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Octane Requirement and Efficiency in a Fleet of Modern Vehicles

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Abstract

In light of increasingly stringent CO_2 emission targets, Original Equipment Manufacturers (OEM) have been driven to develop engines which deliver improved combustion efficiency and reduce energy losses. In spark ignition engines one strategy which can be used to reach this goal is the full utilization of fuel octane number.

Octane number is the fuel´s knock resistance and is characterized as research octane number (RON) and motor octane number (MON). Engine knock is caused by the undesired self-ignition of the fuel air mixture ahead of the flame front initiated by the spark. It leads to pressure fluctuations that can severely damage the engine. Modern vehicles utilize different strategies to avoid knock. One extreme strategy assumes a weak fuel quality and, to protect the engine, retards the spark timing at the expense of combustion efficiency. The other extreme carefully detects knock in every engine cycle and retards the spark timing only when knock is detected. Therefore as fuel octane number improves, the spark is advanced to the knock boundary of that fuel; a process known as knock limited spark advance or KLSA. By employing this strategy the engine is always able to operate at the highest efficiency the fuel permits.

Over the last 20 years Shell has been active in measuring the octane appetite of modern gasoline engines and has published extensively in this area. The latest fleet test program evaluated the octane response of 20 modern gasoline vehicles equipped with a wide variety of engine technologies. Using a selection of vehicles targeting the most popular models and brands across Europe in 2013, vehicle performance and ignition timing were measured in response to fuels with different octane qualities at wide open throttle acceleration and different steady state conditions.

The majority of the 20 vehicles showed performance benefits when running on higher RON fuels. The highest statistically significant (95% confidence) full speed gated acceleration time benefit was 1.9%, whilst the highest power benefit was 3.9% at 2500 rpm for a RON98 versus RON95 comparison. Comparing the different steady state conditions, greatest benefits were generally found at 2500 rpm; an engine speed that is highly representative of real-world driving.

Introduction

Increasingly stringent CO_2 emission targets are an important driver in current gasoline spark ignition engine developments. Current emission legislation requires a fleet average of 95 g/km by 2020 in Europe [1] and 101 g/km (163 g/mile) by 2025 in the US [2].

Improved engine efficiency can be achieved by reducing energy losses and increasing combustion efficiency. This enables engines to meet legislation targets without compromising the customer´s demand for power and performance.

Efficiency Improvement by Fuel Octane Number

Octane number is the fuel's resistance to spontaneous auto-ignition (engine knock). Gasoline engines are designed to burn the fuel with one coherent flame front, which is ignited by the spark and evolves through the whole combustion chamber. Auto-ignition of the fuel-air mixture ahead of the flame front leads to a less controlled combustion. Engine knock causes pressure fluctuations which, when severe, can damage the engine.

The knock resistance of a fuel is traditionally measured as research octane number (RON) and motor octane number (MON) in a cooperative fuels research (CFR) engine. Both octane numbers are defined by the volume percent of iso-octane in n-heptane that is required to achieve the same knock behaviour with this surrogate fuel compared to the real fuel. The RON quality of a fuel is measured at lower temperature to pressure ratios compared to the MON. In modern engines the maximum combustion temperatures are still defined by material properties, but the end gas pressures are increased by boosting and turbocharging. This lowers the temperature to pressure ratio and makes RON more relevant to engine performance in modern vehicles than MON.

Fuel octane number is linked to engine efficiency by KLSA. When knock is detected in a given combustion cycle the spark is retarded in the following cycle. This continues until no further knock occurs. The last spark timing before the knock threshold (e.g. 1 bar pressure fluctuation per 1000 rpm) is exceeded is called KLSA. Retarding the spark timing leads to a loss of engine efficiency because the spark is moved away from the point of optimal spark timing; referred to as maximum brake torque (MBT). This relationship is illustrated by two test fuels that were run in a downsized turbocharged bench engine (see Figure 1). The blue curve represents a fuel with a RON of 97 which translated to a knocklimited engine Brake Mean Effective Pressure (BMEP) of 29.5 bar. In comparison the red curve is of a fuel with an octane number of RON 112 able to achieve a KLSA beyond MBT. The engine BMEP was 30.7 bar. Thus the high octane number fuel increased the engine efficiency in this test by 4.1%. Both fuels had comparable energy content and the fuel flow was kept constant. [3]

