

Understanding the Octane Appetite of Modern Vehicles

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ABSTRACT

Octane appetite of modern engines has changed as engine designs have evolved to meet performance, emissions, fuel economy and other demands. The octane appetite of seven modern vehicles was studied in accordance with the octane index equation $OI = RON - KS$, where K is an operating condition specific constant and S is the fuel sensitivity ($RON - MON$). Engines with a displacement of 2.0L and below and different combinations of boosting, fuel injection, and compression ratios were tested using a decorrelated $RON - MON$ matrix of eight fuels. Power and acceleration performance were used to determine the K values for corresponding operating points. Previous studies have shown that vehicles manufactured up to 20 years ago mostly exhibited negative K values and the fuels with higher RON and higher sensitivity tended to perform better. On investigating this trend for 2012 MY vehicles, it was found that K values were negative and higher in magnitude in several cases in comparison with results from prior research in this area. The octane response correlated well with the spark advance strategy employed by their respective engine management systems. However, in some instances the K values computed were highly negative (-4 and beyond) which would correspond to unrealistic pressure and temperature conditions in the engine from the perspective of chemical kinetics of auto-ignition. It is speculated that this anomalous result has arisen from the spray-mixing properties of some of the fuels in the matrix. Notwithstanding these points, it was consistently found that fuels with higher RON and higher sensitivity performed better showing that the octane response of modern vehicles is moving further away from MON .

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INTRODUCTION

The Engine Management Systems present in modern vehicles have become quite advanced in utilizing fuel octane either towards better performance or higher fuel economy. The demand for higher octane fuel has been on the rise in the recent past largely owing to the emissions standards. For example, the Federal regulations in the U.S require each vehicle manufacturer's average light-duty vehicle fleet to meet a 163 g/mile CO_2 emissions standard by 2025, which is equivalent to 54.5 mpg. [1] Understanding the octane appetite of modern vehicles is therefore quite essential for the development of suitable on-road fuels. However, due to historical reasons Research Octane and Motor Octane Numbers are still the metrics used to characterize a fuel's antiknock quality. These octane indicators correlated reasonably well with engine behavior in the past. But the correlation has drifted considerably in the recent years due to advances in engine infrastructure, mainly influenced by the aforementioned stringent fuel economy standards. In this study, we intend to explore the relationship between engine response and octane quality of the fuel for modern vehicles and to specifically understand if RON and MON can still be used effectively in measuring the octane appetite of modern engines.

Octane number is a measure of how well a fuel resists knock -an abnormal combustion process where the combustion of fuel/air mixture occurs spontaneously in the end gas rather than within a flame front initiated by spark ignition. A combustion flame generated by the spark travels all the way to the cylinder wall during normal combustion. However, in a knocking case the spontaneous end gas combustion occurs at local zones ahead of the flame front. Knock is hard to control since it is related to the fuel chemistry, combustion chamber design, and engine operating conditions. Also, a severe knock accompanies high magnitude pressure oscillations, which can even damage the engine hardware.

The main strategy used by modern engines to avoid knock is *via* a knock sensor which detects knock and eliminates it by retarding the spark timing to lower the pressure and temperature inside the cylinder. However, retarding the spark timing lowers the torque output for a given amount of fuel. Thus, it is important to maintain the spark timing close to optimum timing to maximize the torque output of the engine.

This can be done by using a high octane fuel. Figure 1 (torque vs. spark timing) shows that by using a higher octane fuel, it is possible to advance the spark timing further to achieve higher torque for the

same amount of injected fuel. The increased torque could be utilized either towards faster acceleration or improved fuel economy at a given engine operating point.

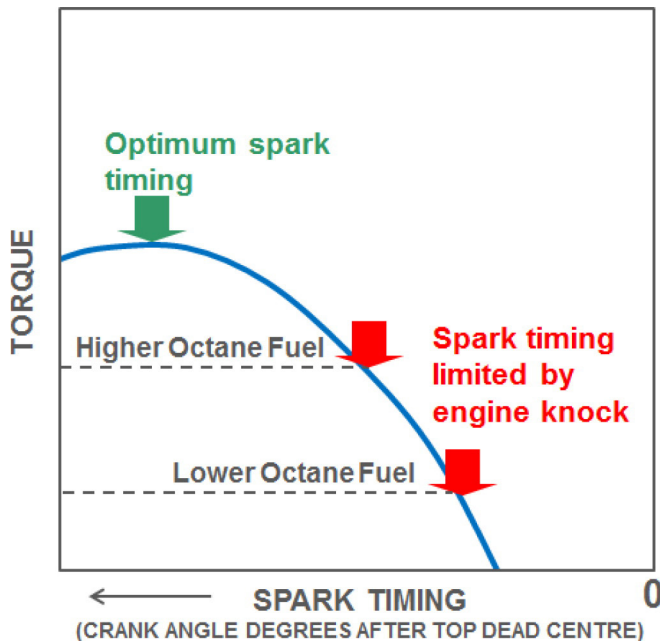


Figure 1. Torque Output vs. Spark Timing for Gasoline Engines.

