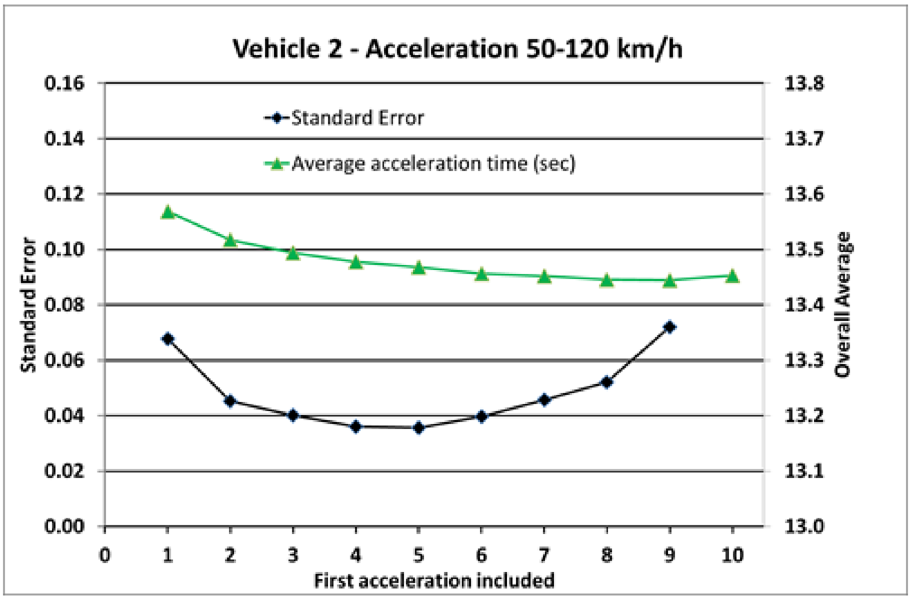
Fuel consumption was calculated using the carbon balance method as outlined in EC directive 70/220 amended to the latest rule. In all tests, second by second measurements were taken to allow analysis of vehicle operation in greater detail at various points in the test. Actual fuel property data were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

3.3.4. Data Handling and Analysis

The full throttle sawtooth accelerations were used to investigate fuel effects on vehicle performance on the full range of test fuels. Analysis was based on the acceleration time from 50km/h to 120km/h, which speed range could be achieved by both vehicles selected. During phase 1 which is reported in a Concawe Report [20] 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 9** shows (as green triangles) the mean acceleration time for one of the vehicles in phase 1 to demonstrate the effect on standard error 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 to 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 of the pervious test programme. 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. 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 during the current study, this time accelerations 5 to 14 were averaged for each test. The average 50km/h to 120km/h acceleration times calculated in this way were then studied for outliers and trends.

Figure 9 Accelerations 5-10 were averaged and accelerations 1-4 were discarded

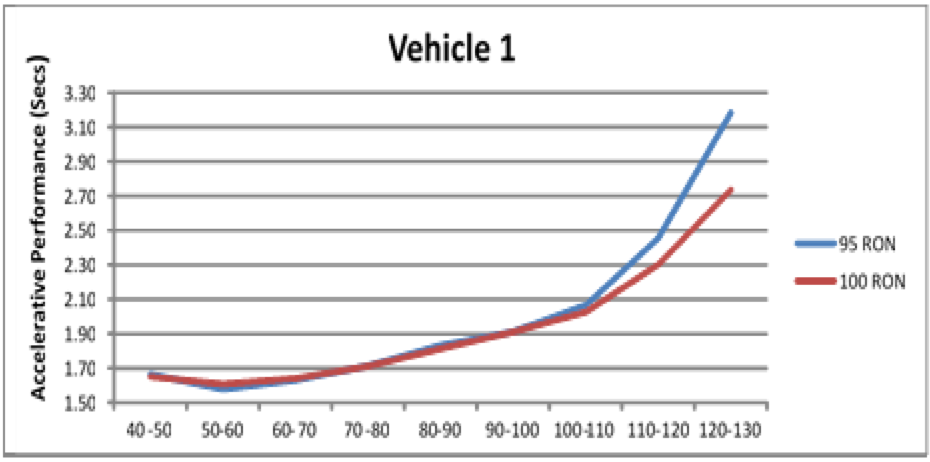


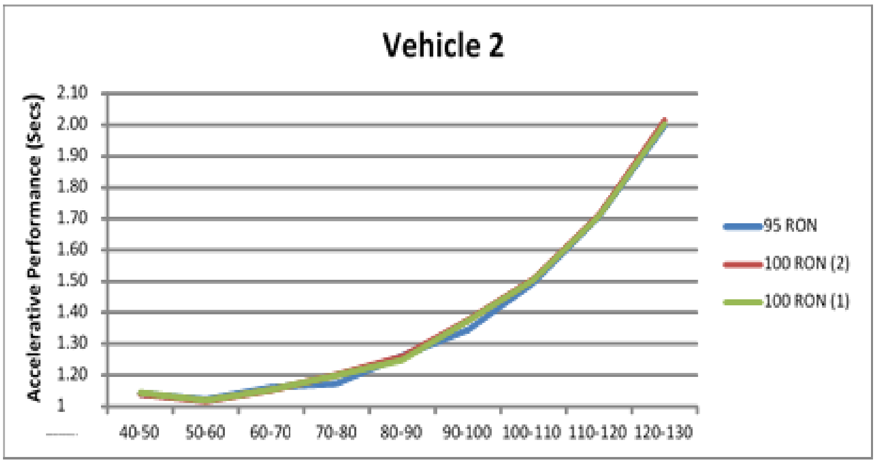
4. TEST RESULTS AND DISCUSSION

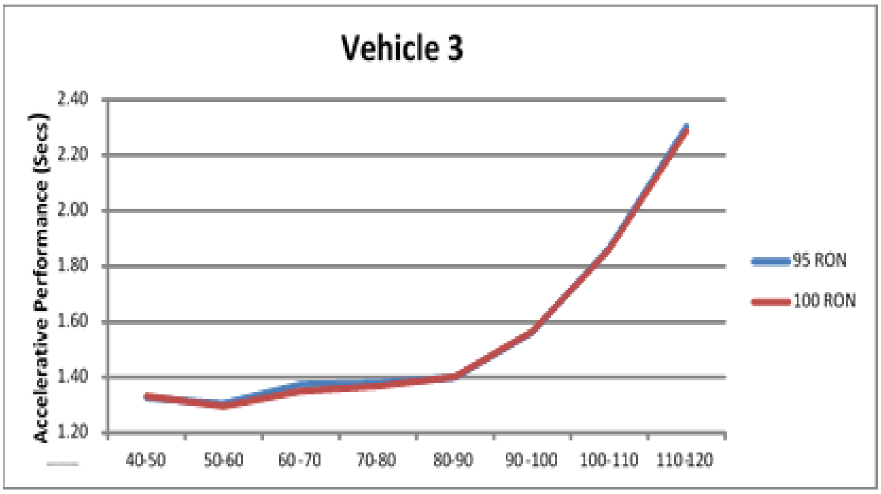
4.1. SCREENING TESTS USING 96 AND 100 RON FUELS

Figure 10 shows comparison of the acceleration performance for the four vehicles for different speed ranges. In general there were unexpectedly small differences between the two screening fuels in all the four vehicles tested. Vehicle 1 showed the most difference particularly above 110km/hr. The greatest differences were still small at around 0.4 secs in accelerating from 120 to 130km/hr. Vehicle 1 also showed differences in mean assisted pressure (**Figure 11**) which were not observed for the other vehicles as well as changes in spark advance.

Figure 10 Comparison of acceleration performance for screening fuels (x-axis shows acceleration changes from e.g. 40 to 50 km/hr etc.)




Vehicle 2
Accelerative Performance (Secs)
2.10
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1
40-50
50-60
60-70
70-80
80-90
90-100
100-110
110-120
120-130
95 RON
100 RON (2)
100 RON (1)


Vehicle 3
Accelerative Performance (Secs)
2.40
2.20
2.00
1.80
1.60
1.40
1.20
40-50
50-60
60-70
70-80
80-90
90-100
100-110
110-120
95 RON
100 RON

