I HEAR YOU KNOCKING: AUTOMOTIVE KNOCK AND THE OCTANE NUMBER

Octane is a saturated hydrocarbon molecule that consists of a chain of eight carbon atoms with eighteen hydrogen atoms. More commonly, octane is a term that is associated with the performance of gasoline fuels, where the octane rating is listed at each gasoline pump at various grades. When filling up a car with gasoline, not many people put much thought into which octane fuel grade to select and simply select what fuel is recommended to use by the vehicle's manufacturer.

However, the development of these fuels is not as simple, and requires extensive research, development, and testing to enhance a fuel's octane rating to ensure effective engine performance. This paper will discuss the history of octane and test methods to determine the octane rating, and will assess how these octane rating test methods correlate to fuel performance in modern engines.

Octane rating is a measure of a fuel's ability to resist knocking. Engine knock is seldomly experienced by drivers of modern-day cars, as a result of highly developed fuels and engines. In a typical gasoline engine, the cylinders are designed so that ignition of the gasoline occurs at the spark plug just before the piston reaches the top dead center position. However, it is possible for fuel ignition to occur prematurely in a pocket of fuel in the cylinder when exposed to heat and large amounts of compression, and this results in engine knocking. High temperatures and compression both contribute to early autoignition of gasoline.

For a given fuel, two factors will influence the autoignition behavior of the fuel: the temperature and the compression. These factors are designed into every vehicle's engine as the operating temperature and the compression ratio. Due to the nature of combustion reactions, the operating temperature is more difficult to reduce to a point where the autoignition of the fuel is improved.

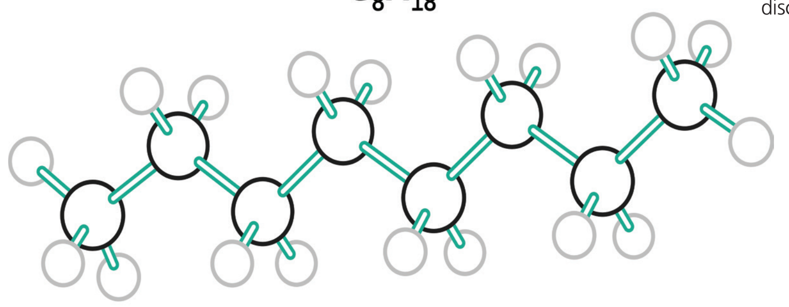
Therefore, the compression ratio is a factor that is used to improve engine knock and fuel autoignition. The compression ratio is the ratio of the cylinder volume when the piston is at bottom dead center to the cylinder volume when the piston is at top dead center. This is essentially a ratio of the cylinder's maximum volume to the cylinder's minimum volume.

On one hand, higher compression ratios can produce higher quantities of work from a thermodynamics point of view and have been shown to have higher thermal efficiencies and can achieve greater performance. But on the other hand, higher compression ratios are more prone to engine knock, since the compression is greater. Due to this, high performance vehicles are typically designed with higher compression ratios, where the typical modern gasoline car is designed with a compression ratio between 8:1 to 10:1. In comparison, diesel engines can operate at higher compression ratios since the diesel cycle introduces diesel fuel into the combustion chamber only when the air in the chamber has been compressed to achieve conditions for ignition, and typically ranges between 18:1 to 23:1.

The compression ratio is a part of the engine design to combat engine knocking. Another method to prevent engine knock is by modifying the composition of the gasoline fuel. Gasoline is a blend of hydrocarbons produced from the distillation of crude oil. Additives are commonly introduced into gasolines to improve the performance as well.

Certain components in a gasoline may contribute to a higher octane rating than others. For example, when the octane rating is measured, it is compared to a blend of two components: iso-octane and n-heptane. Iso-octane has a reference octane rating of 100, while n-heptane has a reference octane rating of 0.

C_8H_{18}



Octane

Octane boosting additives have been used in gasoline since the early 20th century. Engineers working for General Motors discovered that lead, or tetraethyl lead by its chemical name, boosted the octane in gasoline in 1921. Leaded gasoline was the dominant type of gasoline in the United States for years after its octane boosting discovery due to its cheap production cost. However, in the 1970s with the passage of the Clean Air Act, the EPA began to phase out leaded gasoline due to its damages to catalytic converters, which would have possibly caused adverse effects for public health.

As lead became discontinued for use as an octane enhancer, the use of aromatics became more common. Aromatic compounds naturally exist in gasoline but can be added in higher concentrations to increase the octane rating. By 1990, the composition of aromatics in gasoline rose to about 33% in standard gasoline grades and to about 50% in premium grades from a value of only 22%.

