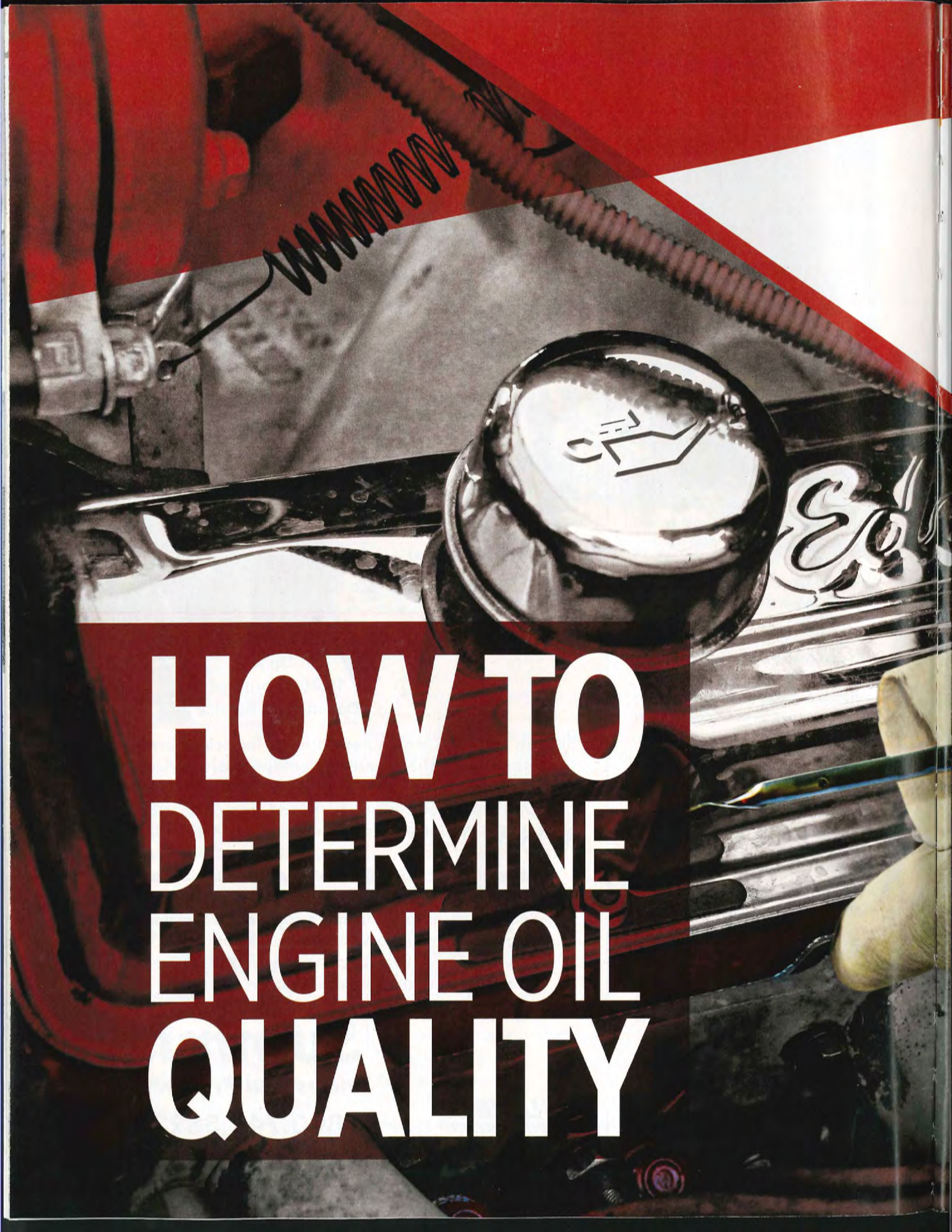

HOW TO DETERMINE ENGINE OIL QUALITY

By Tina Dasbach and Theodore W. Selby

While most engine oils are made to acceptable standards, their general and specific qualities can vary widely. Poor-quality engine oils are often put on the market due to ignorance or greed. Unfortunately, for the uninformed automobile owner, a high-quality engine oil and one of poor quality will look and feel the same.