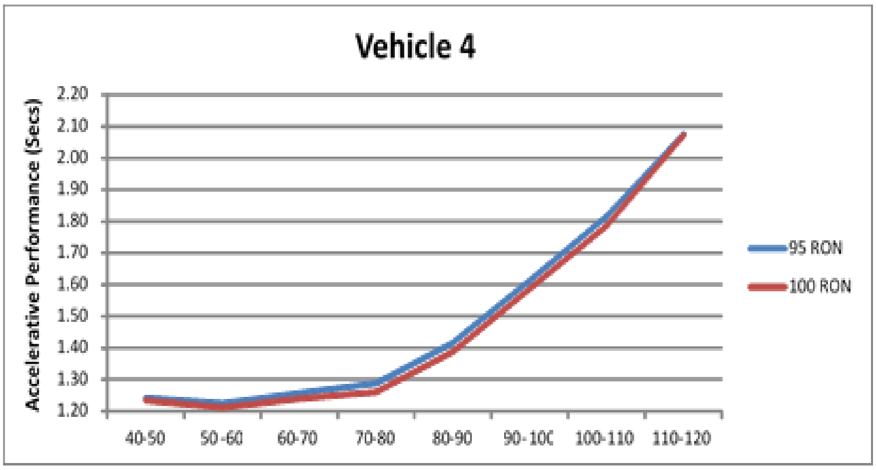
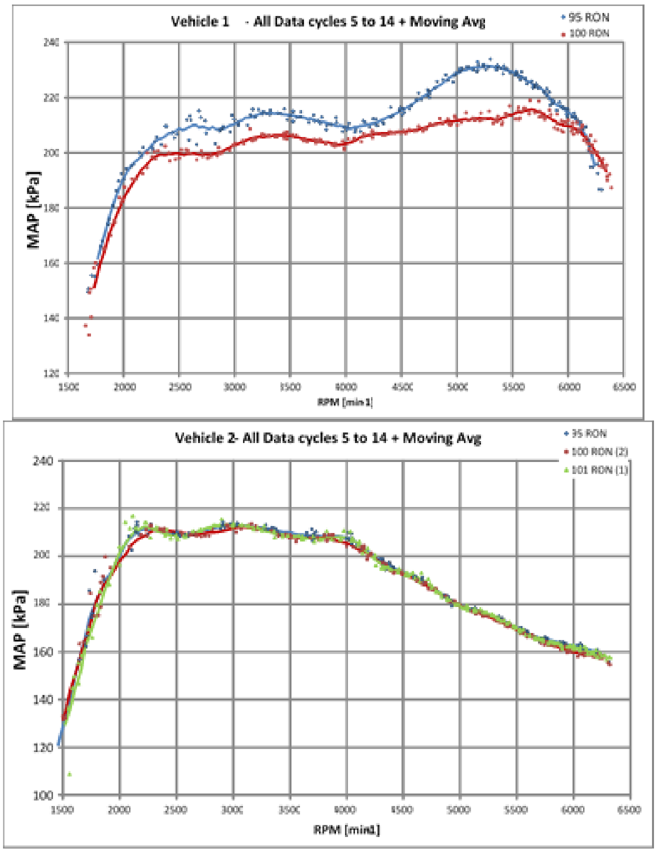
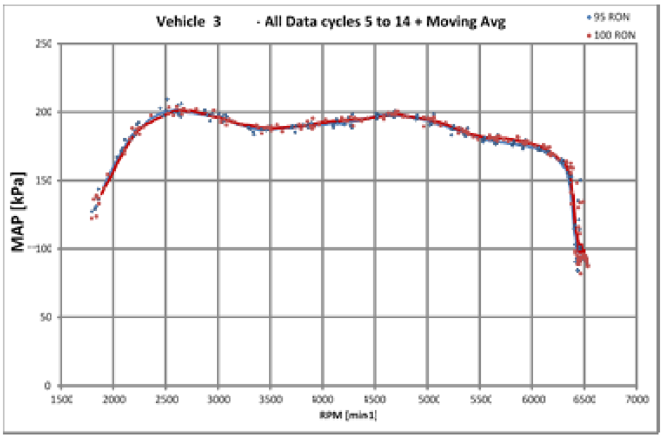
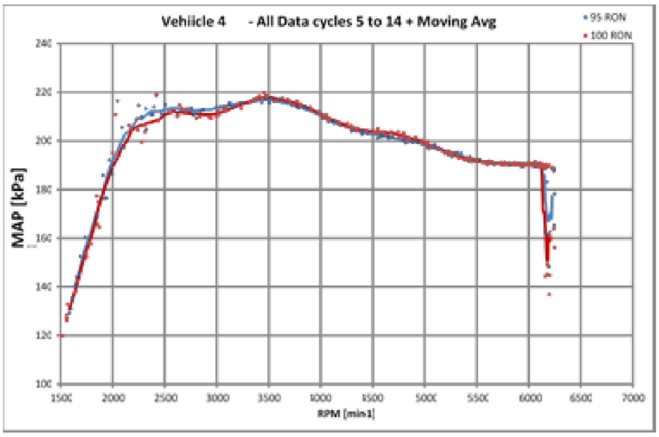

Vehicle 4
Accelerative Performance (Secs)
2.20
2.10
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
40-50
50-60
60-70
70-80
80-90
90-100
100-110
110-120
95 RON
100 RON

Figure 11 Comparison of Mean Assisted Pressure for screening fuels

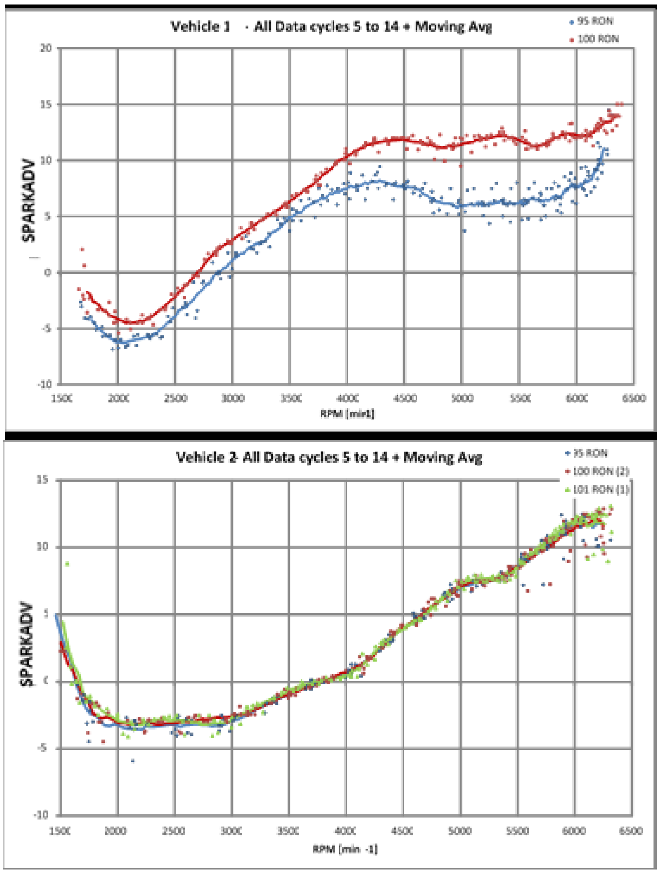


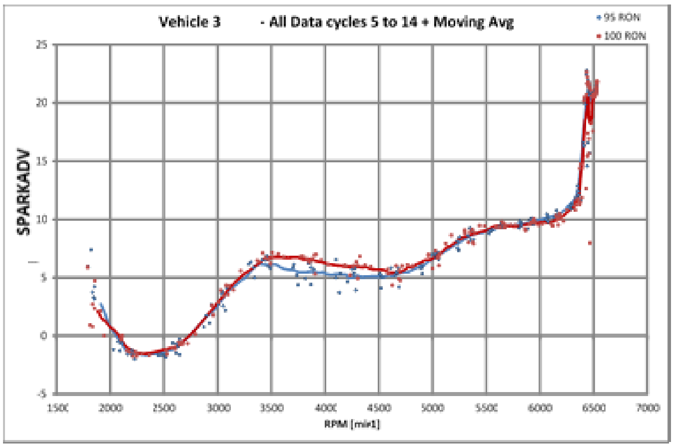


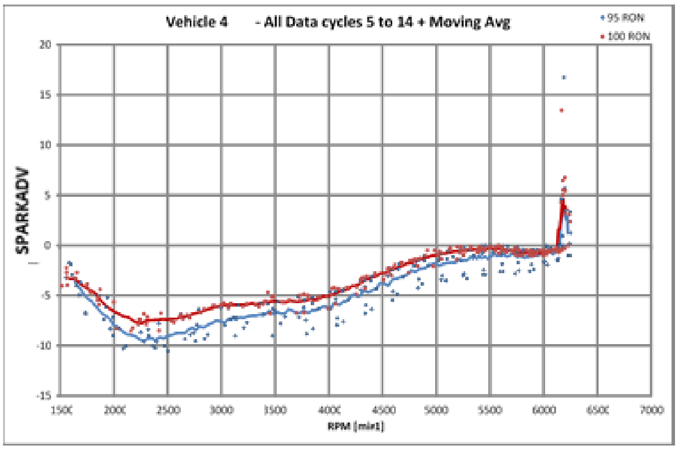


Vehicle 2 showed negligible change in spark advance or boost pressure as well as mean assisted pressure while Vehicles 3 and 4 both showed changes in spark advance and exhaust temperature but not boost pressure. The former is shown in **Figure 12**.