However, as aromatics content increased in gasoline, so did the concerns over the safety of these compounds. In 1990 with Congress passing the Clean Air Act Amendments, the content of aromatics in gasoline was reduced to 25 to 28 percent, since these aromatic compounds, such as benzene, were shown to be highly toxic.

With another octane boosting additive restricted by the EPA, gasoline producers were forced to look for an alternative. In modern fuels, ethanol is a common component that also acts as an octane booster. In its pure form, ethanol has an octane rating of about 100. In the United States, the most common form of gasoline sold is E10, which is a blend of 10 percent ethanol and 90 percent gasoline. Additionally, pure ethanol burns cleaner and is less toxic than octane additives derived from petroleum sources.

In the early 1900s as cars were developed, engine knocking was becoming a prominent issue. As engine knocking is a result of fuel autoignition, there was a demand for a test method to quantify the autoignition properties on a fuel as a measure of the fuel's anti-knocking capabilities. The first drafts of these test methods were developed by Harry Ricardo, and involved running a fuel under set engine conditions and increasing the compression ratio until an audible engine knock was observed. The compression ratios were correlated to a reference fuel blend, but with a high margin of variability with these fuel blends, there was significant limitations on the reliability of the Ricardo method.

In 1920, the Cooperated Fuel Research (CFR) committee was formed by the Society of Automotive Engineers (SAE) and the American Petroleum Institute (API) to determine a methodology to sufficiently assess a fuel's antiknock properties. Ultimately in 1928, the committee settled on a test with a specific engine, the CFR engine, which utilized a variable compression ratio similar to the Ricardo test.

Like the Ricardo test, the CFR engine runs on the fuel and the compression ratio is increased until the engine knocks. However, one key difference between the two engines is that the CFR engine detects knock with a bouncing pin, instead of an audible observation by the operator. Then, the fuel is compared to a primary reference fuel (PRF) that is a binary blend of iso-octane and n-heptane (with reference octane values of 100 and 0, respectively). The octane number of the fuel is then defined as the percentage of iso-octane in the PRF blend that results in engine knocking at the same compression ratio (such that a fuel with an octane rating of 83 would knock at the same compression ratio as a PRF with 83% iso-octane and 17% n-heptane).

One concern with the CFR engine is how the resulting octane number will vary depending on the conditions of the engine. Initially, the tests were standardized with an engine speed of 600 rpm and an intake temperature of 52°C. Under these conditions, the octane number obtained is referred to as the Research Octane Number (RON).

However, the RON method was met with criticism as its use become more widespread. In 1932, tests determined that the RON method does not sufficiently assess the fuel's resistance to knock during driving conditions. This failure was even more prominent in European fuels at the time, where aromatic compounds were more abundant compared to the more paraffin fuels in America.

To address this criticism, the CFR committee developed a new method with a different set of test conditions to better simulate the antiknock capability of fuels during driving conditions. The new method was standardized under more harsh conditions than the existing RON method, with an engine speed of 900 rpm and an intake temperature of 149°C. The octane number that is obtained under these conditions is referred to as the Motor Octane Number (MON).

For a given fuel, the MON is generally lower than the RON by a value of about 8-10. The term "sensitivity" is defined as the difference between the RON and MON measurements. Some fuels are more sensitive than others, with paraffinic fuels typically having lower sensitivity values than aromatic fuels. In America, the octane values that are seen on modern gas pump express the octane number in terms of the Antiknock Index (AKI) format, which is simply the average of the RON and MON values.

Despite issues and complications still existing with the new MON method, it was still an improvement for octane testing. With no clear alternative in the 1930s to these methods, the use of the RON and MON methods became more accepted globally.

These methods are still used today, and are often referred to as test methods ASTM D2699 and ASTM D2700, which are the standard test methods to determine the RON and MON of spark-ignition engine fuel, respectively. The operating conditions are specified in these methods, and the test methods are run on an standardized single cylinder, four-stroke cycle, variable compression ratio, carbureted engine.

Since the development of these octane test methods in the early 1900s, engine technology has advanced significantly. As a result, there is a rise in concerns over the applicability of these test methods to modern engines. For example, the 1930 Ford Model T could output up to 22 hp with 1600 rpm, while a 2008 Ford Fusion can output up to 221 hp with 6250 rpm. It is worth noting that both of these vehicles utilize the same displaced volume in their engines.

Compared to vehicles from 1930, modern engines use only slightly larger displaced volumes, which may surprise some considering the steep increase in vehicle performance since then. However, the compression ratio has increased dramatically over this time period, from a ratio of just above 4:1 in 1930 to a ratio of slightly below 10:1 in 2010. This increase in compression ratio is largely due to the development higher octane fuels and improved engine technology, which can maintain higher compression ratios.

