

Fuel economy

The role of friction modifiers and VI improvers

These two additives are helping lubricant suppliers improve fuel economy and comply with new engine oil specifications.

KEY CONCEPTS

- Fuel economy improvement has become a key objective in the development of PCMOs and HDDEOs.
- Two additives that will play an important role in improving fuel economy are friction modifiers and VI improvers.
- Further reduction of engine oil viscosity can lead to increasing fuel economy, but there may be limitations from the engine design and lubricant standpoints.

THE LUBRICANT INDUSTRY IS FACING enormous challenges to develop products that function optimally under severe conditions for long operating periods. One other factor emerging from the automotive standpoint is ways to improve the vehicular fuel economy. Part of the reason is driven by the challenge faced by the U.S. automotive industry to boost Corporate Average Fuel Economy (CAFE) by 20 percent by 2016. In addition, the U.S. government has established a goal of raising CAFE to 54.5 miles per gallon by 2025, a doubling of the existing CAFE.

The desire to improve fuel economy has also moved to the heavy-duty diesel vehicles, as the U.S. government established requirements for reducing carbon dioxide emissions in August 2011 by 10 to 20 percent for 2018 model year vehicles. The objective is to not only reduce emissions but also improve fuel economy. The U.S. EPA predicts a savings of 530 million barrels of oil over the lifetime of vehicles built between the 2014 and 2018 model years.

One of the main ways to address fuel economy has been through the reduction of engine oil viscosity. This is ongoing for passenger car motor oils (PCMOs) but is in its initial phase for heavy-duty diesel engine oils (HDDEOs).

Both the new PCMO specification, GF-6, and the new HDDEO specification, PC-11, are under development, and each will be split into two categories to take into account the use of lower-viscosity oils. One of the categories will be backward integrated to cover lubricants used in current and older engines. The second category is for lower-viscosity engine oils.

To seek a broad range of opinions, TLT interviewed the following representatives from nine additive suppliers:

- Dr. Jai Bansal, global technical advisor, Infineum USA LP
- Ian Bell, technical director-new product development, Afton Chemical Corp.
- Dr. Frank DeBlase, Chemtura Fellow-petroleum additives and fluids, Chemtura Corp.
- Chris Donaghy, sales director-polymer additives and lubricants, Croda Inc.
- Dr. Carl Esche, Global P.C.M.O. technical manager-petroleum department, Vanderbilt Chemicals, LLC
- David Gray, technical service manager, Evonik Oil Additives USA Inc.
- Mark Rees, global business manager-passenger car engine oil additives, The Lubrizol Corp.
- Dr. Kaustav Sinha, associate scientist, & John Cuthbert, principal research scientist, The Dow Chemical Co.
- Dr. Mark Sztenderowicz, manager-automotive engine oil development, & Alex Boffa, global viscosity index improver-technical team leader, Chevron Oronite Co. LLC

TLT asked these reps to provide further insight into how specific additives may be used to boost fuel economy. The discussions involve the use of friction modifiers, which have been well-known for improving fuel economy and viscosity index (VI) improvers that are being closely examined for their ability to improve the performance of lower-viscosity engine oils (For more information on VI improvers, see the September 2011 TLT issue, available digitally at www.stle.org).¹