Figure 12 Comparison of spark advance for screening fuels





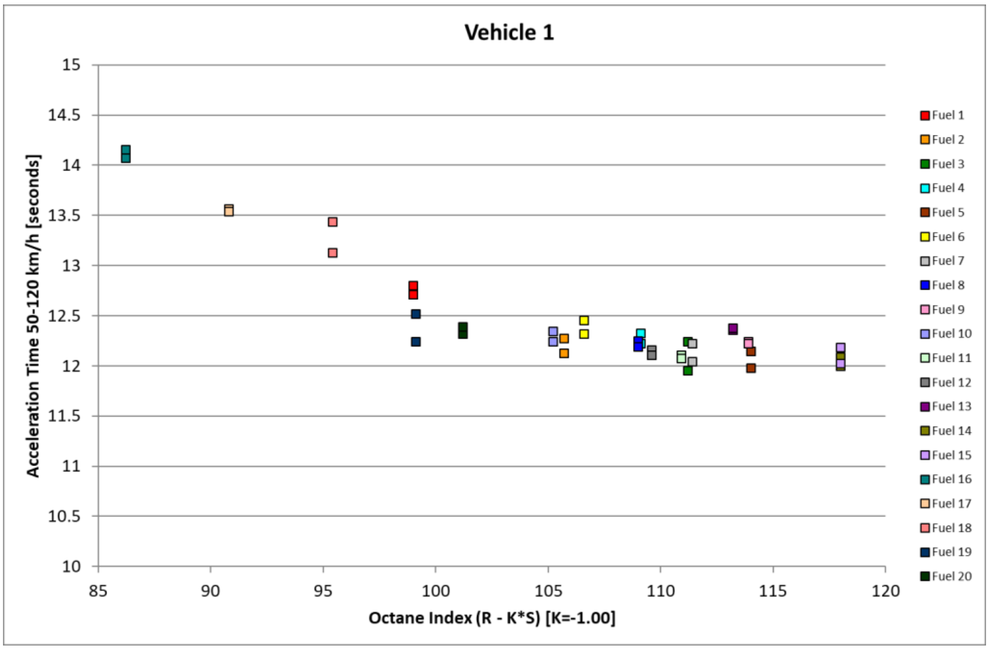


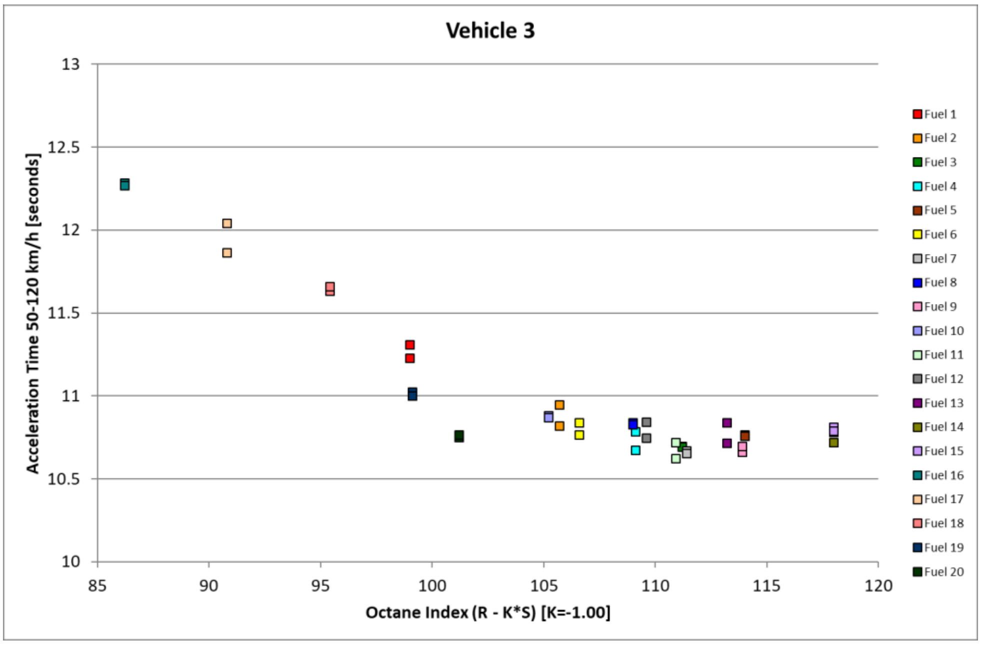
As a result of the screening it was decided to test the full range of fuels on vehicles 1 and 3 to investigate further the behaviour of these two vehicles. Vehicle 1 appeared to be the most sensitive to octane while vehicle 2 seems to be the most insensitive. Vehicles 3 and 4 gave similar sensitivity so only vehicle 3 was tested.

4.2. VEHICLE WIDE OPEN THROTTLE (WOT) ACCELERATION PERFORMANCE ON VEHICLES 1 AND 3 ON FULL FUEL SET

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 95 RON, 91RON and 86RON (fuels 18, 17 and 16, ringed in blue). This is not surprising, because the vehicles were designed for RON levels of 95 (Vehicle 1) or 95 with 98 possible (Vehicle 3) 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, based on visual inspection the correlation was much improved for negative K-values of -1.0. In these cases the fuels aligned along a single trend line and similar trends were seen in both vehicles. Plots for K= -1.0 are shown in **Figure 13**. The plots for K= 0 and K=0.5 are shown in Appendix 2 for information.

Figure 13 Vehicle acceleration correlates well with octane index having negative K-values (R= RON, S= Sensitivity)





Negative K-values such as these are associated with poor correlation with MON which is consistent with what was seen in the previous study with Euro 4 vehicles [20]. What is surprising is that there is some evidence that octane can reduce acceleration times beyond the octane that the vehicle is designed to run on. Particularly in vehicle 3 there appears to be a reduction in acceleration time for the fully formulated fuels beyond the equivalent of 95 RON (Octane Index around 106) which continues for a short while before flattening out for the higher octane fuels. Vehicle 1 shows a similar trend but less marked.

4.3. FUEL ECONOMY TESTING ON VEHICLE 1 USING STANDARDIZED TEST CYCLES

It was decided to carry out a cold Worldwide harmonized Light duty Test Cycle (WLTC) followed immediately by a hot US06 test, the WLTC being representative of a near-future type approval test, the US06 being a higher-load cycle more representative of motorway driving.

Each test cycle was repeated three times. Three fuels from the previous study were reblended and tested (fuels 6, 7 and 9) in that order and then fuel 6 was tested again to look for drift in the results. These fuels were chosen because they represented regular and premium grade fuels around Europe, the fuels all contained ~10% ethanol (E10).

Prior to each fuel change the following procedure was carried out

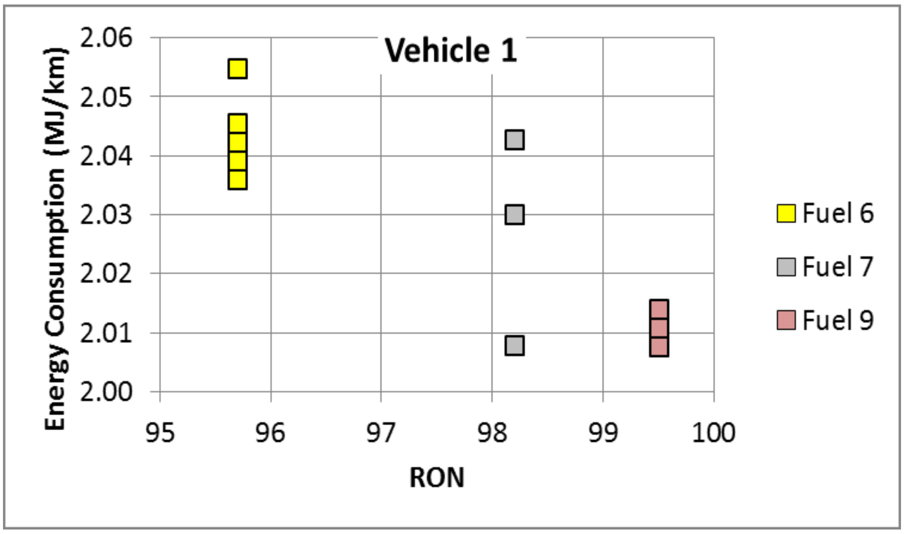
- Drain all fuel
- Change fuel filter
- Fill with 15L test fuel
- Drive on track for 80 km
- Drain fuel
- Fill with test fuel

The vehicle then underwent a preconditioning cycle made up of a WLTC followed by a series of wide-open-throttle accelerations. The vehicle was soaked at 23°C +/- 2°C for a minimum of 6 hours and until the bulk oil and coolant temperatures were within 2°C of the soak target.

4.3.1 Fuel Economy Measurements

To account for changes in volumetric energy density of the test fuels, data are reported in terms of Energy Consumption in MJ/km rather than absolute fuel consumption.

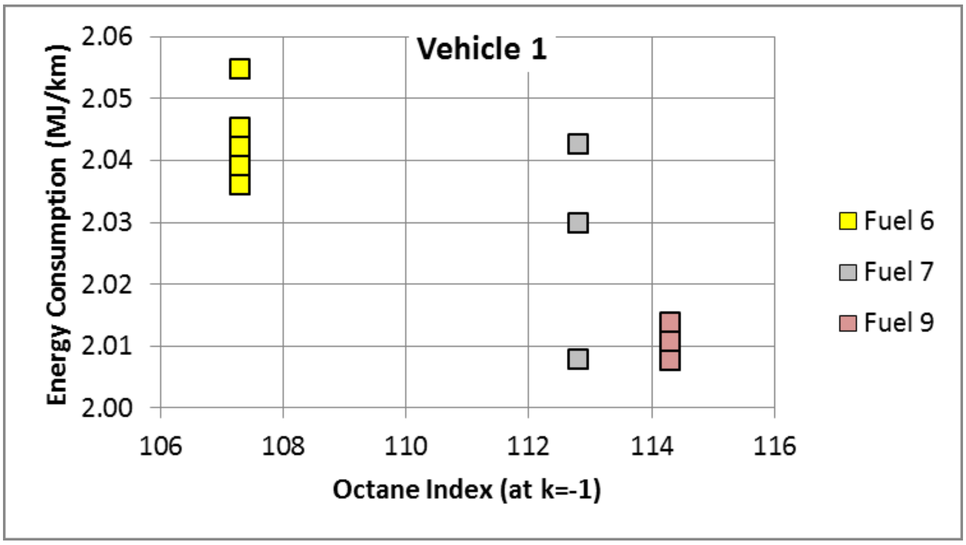
Figure 14 Energy Consumption measured over the WLTC test cycle, shows smaller, but clearer directional response to RON



Even considering high relatively poor repeatability of the Fuel 7 results, **Figure 14** shows a clear directional improvement in energy consumption related to increased RON, of the order of 1.5% improvement across the range of fuels. Being an European car it seems unlikely that the car would be calibrated to take advantage of fuels of greater than 98 RON, which the data may suggest.