Octane number is a measure of how well the fuel resists knock; higher octane number fuels have better knock resistance. There are two main standard testing methods used to measure the octane number: RON (Research Octane Number) and MON (Motor Octane Number). For both tests, fuels are tested in a CFR (Cooperative Fuel Research) engine. The RON test is conducted at 600 rpm with an intake temperature of 52 C [2], while the MON test is conducted at 900 rpm with an intake temperature of 149 C using variable spark timing to further stress the engine [3]. A given fuel is tested under these conditions, and resistance to knock is compared to primary reference fuel (PRF) blends to determine the octane number. (Primary reference fuel blends for octane rating tests are composed of iso-octane (100 octane rating) and n-heptane (0 octane rating) at different ratios). For example, a primary reference fuel blend with 80 vol% iso-octane and 20 vol% n-heptane has an octane rating of 80.

RON and MON themselves are not always good indicators to rate a given fuel's knock resistance in modern engines as their test conditions have a limited range. [4, 5, 6, 7] The RON and MON test conditions were developed in the mid-20th century to correlate with internal combustion engines that were less efficient (higher in-cylinder temperatures, carbureted fuel systems) and had higher displacements compared to modern engines.

Octane Index (OI) was developed to facilitate the use of RON and MON and still be able to correlate with the octane appetite of modern engines. OI is defined as a linear combination of RON and MON along with the use of an engine parameter K as given in Equation 1 below. [8] The work carried out by Kalghatgi (2001) serves as the foundation of engine response studies to fuel octane quality explained in terms of the parameter K.

$$OI = (1-K)*RON + K*MON = RON - KS \quad (1)$$

where K is a constant which depends on the engine design and operating conditions while S is the sensitivity (RON-MON). For a primary reference fuel, RON = MON = OI or S = 0 by definition. However, the chemistry of a real fuel is very different from that of a PRF, and OI depends on K. K values of 0 and 1 correspond to RON and MON tests respectively. In the U.S. gasoline stations, the average of RON and MON is indicated as AKI (Anti Knock Index, K=0.5) as at the time of RON/MON introduction, it was assumed that these test conditions bracket the operating regimes of spark ignition engines.

However, it has been found that for engines produced after 1990s, K values in general tend to be negative for most of the operating regime where they are knock limited. This indicates that the octane index is moving away from MON (and even RON to an extent). From a combustion perspective, in-cylinder parameters for RON test are closer to those in a modern engine than the MON test. For a given end gas pressure at knocking conditions, the end gas temperature in a typical modern engine can be about 100K lower than the RON test and about 250K lower than the MON test, although the actual values depend on the boosting system, scavenging and charge cooling (for GDI) present in an individual engine [9]. Hence, the autoignition propensity of a fuel in a typical modern engine for a given end gas pressure is, in sequence lower than RON and MON tests in a CFR engine. In terms of K values, this phenomenon indicates a negative directional deviation from the bracketed regime of MON (K=1) and RON (K=0) tests; negative K values result in OI values greater than either RON or MON values (according to Eq.1) implying a superior octane response for the corresponding test condition in a typical modern engine vs. the CFR engine.

Researchers have previously conducted experiments on different test bed engines, and found that K values strongly depend on the engine operating conditions and decrease (or become more negative) as an engine becomes more prone to knock. [6, 8, 10, 11] Single cylinder experiments carried out by Heywood and Mittal explored antiknock properties of different fuel blends (PRFs, toluene, di-isobutylene, and ethanol) at various engine operating conditions. They also found negative K values for all operating conditions. Spark location, compression ratio, air-fuel ratio, engine speed, intake air temperature, and pressure were analyzed as well: Only intake air temperature, pressure, and engine speed had strong impacts on K value. [6] Vehicle tests (MY-model years 1994-2001) by Kalghatgi also showed negative K values in general. Furthermore, it was found that K becomes more negative in turbocharged engines as intake (boost) pressure increases. [6] [10]