Engine and Bench Tests

The engine has always been the ultimate platform for identifying the required quality of its oil. Even as engine design has changed to meet performance, fuel efficiency and environmental standards, the engine continues to be the ultimate arbiter of oil quality. However, using the engine to measure oil quality in dynamometer tests can be an expensive proposition. Even so, to help control warranty costs, the development and use of engine tests is unavoidable for engine manufacturers when determining the oil quality needed for a particular design or component.

Although necessary, generating repeatable dynamometer tests for an engine can be challenging. As engine design has progressively increased power from smaller engines, the difficulty of establishing repeatable dynamometer tests has grown even more rapidly. Fortunately, once the quality level has been determined on the dynamometer or in the field, there is a much less expensive approach that can be applied to more precisely appraise the oil quality. This involves using laboratory bench tests designed to correlate closely with engine dynamometer tests or field experience. These bench tests have the capability of providing a relatively inexpensive measure of oil quality. However, the value and significance of this type of test is dependent on a number of factors, including identification of the engine's specific needs, clear and consistent information from the engine either

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in dynamometer tests or field experience, and an understanding of the relationship between the engine's needs and the oil's physical and/or chemical properties.

Engine Oil Properties

To serve the engine, oil must possess certain physical and chemical properties. During the oil's service, the engine generates a number of operating stresses that adversely affect the long-term ability of the oil to function at a consistently high level. Service conditions may also vary widely depending on the environment and the way the vehicle is used. Consequently, choosing an engine oil to meet particular service needs and conditions requires knowledge of several important oil properties, including viscosity.

Viscosity

Viscosity may be defined as a fluid's resistance to flow. Because a fluid's molecules are somewhat attracted to one another, energy is required to pull them apart and create flow. In general, larger molecules have more attraction between them and a higher viscosity. The energy required to overcome this molecule-to-molecule attraction and produce fluid flow can be considered a form of friction. Therefore, viscosity can be defined as a form of molecular friction. Of all the engine oil's physical and chemical qualities, its viscosity and viscometric behavior during use are often considered the most important.

Viscosity and Wear Prevention

This same molecular friction prevents the oil from escaping too quickly when two engine surfaces in relative motion are brought closely together under pressure. This inability of the intervening oil to escape quickly and its level of incompressibility hold the two surfaces apart and prevent wear, a process that is termed hydrodynamic lubrication. The higher the viscosity, the greater the attraction of the oil molecules and the greater the wear protection.

Viscosity Classification

A lubricant's viscosity has always been associated with wear protection. Early in its history, SAE recognized viscosity as important to engine function and instituted the J300 classification system, which establishes viscosity levels for engines by a series of grades. These grades are defined by viscosity levels in one or two temperature zones. Today, the grades are set for engine operating temperatures and for winter temperatures at which the oil affects starting and pumping.

Viscosity at Operating Conditions

In the early years of automotive engines, oils were simply formulated and obeyed Newton's equation for viscosity – the more force used to make the fluid flow (shear stress), the faster it would flow (shear rate). Essentially, the ratio of shear stress to shear rate – the viscosity – remained constant at all shear rates. The engine oils of that time were all essentially single grade and carried no SAE "W" classification.

This viscometric relationship changed in the 1940s when it was discovered that adding small amounts of high-molecular-weight polymers appeared to give the oil the desired flow characteristics for both low-temperature starting and high-temperature engine operation. Accordingly, these polymer-containing oils were listed by the SAE viscosity classification system as multigrade engine oils, as they met the requirements of both viscosity temperature zones.

Since that time, multigrade oils (e.g., SAE 10W-40, 5W-30, 0W-20, etc.) have become very popular. However, they were no longer

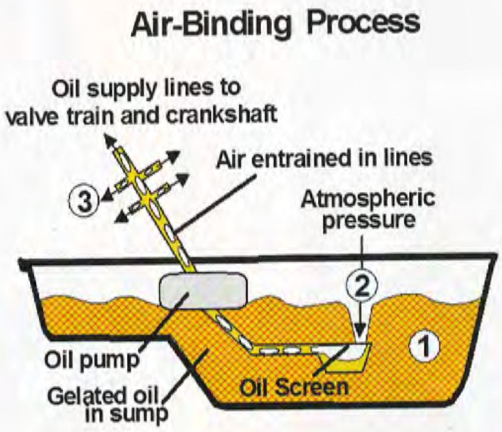

Figure 1. This graphic shows (1) structured oil, (2) a "hole" pulled in gelated oil to an operating oil pump by atmospheric pressure, and (3) air being pumped to the engine's lubrication sites.