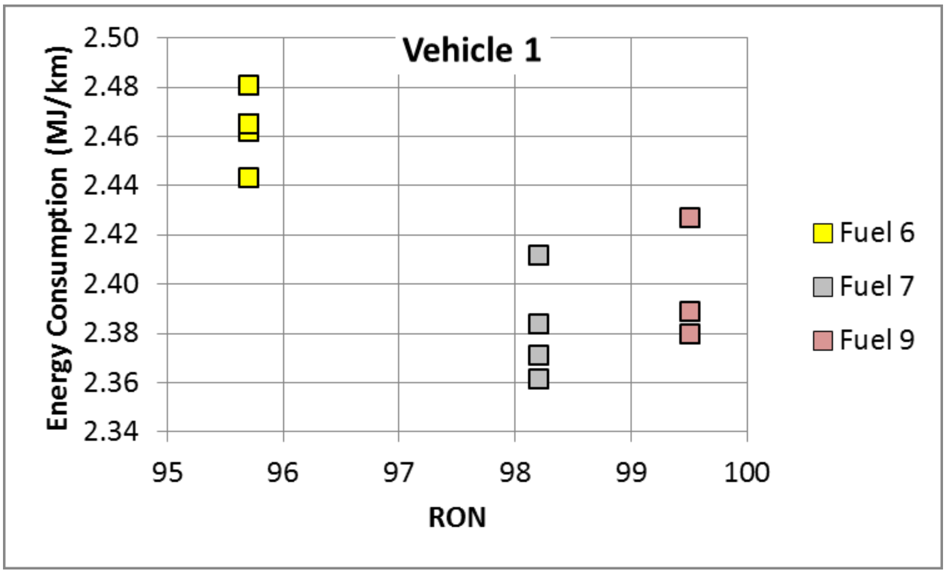
It should be noted that this vehicle would have been originally homologated on the NEDC rather than the WLTC drive-cycle.

Figure 15 No improvement in correlation for octane-index rather than RON for these fuels



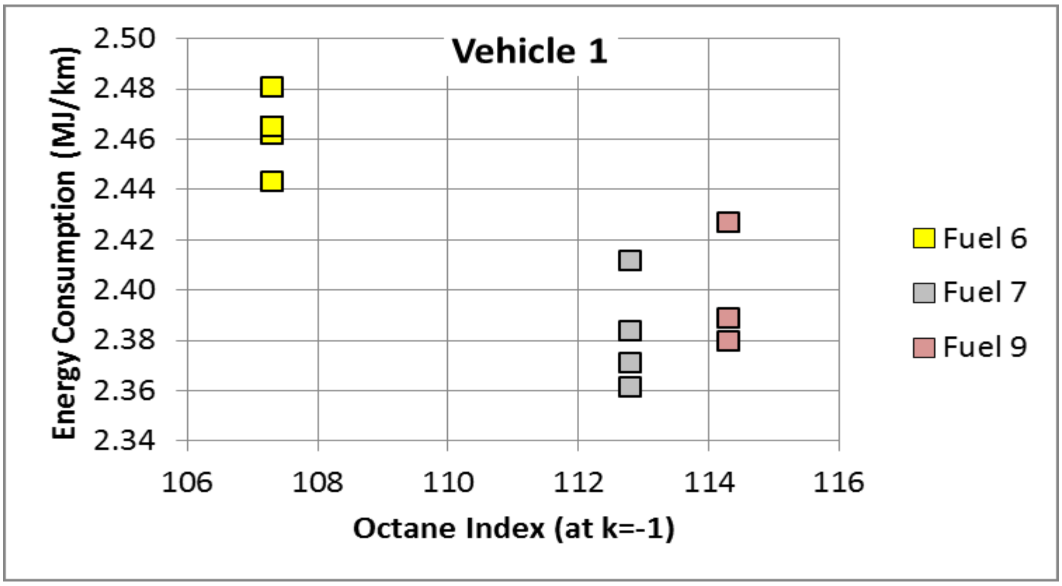
When examining a wider range of fuels, with wider octane sensitivity, the use of octane-index rather than RON is shown to give a better correlation with performance. However, for the range of RON and MON fuels explored in this subset, the use of octane-index did not demonstrate a better correlation with energy consumption that the use of RON alone (**Figure 15**).

Figure 16 Energy consumption measured over the US06 test-cycle shows directional improvement with RON.



When tested over the US06 drive-cycle, **Figure16** illustrates that, as expected for a higher-load drive-cycle, increasing RON from 95.7 to 98.2 led to a greater benefit in energy consumption relative to the WLTC results. However, no further benefit was measured as a result of using the highest octane fuel. **Figure 17** shows the data plotted against Octane index.

Figure 17 No improvement in correlation with the use of octane-index (at k=-1) rather than RON

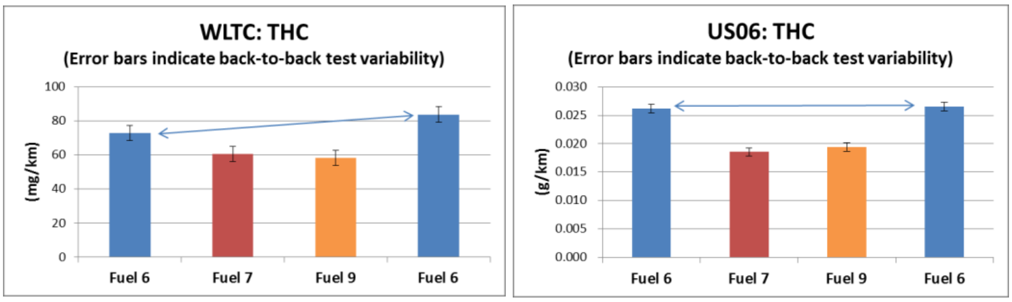


4.3.2 Regulated Emissions Measurements

Each bar in the following charts is an average results of three WLTC tests, the error bars illustrate the back-to-back variability of testing of the two Fuel 6 results. Conventional wisdom would suggest that drive-cycle exhaust emissions would be unlikely to change as a direct result of octane, but more likely to change as a result of composition changes to the fuel and the resulting physical properties.

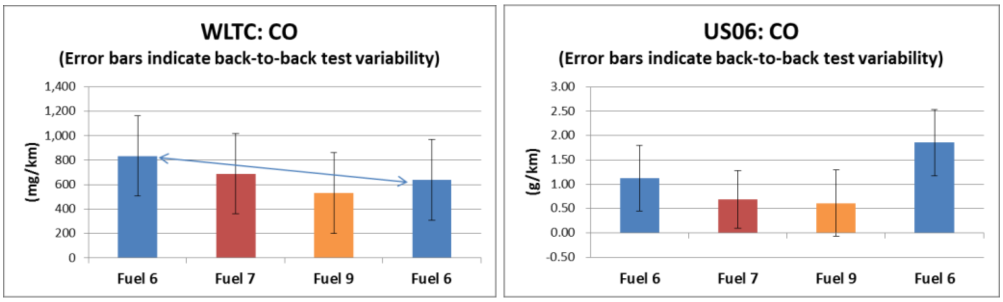
The exception to this rule would during high-load engine operation, where an engine may operate on the rich side of stoichiometric in order to protect exhaust system components. To examine this circumstance, the exhaust emissions were also measured during the US06 test cycle.

Figure 18 Fuels 7 and 9 showed some reduction in unburnt hydrocarbon emissions relative to the reference (Fuel 6)



The impact of fuel composition on hydrocarbon emissions can be seen in Figure 18, Fuels 7 and 9 both demonstrate significantly lower emissions than the baseline Fuel 6 on both WLTC and US06 cycles. Whilst it is unlikely that such benefits in hydrocarbon emissions would result from changes in octane, it can be seen in the fuel analysis table in Appendix 1, that the back-end distillation characteristics of Fuels 7 and 9 are more volatile than that of Fuel 6.

Figure 19 There was no significant change in CO emissions for any fuel when tested over the WLTC and US06 cycles.



Whilst it may appear that Fuels 7 and 9 offer a reduction in CO emissions these are not considered to be statistically significant, this may in part be due to the high variability of the Fuel 6 results. A reduction in CO may be expected, particularly over the US06 cycle, as a result of over-fuelling during the high load operation required for component protection when engine knock is experienced. There was no significant change in NOx emissions over the WLTC and US06 test cycles.