In this work, the octane appetite of *modern* engines in 2012 MY vehicles was studied in order to observe the evolution of K values brought about by changes in engine design and to infer the relevance of RON and MON in deciphering the octane response of these vehicles. This study was carried out in two phases. In Phase I, vehicles V1-V4 were tested. The vehicle V4 (equipped with

naturally-aspirated direct-injection technology) exhibited highly negative K values (as low as -4.2) implying unrealistic engine intake conditions, while the other three vehicles displayed negative but interpretable K values (as low as -1.7). The V4 result was surprising in view of some of the lowest K values reported in literature under similar test conditions (as low as -1.1 [12]). To test the reproducibility of the computed results, three more vehicles were tested in Phase II with one of the vehicles - V6 being identical to V4. The observations from Phase II confirmed the validity of K values from Phase I and showed that fuel properties other than RON and MON can, in some cases, strongly influence the octane response of modern vehicles. However, in general, it was seen that K values of modern engines continue to become more negative (resulting in bigger OI values) when compared to similar tests carried out previously in literature. [12] In other words, fuels with higher RON and higher sensitivity (i.e. lower MON) were the best performers in agreement with prior research in this area. The experimental details and the observed results are presented in the following sections.

EXPERIMENTAL DETAIL

Vehicles

The main objective of this work was to understand the octane appetite of modern vehicles by studying the impact of RON and MON on vehicle performance metrics such as acceleration times and steady state torque output and in-turn to compute the trends of K values. In order to achieve this goal, seven 2012 MY vehicles representing American, European and Asian OEMs (sold in the North American market) shown in Table 1 were tested; these vehicles were comprised of engines with a displacement of 2.0L and below and different combinations of boosting, fuel injection, and compression ratios. All vehicles chosen were equipped with manual transmissions. This allowed for vehicles to be tested at high Mean Effective Pressure (MEP) under low engine speeds at a fixed transmission gear.

Each vehicle received a specification check and an initial power check. Power checks were performed to confirm that vehicles were performing at their officially rated performance. Then appropriate gears were selected for each testing. For example, the fifth gear was selected for 25-80 mph acceleration in V1 as the vehicle was able to idle smoothly in 5th gear at speeds of 25 mph or below; acceleration in fifth gear also meant a longer duration for the speed trace which ensured a better resolution of engine response to the fuel octane.

In general, vehicles were tested on a chassis dynamometer for acceleration times within a speed range of 22 - 80 miles per hour (in 4th-6th transmission gears) and steady state torque analog measurements (dynamometer tractive force) at engine speeds of 1500, 2500, and 3500 rpm at wide-open throttle (WOT) conditions. The speed range for accelerations was optimized for each vehicle and not identical across vehicles as the main intent of the study was to understand the response of a given vehicle to different octane quality fuels rather than to compare different vehicles under identical test conditions.

Table 1. Engine Specifications of Test Vehicles

Vehicle (2012)	Engine Size (L)	Direct Injection	Turbo-charged
V1	1.8	X	X
V2	1.4	X	✓
V3	2.0	✓	✓
V4	1.6	✓	X
V5	2.0	✓	X
V6	1.6	✓	X
V7	2.0	✓	X
Compression Ratio		9.5:1 – 12.0:1	

*V4 and V6 are of identical make and model.

Fuels

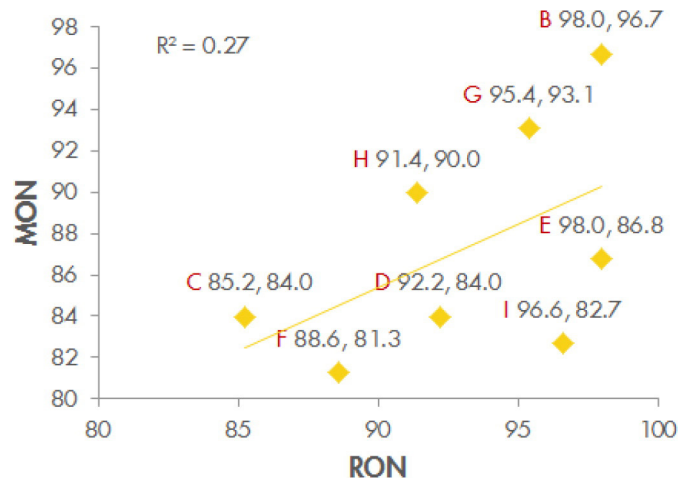


Figure 2. Decorrelated RON-MON Fuel Matrix Used for Testing the Octane Response. Octane numbers were obtained in accordance with ASTM D2699 (RON) and ASTM D2700 (MON).

The tests were conducted using a matrix of eight fuels. In order to successfully obtain the K value, and hence the octane index (OI), it is quite essential to test with a decorrelated RON vs. MON matrix. In the absence of such a decorrelation, the relationship between the octane index and fuel octane quality becomes a single parametric model and would invalidate the K value methodology used [8]. In other words, it is not possible to establish the independent effects of RON and MON on performance metrics if there is a simple correlation between RON and MON in the fuels matrix. Hence, custom fuels were blended in-house to achieve the targeted RON and sensitivity (S) values. A plot of RON vs. MON for the test fuels is shown in Figure 2; the R^2 is 0.27 for a linear fit of the data implying a decorrelated RON-MON fuel matrix. (Note: The fuels used in this study are experimental blends and do not necessarily represent fuels retailed in the marketplace.)

