

The Shift in Relevance of Fuel RON and MON to Knock Onset in Modern SI Engines Over the Last 70 Years

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ABSTRACT

Since the advent of the spark ignition engine, the maximum engine efficiency has been knock limited. Knock is a phenomena caused by the rapid autoignition of fuel/air mixture (endgas) ahead of the flame front. The propensity of a fuel to autoignite corresponds to its autoignition chemistry at the local endgas temperature and pressure. Since a fuel blend consists of many components, its autoignition chemistry is very complex.

The octane index (OI) simplifies this complex autoignition chemistry by comparing a fuel to a Primary Reference Fuel (PRF), a binary blend of iso-octane and n-heptane. As more iso-octane is added into the blend, the PRF is less likely to autoignite. The OI of a fuel is defined as the volumetric percentage of iso-octane in the PRF blend that exhibits similar knocking characteristics at the same engine conditions.

Since the OI is dependent on the engine operating conditions, it is typically measured at two standard test conditions: the Research and Motor Octane Number (RON and MON) tests. These tests are intended to bracket the knock-limited operating range, and the OI is taken to be a weighted average of RON and MON:

$$OI = K \text{ MON} + (1-K) \text{ RON} = \text{RON} - K S$$

where K is the weighing factor and S is the fuel sensitivity (RON-MON). When the tests were established in 1932, the MON test matched the OI on the road, hence the average value of K was 1; however, recent studies have found that the average value of K is negative.

The parameter K, which is independent of a fuel, can be used to show the relevancy of the RON and MON tests. When $K = 0.5$, the average of the RON and MON tests is a good indicator of a fuel's antiknock performance. However, when K is negative, for a given RON, fuels with a higher sensitivity have better antiknock performance; therefore, an increase in RON or MON does not necessarily correlate to better antiknock performance.

In the decades following the development of the octane number, tests were performed to determine the value of K. However, as K approached a value of 0.5, these tests ceased to be performed.

The Coordinated Research Council (CRC) collected data from 1951 to 1991 to determine the required fuel octane number to avoid fleet vehicles from knocking. The tests typically included both PRFs and reference fuels representative of commercial gasoline, the latter having a non-zero sensitivity. Therefore, a value of K can be determined for each test. Using the data from 1951, 1961, 1971, 1981, and 1991, the average values of K were found for each year.

The study then explores the changes in the engine operating conditions that would cause these changes. To better understand these relationships, the values of K for modern and historic engines were determined by WAVE engine models. The models found that the average value of K is positive for a historic engine, but is negative for modern engines.

This study found that for domestic engines, K is now negative, having decreased from a value of 1 in 1930. This decrease in K is primarily due to better engine cooling, better engine breathing, and the usage of fuel injectors.

INTRODUCTION

The term knock refers to the engine noise that accompanies the rapid autoignition of unburned fuel and air as the flame propagates across the chamber [1]. The noise is created by the rapid pressure rise and oscillations caused by the autoignition process.

Typically, knock is an annoying metallic clanking noise, and heavier knock can be an indication that engine damage is occurring. Therefore, engine manufacturers strive to avoid knock. Since the autoignition process occurs more rapidly at higher pressures and temperatures, the maximum allowable pressure and temperature in an engine is set by the autoignition chemistry of the fuel. Hence, the maximum compression ratios and boosting percentages are currently knock-limited. To advance these knock limits, it is necessary to use a fuel that is resistant to autoignition.

A fuel's propensity to autoignite and cause knock is quantified in terms of an octane index (OI). The concept behind the OI is that a fuel's complex chemistry can be compared to a simpler, more predictable binary fuel blend. The binary blend used in these comparisons is a primary reference fuel (PRF), a blend of iso-octane and n-heptane. As the percentage of iso-octane increases in the blend, the fuel mixture is less likely to autoignite. The OI of a fuel is the volumetric percentage of iso-octane in the PRF that knocks at the same intensity at the same conditions. For example, if at a given condition, a fuel's knocking behavior is similar to a blend of 96 percent iso-octane, 4 percent n-heptane (PRF96), the fuel would have an OI of 96. However, the OI depends on the engine conditions, so at another condition the fuel could have an OI of 87.