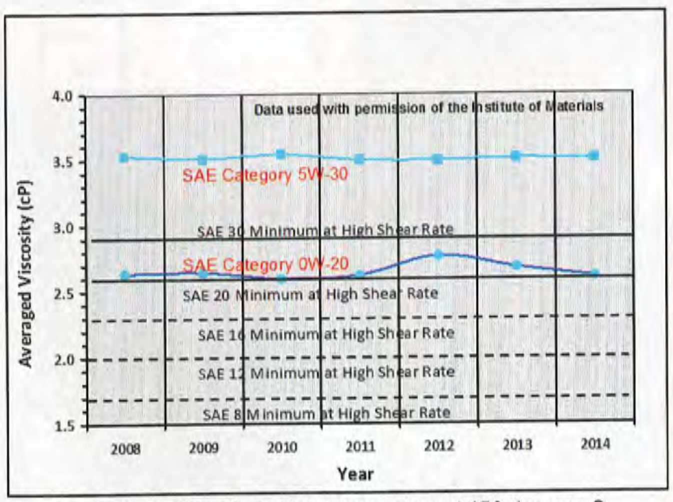

Figure 2. Engine oils at high shear rate and 150 degrees C

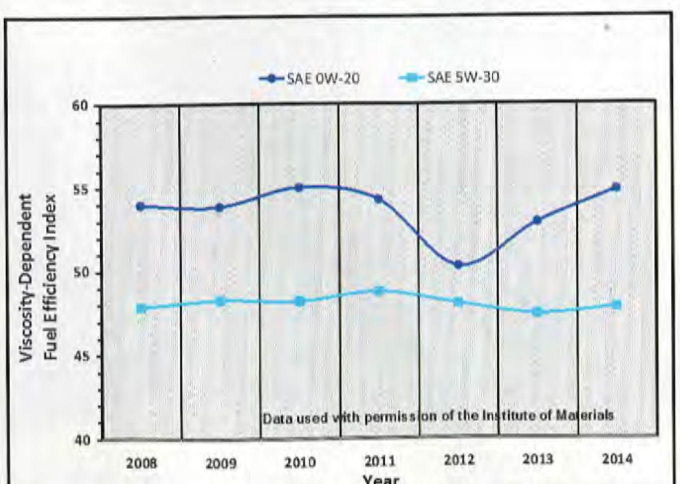

Figure 3. Engine oil viscosity's effect on fuel efficiency

Newtonian in flow characteristics, as the viscosity was found to decrease with increasing shear rate. This was considered important in lubricating engines that operated at high shear rates (as measured in millions of reciprocal seconds), in contrast to the several hundred reciprocal seconds of the low-shear viscometers then being used to characterize engine oils.

High Shear Rate Viscometry

Consequently, the need arose to develop a high shear rate viscometer to reflect the viscosity in engines under operating temperatures. In the early 1980s, an instrument and a technique were developed that could reach several million reciprocal seconds at 150 degrees C as well as exert high shear rates at other temperatures on both fresh and used engine oils. The instrument was called the tapered bearing simulator viscometer. The technique was accepted by ASTM as test method D4683 for use at 150 degrees C (and more recently as D6616 for use at 100 degrees C). This critical bench test of engine oil quality became known as high temperature, high shear rate (HTHS) viscosity. Minimum limits were then imposed for various grades in the SAE viscosity classification system.

Interestingly, it was later shown that this instrument was unique and basically absolute in providing measures of both shearing torque or shear stress and shear rate while operating. It is the only known viscometer capable of doing this.

Viscosity and Oil Gelation at Low Temperatures

Multigrade engine oils were originally introduced to reduce oil viscosity at low temperatures to aid in engine startup. This important benefit was immediately apparent, and multigrade oils have since become the most popular form of engine lubricant around the world.

