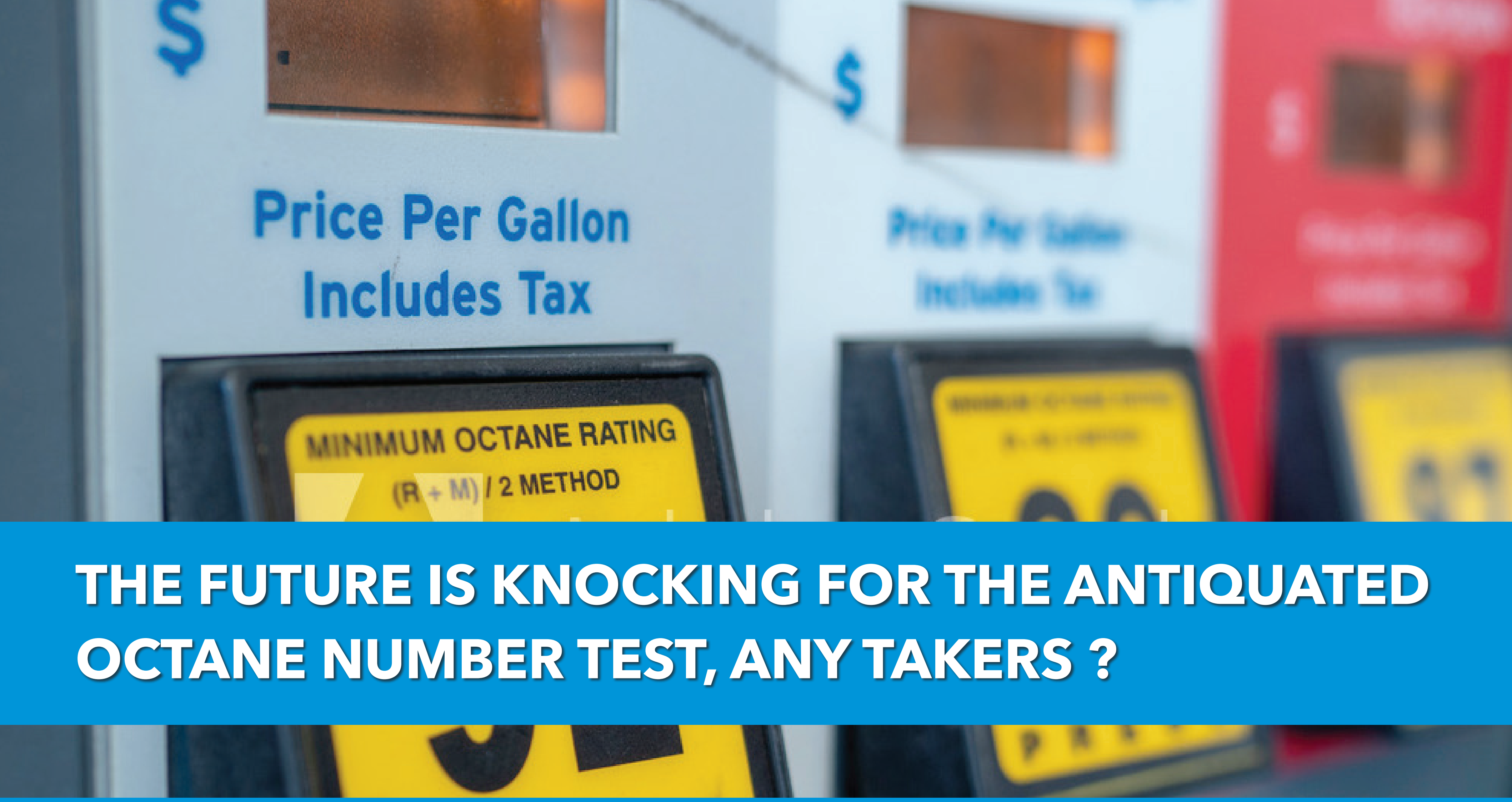

THE FUTURE IS KNOCKING FOR THE ANTIQUATED OCTANE NUMBER TEST, ANY TAKERS ?

Although many older drivers will recall their cars knocking when driving uphill on hot days, the average driver under the age of fifty likely has never heard an engine knock. Indeed, different techniques have been implemented in engines to avoid that annoying "pinging" sound. However, this does not mean that knock has been conquered. Rather, knock is a large issue that continues to plague modern engine design, including impacts to the overall vehicle performance and efficiency [1].