Figure 20 No significant change in NOx emissions for any test fuel over the WLTC and US06 cycles

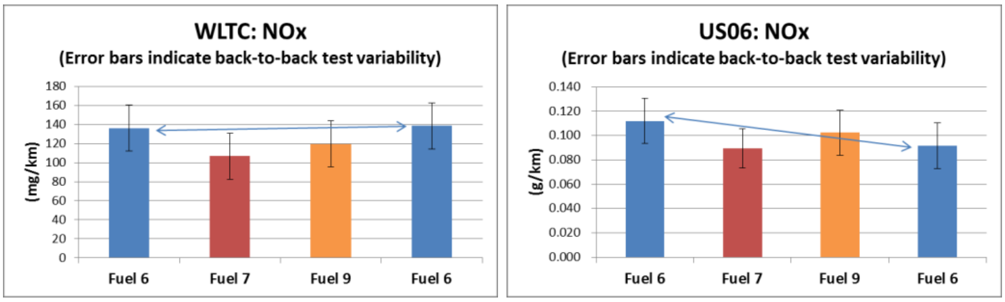
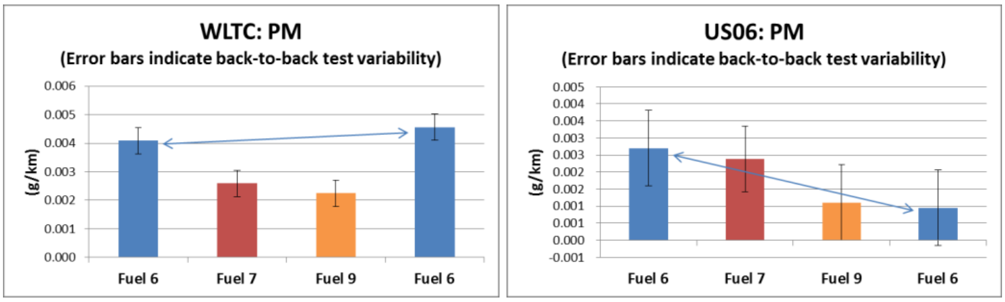
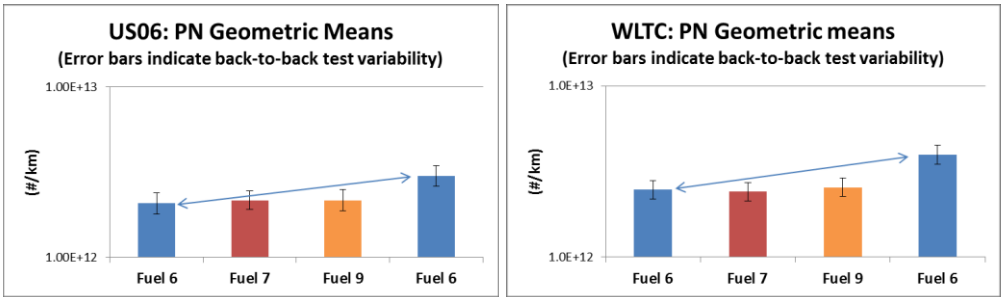


Figure 21 Fuels 7 and 9 showed significant reduction of Particulate Mass for WLTC but not in US06.



Whilst no significant variation in particulate mass was measured over the US06 cycle, this was not the case for the WLTC where a clear distinction could be seen between Fuel 6 and the other cases. Increases in particulate emissions are often associated with the level of fuel impingement on the piston and cylinder walls as a result of the relatively poor fuel vaporisation following a cold-start, whilst the WLTC cycle started from cold, the US06 cycle did not.

Figure 22 No significant impact on Particulate Number could be seen



However, in terms of particulate number, no significant differences could be seen from any fuel over either cycle.

5. CONCLUSIONS

Following on from a previous study of fuel properties on vehicle performance, four modern, direct-injection, turbocharged vehicle were tested on a small series of fuels to understand their appetite for RON and MON. This screening work highlighted, that whilst two of the vehicles seemed insensitive to RON > 95, the other two vehicles did display some sensitivity.

The two more sensitive vehicles, which were designed and sold for use on 95 RON fuel, were acceleration tested on a full matrix of 20 fuels, and demonstrated a reasonable correlation between acceleration and fuel RON but not MON. The correlation is better with octane index with k=-1. Both vehicles showed a strong correlation between acceleration performance and octane in the range 86 < RON <95, with vehicle 1 also showing some further benefit beyond 95.

Vehicle 1 was tested over two legislative drive cycles on three fuels, to understand how these benefits, attributed to octane, at full-load would translate to vehicle efficiency over a representative drive cycle. For the higher load US06 cycle, the benefits of moving to higher octane fuel were on average about double those observed for the WLTC in moving from the lowest to the highest RON fuels.

With regard to drive-cycle tailpipe emissions, both the 98 and 100 RON fuels were seen to reduce the unburnt hydrocarbon emissions over both WLTC and US06 cycles and particulate mass emissions over the cold-start WLTC, it seems plausible that these reductions were due to both their increased volatility and RON relative to the 95 RON Fuel 6.

Whilst this study illustrated the thermal efficiency, and to some extent, tailpipe emissions benefits that could be attributed to higher octane fuels, the magnitude of these benefits was curtailed by the vehicles tested and their inability to fully optimize their operation for fuels in excess of 95 RON. A further study currently being conducted at Concawe aims to understand the magnitude of these benefits when tested in a higher compression ratio vehicle, optimized to take full advantage of higher octane fuels.

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
CORC	Cooperative Octane Requirement Committee
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 stoichiometric AFR)
LCV	Lower Calorific Value (same as LHV)
LHV	Lower Heating Value (same as LCV)
MJ	Mega joule
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

The authors would like to thank Millbrook Proving Ground, UK for carrying out the test work and Coryton Advanced Fuels, UK for preparing the fuels.

8. REFERENCES

1. Huber, K, Hauber, J, Raba, A and Nell, R. New Test Procedure to Determine Fuel's Knock Resistance. MTZ 07-08I2013 *Volume 74, p62-69*

2. CRC Octane Group, Fuel Antiknock Quality – Engine Response to RON versus MON - Scoping Tests. CRC Report No. 660, May 2011

3. Chow, E, Heywood, J and Speth, R. Benefits of a Higher Octane Standard Gasoline for the U.S. Light-Duty Vehicle Fleet. SAE Paper 2014-01-1961

4. CRC. Review To Determine The Benefits Of Increasing Octane Number On Gasoline Engine Efficiency: Task 1 Report. CRC Project No. CM-137-11-1, December 2011

5. CRC. Review To Determine The Benefits Of Increasing Octane Number On Gasoline Engine Efficiency: Analysis And Recommendations – Tasks 2-5. CRC Project No. CM-137-11-1b, September 2012

6. Bisordi, A et al, Evaluating Synergies between Fuels and Near Term Powertrain Technologies through Vehicle Drive Cycle and Performance Simulation. SAE Paper 2012-01-0357

7. Stansfield, P et al, The Performance of a Modern Vehicle on a Variety of Alcohol-Gasoline Fuel Blends. SAE Paper 2012-01-1272

8. Foong, T, The Effect of Charge Cooling on the RON of Ethanol/Gasoline Blends. SAE Paper 2013-01-0886

9. Kalghatgi, G. T., Fuel Anti-Knock Quality - Part I, Engine Studies. SAE Paper 2001-01-3584

10. Kalghatgi, G. T., Fuel Anti-Knock Quality - Part II, Vehicle Studies - How Relevant is Motor Octane Number (MON) in Modern Engines? SAE Paper 2001-01-3585

11. Kalghatgi, G. T., Nakata, K., and Mogi, K., Octane Appetite Studies in Direct Injection Spark Ignition (DISI) Engines. SAE Paper 2005-01-0244

12. Kalghatgi, Gautam T., Auto-ignition Quality of Practical Fuels and Implications for Fuel Requirements of Future SI and HCCI Engines. SAE Paper 2005-01-0239, 2005.

13. Mittal, V. and Heywood, J., The Relevance of Fuel RON and MON to Knock Onset in Modern SI Engines. SAE Technical Paper 2008-01-2414, 2008

14. Bell, A., Modern SI Engine Control Parameter Responses and Altitude Effects with Fuels of Varying Octane Sensitivity. SAE Technical Paper 2010-01-1454, 2010

15. Davies, T., Cracknell, R., Lovett, G., Cruff, L. et al., Fuel Effects in a Boosted DISI Engine. SAE Technical Paper 2011-01-1985, 2011

16. Amer, A., Babiker, H., Chang, J., Kalghatgi, G. et al, Fuel Effects on Knock in a Highly Boosted Direct Injection Spark Ignition Engine. SAE Int. J. Fuels Lubr. 5(3):1048-1065, 2012. SAE Technical Paper 2012-01-1634

17. Remmert, Sarah et al, Octane Appetite: The Relevance of a Lower Limit to the MON Specification in a Downsized, Highly Boosted DISI Engine. SAE Technical Paper 2014-01-2718.

18. Stradling, R. et.al, Effect of Octane on the performance of two gasoline direct injection passenger cars. SAE Technical Paper 2015-01-0767, 2015

19. Stradling, R. et al, Effect of Octane on Performance, Energy Consumptions and emissions of two Euro 4 passenger cars, Transportation Research Procedia (2016)