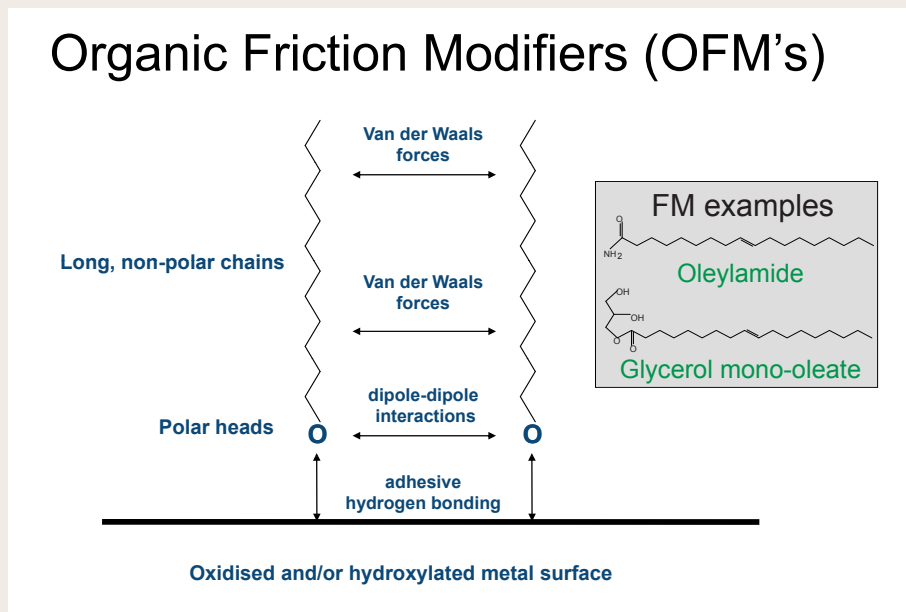


Figure 1 | Friction modifiers such as the two organic types shown arrange themselves to metal surfaces in a stacked vertical manner similar to carpet fibers. (Courtesy of Croda Inc.)

FUNCTIONS OF A FRICTION MODIFIER

STLE-member Chris Donaghy, sales director-polymer additives and lubricants for Croda Inc. in New Castle, Del., says, “There are two types of friction modifiers: organic friction modifiers (carbon, hydrogen and oxygen only) and metal-containing friction modifiers (MFMs) such as molybdenum dithiocarbamate (MoDTC). Organic friction modifiers consist of two key segments—a polar group that can attach to metal surfaces and a lipophilic group that provides not only oil solubility, but also a cushioning or spring-like effect to prevent surfaces from coming into contact.”

“Friction modifiers minimize light surface contacts (sliding and rolling) that may occur in a given machine design,” Donaghy says. “As long as the frictional contact is light, these molecules provide a cushioning effect when one of the coated surfaces connects with another coated surface. If the contact is heavy, then the molecules are brushed off, eliminating any potential additive benefit.”

Donaghy indicates that friction modifiers orient themselves to metal surfaces in a similar fashion to carpet fibers, as shown in Figure 1. He adds,

“Each friction-modifier molecule is stacked vertically besides another.” Two examples seen in Figure 1 are glycerol monooleate and oleylamide.

Dr. Jai Bansal, global technical advisor for Infineum USA LP in Linden, N.J., says, “Friction modifiers provide a highly labile and lower friction film separating the contacting metal surfaces.”

Dr. Frank DeBlase, Chemtura Fellow, petroleum additives and fluids for Chemtura Corp. in Naugatuck, Conn., discusses the mechanisms for how friction modifiers adsorb onto metal surfaces. “In the boundary lubrication region, surface metal-metal asperities contact occurs and the bulk hydrodynamic forces separating these contacts are insufficient or not available,” DeBlase says. “Friction modifiers reduce the coefficient of friction by forming ordered structures on metal surfaces through chemisorptions, physisorptions or more complex physisorption-chemisorption transitions. The latter transitions can occur, particularly at higher temperatures and pressures (e.g., >130 C, and 100 Newton applied force).”

DeBlase summarizes, “There is a range of intermolecular attractive forces acting in concert: dipole-dipole,

ionic, coordinate covalent bond interactions to the metal surfaces and additional weaker van der Waals interactions between the nonpolar hydrocarbon chains. The combination of all of these molecular designed forces is responsible for the development of the friction-modifier ‘assembled’ structures at these boundaries.”

STLE-member Dr. Carl Esche, Global P.C.M.O. technical manager, petroleum department for Vanderbilt Chemicals, LLC, in Norwalk, Conn., says, “The MFM forms a molybdenum-sulfur bond to the metal surface to reduce friction. Molybdenum is the traditional metal used but recently other metals have been investigated for their friction-reducing properties, with one example being tungsten.”

‘Current work is showing that a total fuel economy improvement (FEI) value for XW-20 oils of 3.6 can be realized for GF-6 as compared to 2.6 for GF-5.’

– Dr. Frank DeBlase, Chemtura Corp.