Knock is caused from the chemical autoignition of gasoline associated with the high temperatures and pressures in the engine. The autoignition of the fuel can occur during the combustion phase of the engine cycle, when a portion of the fuel has combusted, resulting in a high temperatures and pressures, which help drive the chemistry [2]. This autoignition event is very rapid and results in a large energy release that causes the engine to resonate, creating the namesake sound. Avoiding this autoignition event, and hence knock, requires reducing the peak temperatures and pressures in the engine.

The first step in avoiding knock is reducing the in-cylinder temperatures. Increased engine cooling results in engine efficiency losses, so the cylinder walls are maintained around 100°C. However, the intake air can be cooled with no efficiency losses, while also lowering in-cylinder temperatures. For modern engines with open intake systems, it is impractical to cool the intake air below atmospheric temperature. However, for turbocharged or supercharged engines, the charged air can be cooled through a combination of intercooling and direct injection. Even with these cooling effects, lowering the temperature is typically not enough to avoid knock. Therefore, the temperatures reductions must be coupled by decreasing the peak pressure of the air in the cylinder.

The peak pressure at full load can be reduced by two methods. The first method is to limit the compression ratio of the engine. However, the compression ratio of the engine is tied to the overall efficiency of the engine. The compression ratios of modern spark ignition engines are around 12, the maximum value that can help stave off knock at higher engine speed [3]. Historic trends show that as fuels became more resistant to knock, the compression ratio gradually increased [4]. The second technique is related to the spark timing. By making the spark occur later in the cycle, the pressure increase from combustion occurs while the cylinder is expanding, reducing the peak pressure. This technique is used by modern knock sensors, which change the spark timing when an accelerometer picks up that an engine is starting to knock [5]. However, a later spark timing results in a decrease in the energy output for the engine cycle and decreased performance.

Knock will only occur at those engine operating conditions associated with high in-cylinder pressures and ample time for the autoignition chemistry to occur. As such, it typically occurs at loads greater than 80 percent of full load and engine speeds below 2500 RPM. During these conditions, the engine will use a non-optimal spark timing to avoid knock [6]. This engine operating range is important because the full load, low-speed engine range is typically used when the vehicle rapidly accelerates [7]. Many cars advertise their 0 to 60 mph acceleration times, with this time often equated to vehicle performance. During this acceleration event, the engine will seldom leave the knock-limited range of conditions.

Vehicles and engines are designed around efficiency and performance. Knock is the underlying driver for both of these design parameters. Although drivers will likely never hear their engine knock due to the knock control system (which trades off performance and efficiency to avoid knock), knock is as relevant to modern engines as it was to older engines. Therefore, it is imperative that fuels continue to improve to allow for more efficient and better performing engines [8].

Unfortunately, the development of fuels to avoid knock has been hindered by the octane number tests. The octane number test quantifies a fuel's propensity to knock; fuels in-turn are blended achieve certain octane requirements. These tests compare the antiknock performance of a fuel to a set of standard reference fuels at two set test conditions – the research and motor condition. The research test condition, which provides the research octane number (RON), represents engine temperatures and pressures that are comparable to modern engines. The motor test condition, which provides the motor octane number (MON), uses significantly higher temperatures to represent more demanding test conditions. Numerous studies have shown that while the RON still captures antiknock performance in modern engines, the MON does not. In fact, numerous studies have found that if two fuels have the same RON, the one with the lower MON will have better antiknock performance [9].

Figure 1: Combination Octane Rating Unit Engine for RON and MON determination of Gasoline

An issue arises that regulations set the minimum RON and MON values for standard and premium fuels, with the pump then simply providing the average of the two values, as shown in Figure 1 [10]. For example, premium fuels must have a RON value greater than 96 and a MON value greater than 86, such that the pump will display a value a minimum value of 91. Increasing the RON value of a fuel is fairly straightforward, since the base stock of fuel will have a reasonably high RON. However, the high temperatures associated with the MON test makes it significantly harder to increase the MON. Increasing MON requires additional refining to increase the iso-paraffin content of the fuel; this process is expensive and energy intensive.

The underlying issue is that the tests have not been significantly updated since 1928. When the tests were developed, the average fuel octane number was considered 50, with 100 being the holy grail of fuels. Soon after the development of the tests, advancements in catalytic cracking technology resulted in higher octane fuels (around 90) becoming common-place [11]. However, the octane numbers of fuels have not significantly increased in the past 50 years as shown in Figure 2. Since society typically equates the octane scale to a grade scale, a 90 octane fuel equates to an A, so there is no innate push for higher octane fuel. However, a high octane number simply indicates that a fuel behaves very similarly to iso-octane, a fuel known as having good anti-knock properties. Many other fuels have significantly better anti-knock properties, especially in the range of engine conditions relative to knock in modern engines.