Furthermore, modern engine technology has allowed cooler engine operating temperatures to exist. High temperatures can contribute to fuel autoignition and engine knock. With improved cooling technology, "hot spots" that appear in the engine are removed, reducing the autoignition tendencies of a fuel.

Another significant difference between older and modern engines is the removal of the carburetor. Early engines used carburetors to help heat the intake air and vaporize the fuel. Since 1990, new engines now use fuel injectors as opposes to carburetors to accomplish this. A fuel injector does not require the intake air to be heated in order to vaporize the fuel, like a carburetor does. It is worth noting that the test engine used in the RON and MON test methods still utilizes a carburetor, a now outdated part of the engine system.

With such drastic changes to engines over the last 90 years, it is clear that there may be concerns with how the technology and method used to measure the octane ratings is outdated. To mathematically demonstrate how these methods may not accurately measure octane in modern engines, a weighing factor (K) was designed in a linear interpolation model for the octane index (OI) by Kalghatghi. The OI is the PRF that a fuel is behaving like at on-the-road conditions, such that a higher OI indicates better antiknock performance. The K factor is defined in Equation 1.

$$OI = RON - K*(RON-MON)$$

K is assumed to only be dependent on the engine operating conditions, since it is designed to be independent of the fuel. If K is equal to 0, the octane index OI is the same as the RON, and if K is equal to 1, the octane indexOI is the same as the MON. In America, the AKI (average of RON and MON) is used to define a fuel's octane, thus the K value is taken as 0.5.

K can also be negative, which would indicate a failure in the current octane rating system, since an increase in the MON may not produce improved antiknock performance.

Fundamentally, the reason K is negative is tied to the octane tests being based on iso-octane and n-heptane, both of which are paraffinic fuels. Paraffins have worse antiknock avoidance at low temperatures and better at higher temperatures compared to aromatics, olefins, or alcohols. The high temperatures in the octane number tests, especially the MON, creates a bias towards using a paraffinic fuel. However, modern engine operating temperatures are more conducive for other fuel types.

Analyzing historical K values may indicate that there are increasing levels of inaccuracyies in the octane number testsing. Data from 1951 shows that even under high engine speeds, the K value is below 0.5, signifying that the assumption of K equal to 0.5 as labelled on all gasoline pumps in America is incorrect. Since 1951, the values of K have only decreased, and based off the published data, the value of K could potentially be around 0 as of 2001. This trend of decreasing K value is a result of improvements to the modern engine, such as decreased operating temperatures, the introduction of the fuel injector, and increased air intake pressures.

Furthermore, there has been a large increase in the percentage of tests with negative K values. In 1951, only about 10% of tests results in a negative K value, where in 1991, approximately 45% of tests produced a negative K value. As stated previously, a negative K value would indicate a failure in the current octane number measuring system to quantify a fuel's antiknock capabilities.

With increased compression ratios, turbocharging, direct-injecting, and countless other engine improvements being introduced to new engines, the K value is expected to continue to decrease into the negative regime. At a K value of 0, the MON test loses its relevancy, as the octane index is then a function of the RON exclusively. As K becomes negative, the results drawn from both the RON and MON tests on the octane index become uncertain, which is expected to happen as engineers design newer engines.

The octane tests have been used for 90 years and have become entrenched in society. Moreover, knock is an important issue. As such, there is no expectation that the octane number system will go away. However, several alternatives have been proposed to fix its issues. The first method is to change the reference fuels to include toluene, an aromatic, into the blend. This recommendation was first made by Henry Ricardo in the 1930s, but it has been revisited with the increased push from the automotive and fuel industries. A second method is reevaluating the importance of the MON in the octane rating given at the fuel pump. The value at the pump is currently the average of the RON and MON, associated with a value of K as 0.5. By changing the weightings, the octane rating on the pump can reflect the negative K values. A third method involves changing the test conditions to better capture modern engine operating conditions. Different universities, laboratories, and fuel companies are evaluating these different alternatives. When most people purchase gasoline, they do so without a full understanding of the fuel's octane number. Even people familiar with knock will generally assume that the higher the octane number, the lower the propensity for the fuel to knock. While originally conceived as a simple method of capturing the antiknock properties of a fuel, complex fuel chemistry coupled with the intricacies of modern engines result in a much more complicated relationship.