With easier engine startability at low temperatures, another problem became evident – oil pumpability. This was a considerably more serious issue, as lack of oil pumpability could destroy the engine. In cold-room dynamometer tests, it was determined that there were two forms of the pumpability problem. The first was simply related to high viscosity and called flow-limited behavior. The second was less obvious and involved the gelling of the oil under a long, deep cooling cycle. This was labeled "air-binding," since the oil pump became air-bound as the result of a column of oil being pulled from the sump and the oil not filling this void, as shown in Figure 1.

This knowledge and bench test, which initially seemed to predict both forms of failure, were not enough. In the winter of 1979-80 in Sioux Falls, South Dakota, a cooling cycle showed that air-binding could occur under relatively mild cooling conditions. Over a 24-hour period, a number of engines containing oil were ruined. The cooling cycle had produced a condition in which the oil became air-bound. The costly incident revealed the need for a more sensitive bench test that would accurately predict the tendency of air-binding pumpability failures.

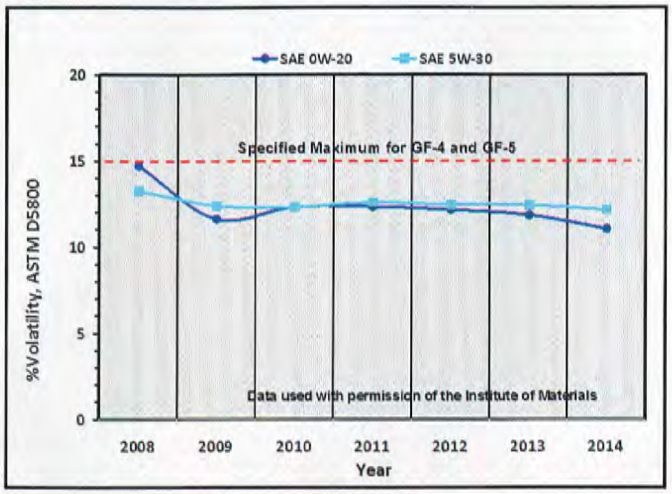

Figure 4. Volatility of SAE 0W-20 and 5W-30 engine oils

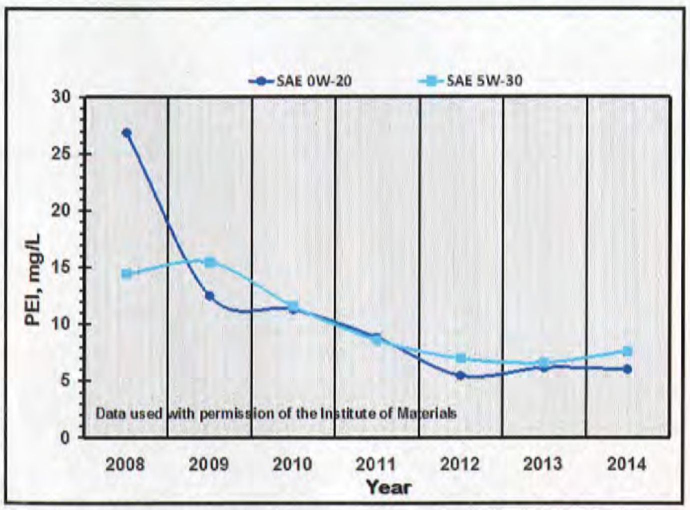

Figure 5. Phosphorus emission index generated in Selby-Noack volatility bench test