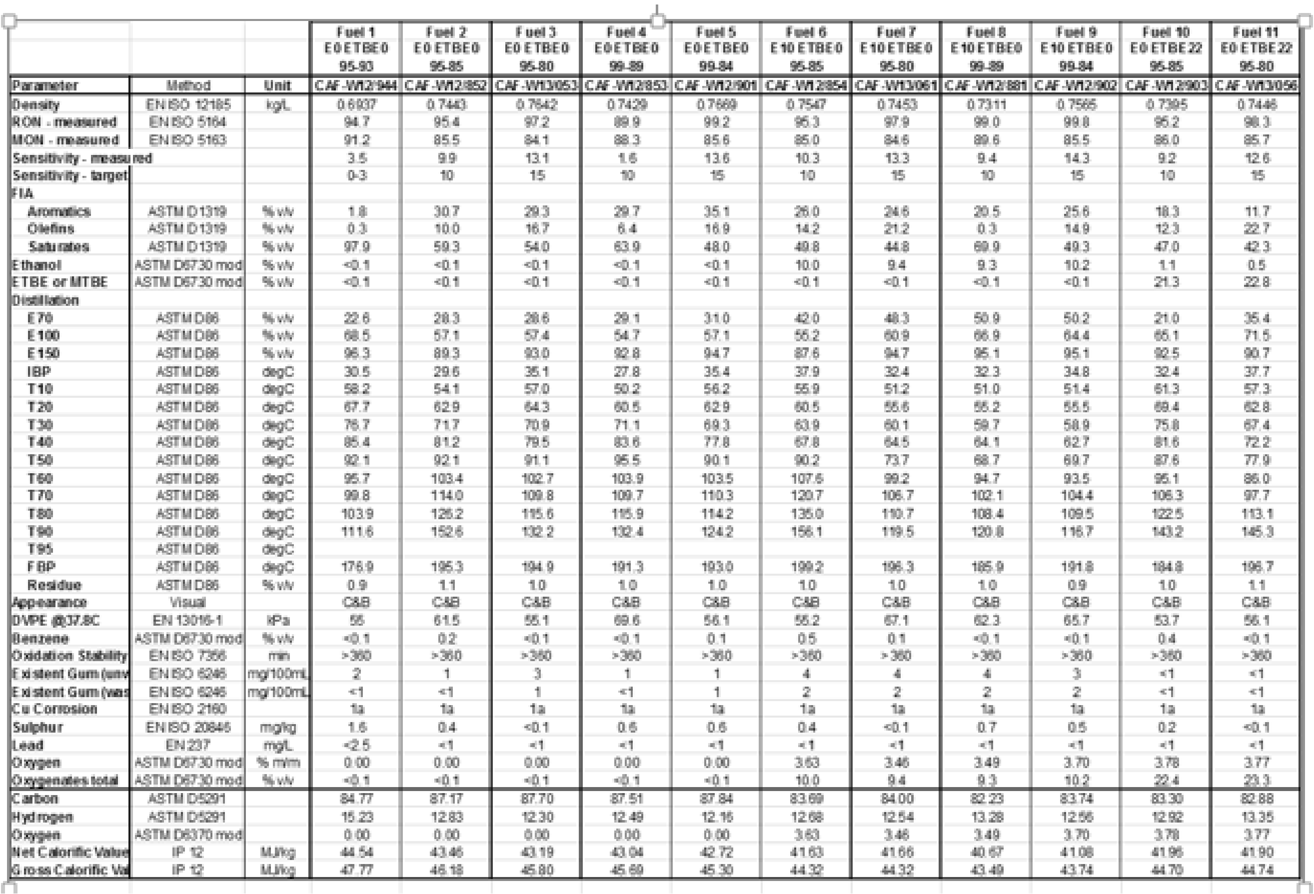
20. Concawe report 13/16, Phase 1: Effect of fuel octane on the performance of two Euro 4 Gasoline Passenger Cars, Concawe 2016

21. EN ISO 5164 “Petroleum products – determination of knock characteristics of motor fuels – Research method”.

22. EN ISO 5163 “Petroleum products - determination of knock characteristics of motor fuels - Motor method”

23. Williams, J, et.al. Effect of Octane on the performance of Euro 5 and Euro 6 gasoline passenger cars, SAE paper no. 2017-01-0811, 2017.