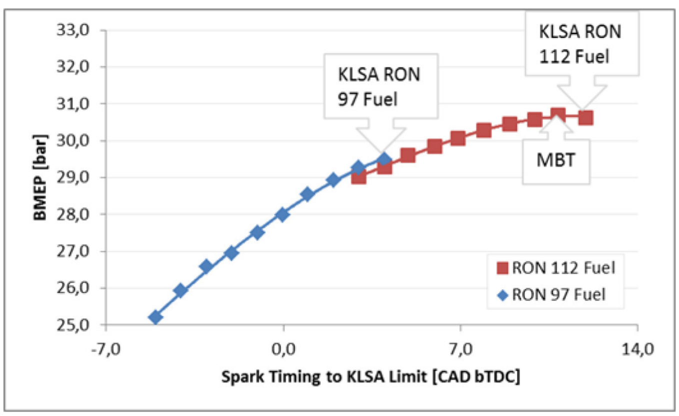

Figure 1. Brake Mean Effective Pressure as a function of Spark Timing. [3]

In general vehicles operate more efficiently at optimum spark timing. This means the vehicle needs to burn less fuel for constant torque at optimum spark timing or it gets higher torque for a constant fuel flow.

The octane quality of the fuel is more important for modern downsized and turbocharged engines compared to older engine technologies, because they typically operate close to engine knock to realize maximum efficiency.

Design of the Test Program

The goal of the test program was to evaluate the octane appetite of modern vehicles. Between 1994 and 2007 Shell investigated the performance effects linked to octane number of circa 50 vehicles [4, 5]. In 2012 it was recognized that the database should be updated to include vehicles based on new technologies (e.g. downsized direct-injection turbo-charged engines). On the basis of market relevance and robustness, a test fleet of 20 modern gasoline vehicles was selected and tested at an external test house.

Many studies have investigated the relationship of RON and MON with regard to engine performance as described by K-values [3, 4, 5, 6, 7, 8]. A prerequisite to calculate K-values is a test fuel matrix with de-correlated RON and MON values. The focus of this study was the evaluation of market representative fuels and their effect on engine performance. Those market representative fuels typically exhibit correlated RON and MON values. Thus the calculation of K-values was not in the scope of this study.

Vehicle Selection

Table 1. Market representative test fleet.

Model	Power [kW]	Engine [L]	Compression Ratio	Comments
BMW 3-er	135	2.0	10.0	Euro V, DI, TC
Fiat Punto	44	1.2	11.1	Euro IV, PFI
Ford Fiesta	60	1.25	11.0	Euro V, PFI
Ford Fiesta	71	1.4	11.0	Euro IV, PFI
Ford Focus	92	1.6	11.0	Euro V, PFI
Ford Ka	51	1.3	11.1	Euro IV, PFI
Honda Civic	103	1.8	10.5	Euro IV, PFI
Mini	90	1.6	11.0	Euro V, PFI
Nissan Qasquai	86	1.6	10.7	Euro V, PFI
Opel Astra	74	1.4	10.5	Euro V, PFI
Opel Astra	85	1.6	10.8	Euro V, PFI
Opel Corsa	63	1.2	10.5	Euro V, PFI
Peugeot 207	54	1.4	10.5	Euro V, PFI
Renault Clio	55	1.2	9.8	Euro V, PFI
Renault Megane	81	1.6	9.7	Euro IV, PFI
Skoda Octavia	75	1.6	10.5	Euro IV, PFI
Suzuki Swift	67.5	1.3	9.5	Euro IV, PFI
Toyota Yaris	74	1.3	11.5	Euro V, PFI
VW Golf	90	1.4	10.0	Euro V, DI, TC
VW Polo	44	1.2	10.5	Euro V, PFI

Vehicles were chosen to provide robust fleet coverage across Europe. An initial fleet of 16 cars was selected that represented 32% of specific engine models and brands in the UK passenger car market in 2013 and had been determined by taking the top 16 cars from 2011 car sales and future car parc data for the UK. The fleet represented 54% by amalgamated brands (i.e. by including all brands with that engine). Another 4 cars were then added based on sales across Europe to give a better EU representation. It is noted that the inclusion of these additional 4 cars improves the % representation of cars in the UK, but representation of other European markets varies. The complete vehicle list is shown in Table 1.

