

Lubricant Reactivity Effects on Gasoline Spark Ignition Engine Knock

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ABSTRACT

The performance and efficiency of spark ignited gasoline engines is often limited by end-gas knock. In particular, when operating the engine at high loads, combustion phasing is retarded to prevent knock, resulting in a significant reduction of engine efficiency. Since the invention of the spark ignition (SI) engine, much work has been devoted to improve and regulate fuel characteristics, such as octane number, to suppress engine knock. The auto-ignition tendency of the engine lubricant however, as described by cetane number (CN), has received little attention, as it has been assumed that engine lubricant effects on knock are insignificant, primarily due to low levels of average oil consumption. However, with modern SI engines being developed to operate at higher loads and closer to knock limits, the reactivity of engine lubricants can impact the knock behavior.

Unconventional oil formulations and additives have been found to lower the lubricant reactivity while maintaining necessary lubricating properties. Lubricants with low combustion reactivity allowed the engine to be operated with improved combustion phasing (spark timing) or higher geometric compression ratio, both of which enable the engine to operate at higher efficiency. Additionally, higher operating loads at a given combustion phasing (e.g. MBT timing) and compression ratio were feasible using lubricants with low combustion reactivity.

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INTRODUCTION

For spark-ignited engines, specific power and efficiency are often limited by the onset of knock. Knock is described as very rapid, uncontrolled combustion where very high combustion temperatures combined with in-cylinder pressure waves cause rapid heat transfer from the combustion gases to the combustion chamber components. Due to this increase in heat transfer, damage to the combustion chamber components can occur very quickly, often within a few engine cycles. Generally, engine knock is characterized by auto-ignition of the combustible mixture at the outer regions of the combustion chamber (end-gas knock). These outer regions are located around the top land crevice of the piston. During normal engine operation, a mixture of oil and unconsumed fuel can accumulate in the top land region. The combination of the high auto-ignition potential of the oil and high gas temperatures during combustion lead to an increased probability that end-gas auto-ignition might be promoted by the presence of accumulated lubricant and/or lubricant-fuel mixture [1]. The typical reactions to knock - reducing compression ratio, reducing load and/or retarding combustion phasing - all result in a reduction of engine efficiency. The

purpose of this study was to determine if, by formulating a low reactivity oil, the tendency for end-gas auto-ignition might be reduced, allowing the engine to be operated more efficiently.

To quantify the reactivity of the lubricant, the CN for the test lubricants was obtained using the Ignition Quality Tester (IQT) [2,3,4,5]. CN is generally used to describe the reactivity of diesel fuels and their associated ignition behavior (ignition delay). The IQT correlates the CN with a measured ignition delay (ASTM D6890). For example, fuels with short ignition delay, thus high reactivity, are quantified by high CN where as fuels with long ignition delays and thus low reactivity have a low IQT derived CN. Also, the CN and research octane number (RON) of fuels can be correlated using the IQT and primary reference fuels (PRFs) (Figure 1), which indicates that there is generally an inverse relationship between CN and RON for PRFs. Since ON of typical gasoline fuels is quantified by RON and the motored octane number (MON), the correlation between CN and ON can vary somewhat based on RON, MON or the Anti Knock Index ($AKI = (RON + MON) / 2$). Since the IQT combustion bomb allows usage of liquids other than diesel, such as