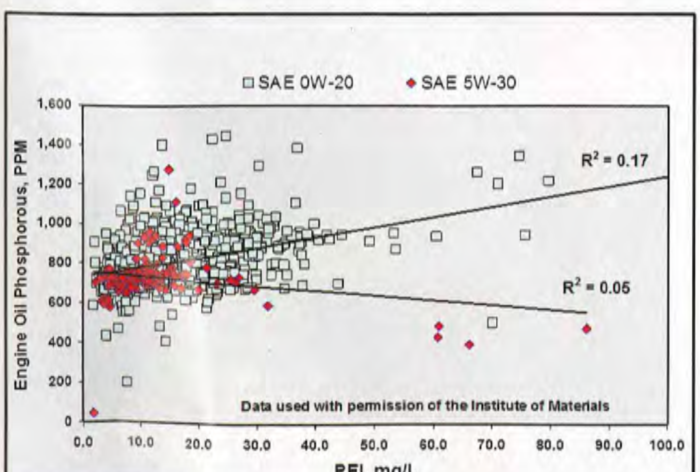

Figure 6. Phosphorus content of engine oil and PEI

Gelation Index

The air-binding engine oil that caused the Sioux Falls failures provided a solid case study. A new bench test instrument and technique were developed to indicate any tendency of the test oil to gelate. The technique, which involved continuous low-speed operation of a cylindrical rotor in a loosely surrounding stator, was immediately incorporated into engine oil specifications and later became ASTM D5133. This not only showed the oil's tendency to become flow-limited but also specified the degree of gelation that might occur over the measured temperature range (typically minus 5 to minus 40 degrees C). The parameter was called the gelation index. Today, engine oil specifications for multigrade oils require a maximum gelation index of 12.

Viscosity and Energy Absorption

As beneficial as viscosity is to the engine in preventing wear through hydrodynamic lubrication, it also has some negative aspects that can affect the engine's operating efficiency. The oil's molecular friction, which separates two surfaces in relative motion, requires energy to overcome it. This is a significant amount of energy from the engine in exchange for the provided wear protection. Therefore, careful formulation of the oil viscosity is critical to vehicle owners and to governments mandating fuel economy limits. Lowering oil viscosity can be an important step in reducing viscous friction to improve fuel efficiency. Interestingly, over the last several years, there has been an increase in the number of automobiles operating with engine oils that have lower viscosity levels, thus markedly improving their engine efficiencies.

A decade ago, the lowest SAE viscosity grades were SAE 0W-20 and 5W-20 oils, with SAE 20 carrying the minimum high shear rate viscosity of 2.6 centipoise (cP) to simulate engine operation at 150 degrees C. Figure 2 shows data from engine oils sold in North and South America as well as for SAE 5W-30 engine oils.

Japanese automakers have recently called for even lower viscosity grades. As a consequence, the SAE has introduced three new operating grades identified as SAE 16 (2.3 cP minimum at 150 degrees C), SAE 12 (2.0 cP minimum at 150 degrees C) and SAE 8 (1.7 cP minimum at 150 degrees C). These grade requirements are also shown in Figure 2 for comparison. None of these lower grade oils has yet to reach the market for analysis. Since viscosity is directly related to the amount of energy expended by the engine for wear protection through hydrodynamic lubrication, such a decrease in

Engine Oil Database

Thirty years ago, based on concerns expressed by engine manufacturers about the quality of some oils, the Institute of Materials (IOM) began to compile an engine oil database. Engine oils were collected directly from the market and analyzed by selected laboratories through a series of bench tests. The results were then published. The database, which is available at www.instituteofmaterials.com, now covers more than 14,000 engine oils worldwide.

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viscosity would be expected to have important benefits in fuel efficiency but only in engines designed for their use.

Viscosity-dependent Fuel Efficiency Index

Given the influence that oil viscosity has on the engine, a technique was developed to calculate the effects of engine oils on fuel efficiency. To be meaningful, the viscosity values had to be obtained at the high shear rates associated with operation in specific sections of the engine.

Earlier dynamometer work had identified the percentage of friction and operating temperature of the five main lubricating sites in a reciprocating gas-fueled engine responsible for nearly all efficiency loss. This information was used to develop the viscous fuel efficiency index (V-FEI) parameter. With this value, which ranges from 0 to 100, the higher the V-FEI of a given engine oil, the less energy is lost to viscosity, and consequently, the more fuel efficient the engine is. Although different engine designs may have different levels of friction in the essential lubricating areas, use of this friction data provides a comparative value for engine oils.

Figure 3 shows the average value of SAE 0W-20 and 5W-30 engine oils from the North and South American markets from 2008 to 2014. For comparison, the average V-FEI for SAE 0W-20 and 5W-30 in an earlier study was 46 and 47 respectively.

As expected, it was determined that the yearly averaged multigrade SAE 0W-20 oils contributed more fuel efficiency to the engine than did the averaged multigrade SAE 5W-30 oils because of the viscosity differences shown in Figure 2. With the exception of 2012, the increase in V-FEI is equivalent to nearly 7 to 8 percent in viscosity-dependent fuel efficiency. The decrease shown in the average fuel efficiency of SAE 0W-20 engine oils collected in 2012 may indicate the development of formulations meeting automakers' concerns that the benefits of hydrodynamic lubrication will not be lost in efforts to improve fuel efficiency.