Test Sequence

Table 2. Test Sequence Utilized for Testing Each Vehicle

Day	Test 1	Test 2	Test 3	Test 4
1	I	E	B	F
2	C	G	D	H
3	G	C	E	I
4	F	B	H	D
5	H	D	I	E
6	B	F	G	C

The test sequence was designed with enough repeats for statistical robustness and a randomized order of fuels to eliminate any temporal effects thereby facilitating an unbiased comparison amongst tested fuels for a given vehicle. For each vehicle, a total of eight fuels were tested for six days with three repeats for each fuel. This resulted in 27 accelerations (9x3) and 15 steady states (5x3) for a given fuel. The test schedule is shown in [Table 2](#).

In terms of test robustness, good test repeatability was obtained. Day-to-day variations (three repeats across six days) in acceleration time and steady state signals for vehicles using the matrix of eight fuels averaged at a standard deviation of about 2.0%, whereas, the variations for back to back repeats for each fuel (nine repeats for acceleration and five repeats for steady states) averaged at a standard deviation of 1.0%.

Acceleration and Steady State Test Procedure

The power and acceleration generated by an engine equipped with knock sensors depends on the octane quality of the fuel. [13]. The octane appetite of a vehicle could be ideally measured from spark timing data which allows other effects such as fuel air mixing and flame speed to be disentangled from the anti-knock quality of the fuel. However, it is not always practical to do this for a fleet of vehicles and hence the octane appetite of a *vehicle* is best measured *via* the acceleration performance and steady-state torque output on different fuels. [12] Hence, acceleration times and dynamometer tractive force (proportional to engine torque) were used to compute K values and corresponding octane indices.

The engine was warmed up with a preconditioning procedure. The procedure included US-06 drive cycles and accelerations which were repeated until the acceleration time stabilized. Then the acceleration procedure was followed for two gear set points. The DAQ (Data Acquisition) system was started before placing the vehicle in the desired gear. At least ten accelerations from idle to 80 mph at WOT were performed using a robot pedal during each fuel repeat (nine accelerations used for data analysis).

For steady state measurement, the dynamometer was set to “hold speed” mode after preconditioning. Then ten steady state WOT (Wide Open Throttle) excursions were carried out for 1500, 2500, and 3500 RPM (five steady state excursion used for data analysis). Steady state tractive force measurements were captured at the stated engine speeds. All data were collected and compiled at 10 Hz by the DAQ system except for vehicle speed which was recorded at 100 Hz.

RESULTS AND DISCUSSION

Acceleration Tests

Acceleration times and steady state dynamometer tractive forces were used as performance metrics to compute K values. Octane index is represented by the weighted combination of RON and MON, and K defines the relative importance of RON and MON in octane quality of the engine. [12]

OI depends on the K-value which is determined *via* linear fitting or an iterative quadratic/exponential fitting until the error sum between the fitted engine performance parameter and octane index is minimized. An example result plot is shown in the [Figure 3](#). The plot shows that acceleration times correlate better with RON rather than MON; however, the correlation is much better using OI instead of RON or MON in agreement with literature. [12] K values computed from acceleration times are presented in [Figure 4](#).

For each vehicle, K values were calculated for a different acceleration range and gear shown above the x-axis for the plots in [Figure 4](#). Three different curve fitting methods were used: linear, quadratic, and exponential. The fitting model that gave the highest R^2 value for the fit was used to obtain the corresponding K value; every K value reported had an R^2 minimum set at 0.8 to be deemed as a significant fit. (R^2 values are shown in [Tables A1](#) and [A2](#)) As an example, for V2, in 6th/30-50 mph condition, the R^2 for fits from all models was <0.8 and hence no value of K is shown.

It is seen from [Figure 4](#) that all the K values obtained are negative. This indicates that the octane index is moving more away from MON. When engines are operated under less knocking conditions such as at low loads in the same gear, K values generally became more positive. This is also consistent with the previous study by Kalghatgi. [8]

K values become increasingly negative with the increase in knock propensity. Therefore, one can expect to see a more negative K value at lower engine speeds at a given load condition. For e.g. V1 at the same gear, a full range of acceleration test (25-80 mph) resulted in a less negative K-value than that from a low range acceleration test (25-50 mph) - as engines are operated at higher speeds in a lower gear, the speed conditions allow less time for the end gas to spontaneously combust, so the engines are less prone to knock. However, for the same acceleration range higher gear operation generally resulted in a more negative K value as engines are relatively more prone to knock.