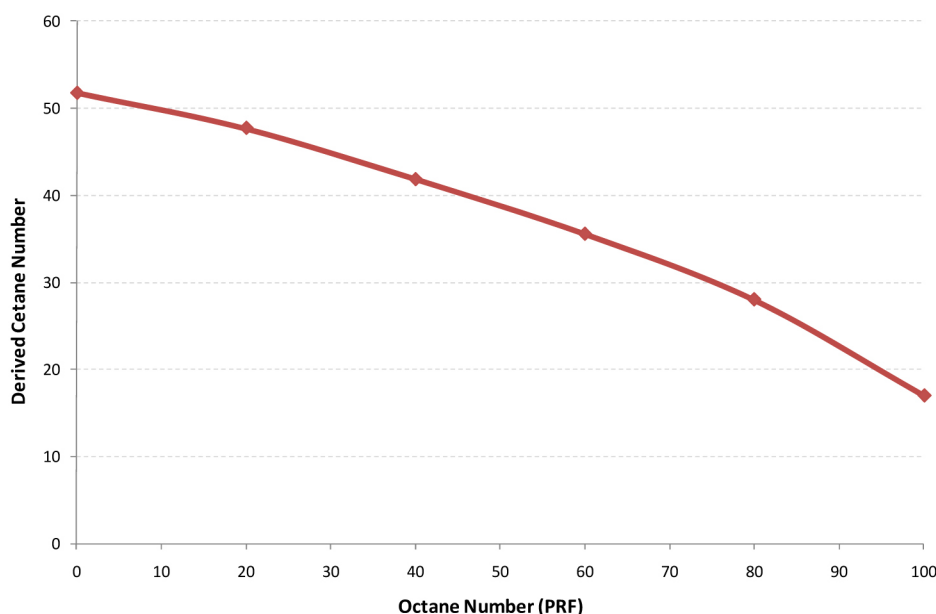


Figure 1. Correlation between IQT derived CN and RON (PRF fuels)

gasoline and fuel/lubricant mixtures, the IQT derived CN was chosen to describe the reactivity of lubricants.

Once some low reactivity lubricants were identified, the final stage of the study involved evaluating the lubricants in a single-cylinder, variable compression ratio (VCR) engine. Knock limits were identified with a baseline lubricant as a function of compression ratio, spark advance and load and then alternative, low and high reactivity lubricants were examined for their effect on the knock limited conditions. The goal of this portion of the experiment was to document the increased knock resistance of the alternative lubricants and establish how much, if any, fuel economy improvement was available.

EXPERIMENTAL SETUP

The initial screening of lubricants was performed using the IQT in a method that generally follows ASTM D6890. The combustion chamber is filled with compressed air at an elevated pressure and temperature. Using a pump-line-nozzle injector, the test fluid was injected and the ignition delay measured. Based on the ignition delay time, the IQT CN can be derived. The IQT apparatus is shown in Figure 2.

Due to the effect of air-fuel ratio on ignition delay, it is important to keep the mass of injected fuel constant and, as much as possible, maintain a constant atomization behavior between fuels. To mitigate any lubricant viscosity effects on the IQT predicted CN, the test lubricants were diluted with a low-viscosity solvent, such as n-heptane, and blended at five different ratios ranging between 5% lubricant and 95% solvent to 30% lubricant and 70% solvent by volume. The ignition delay and IQT CN of each sample was measured a total of 32 times to obtain statistically valid averages. Using the IQT CN from the five blends allowed a prediction of the

reactivity of the pure lubricant using linear regression as illustrated in Figure 3. Despite some uncertainty caused by using this method, distinction between high, mid and low reactivity lubricants was possible. Based on the IQT results and other chemical properties such as viscosity, four different lubricants were identified to be suitable for engine testing.

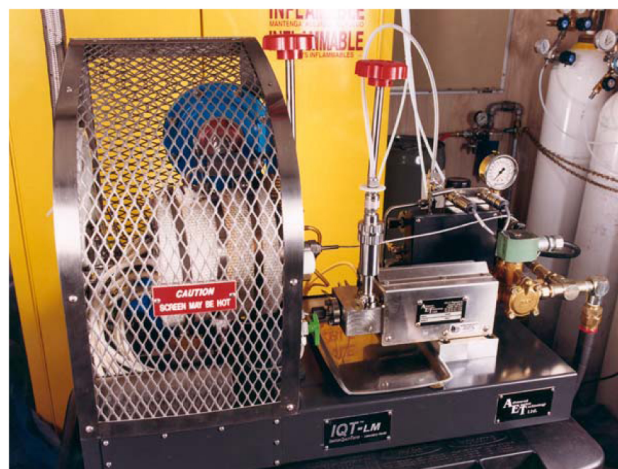


Figure 2. Ignition Quality Test Apparatus

The VCR engine used in the testing (Figure 4) was operated as a conventional, naturally aspirated, spark-ignition engine. With the exception of a custom built mechanism to change the geometric compression ratio during operation, the single-cylinder VCR engine is of a typical IC engine design. The engine has a displacement of 0.7 liter, is equipped with a “typical” PFI injection system and centrally mounted spark plug. The test engine is connected to an eddy-current dynamometer and is equipped with temperature and pressure control systems for intake air (also humidity), oil, coolant,