Besides the primary type, Ian Bell, technical director-new product development for Afton Chemical Corp. in Richmond, Va., defines a second friction modifier type. “This second type can be described as chemicals that decompose under the high temperatures and pressures within an engine and their decomposition products form graphitic layered structures on the engine surface,” Bell says. “These impart very low friction characteristics due to the crystalline layer structure of the decomposition species.”

STLE-member Dr. Mark Sztenderowicz, manager-automotive engine oil development for Chevron Oronite Co. LLC in Richmond, Calif., points out the engine areas where friction modifiers are most effective. “Friction modifiers provide a reduction in friction under boundary or mixed lubrication conditions where there is some surface-to-surface contact,” Sztenderowicz says. “In engines, these are the areas with higher loads and lower

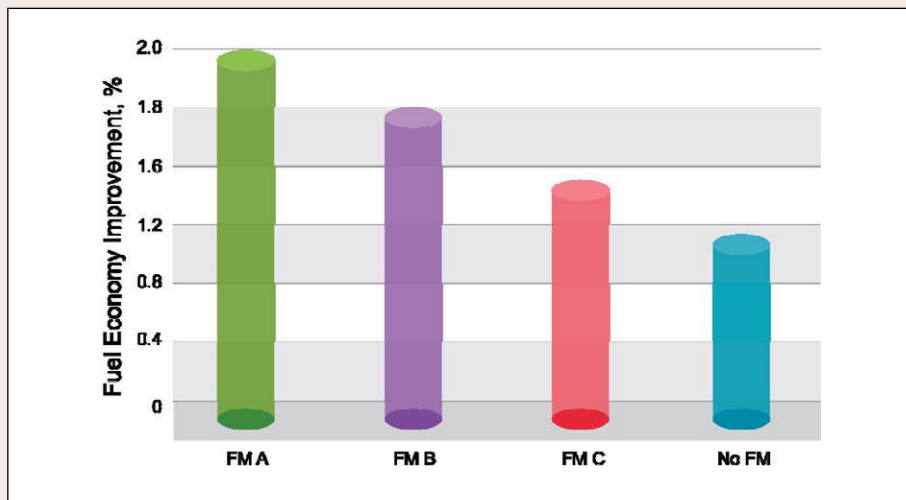


Figure 2 | The impact friction modifiers have in improving fuel economy is dependent upon the specific type used and the other components present in the engine oil formulation, as shown in this Sequence VID engine test data. (Courtesy of Chevron Oronite Co. LLC)

relative speeds between parts such as the interface between cams and followers and cylinder liners and piston rings where the piston is near top or bottom center.”

USE IN PCMOs

Most respondents indicated that friction modifier use started in the 1970s when fuel economy standards were established. DeBlase mentioned that usage of friction modifiers started in automatic transmission fluids in the 1950s.

Esche feels that organic friction modifiers were first developed in the early 1960s as partial esters of fatty acids.² Shortly thereafter, MFMs were invented, as noted in a U.S. Patent issued in 1967.³ Esche says, “MFMs hit their stride in the 1970s with the advent of two oil embargos. They are now used not only for friction modification but also for their antiwear and antioxidant properties.” Previously, fatty acid esters and molybdenum-containing compounds were used in various types of lubricants for purposes not related to friction reduction.

EFFECTIVENESS OF FRICTION MODIFIERS

Sztenderowicz states that friction-modifier effectiveness is variable and depends on the lubricant formulation, engine design and operating conditions. He says, “Friction modifiers pro-

vide a benefit ranging from a few tenths of a percent to one percent in standardized engine and vehicle testing compared with similar oils containing no friction modifier. Under some conditions, friction modifiers can provide even higher impacts.”

The impact of different friction modifiers in a prototype ILSAC GF-6 passenger car engine oil formulation is shown in Figure 2. Sztenderowicz says, “Each of the friction modifiers provides a fuel economy improvement benefit relative to a reference engine oil (with no friction modifier), but the impact of each one is different and depends on the other components in the engine oil formulation.”

While friction modifiers are effective (otherwise they would not be seeing continued use in automotive lubricants), their absolute value is impossible to quantify, according to Bell. “The lubricants industry would not be able to achieve the challenging fuel economy targets seen in the industry now if it were not for the use of friction modifiers,” Bell says. “The absolute impact of friction modifiers on fuel economy is highly dependent upon the vehicle/engine and the operating conditions.”