RON, MON, SENSITIVITY, AND K

Since the OI depends on the engine operating conditions, it is measured at two different test conditions for fuel rating purposes. These two conditions are the Research and Motor Octane Number (RON and MON) tests, which are described in detail in [2] and [3] respectively.

The tests are done in a Cooperative Fuel Research (CFR) engine at the conditions shown in Table 1. The inlet conditions and engine speed are fixed, and the compression ratio is increased until the engine knocks at a given intensity. The procedure is then repeated for different PRFs until a PRF is found that knocks at the same intensity at the same compression ratio. The RON and MON of a fuel are the Octane Indices measured in these specific tests [2,3].

The main differences between the RON and MON tests are the intake air temperature and the engine speed.

These two parameters are also different from those in modern engines. Modern engines have intake air temperatures that are well below the RON and MON tests. In particular, the intake air temperature of the MON test is over 100°C above that of modern engines. Additionally, though cars can idle at 600 rpm, they seldom operate at full load at engine speeds below 1200 rpm.

The difference between the RON and MON is termed the sensitivity, S:

$$S = \text{RON} - \text{MON} \quad (1)$$

By the definition of an octane number, the sensitivity of a PRF is 0. However, most commercial fuels have a sensitivity of 8 [4].

Parameter	RON	MON
Intake Air Temperature	52°C	149°C
Intake Air Pressure	atmospheric	atmospheric
Coolant Temperature	100°C	100°C
Engine Speed	600 rpm	900 rpm
Spark Timing	13° BTC	14-26° BTC
Compression Ratio	4-18	4-18

Table 1: The engine conditions for the RON and MON tests [2,3]

Since the RON and MON are the OI of a fuel at two fixed conditions, the OI can be interpolated from these values using a weighing factor, K:

$$\text{OI} = (1-K) \text{RON} + K \text{MON} = \text{RON} + K \times S \quad (2)$$

K is based off the work by Kalghatgi and is assumed to be independent of the fuel, depending only on the engine operating condition [5,6]. It should be noted that K = 0 corresponds to the RON test and K = 1 corresponds to the MON test. Since the OI posted on retail gasoline dispensers in the United States is (R+M)/2, this value of K=0.5 is used to define a fuel's "on the road" octane number.

An experimental study presented in a previous paper [7] determined how different engine parameters govern K. The results show that K increases with engine speed, increases with intake air temperature, and decreases with intake air pressure. These trends indicate that K should decrease as the air charge entering the engine increases.

Between 1930 and the present, the average value of K has decreased from a value of 1. Recent studies have found that the average value is slightly negative [5,6]. When K is negative, for a given RON, fuels with a higher sensitivity (i.e. lower MON) have better antiknock performance. Additionally, when K is negative the current octane number system fails since an increase in

RON or MON does not necessarily result in an increase in antiknock performance.

CHANGES IN ENGINE TECHNOLOGY BETWEEN 1930 AND PRESENT

The RON and MON tests were designed to be representative of commercial American engines in 1930. Though the tests have not changed, engine technology has advanced significantly since then. Engine computer units now allow for advanced engine controls, replacing antiquated servos and mechanical devices. Engine geometries are designed using CFD and chemical kinetic modeling to optimize burn speeds and minimize knock. All of these changes can be exemplified through the change in engine performance. The 1930 Ford Model T engine could produce a maximum of 22 HP, corresponding to 1600 RPM. Meanwhile, the 2008 Ford Fusion engine, which has the same displaced volume as the Model T, produces a maximum of 221 HP corresponding to 6250 RPM [8].