The general envisaged purchase standard for all vehicles was that the vehicles should have run circa 10,000 - 25,000 km in the field to avoid the need for a run-in period to stabilize measurements. In addition they should be in perfect operational condition (e.g. no EMS fault codes, no engine modifications and no accidents).

Fuel Selection

In order to evaluate the octane appetite of modern vehicles, test fuels with a broad octane number range were used. They represented regular and premium fuels available in different markets worldwide with a focus on Europe. The fuels were formulated, using standard refinery streams, to meet EN228 summer specifications. The RON91 and 93 fuel grades did not meet the octane number requirement of EN228, but were included to reflect octane quality of Asia and Oceania. The RON99 fuel and the De-Greening Fuel (DGF) were formulated to meet the EN228 winter specifications of the UK. All fuels were additivated with market representative Deposit Control Additive (DCA) and contained 5%v ethanol (E5) without any further oxygenates. The complete list of test fuels is shown in Table 2.

Table 2. Properties of test fuels.

Fuel	RON	MON	AKI
RON91	91	84	87
RON93	93	85	89
RON95	95	86	91
RON97	97	87	92
RON98	98	88	93
RON99	99	87	93
RON100	100	89	95
DGF	95	85	90

Test Procedure

The test procedure was designed to evaluate the response of 20 vehicles to different research octane number fuels via a series of WOT accelerations and WOT constant speed tests at 2500, 3500 and 4500 rpm.

Prior to testing each vehicle underwent a preparation stage which started with a safety service and general checks, including EMS error-code read out. Any defects potentially influencing the test data were rectified. All used vehicles received new air filters and tyres were replaced in case they were not suitable for Chassis Dynamometer (CD) WOT tests. Tyre pressure was set to the OEM recommended maximum pressure setting. All vehicles were run on the CD for preparation and went through a second safety service and general check. Once the vehicle was accepted for testing, it meant it had neither obvious mechanical faults nor any On-Board Diagnostics (OBD) fault codes that could prevent it from running as per OEM design.

The test sequence was shaped to allow the direct comparison of different octane number fuels rather than modelling. Thus it included sufficient repeats for each RON comparison to be able to differentiate even small differences with 95% statistical confidence. The sequence is described in Table 3.

Table 3. Sequence of 95 octane efficiency tests divided in 5 test series with a de-greening stage at the beginning of every series.

	Test series 1	Test series 2	Test series 3	Test series 4	Test series 5
De-Greening	DGF	DGF	DGF	DGF	DGF
1st test	93	91	95	95	95
2nd test	95	95	99	97	98
3rd test	97	98	95	95	100
4th test	95	95	99	97	98
5th test	93	91	95	95	95
6th test	97	98	99	97	100
7th test	95	95	95	95	98
8th test	97	98	99	97	100
9th test	95	95	95	95	98
10th test	93	91	99	97	95
11th test	95	95	95	95	98
12th test	97	98	99	97	100
13th test	95	95	95	95	98
14th test	97	98	99	97	100
15th test	93	91	95	95	95
16th test	97	98	99	97	100
17th test	95	95	95	95	98
18th test	97	98	99	97	100
19th test	93	91	95	95	95

The full test sequence for each vehicle was comprised of five test series, starting with a de-greening stage and followed by 19 octane efficiency tests. (The de-greening stage is an extended stabilization phase during which the lubricant is run in and was achieved by running the vehicle for 500 km at various speeds between 100 and 120 km/h, immediately followed by one run through an octane efficiency test with de-greening fuel for warm-up. It is important to control the oil temperature, otherwise change in oil viscosity can influence the test results. The trigger oil temperature was determined for each car during the de-greening stage at the beginning of each test series and represents an engine temperature after a short cool down period between WOT accelerations. It was not set higher than 110 °C. After a short stop for lubricant sampling the vehicle was started with the first octane efficiency test in the respective test series). Once started on a test series there were no stops allowed until the end of the series. Between each test series the vehicle was stopped, engine oil and filter changed and the vehicle condition was checked

Each of the 19 octane efficiency tests in a test series followed the same procedure.