https://auto.howstuffworks.com/fuel-efficiency/fuel-consumption/question90.htm

https://www.eesi.org/papers/view/fact-sheet-a-brief-history-of-octane

https://www.davidowen.net/files/octane-and-knock-8-1987.pdf

http://octanecompound.weebly.com/history.html

https://www.frontiersin.org/articles/10.3389/fmech.2015.00016/full

http://www.autos.ca/car-history-and-auto-shows/feature-a-brief-history-of-octane/

https://www.bellperformance.com/blog/bid/101182/What-Does-Octane-Do-In-Gasoline-Octane-Ratings

https://www.proctorhonda.com/octane-ratings

https://www.chicagotribune.com/news/ct-xpm-1992-08-16-9203140056-story.html

https://www.fuelfreedom.org/what-is-octane/

https://www.consumer.ftc.gov/articles/0210-paying-premium-high-octane-gasoline

https://www.cheatsheet.com/automobiles/engines-exposed-what-is-octane-and-why-does-it-matter.html/

https://www.worldofmolecules.com/fuels/octane.htm

https://shop.advanceautoparts.com/r/advice/car-technology/does-the-type-of-gasoline-you-use-really-matter

https://www.cnet.com/roadshow/news/why-do-we-have-midgrade-89-octane-gas-at-the-pump/

https://www.researchgatenet/publication/275541824_Calculation_of_Gasoline_Octane_Numbers_Taking_into_Account_the_Reaction_Interaction_of_Blend_Components

https://www.kbb.com/car-advice/articles/premium-gas-when-and-why/

https://auto.howstuffworks.com/premium-gas-luxury-vehicles.htm

https://www.edmunds.com/fuel-economy/to-save-money-on-gas-stop-buying-premium.html

https://www.cartalk.com/content/premium-vs-regular-1

https://www.freep.com/story/money/cars/mark-phelan/2017/04/25/new-gasoline-promises-lower-emissions-higher-mpg-and-cost-octane-society-of-automotive-engineers/100716174/

https://www.scientificamerican.com/article/fact-or-fiction-premium-g/

https://www.truecar.com/blog/2011/03/03/premium-vs-regular-gas/

https://www.thoughtco.com/what-kind-of-gasoline-to-use-532752

https://www.ncconsumer.org/news-articles-eg/high-octane-fuel-doesnt-always-equal-better-performance-or-better-gas-mileage.html

"The Development of the Octane Number Tests and their Impact on Automotive Fuels and American Society," Vikram Mittal, Int. J. For The History of Eng. & Tech., 2016, Vol. 86, No. 2, pp. 213-227.

"The Shift in Relevance of Fuel RON and MON to Knock Onset in Modern SI Engines Over the Last 70 Years," Vikram Mittal and John B. Heywood, SAE International Journal of Engines, 2010, Vol.2, No. 2, pp. 1-10.

Kalghatgi, G.T., "Fuel Anti-Knock Quality – Part 1, Engine Studies", SAE paper 2001-01-3584, 2001.

Kalghatgi, G.T., "Fuel Anti-Knock Quality – Part 2, Vehicle Studies—How Relevant is Motor Octane Number (MON) in Modern Engines", SAE paper 2001-01-3585, 2001.

Author Contact Details

Dr. Raj Shah, Koehler Instrument Company • Holtsvile, NY 11742 USA • Email: rshah@koehlerinstrument.com • Web: www.koehlerinstrument.com

Dr. Raj Shah is currently a Director at Koehler Instrument Company, NY (a renowned manufacturer of petroleum testing instruments) and an active ASTM member for the last 25 years. He held numerous leadership positions within various ASTM committees and is recipient of the ASTM award of Excellence (thrice : a sui generis distinction) and the ASTM Eagle Award. A Ph.D in Chemical Engineering from Penn State University, and a Fellow from The Chartered Management Institute, London, Dr. Shah recently coedited , a reference bestseller titled "Fuels and lubricants handbook", published by ASTM. https://www.astm.org/DIGITAL_LIBRARY/MNL/SOURCE_PAGES/MNL37-2ND_foreword.pdf

He is an elected fellow at Energy Institute, NLGI, STLE, IChemE, INSTMC, AIC, CMI, and RSC and a Chartered Petroleum Engineer. A recently elected Fellow by the Institution of Chemical engineers, UK, Dr. Shah was also recently honored with an esteemed engineer designation by Tau Beta Pi, the highest engineering honor society in USA. More information on Raj can be found at https://www.che.psu.edu/news-archive/2018/Alumni-Spotlight-Raj-Shah.aspx

Dr. Vikram Mittal, Assistant Professor at the United States Military Academy in the Department of Systems Engineering

He earned his doctorate in Mechanical Engineering at the Massachusetts Institute of Technology where he researched the relevancy of the octane number in modern engines. His current research interests include system design, model-based systems engineering, and engine knock.