Donaghy agrees that the benefit of friction modifiers is based on the factors described previously. He says, “In commonly used bench engine tests,

friction modifiers are capable of increasing fuel efficiency by up to 2-3 percent. In formulating engine oils, other components also can be surface active and interfere with the surface activity of the friction modifier. Specifically, polar compounds used in engine oil formulations can also act as solubilizing agents and prevent the friction modifier from reaching the metal surface.”

Such problems may necessitate increasing the concentration of or even changing the friction modifier type used.

Esche contends that engine oil lubricants have only about a 10 percent or less influence on the total friction/energy loss in an engine. Axel and transmission lubricants can affect another 5 percent or less of the friction/energy losses.

The benefits of both organic friction modifiers and MFMs are shown in the Sequence VID consortium data in Figure 3. Esche adds, “This data shows that friction modifiers have a positive effect on engine oils across several different viscosity grades. It also shows the performance advantage a molybdenum-based friction modifier has over an organic friction modifier.”

Generally speaking, it is common

‘Formulating engine oils is a balance between engine durability, which is paramount, emission system durability and fuel efficiency.’

– Mark Rees, The Lubrizol Corp.

knowledge in the industry that the more friction modifier added to the formulation, the better the fuel economy. Consequently, today’s formulators are adding more friction modifiers to the engine oil.

DeBlase believes that common friction modifiers can be effective in reaching an additional 1.5-2.5 percent fuel economy improvement for organic types and just over 3 percent for very effective organic and metal-containing types above the gain realized from decreasing oil viscosity. “For HDDEOs (for example, 15W-40 reduced to 5W-40), an additional 1 percent fuel economy improvement is possible, but this may be tempered if boundary friction increases at the same time,” DeBlase says. “This necessitates the need for greater use of friction modifiers to meet the demands generated by high loads and low viscosity.”

Bansal feels that friction-modifier

effectiveness has been going down over time because of engine improvements made by OEMs. He says, “Strides made in the last two decades by OEMs to minimize friction losses in the engine has made it more difficult for friction modifiers to do their job. As a result, modern engines tend to operate more in the hydrodynamic and mixed lubrication regimes and less in the boundary regime where friction modifiers are most effective.”

SCREENING TESTS

Most of the respondents cite the challenge of correlating bench screening tests to real-world engine tests such as automobile fleet trials. “Screening tests are notoriously unrepresentative of real-world operations. However, it is challenging to conduct powerful research and formulation evaluations in non-standard conditions. We have a dilemma,” Bell says. “There exist many frictional and surface chemistry tests that can be used to evaluate lubricant chemistry. Common instruments used in these screening tests include the Mini-Traction-Machine (MTM) and High-Frequency Reciprocating Rig (HFRR). These are quick, cheap and repeatable. However, they are nothing more than indicative of how a system responds under a unique set of operating conditions, and we know that vehicles in the field see many sets of conditions.”

Bell continues, “Electrically motored engines are the next level of testing options, but while they are clearly more relevant to operating conditions and are relatively reliable, they lack the full operational influence of a fired engine, and as such they can only assess the instantaneous frictional performance of a lubricant.”

Bell finishes by stating that fired-engine tests also have their limitations. Although they are a lot more closely linked to vehicle operation, they are limited to one type of hardware and limited operational conditions. He says, “The ultimate screening and evaluation tool is a fully operational vehicle, operating under a repeatable and appropriate driving cycle and prac-