- It started with a run-in period of 20 WOT accelerations in the gear that gave the closest vehicle speed to 120 km/h at 4500 rpm. Afterwards the vehicle was run at acceleration start speed until the oil temperature was back to the trigger temperature.
- 15 WOT accelerations were run, in the same gear as used in the first step, from 1200 to 4550 rpm. The time between engine speed gates (1500 to 2500 and to 3500 and to 4500 rpm) was recorded. After each WOT acceleration the vehicle was run at low speed until the oil temperature reached the trigger temperature again.
- Finally the vehicle was run at constant WOT speeds at 2500, 3500 and 4500 rpm for one minute each to measure the maximum power output at these engine speeds. The first 45 seconds were used as stabilization and the remaining 15 seconds for data recording.

Results and Discussion

Results for Vehicle X, which is representative of the octane number-responsive vehicles in this test, are shown here. (Detailed results for each of the vehicles are not shown since this study focuses on the representative fleet). A summary of general trends in the fleet is provided after results of Vehicle X.

Vehicle X - Acceleration

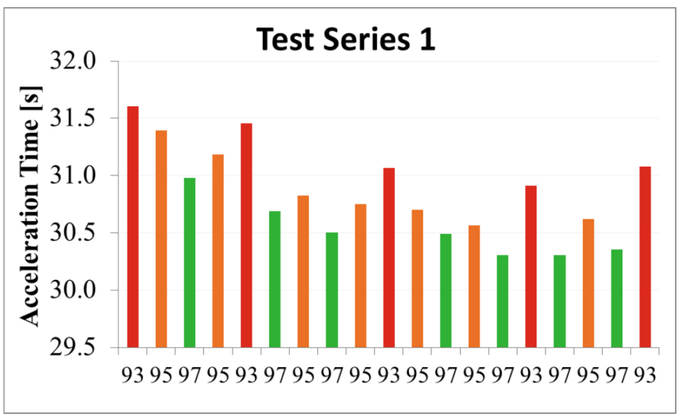

Figure 2. Comparison of full acceleration time (from 1500 to 4500 rpm) for Vehicle X during test series 1.

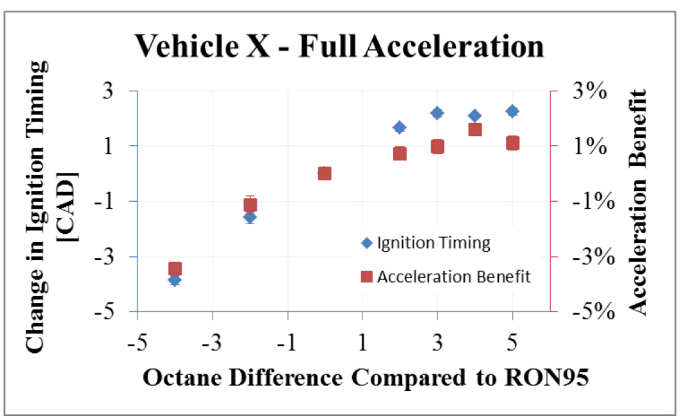

Figure 3. Full acceleration (from 1500 to 4500 rpm) benefit and change in ignition timing for fuels with different octane number compared to RON95.

The comparison of full acceleration time between a RON93, RON95 and RON97 fuel can be seen in Figure 2 for Vehicle X during test series 1. The declining trend in acceleration time could be caused by a decline of intake air and fuel feed temperature during the test series. The trend was statistically removed to give the acceleration benefits of fuels with different RON. The results of test series 1 and the remaining comparisons can be seen in Figure 3. RON95 was defined as baseline, as it is the minimum specification requirement in Europe.

Vehicle X was responsive to fuel octane number. An increase of fuel octane number caused a faster acceleration. This effect can be attributed to the corresponding change in ignition timing.

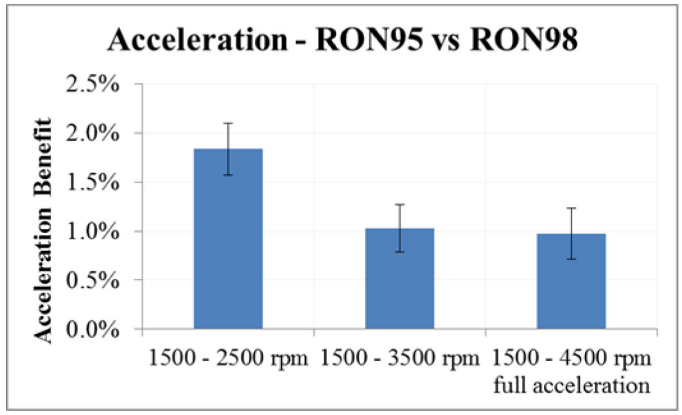

Figure 4. An example of a comparison of acceleration benefits for different engine speed gates for RON98 relative to RON95 fuel. Error bars represent 95% confidence intervals on the benefit.