Figure 1 shows the change in the average engine displaced volume and compression ratio between 1930 and the present [8-14]. The compression ratio increased rapidly between 1930 and 1960. It then leveled off between 1960 and 1980 and continued to rise from 1980 to 2008. The displaced volume increased steadily between 1950 and 1970. The value then sharply declined between 1970 and 1980 and stayed relatively constant around 3.3 L until the present.

The increase in compression ratio between 1930 and 1960 can be attributed to the commercial availability of high octane fuels. The development of the octane tests allowed for the standardized testing of fuels, hence fuels could be optimized to avoid knock. Further, during World War II, the United States developed many techniques, such as catalytic cracking, to mass produce high octane fuels. These techniques slowly spread into the commercial sector, and by 1960, new cars were utilizing this high octane fuel such that the engines could operate at higher compression ratios. [15]

Between 1960 and 1970, the compression ratio stayed constant, but the average displaced volume increased significantly. The methodology at the time to increase engine power was to make larger engines. However, this trend was non-sustainable due to the oil crisis in the mid 1970s. Between 1970 and 1980, the average displaced volume decreased by 35%. The compression ratio also decreased between 1970 and 1980 because tetraethyl lead, a key antiknock agent, was being removed from fuels on the market.

Between 1980 and 2008, advancements in engine technology facilitated an increase in compression ratio, allowing for the engine power output to increase without increasing the displaced volume.

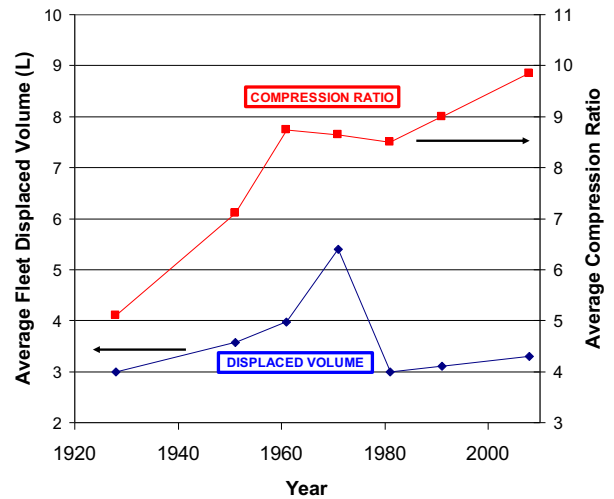


Figure 1: The average displaced volume and compression ratios in 1951-1991.

Engine breathing technology has advanced significantly since 1930. Engine designers strive to increase the volumetric efficiency of the engine, hence decreasing the pressure losses in the intake manifold. Consequently, with fewer losses in the intake manifold, the air charge entering the engine at wide open throttle increases. The results from [7] found that K decreases as the intake air pressure increases, which also corresponds to an increase in air charge entering the engine.

Figure 2 shows the torque versus engine speed curve for different intake air systems. The increase in torque corresponds to an increase in the air charge entering the engine due to better engine breathing. The figure is from 1989, so the “contemporary 2-valve” engine corresponds to those that would have been present in 1990 engines [16]. Figure 3 shows that in 1990, half of the car engines used a four valve system and half used a two valve system [17]. A linear extrapolation gives that a negligible number of engines had 4 valves before 1980. The major improvement between “historic” and “contemporary” 2-valve engines is engine tuning. Between 1950 and 1980, the increase in air charge in the engine increased due to tuning, which decreased the losses in the intake system, especially at higher speeds. The use of 4-valve cylinders further enhanced this trend by increasing the flow area.

Another major change in engine technology has been the decreasing temperatures in the engine. The biggest advancement in early engine design in the 1930s was the “notable strides in engine cooling. [18]” These engine cooling techniques included full-length cylinder jackets which allowed for the free circulation of water around the cylinder. These techniques eliminated hot spots which were a common source of autoignition. The better engine cooling resulted in a decrease in end-gas temperatures, which would decrease the value of K [7].