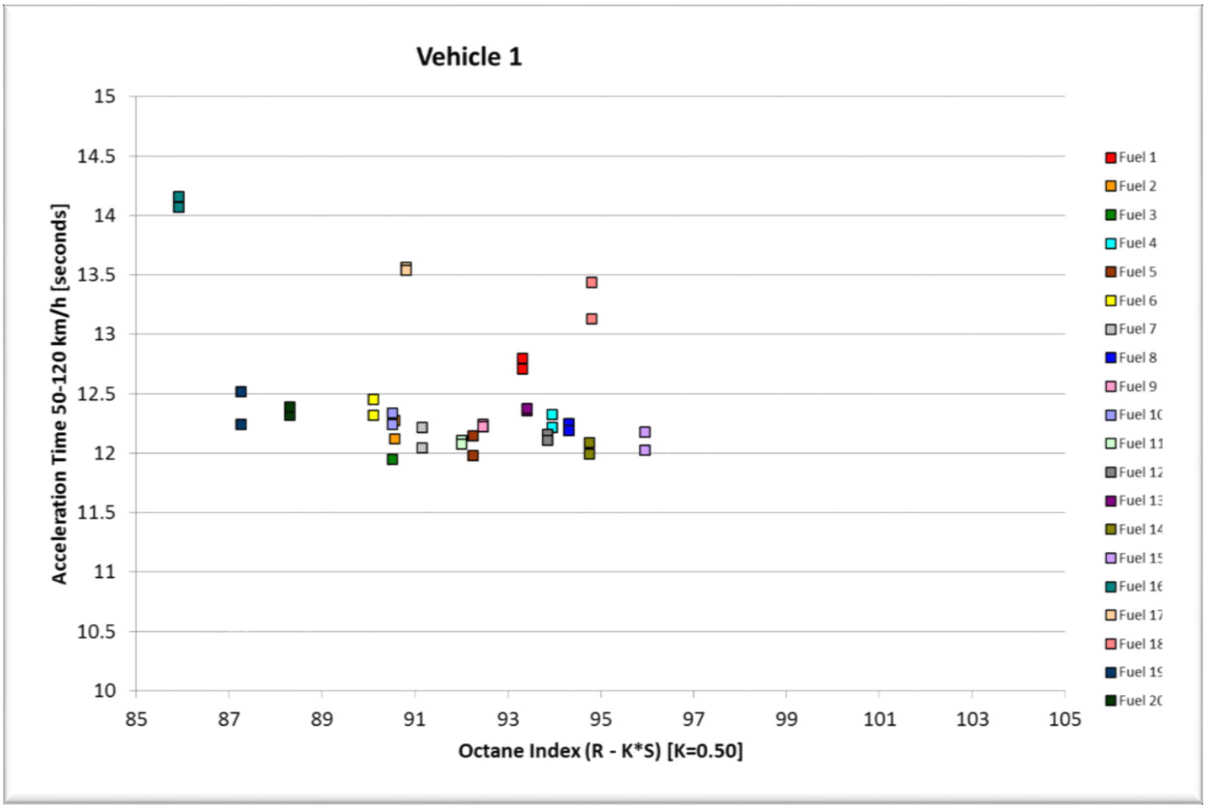
APPENDIX 1 - TEST FUEL INSPECTION DATA

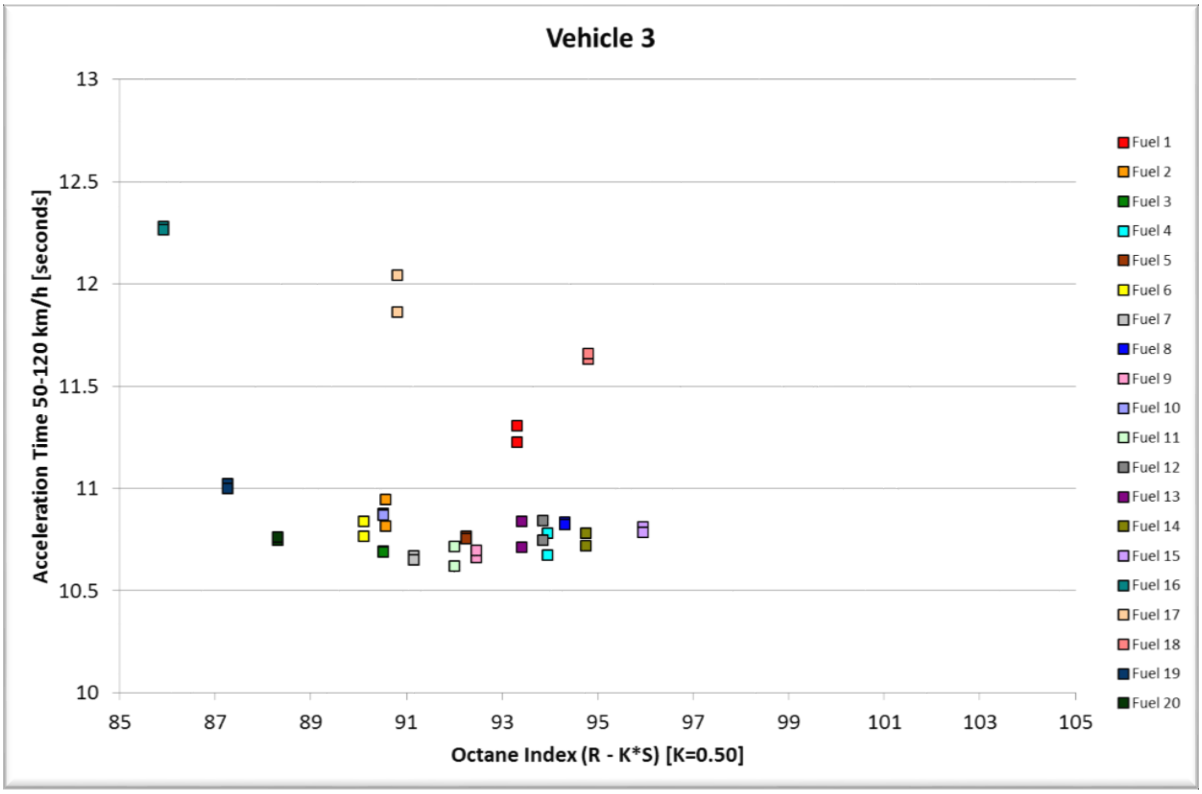


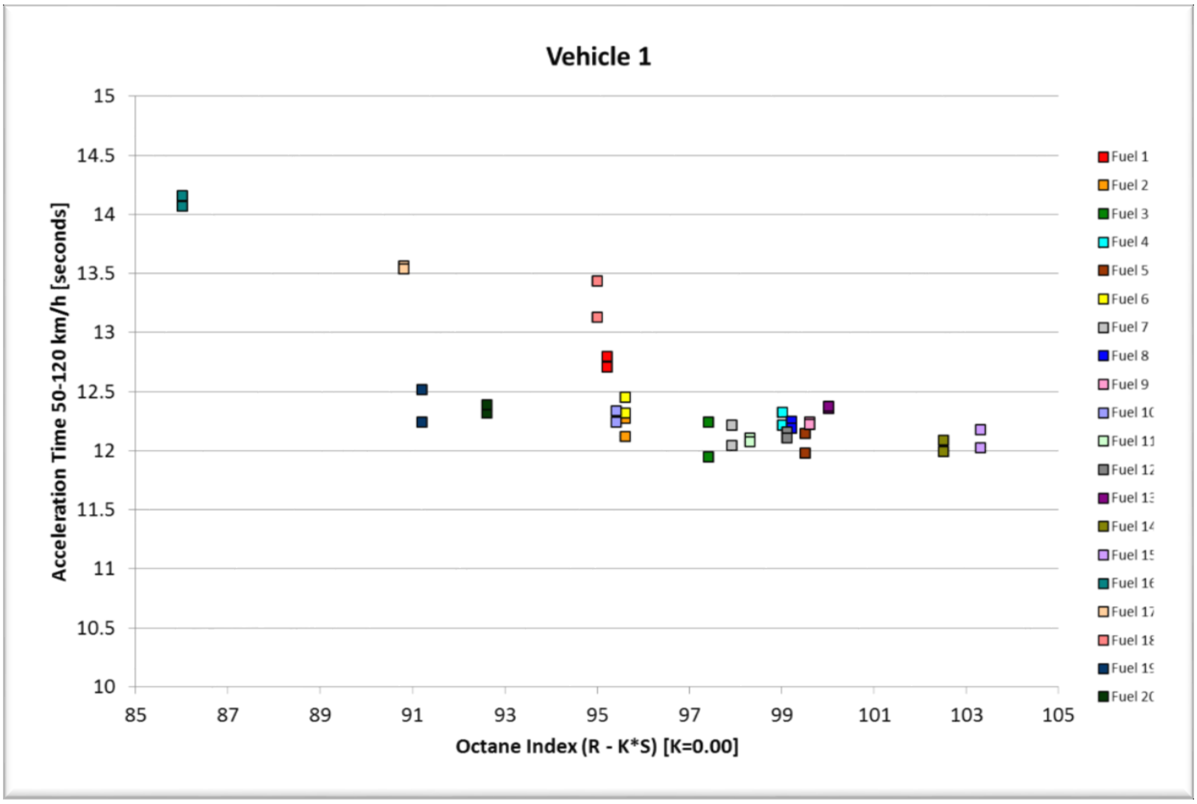
			Fuel 1 E0 ETBE0 95-93	Fuel 2 E0 ETBE0 95-85	Fuel 3 E0 ETBE0 95-80	Fuel 4 E0 ETBE0 99-89	Fuel 5 E0 ETBE0 99-84	Fuel 6 E10 ETBE0 95-85	Fuel 7 E10 ETBE0 95-80	Fuel 8 E10 ETBE0 99-89	Fuel 9 E10 ETBE0 99-84	Fuel 10 E0 ETBE22 95-85	Fuel 11 E0 ETBE22 95-80
Parameter	Method	Unit	CAF-W12/944	CAF-W12/852	CAF-W13/053	CAF-W12/853	CAF-W12/901	CAF-W12/854	CAF-W13/061	CAF-W12/881	CAF-W12/902	CAF-W12/903	CAF-W13/056
Density	EN ISO 12185	kg/L	0.6937	0.7443	0.7642	0.7429	0.7669	0.7547	0.7453	0.7311	0.7565	0.7395	0.7446
RON - measured	EN ISO 5164		94.7	95.4	97.2	89.9	99.2	95.3	97.9	99.0	99.8	95.2	98.3
MON - measured	EN ISO 5163		91.2	85.5	84.1	88.3	85.6	85.0	84.6	89.6	85.5	86.0	85.7
Sensitivity - measured			3.5	9.9	13.1	1.6	13.6	10.3	13.3	9.4	14.3	9.2	12.6
Sensitivity - target			0-3	10	15	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	18.3	11.7
Olefins	ASTM D1319	% v/v	0.3	10.0	16.7	6.4	16.9	14.2	21.2	0.3	14.9	12.3	22.7
Saturates	ASTM D1319	% v/v	97.9	59.3	54.0	63.9	48.0	49.8	44.8	69.9	49.3	47.0	42.3
Ethanol	ASTM D6730 mod	% v/v	<0.1	<0.1	<0.1	<0.1	<0.1	10.0	9.4	9.3	10.2	1.1	0.5
ETBE or MTBE	ASTM D6730 mod	% v/v	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	21.3	22.8
Distillation													
E70	ASTM D86	% v/v	22.6	28.3	28.6	29.1	31.0	42.0	48.3	50.9	50.2	21.0	35.4
E100	ASTM D86	% v/v	68.5	57.1	57.4	54.7	57.1	56.2	60.9	66.9	64.4	65.1	71.5
E150	ASTM D86	% v/v	96.3	89.3	93.0	92.8	94.7	87.6	94.7	95.1	95.1	92.5	90.7
IBP	ASTM D86	degC	30.5	29.6	35.1	27.8	35.4	37.9	32.4	32.3	34.8	32.4	37.7
T10	ASTM D86	degC	58.2	54.1	57.0	50.2	56.2	55.9	51.2	51.0	51.4	61.3	57.3
T20	ASTM D86	degC	67.7	62.9	64.3	60.5	62.9	60.5	55.6	55.2	55.5	69.4	62.8
T30	ASTM D86	degC	76.7	71.7	70.9	71.1	69.3	63.9	60.1	59.7	58.9	75.8	67.4
T40	ASTM D86	degC	85.4	81.2	79.5	83.6	77.8	67.8	64.5	64.1	62.7	81.6	72.2
T50	ASTM D86	degC	92.1	92.1	91.1	95.5	90.1	90.2	73.7	68.7	69.7	87.6	77.9
T60	ASTM D86	degC	95.7	103.4	102.7	103.9	103.5	107.6	99.2	94.7	93.5	95.1	86.0
T70	ASTM D86	degC	99.8	114.0	109.8	109.7	110.3	120.7	106.7	102.1	104.4	106.3	97.7
T80	ASTM D86	degC	103.9	126.2	115.6	115.9	114.2	135.0	110.7	108.4	109.5	122.5	113.1
T90	ASTM D86	degC	111.6	152.6	132.2	132.4	124.2	156.1	119.5	120.8	116.7	143.2	145.3
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	184.8	196.7
Residue	ASTM D86	% v/v	0.9	1.1	1.0	1.0	1.0	1.0	1.0	1.0	0.9	1.0	1.1
Appearance	Visual		C&B	C&B	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	53.7	56.1
Benzene	ASTM D6730 mod	% v/v	<0.1	0.2	<0.1	<0.1	0.1	0.5	0.1	<0.1	<0.1	0.4	<0.1
Oxidation Stability	EN ISO 7356	min	>360	>360	>360	>360	>360	>360	>360	>360	>360	>360	>360
Existent Gum (unw	EN ISO 6246	mg/100mL	2	1	3	1	1	4	4	4	3	<1	<1
Existent Gum (was	EN ISO 6246	mg/100mL	<1	<1	1	<1	1	2	2	2	2	<1	<1
Cu Corrosion	EN ISO 2160		1a	1a	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	0.2	<0.1
Lead	EN 237	mg/L	<2.5	<1	<1	<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	3.78	3.77
Oxygenates total	ASTM D6730 mod	% v/v	<0.1	<0.1	<0.1	<0.1	<0.1	10.0	9.4	9.3	10.2	22.4	23.3
Carbon	ASTM D5291		84.77	87.17	87.70	87.51	87.84	83.69	84.00	82.23	83.74	83.30	82.88
Hydrogen	ASTM D5291		15.23	12.83	12.30	12.49	12.16	12.68	12.54	13.28	12.56	12.92	13.35
Oxygen	ASTM D6370 mod		0.00	0.00	0.00	0.00	0.00	3.63	3.46	3.49	3.70	3.78	3.77
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	41.96	41.90
Gross Calorific Va	IP 12	MJ/kg	47.77	46.18	45.80	45.69	45.30	44.32	44.32	43.49	43.74	44.70	44.74