A noteworthy effect was found by comparing the acceleration benefits of different engine speed gates (see Figure 4). In every comparison of acceleration benefits with different fuels in Vehicle X the highest benefit was found between 1500 and 2500 rpm. This is the engine speed range that is most relevant to customers as it reflects typical driving styles.

Vehicle X - Power

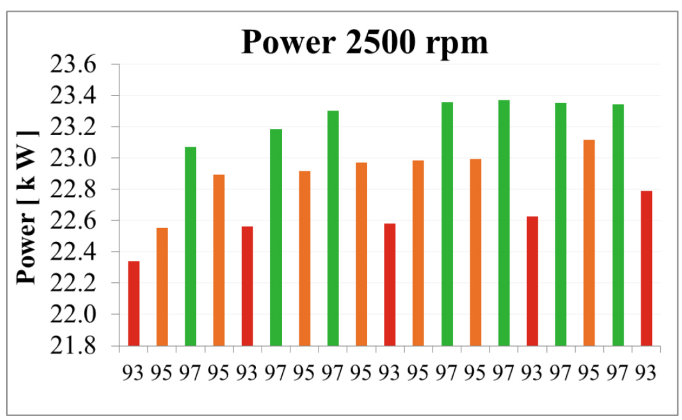

Figure 5. Comparison of engine power at 2500 rpm for Vehicle X during test series 1.

Figure 5 shows the engine power for a RON93, RON95 and RON97 fuel. The statistical analysis followed the same approach as used in the acceleration tests and resulted in the overview given in Figure 6.

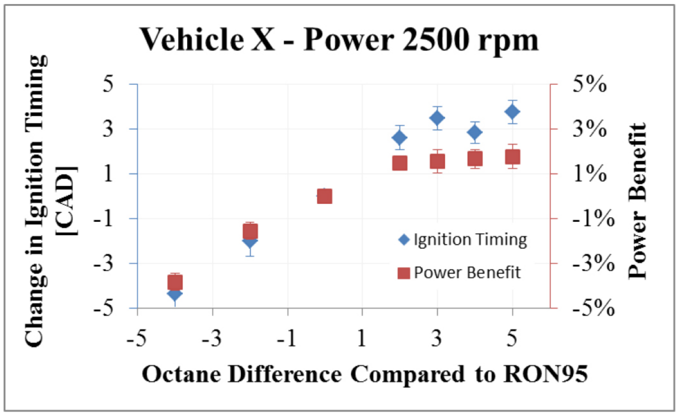

Figure 6. Power benefit and change in ignition timing for fuels with different octane number compared to RON95.

Compared to a RON95 fuel, Vehicle X retarded the ignition timing for lower RON fuels, which led to a decrease in engine power. In contrast the power response to a high octane number fuel was the opposite; namely Vehicle X was able to utilize a benefit from high octane number fuels by advancing the ignition timing.

As noted, the main focus of the study was on the representative fleet, for which the results are now shown.

Vehicle Fleet Trends - Acceleration

During the fleet test 8 fuel-pairs were compared directly with each other in five test series. Some test series included more than one fuel pair. The direct comparisons are listed in Table 4.

Table 4. List of direct comparisons during the fleet test.CAD is Crank Angle Degree. It measures the change in ignition timing.