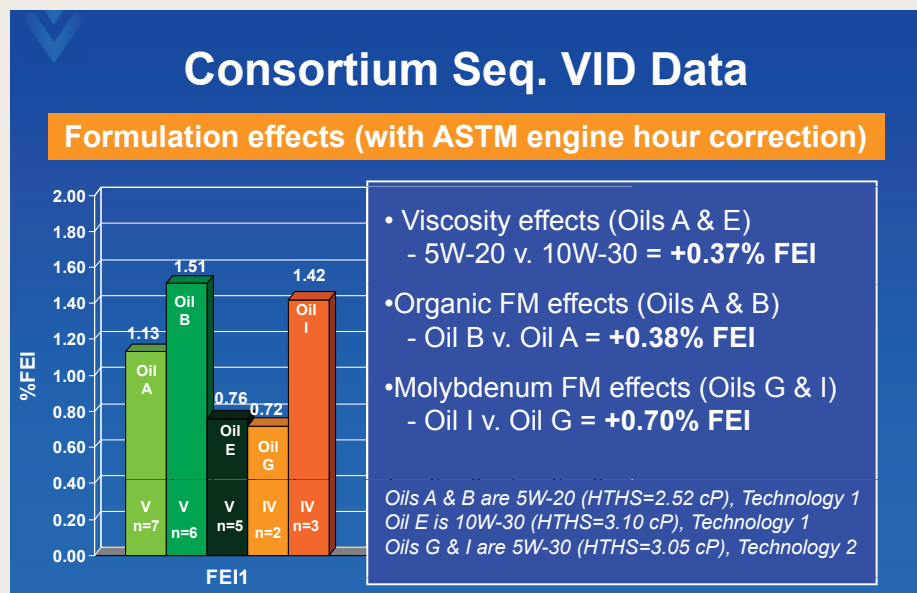


Figure 3 | Consortium Sequence VI data shows the fuel economy improvements obtained through changes in engine oil viscosity and the use of organic friction modifiers and metal-containing friction modifiers (MFMs) in several PCMO viscosity grades. (Courtesy of Vanderbilt Chemicals LLC)

tically on a dynamometer. These can be run very quickly and accurately, affording very precise data and evaluations.”

Bansal agrees, “Many bench screening tools are used in the lubricant industry to measure the performance of friction modifiers. However, little or no effort has been reported in the literature to determine the relevance of these tools to the real world. Realistically, it is nearly impossible to replicate the exact engine environment in a bench scale test. Therefore, we believe that a suitably field-correlated engine test is the only reliable method to evaluate the fuel efficiency performance of a friction modifier.”

‘Due to cost constraints, bench testing is the preferred route to screen a large number of candidate engine oils.’

**– Dr. Carl Esche,
Vanderbilt Chemicals, LLC**

Sztenderowicz also agrees with the approach of using field testing but cautions that there is a trade-off with the cost involved. He says, “Field testing, engine test stand or chassis dynamometer testing is most relevant, especially when realistic driving cycles are used. However, such testing is expensive and is subject to two important limitations. First, variability for such tests can be high, making it hard to discern differences between two engine oil formulations. Second, the results are specific to engines or vehicles used, as well as the operating conditions and, therefore, may not relate directly to others.”

Sztenderowicz continues, “For this reason, a variety of laboratory bench friction tests can be used as screeners to evaluate friction modifiers. These are usually very repeatable, easily adjusted to cover a wide range of conditions and are relatively inexpensive.”

DeBlase believes that the Cameron Plint TE-77, MTM and HFRR tribology tests are useful in assessing the performance of friction modifiers in lab screening tests. He says, “The Camer-

on Plint TE-77 operates in the friction mode (dowel-pin-on-plate) to provide a coefficient of friction (COF) versus temperature profile in the range between 60 C-165 C. This test allows a complete characterization from milder conditions at low temperatures to higher temperatures where physisorption to chemisorptions transitions can occur.”

“The MTM provides a range of friction conditions from hydrodynamic, mixed to boundary lubrication when operated in the Stribeck configuration, providing COF versus entrainment speed at isothermal temperatures (e.g., 50 C, 80 C, as well as higher, 120 C-150 C). HFRR measurements can provide simultaneous measurements of both a wear-scar and the boundary coefficient of friction and offer a high-speed, reciprocating measurement of friction on smaller volume samples,” DeBlase continues. “These measurements can be done isothermally or at a temperature ramp, similar to the Cameron Plint. Another option is the SRV tribology testing instrument that can provide boundary layer coefficient of friction data with a flexible array of specimen geometries such as ball-on-disk, pin-on-disk, cylinder-on-disk and disk-on-disk.”

DeBlase finishes up by cautioning that no-harm testing needs to be done to make sure that specific friction modifiers do not function adversely under operating oxidation conditions that could result in metal corrosion or elastomeric degradation. “Friction-modifier additives must also be evaluated in the presence of variations in base oil types (both mineral oil and synthetic) and in the presence of other additives such as antioxidants, antiwear, dispersants, detergents and VI improvers,” DeBlase says. “The Falex four-ball wear (ASTM D4172) and Cameron Plint wear tests are useful to insure compatibility between extreme pressure, antiwear additives and friction modifiers.”