Figure 2: The change in fuel Octane Number with time. Note that there has not been any significant increase since 1955.

This issue becomes more significant with the increased usage of non oil-based fuels, particularly biofuels. Biofuels, including ethanols, are often negatively penalized by the MON test [12]. At normal engine operating conditions and those of the RON test, biofuels typically have exceedingly good antiknock properties. However, at the unrealistically high temperatures associated with the MON test, they perform poorly. With the current octane standards, biofuels are penalized for poor antiknock performance at irrelevant conditions.

In order to realign the octane test methods towards newer naturally-aspirated and turbocharged engines there are several methods of improvement. The simplest method takes into account the various issues of the octane number test such as the decreasing relevance of the MON and attempts to adjust policies appropriately, in this case changing minimum MON values necessary for fuels or phasing it out entirely. Adjusting the current policy for the incorrect alignment of the MON test conditions with modern engines alone is unable to fully amend the current issues surrounding the octane test methods [13]. On the contrary, adjusting policies for the octane number and testing methods should act as an outline for the correct path to improve and rectify the test conditions of the RON and MON.

With the reconstruction of the overarching policies concerning the octane number the method to rectifying the foundation of the octane test methods becomes clear. While also apparent in the comparison of operating conditions of modern engines to engines from the past, modern engines run at lower temperatures, higher rpm, and greater intake air pressure, especially when considering modern turbocharged engines. As such, the RON and MON test conditions should be modified to also reduce the temperature and increase the rpm and intake pressure to then become a more reliable metric for analyzing the anti-knock properties of fuels.

Even then the best octane rating possible would be limited to the anti-knock properties of iso-octane used as part of the reference fuel for the RON and MON tests. As mentioned, premium fuels must maintain a minimum 91 octane rating which is near the limit of the current reference fuel. Thus, the reference fuel blend can be modified such that it has greater anti-knock properties such as by replacing iso-octane with toluene [14]. As toluene has a much greater resistance to knock compared to iso-octane, its utilization in a new reference fuel would allow RON and MON values to shift downwards encapsulating a broader range of the ever increasingly knock resistant fuels and allowing greater room for improvement of anti-knock performance for modern fuels.

Simple policy changes and updates to the octane number system, briefly discussed previously, would provide substantial benefit to the oil industry, gasoline consumers, and the environment. For the oil industry, they would no longer have to sink money into refining fuels to have a higher MON. The base stock of fuel consists of aromatics, olefins, paraffins, and napthenes. Typically, the olefins are very attractive in terms of a number of fuel properties including RON value; however, they typically have a low MON value. Meanwhile, the paraffins are not quite as attractive, but they have a higher MON value. As such, refiners typically have to replace the olefins with paraffins to achieve minimum MON values [13]. The process is energy intensive, costly, and counter-productive. By leaving the olefins in the blend, the fuel would have better antiknock performance at normal engine operating conditions. Taking away this step in the refining process would save the oil industry a substantial amount of money, while also reducing the energy cost of the fuel.

Some of this reduced cost may make its way to the cost per gallon of gasoline. However, there are numerous externalities that factor into this cost. Rather, consumers would initially see a benefit in performance. The better fuel would result in the engines not needing to adjust spark timing at the high-load, low-speed condition to avoid knock. Since the spark timing is adjusted through a closed-loop control system with the knock-sensor, no modifications would be required for the engine. On the longer term, consumers will start to see more efficient vehicles. Fixing the octane number system will allow engines to be designed at a higher compression ratio, which in turn would increase the engine efficiency. Additionally, car manufacturers could increase the boost levels of turbochargers, allowing for engines that are more efficient. Simply getting rid of the MON requirement could allow the compression ratio to increase by a value of 0.5, which would decrease the fuel consumption by almost 2 percent [15]. However, larger gains can be made through the implementation of biofuels and by focusing knock-research for fuels onto the relevant engine range conditions.