	RON	No. of vehicles responsive to octane change	Avg. fleet IT change	No. of vehicles with benefit	Avg. fleet benefit
Full Acceleration	91 vs 95	16 (80%)	1.61 CAD	18 (90%)	1.76%
	91 vs 98	19 (95%)	2.21 CAD	17 (85%)	2.07%
	93 vs 95	12 (60%)	0.49 CAD	17 (85%)	0.61%
	93 vs 97	13 (65%)	1.00 CAD	15 (75%)	0.92%
	95 vs 97	13 (65%)	0.51 CAD	10 (50%)	0.40%
	95 vs 98	12 (60%)	0.60 CAD	11 (55%)	0.44%
	95 vs 99	10 (50%)	0.59 CAD	20 (100%)	1.12%
	95 vs 100	11 (55%)	0.64 CAD	12 (60%)	0.52%

At least 50% of the vehicle fleet was able to generate an acceleration benefit from the higher octane number fuels in each fuel pair comparison. They retarded the spark for fuels with lower than 95RON and advanced it for fuels with higher RON. Only one vehicle did not respond to changes in fuel quality at all. Almost all vehicles showed the largest acceleration benefit for the comparison of RON91 vs. RON98 fuel. This is not surprising as this fuel pair had the largest octane number difference in the test matrix. The highest benefit found was a 4.6% quicker acceleration time for the RON98 fuel. Comparing RON95 and RON98, the highest benefit was 1.9%. The fleet average acceleration benefits for all fuel pairs compared to the RON95 fuel are displayed in Figure 7.

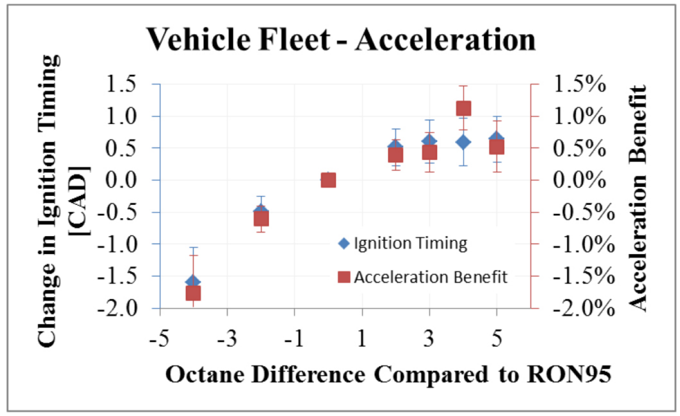

Figure 7. Fleet average full acceleration (from 1500 to 4500 rpm) benefits compared to RON95. Error bars indicate vehicle to vehicle variability.

Over the whole acceleration test matrix only one fuel pair showed a statistically significant disadvantage in ignition timing for one vehicle, but this did not translate to a significant slower acceleration time for the higher octane number fuel. However 14 out of 160 tests showed a significantly longer acceleration time for the higher octane number fuel in the respective comparison. Those disadvantages were on average -0.21% and they were not associated with retarded spark timing for the higher octane number fuel. Thus it is assumed that other sources of interference in the vehicle were at play during the measurements.

The RON99 fuel enabled a surprisingly large acceleration benefit for the vehicle fleet in comparison to the other fuels. It is clear from the ignition timing that this effect is not based on octane number or sensitivity of the fuel as both would translate to a different ignition timing. Thus the surprising benefit of this fuel needs to be attributed to factors other than octane number (e.g. flame speed [9]).

Vehicle Fleet Trends - Power

At least 50% of all vehicles in the test fleet were able to generate a power benefit from higher octane number fuels than RON95 in the 2500 rpm steady state test. 10% of the fleet did not respond to any changes in fuel octane number. The highest benefit of each vehicle was typically found for the RON91 vs RON98 comparison. The highest benefit in the test fleet was 8.7% more power from the RON98 fuel. Comparing the more EU market relevant RON95 and RON98 fuels the highest benefit was 3.9%. The average fleet benefits are shown in Figure 8.

Not all vehicles that advanced their ignition timing derived a power benefit. A vehicle that advances the ignition timing realizes a more efficient combustion. This can translate to higher torque for a fixed fuel flow, better fuel economy for fixed torque or a mixture of both scenarios.

Table 5. Overview of fleet power results for all direct fuel comparisons.