Donaghy agrees about the types of bench screening tests that are used to screen friction modifiers. “The MTM has the advantage in that friction can

be determined in pure sliding, pure rolling and a mixture of sliding and rolling conditions. The SRV, HFRR and the Cameron Plint are limited in that they measure friction only in sliding contacts,” Donaghy says. “The SRV test is perhaps the most versatile of the three sliding contact tests in that it is feasible to determine friction between materials actually used in an engine (for example, by taking a slice of the cylinder liner and the piston rings).”

Esche indicates that the efficacy of a friction modifier ultimately comes down to its performance in an engine test. He says, “Due to cost constraints, bench testing is the preferred route to screen a large number of candidate engine oils. Once the top several candidate oils have been selected, they are then run in an engine test. The engine test may be a stand-alone engine in a test stand or a vehicle that has been placed on a chassis dyno. In either case, the fuel economy of the engine oil is determined by the amount of fuel consumed during the test.”

SEQUENCE VIE FUEL ECONOMY ENGINE TEST

In GF-6 the key engine test to evaluate fuel economy has been designated as the Sequence VIE test. A new lower-viscosity grade known as SAE 16 has been approved and may provide additional fuel economy benefits, but those will need to be established. Oils used in SAE 16 will have a viscosity of 0W-16.

The new viscosity grade will require that GF-6 be split into two categories known as GF-6A and GF-6B. All oils that are backward compatible with older engines will be in GF-6A. The new SAE 16 will be assigned to GF-6B and not be backward compatible.

The industry representatives contacted were asked for comments on the Sequence VIE and whether testing will differ for the new SAE 16 viscosity grade. For the most part, most respondents indicated that it is too early to tell how the new engine test will work with specific friction modifiers.

DeBlase says, “Current work is showing that a total fuel economy im-

provement (FEI) value for XW-20 oils of 3.6 can be realized for GF-6 as compared to 2.6 for GF-5. A similar improvement from 1.9 to 2.9 can be achieved for XW-30 oils.”

The FEI is determined from measuring the fuel economy of virgin engine oil (FEI1) and engine oil aged for 100 hours (FEI2). DeBlase states that this increase is for GF-6A oils, while work is in progress to determine the FEI for new lower viscosity GF-6B oils.

DeBlase adds, “If oil oxidation occurring from the FEI2 impacts the friction-modifier additive needed, then friction-modifier additive durability will also be very important to help reach the FEI level targets. In addition for longer drain intervals, friction modifier durability will no doubt be important.”

Donaghy says, “The Sequence VI engine test uses a different engine than was used in the Sequence VID (current GF-5 test), but it is expected that friction modifiers will provide a similar effect in the new engine. The SAE 16 specification will give rise to a decrease in viscosity at higher operating temperatures in the engine, which will lead to thinner films and potentially higher wear. This need not be a high concern for new engines designed to operate under thin film/boundary lubrication, but the use of friction modifiers to increase film thickness and still maintain low friction will still be highly desirable.”

Bansal says, “On fundamental principles, the SAE 16 grade should provide better fuel economy performance than other grades, primarily due to lower energy losses in the hydrodynamic mode. However, it remains to be seen whether the Sequence VIE test is configured for the appropriate balance of the various lubrication regimes to be able to accurately measure the hydrodynamic response of this very light grade.”