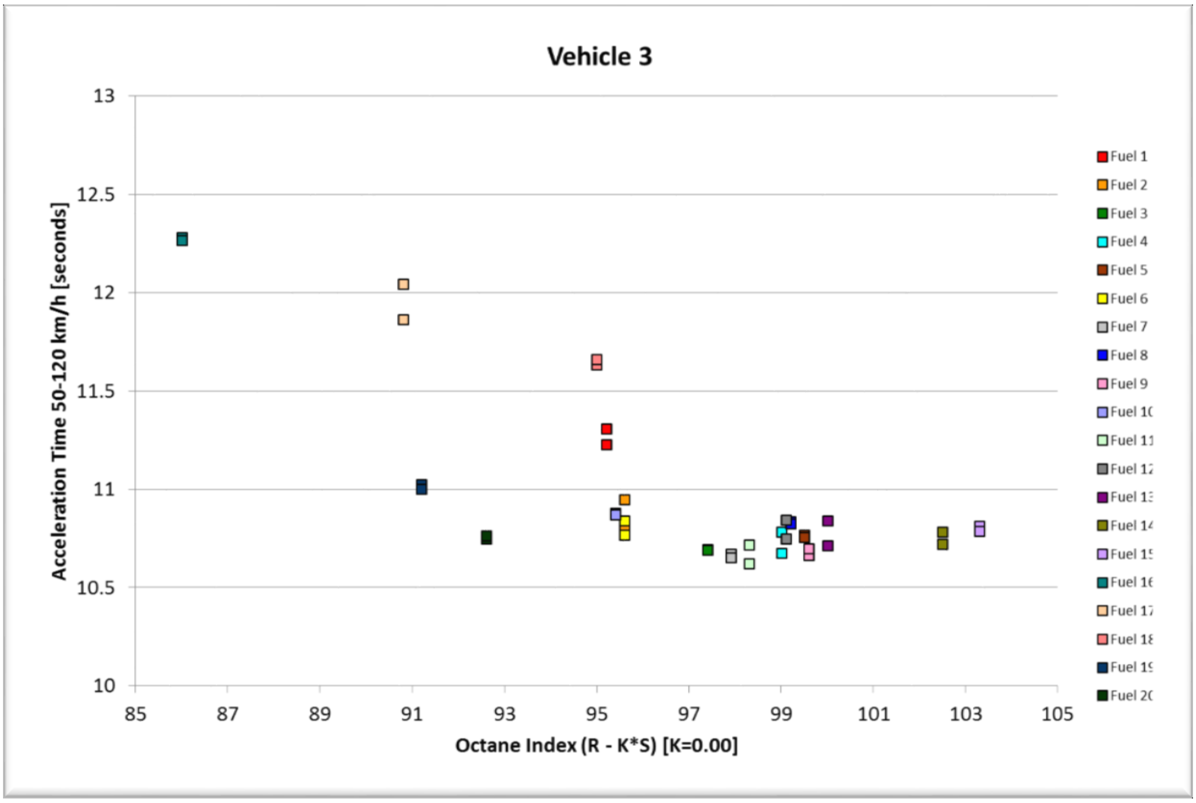
			Fuel 12 E0 ETBE22 99.89	Fuel 13 E0 ETBE22 99.84	Fuel 14 E20 ETBE0 102.87	Fuel 15 E0 ETBE44 102.87	Fuel 16 PRF86	Fuel 17 PRF91	Fuel 18 PRF95	Fuel 19 E0 ETBE0 91.83	Fuel 20 E10 ETBE0 93.84	Fuel 21 RON96	Fuel 22 RON100
Parameter	Method	Unit	CAF-W12/882	CAF-W12/942	CAF-W12/930	CAF-W12/931	CAF-W12/855	CAF-W12/856	CAF-W12/857	CAF-W14-993	CAF-W14/993	CAF-W15/098	CAF-W14/946
Density	EN ISO 12185	kg/L	0.7389	0.7475	0.7687	0.7536	0.6956	0.6960	0.6965	0.7441	0.737	0.7481	0.7364
RON - measured	EN ISO 5164		98.9	99.7	102.5	103.3	85.9	90.6	95.0	91.2	92.6	95.9	100.1
MON - measured	EN ISO 5163		88.6	87.0	86.9	89.4	85.8	90.9	94.8	83.3	84	86.2	88.1
Sensitivity - measured			10.3	12.7	15.6	13.9	0.1	-0.3	0.2	7.9	8.6	9.7	12.0
Sensitivity - target			10	15	15	15	0	0	0	8	8	-	-
FIA													
Aromatics	ASTM D1319	% v/v	18.8	10.6	27.8	10.7	0.2	0.2	0.3	29.9	19.1	30.4	29.5
Olefins	ASTM D1319	% v/v	9.2	18.7	12.6	12.4	0.2	0.2	0.2	3.9	10.7	3.6	14.1
Saturates	ASTM D1319	% v/v	48.9	47.8	40.4	29.9	99.6	99.6	99.5	66.2	61.7	56.1	43.5
Ethanol	ASTM D6730 mod	% v/v	1.0	1.2	19.2	1.3	<0.1	<0.1	<0.1	<0.1	9.5	9.9	<0.1
ETBE or MTBE	ASTM D6730 mod	% v/v	22.1	21.7	<0.1	45.6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	12.9
Distillation													
E70	ASTM D86	% v/v	24.8	27.9	38.6	27.3	0.0	0.0	0.0	20	41.4	41.4	33.8
E100	ASTM D86	% v/v	63.7	66.4	63.9	79.8	97.6	97.9	97.6	48	58	59.3	58.8
E150	ASTM D86	% v/v	93.4	87.5	95.0	95.0	99.1	99.3	99.1	91.5	91.2	92.4	92.2
IBP	ASTM D86	degC	28.3	37.1	32.0	43.7	95.2	95.1	94.9	31	40.4	37.5	21.9
T10	ASTM D86	degC	55.3	59.6	53.5	63.4	97.2	97.3	97.3	59.1	57.2	56.8	44.7
T20	ASTM D86	degC	65.7	65.8	60.3	67.5	97.5	97.5	97.6	69.9	60.8	61.3	55.4
T30	ASTM D86	degC	74.7	71.0	65.9	70.9	97.6	97.7	97.7	80.6	64.1	65	65.9
T40	ASTM D86	degC	82.6	76.9	70.5	74.4	97.7	97.7	97.8	91.5	67.9	68.9	76.4
T50	ASTM D86	degC	89.7	84.1	73.4	78.1	97.7	97.8	97.8	102	89.5	86.5	88
T60	ASTM D86	degC	97.0	93.5	79.1	82.6	97.8	97.8	97.9	111.7	102.2	100.6	101.8
T70	ASTM D86	degC	106.2	106.3	112.7	89.0	97.9	97.9	98.0	120.7	113.2	110.6	115.1
T80	ASTM D86	degC	118.5	121.6	118.3	100.2	97.9	98.0	98.1	130.6	125	120.5	126.8
T90	ASTM D86	degC	138.0	163.1	131.2	116.5	98.2	98.3	98.3	146.1	146.8	138.2	144.7
T95	ASTM D86	degC											
FBP	ASTM D86	degC	188.4	196.4	178.4	186.2	104.9	104.5	106.7	183.1	179.1	186.1	177.6
Residue	ASTM D86	% v/v	1.0	1.1	1.0	1	0.9	0.7	0.9	1	1	1	1
Appearance	Visual		C&B	C&B	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	64.7	53.9	64.2	44.7	21.8	13.3	13.8	53.3	53	59.4	88.5
Benzene	ASTM D6730 mod	% v/v	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.67	<1.0	<0.1	0.35
Oxidation Stability	EN ISO 7356	min	>360	>360	>360	>360	>360	>360	>360	>360	>360	>360	>360
Existent Gum (unw	EN ISO 6246	mg/100mL	1	1	<1	2	<1	<1	<1	-	-	-	-
Existent Gum (was	EN ISO 6246	mg/100mL	1	<1	<1	1	<1	<1	<1	-	-	-	-
Cu Corrosion	EN ISO 2160		1a	1a	1a	1a	1a	1a	1a	-	-	-	1a
Sulphur	EN ISO 20846	mg/kg	0.5	0.7	0.3	0.2	0.1	0.1	<0.1	<1.0	<1.0	<1.0	4
Lead	EN 237	mg/L	<1	<1	<2.5	<2.5	<2.5	<1	<2.5	<2.5	<2.5	-	<2.5
Oxygen	ASTM D6730 mod	% m/m	3.88	3.84	6.84	7.58	0.00	0.00	0.00	0	0	3.6	2.37
Oxygenates total	ASTM D6730 mod	% v/v	23.1	22.9	19.2	46.9	<0.1	<0.1	<0.1	<0.1	9.5	9.9	12.9
Carbon	ASTM D5291		83.10	82.70	81.04	79.76	84.66	84.63	84.63	86.5	82.55	83.09	84.38
Hydrogen	ASTM D5291		12.98	13.46	12.11	12.66	15.34	15.37	15.37	13.5	13.91	13.26	13.25
Oxygen	ASTM D6370 mod		3.88	3.84	6.84	7.58	0.00	0.00	0.00	0	3.54	3.66	2.37
Net Calorific Value	IP 12	MJ/kg	41.82	41.91	39.66	40.20	44.56	44.65	44.03	46.18	45	43.94	44.94
Gross Calorific Va	IP 12	MJ/kg	44.58	44.77	42.23	42.89	47.81	47.91	47.29	43.31	42.05	41.12	42.13

APPENDIX 2 - ACCELERATION DATA WITH K= 0.5 AND K=0






Vehicle 1
Acceleration Time 50-120 km/h [seconds]
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
85
87
89
91
93
95
97
99
101
103
105
Octane Index (R - K*S) [K=0.00]
Fuel 1
Fuel 2
Fuel 3
Fuel 4
Fuel 5
Fuel 6
Fuel 7
Fuel 8
Fuel 9
Fuel 1(
Fuel 11
Fuel 1:
Fuel 1:
Fuel 14
Fuel 1!
Fuel 16
Fuel 1;
Fuel 18
Fuel 1!
Fuel 2(


Vehicle 3
Acceleration Time 50-120 km/h [seconds]
13
12.5
12
11.5
11
10.5
10
85
87
89
91
93
95
97
99
101
103
105
Octane Index (R - K*S) [K=0.00]
Fuel 1
Fuel 2
Fuel 3
Fuel 4
Fuel 5
Fuel 6
Fuel 7
Fuel 8
Fuel 9
Fuel 1(
Fuel 11
Fuel 1:
Fuel 1:
Fuel 14
Fuel 1!
Fuel 16
Fuel 1;
Fuel 18
Fuel 1!
Fuel 2(

Environmental Science
for European Refining

Concawe
Boulevard du Souverain 165
B-1160 Brussels
Belgium

Tel: +32-2-566 91 60
Fax: +32-2-566 91 81
e-mail: info@concawe.org
http://www.concawe.eu

ISBN 978-2-87567-104-2