In addition to the aforementioned efficiency, fixing the octane tests would also create several benefits for the environment. First, the environmental impact of a vehicle is characterized by the "well to wheel" carbon footprint. The "well to wheel" carbon footprint includes how much energy was expended in drilling, refining, and transporting the oil, in addition to the actual energy expended to provide vehicle movement [16]. By reducing the amount of energy required in the refining of the fuel, there is an overall savings in the "well to wheel" footprint. Second, biofuels offer numerous environmental benefits. Although, they have other issues, the current octane test system penalized biofuels for having a low MON. By correcting the test, biofuels would overcome one of their hurdles. Additionally, biofuels typically have exceedingly good antiknock performance in the temperature ranges associated with modern engines, so they can potentially be used as an antiknock additive. The increased use of biofuels would further reduce the "well to wheel" carbon footprint.

There are few scenarios that are win-win for all parties involved. Fixing the octane number tests to ensure relevancy is a case where all parties would benefit. The cost of refining fuels would decrease, benefitting the oil industry. Meanwhile, consumers would be getting better fuels that allow for increased engine performance. Additionally, the environment would benefit from increased use of biofuels, a smaller well-to-wheel carbon footprint for gasoline, and more efficient engines.

References:

[1] Turns, S., An Introduction to Combustion: Concepts and Applications, 2nd Edition. New York: McGraw-Hill, 2000.

[2] Livengood, J., Wu, P., "Correlation of Autoignition Phenomena in Internal Combustion Engines and Rapid Compression Machines," Symposium for International Combustion, 1955

[3] Heywood, J., Internal Combustion Engine Fundamentals, New York: McGraw Hill, 1988.

[4] Mittal, V., "The Development of the Octane Number Tests and their Impact on Automotive Fuels and American Society," International Journal for the History of Engineering & Technology, vol. 86, 2016, doi: 10.1080/17581206.2016.1223940

[5] Ferguson, C. and Kirkpatrick, A., Internal Combustion Engines: Applied Thermosciences, West Sussex, UK: Wiley, 2016.

[6] Mittal, V., and Heywood, J., "The Shift in Relevance of Fuel RON and MON to Knock Onset in Modern SI Engines Over the Last 70 years." SAE International Journal of Engines, 2(2):1-10, 2010, doi: 10.4271/2009-01-2622

[7] Gillespie, T.D., Fundamentals of Vehicle Dynamics, Warrendale, PA: Society of Automotive Engineers, 1992.

[8] Marshall, E.L., "Early Liquid Fuels and the Controversial Octane Number Tests." The Piston Engine Revolution, Manchester, UK: Newcomen, 2011.

[9] Kalghatgi, G.T., "Fuel Anti-Knock Quality – Part 1, Engine Studies", SAE Technical Paper 2001-01-3584, 2001. doi: 10.4271/2001-01-3584

[10] US Energy Information Administration. "Gasoline Explained." Available: https://www.eia.gov/energyexplained/gasoline/octane-in-depth.php

[11] Tamm, D., Devenish, G., Milburn, K, "Future Gasoline Octane Scenarios" US Energy Information Administration Report, 2018. Available: https://www.eia.gov/analysis/octanestudy/pdf/phase2.pdf

[12] Waqas, M., Morganti, K., Masurier, J., and Johansson, B., "Blending Octane Number of Ethanol on a Volume and Molar Basis in SI and HCCI Combustion Modes," SAE Technical Paper 2017-01-2256, 2017, https://doi.org/10.4271/2017-01-2256.

[13] European Oil Company Organization for Environment, Health and Safety (CONCAWE), "Assessment of the Energy Balances and Economic Consequences of the Reduction and Elimination of Lead in Gasoline." CONCAWE Report 11/83R.

[14] Kalghatgi, G., Head, R., Chang, J., Viollet, Y. et al., "An Alternative Method Based on Toluene/n-Heptane Surrogate Fuels for Rating the Anti-Knock Quality of Practical Gasolines," SAE International Journal of Fuels and Lubricants. 7(3):2014, doi:10.4271/2014-01-2609.

[15] Guibet, J.C., Fuels and Engines, Institute Francais du Petrole Publications, 1999.

[16] Elgowainty, A., Han, J., Poch, L., Wang, M., Vyas, A., Mahalik, M., & Roussea, A., "Well to Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-In Hybrid Electric Vehicles." DOE Report, 2010. Available https://www.energy.gov/sites/prod/files/2014/03/f9/67242.pdf

Figure 3: Carburetor Bowl / Float Chamber Assembly for Combination Octane Rating Unit Engine

Dr. Vikram Mittal, Assistant Professor at the United States Military Academy in the Department of Systems Engineering 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, Alternative fuels, model-based systems engineering, and engine knock.

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

Author Contact Details

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