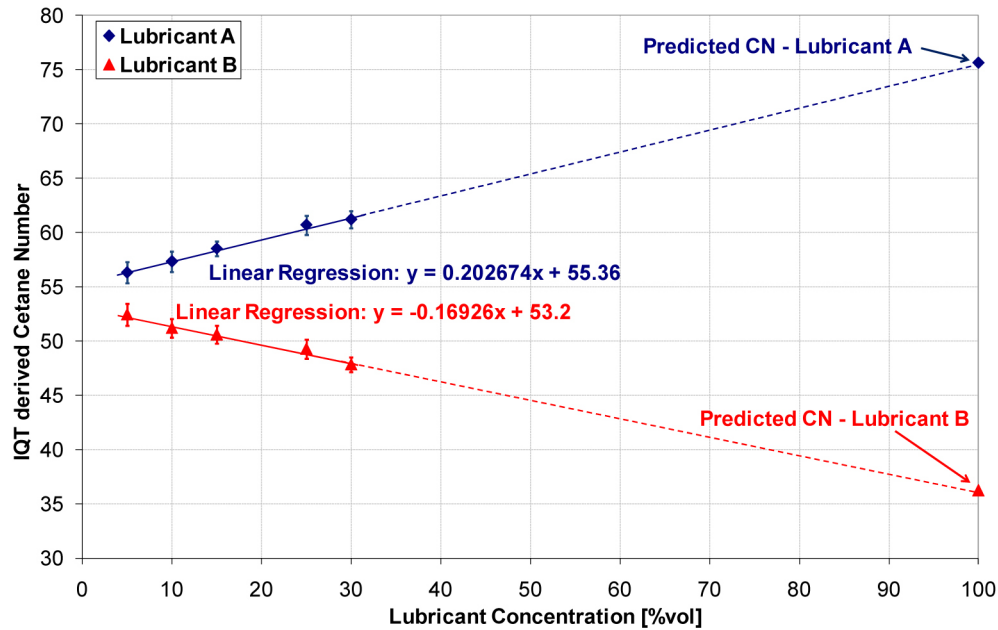


Figure 3. IQT Derived Lubricant Cetane Number Determination

fuel and exhaust (pressure only). The piston is equipped with 3 piston rings with the third ring being an oil control ring. Total oil consumption for this engine was determined to be approximately 50 grams per hour. This oil consumption rate was derived from measuring the oil level in the engine oil pan prior and after operating the engine for a prolonged period (approximately 50 hours). However, besides some inaccuracies in the measurement, the derived oil consumption value is somewhat exaggerated due to small external oil leaks, mostly around the variable compression ratio mechanism components. Therefore, it is believed that the amount of oil consumed in-cylinder is somewhat lower than the reported 50g/hour though the exact value is unknown. Operating speeds are 600 to 2000 rpm with loads ranging from idle to approximately 10 bar IMEP (Indicated Mean Effective Pressure). A stoichiometric air/fuel ratio, determined by exhaust gas lambda sensor, was maintained at all times. A standard certification grade gasoline fuel (Halterman H-EEE), was used to improve consistency and repeatability.

Three knock analysis mechanisms, based on cylinder pressure, were incorporated in the engine control and data acquisition system. Knock is characterized by high frequency pressure waves during combustion, typically in the range of 3 to 6 kHz for this engine with a bore size of 95mm, as compared to non-knocking pressure frequencies in the range of 15 to 100 Hz [7]. Because of the separation in frequency, the knock signals can be distinguished using a high-pass or band width filter and quantified using the following three analysis methods (also shown in Figure 5). Knock values were calculated from in-cylinder pressure measurement for 300 consecutive engine cycles. For the data presented in this

paper, the average of the 300 knock intensity values was chosen. Similarly, the average values of pressure and heat release parameters calculated for each individual engine cycle were used for the analysis.