	RON	No. of vehicles responsive to octane change	Avg. fleet IT change	No. of vehicles with benefit	Avg. fleet benefit
Steady State – 2500 rpm	91 vs 95	17 (85%)	2.22 CAD	16 (80%)	2.08%
	91 vs 98	18 (90%)	3.46 CAD	16 (80%)	2.83%
	93 vs 95	12 (60%)	0.61 CAD	12 (60%)	0.60%
	93 vs 97	14 (70%)	1.59 CAD	12 (60%)	1.09%
	95 vs 97	11 (55%)	1.01 CAD	10 (50%)	0.59%
	95 vs 98	12 (60%)	1.36 CAD	10 (50%)	0.79%
	95 vs 99	11 (55%)	1.19 CAD	19 (95%)	1.13%
	95 vs 100	11 (55%)	1.46 CAD	11 (55%)	0.92%
Steady State – 3500 rpm	91 vs 95	12 (60%)	1.39 CAD	11 (55%)	0.87%
	91 vs 98	12 (60%)	2.09 CAD	10 (50%)	1.11%
	93 vs 95	7 (35%)	0.38 CAD	9 (45%)	0.18%
	93 vs 97	8 (40%)	0.87 CAD	7 (35%)	0.26%
	95 vs 97	6 (30%)	0.40 CAD	5 (25%)	0.12%
	95 vs 98	6 (30%)	0.52 CAD	5 (25%)	0.23%
	95 vs 99	7 (35%)	0.59 CAD	19 (95%)	0.69%
	95 vs 100	6 (30%)	0.57 CAD	9 (45%)	0.30%
Steady State – 4500 rpm	91 vs 95	9 (45%)	0.64 CAD	8 (40%)	0.37%
	91 vs 98	9 (45%)	1.29 CAD	9 (45%)	0.57%
	93 vs 95	4 (20%)	0.17 CAD	6 (30%)	0.19%
	93 vs 97	6 (30%)	0.51 CAD	6 (30%)	0.25%
	95 vs 97	5 (25%)	0.44 CAD	6 (30%)	0.16%
	95 vs 98	4 (20%)	0.43 CAD	4 (20%)	0.10%
	95 vs 99	7 (35%)	0.53 CAD	20 (100%)	0.67%
	95 vs 100	4 (20%)	0.48 CAD	4 (20%)	0.13%

In comparison to 2500 rpm, the steady state tests at 3500 rpm and 4500 rpm showed smaller fleet benefits and a lower number of vehicles with a statistically significant benefit. It is well known that the low speed high load condition is usually most knock limited. In comparison to the higher engine speed conditions the fuel has the longest residence time in the combustion chamber and thus highest likelihood to auto-ignite at low speed. Subsequently knock resistant fuels have the largest impact under this condition.

Some vehicles have been found to be insensitive to octane number changes in the RON95 to RON98 region over pretty much the whole speed and load range. This is caused by a low compression ratio and/or a conservative engine calibration which limits the maximum spark advance. However efficiency is sacrificed when an engine never operates on the limits of knock. Thus this is becoming less common in modern vehicles which have higher compression ratios.