Engine Oil Volatility

Another aspect to consider when reducing the viscosity in engine oil formulations is that such a reduction is most frequently obtained by using base oils with higher volatility. Volatized oil reduces the amount of lubricant serving the engine and may carry exhaust catalyst-contaminating components, negatively affecting the catalyst's smog-reducing ability. The oil remaining after the loss of the more volatile components will also be more viscous and energy-absorbing.

Figure 4 shows the response of two of the most volatile multigrade engine oil classifications. Also shown is the specified maximum volatility set by the International Lubricant Standardization and Approval Committee (ILSAC). In the last few years, it is evident that the SAE 0W-20 and 5W-30 classification categories were designed to meet the ILSAC volatility specification by a comfortable margin. These results suggest that volatility control may be less demanding with the more recently classified multigrade oils identified as SAE 0W-16, 0W-12 and 0W-8.

Phosphorus Emissions and Volatility

Soluble phosphorus compounds such as zinc dialkyldithiophosphate (ZDDP) have been used in formulating engine oils for many years. These anti-wear and antioxidation compounds have provided considerable support to the design of modern engines.

In the mid-1900s, the reciprocating engine was identified as a major contributor of air pollution. Unburned or partially burned hydrocarbons from the engine exhaust were modified by sunlight into noxious gaseous hydrocarbons, which produced smog in some large cities. As a consequence, exhaust catalytic converters were developed in the 1970s to treat the exhaust gas and convert it into carbon dioxide and water. Unfortunately, in the years following the catalytic converter's development, it was discovered that certain elements in gasoline or engine oil, including phosphorus and sulfur, would deactivate the catalyst by coating it. This ultimately led to restrictions on the quantity of these chemicals in engine oil and fuel.

Phosphorus Emission Index

The Selby-Noack volatility test was developed in the early 1990s as a better and safer approach for determining engine oil volatility. It collected the volatile component of the volatility test for further analysis, which was helpful in detecting phosphorus and sulfur. In the first analyses of volatiles collected from the bench test, it was apparent that the phosphorus additives in the engine oils were also producing phosphorus through additive decomposition. On the basis of these findings, a parameter related to the amount of phosphorus released during the test was developed called the phosphorus emission index (PEI).

Figure 5 shows the change in PEI over the last eight years. It is evident that considerable progress has been made in reducing the phosphorus decomposition and/or volatility of these two multigrade SAE classifications. The reduction of the PEI to 6 to 10 milligrams per liter of engine oil is a significant change in protecting the catalytic converter from the effects of phosphorus.

With the trend toward smaller, fuel-efficient and turbocharger-equipped engines generating higher temperatures during operation, a bench test that can reveal an oil formulation's phosphorus emission tendencies would be useful in designing lubricants best suited to the engine and the environment.

Phosphorus Content and Volatility

How much influence the phosphorus in an engine oil has on the amount of phosphorus volatilized during engine operation is an important question affecting the choice of additives in oil formulation. Figure 6 shows the phosphorus content in a number of SAE 0W-20 and 5W-30 engine oils vs. the PEI values obtained. The data reveals that phosphorus volatility generated by the Selby-Noack test is virtually unrelated to the amount of phosphorus present in the oil as an additive. The lack of correlation between the phosphorus in the engine oil and the amount of phosphorus volatilized is evident in the low correlation coefficient (R^2) values. This parameter would be near a value of one if phosphorus concentration affected its volatility. As shown in Figure 6, the values obtained from the data are much lower, with R^2 at 0.05 for SAE 0W-20 and 0.17 for SAE 5W-30 engine oils.

The PEI data are primarily clustered at values from 2 milligrams per liter to about 30 milligrams per liter. However, a small number of PEI values exceed 40 milligrams per liter. These engine oils are likely to be more harmful to the exhaust catalyst. However, as has been shown in Figure 5, PEI levels have been decreasing markedly over the last few years.

Without question, the quality of engine oils will play a much greater role in the smaller, more powerful turbocharged engines that are entering the automotive market. However, it is essentially impossible to establish the quality of an engine oil by appearance. This determination can only be made by using the oil or pre-testing it. Obviously, the latter is the much preferred option for automobile owners, who have a significant investment in and need for a well-functioning and durable engine. ■