Figure 4. Single-Cylinder VCR Engine

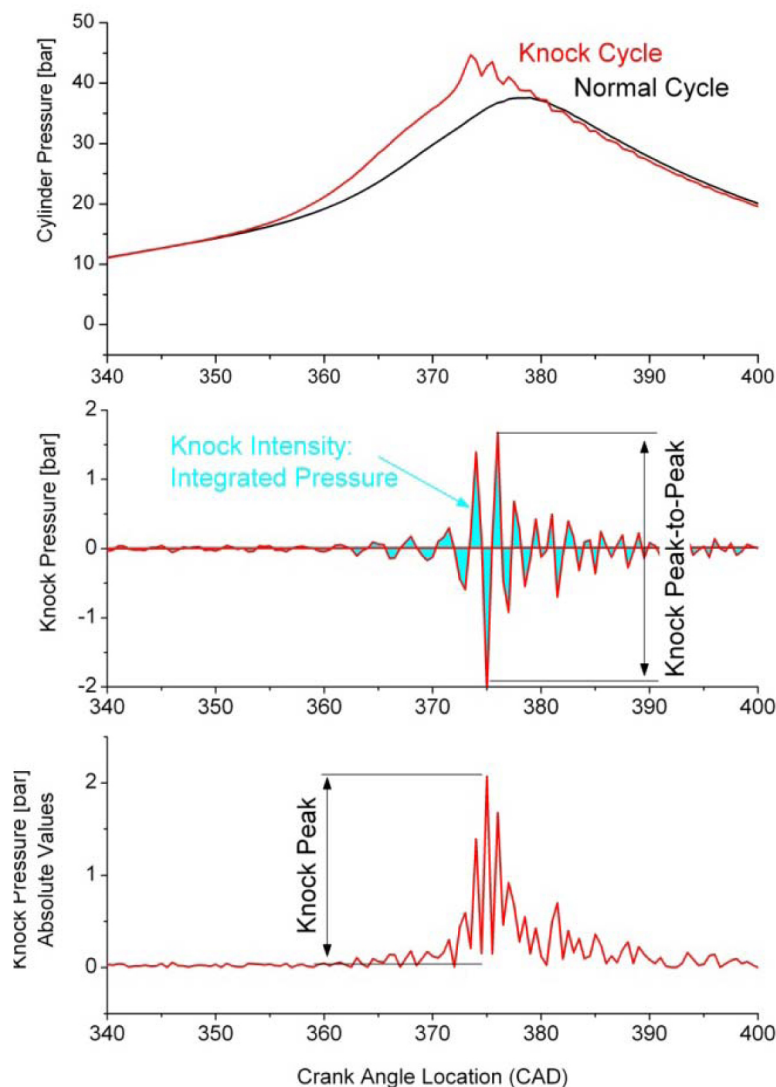


Figure 5. Knock Pressure and Knock Intensity

- Knock peak-to-peak pressure: Max to min amplitude of knock pressure wave
- Knock peak pressure: Max value of knock pressure wave (absolute values)
- Knock Intensity: Time integrated knock pressure wave

IQT ANALYSIS RESULTS

While evaluating several commercially available lubricants in the IQT, it was recognized that most of these lubricants exhibit very high combustion reactivity (IQT derived CN of >75, as reference US low sulfur diesel fuel has a CN of approx 42). The primary focus of lubricant development has been to reduce engine wear, lower friction losses and improve engine and lubricant durability whereas combustion reactivity was of no or little concern. Generally, engine lubricants consist of a lubricant base stock and various additives to reduce wear, decrease oxidation tendencies (anti-oxidants), reduce friction and modify viscosity. Generally,

lubricant base-stocks used for automotive applications are grouped using API Group numbers, as described in [Figure 6](#). Furthermore, many commonly available base stocks can be categorized as following:

- Petroleum/ Mineral oil base stocks; used in many “standard” mineral based engine oils (Group 1 through 3 lubricants)
- Poly-alpha-olefin (PAO); used in many fully synthetic oils (Group 3+ or Group 4 lubes)
- Other unconventional base stocks such as Esters; often found in lubricants used for turbine and aircraft engines (Group 5 or others)

[Figure 7](#) illustrates the IQT derived Cetane Number for various commercially available lubricants. The IQT derived CN for this lubricants were obtained using the measurement method previously described (see [Figure 3](#)). Besides Oil #3, which is formulated from an Ester base stock, all IQT tested