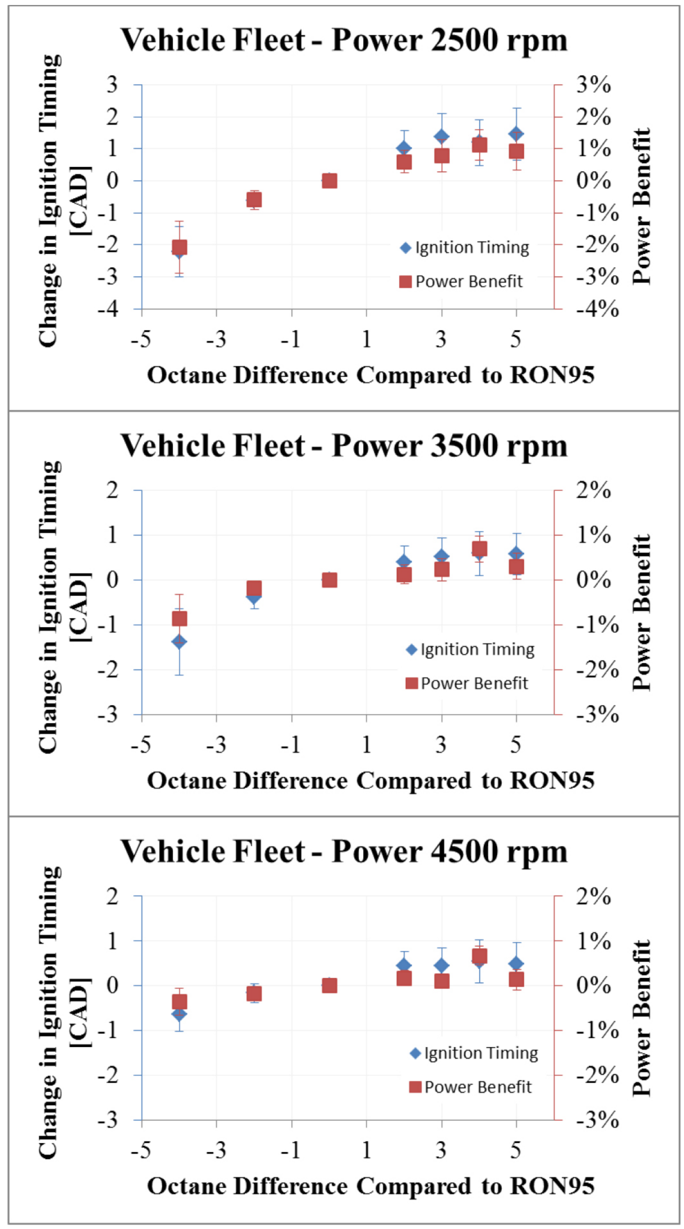

Figure 8. Fleet average power benefits compared to RON95. Error bars indicate vehicle to vehicle variability.

During the power tests, 3 out of 480 evaluated comparisons gave statistically significant poorer (retarded) ignition timing for the fuel with higher octane number. However this did not translate to less vehicle power in the respective comparisons. In 29 cases a non-statistically significant difference, or an advance, in ignition timing of the higher octane number fuel translated to a reduction in vehicle power of, on average, -0.32%. It is assumed that these results were caused by interference of the vehicle during the test.

Although the incremental benefits of higher octane number fuels tend to level off as the octane number is increased, most cars still experience a significant benefit in moving from RON95 to higher octane grades.

Strategies to utilize high octane number fuels vary widely amongst OEMs. The general strategy depends if vehicle cost or vehicle performance is the primary focus. Thus it might be expected that high performance vehicles are always octane number responsive, which is not the case. Other considerations like risk avoidance play a role as well. Therefore it is possible that when new models are introduced they are calibrated quite conservatively and then more aggressively towards performance once market experience with the vehicle has been gained. Conservative calibration is also adopted for vehicles going into markets where fuel octane number quality varies widely and is often very low. Another restraint might be the protection of engine parts as aggressive ignition timings lead to higher peak pressures in the engine.

Conclusions

The octane appetite of a vehicle fleet was evaluated; 16 of the vehicles represented 32% of specific engine models and brands in the UK passenger car market in 2013, with another 4 being added to increase representation of other European markets. It was found that at least half of the vehicle fleet was able to generate a power or acceleration benefit with high octane number fuels compared to the EN228 specification minimum of RON95 although none of the vehicles was recommended for fuels with higher than RON95. 10 - 20% of the fleet did not respond to fuel octane number at all. The highest statistically significant (95% confidence) full speed gated acceleration time benefit was 1.9%, whilst the highest power benefit was 3.9% at 2500 rpm for a RON95 versus RON98 comparison.

In general vehicles are able to benefit from high octane number fuels by advancing the spark timing closer to MBT as high octane number fuels are less prone to auto-ignition. This increases engine efficiency, which results in higher torque for a given amount of fuel, better fuel economy for the same torque or mixture of both. In this test program no vehicle was specifically designed to gain the maximum possible benefit from high octane number fuels. Thus the highest benefits found give an indication of the potential that fuels with high octane number could unlock in modern vehicles.

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Abbreviations

AKI - Anti-Knock Index

BMEP - Brake Mean Effective Pressure

CAD - Crank Angle Degree

CD - Chassis Dynamometer

CFR - Cooperative Fuels Research

DCA - Deposit Control Additive

DGF - De-Greening Fuel

E5 - Gasoline Containing 5%v Ethanol

EMS - Engine Management System

EU - European Union

IT - Ignition Timing

KLSA - Knock-Limited Spark Advance

MBT - Maximum Brake Torque

MON - Motor Octane Number

OBD - On-Board Diagnostics

OEM - Original Equipment Manufacturer

RON - Research Octane Number

SI - Spark Ingnition

TC - Turbo Charger

UK - United Kingdom

WOT - Wide-Open Throttle

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