Bell says, “The current intent for 0W-16 low viscosity engine oils is that they will exhibit improved fuel economy over XW-20 (0W-20 or 5W-20) oils in the Sequence VIE test. Data pre-

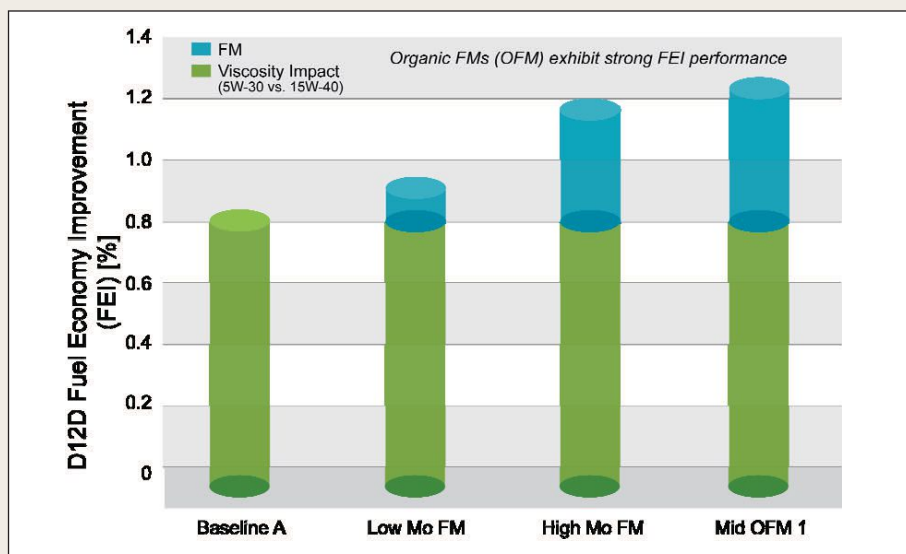


Figure 4 | Fuel economy improvements are seen by reducing viscosity and using friction modifiers in the Volvo D12D diesel engine. A better benefit is seen by reducing viscosity as compared to using friction modifiers. (Courtesy of Chevron Oronite Co. LLC)

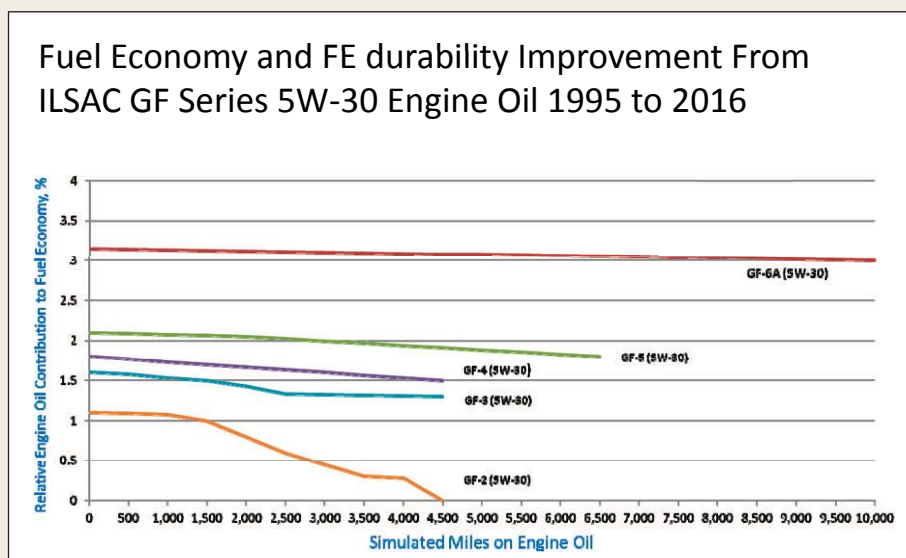


Figure 5 | In moving from GF-2 in 1995 to the development of GF-6A (due to be available in 2016), the contribution of the engine oil to fuel economy has shown a progressive improvement. (Courtesy of The Lubrizol Corp.)

sented within the industry has demonstrated that these fluids can perform significantly better than the current GF-5 specification limits for SW-20 oils when tested in the Sequence VID test. Whether or not this improvement will be observed in the new hardware and test will be determined through industry matrix testing.”

FRICITION MODIFIERS VS. REDUCING VISCOSITY

Both friction modifiers and reducing the viscosity of engine oils have been shown

to improve the fuel economy of automobiles. But how do they compare and potentially complement each other?

Sztenderowicz says, “Usually, reducing viscosity has a larger benefit than friction modifiers when moving from ‘traditional’ viscosity grades to the latest OEM-recommended low-viscosity grades. This is shown in Figure 4 in which the effects of both reduced viscosity (from 15W-40 to 5W-30) and the addition of three friction modifiers is shown for a heavy-duty diesel engine.”

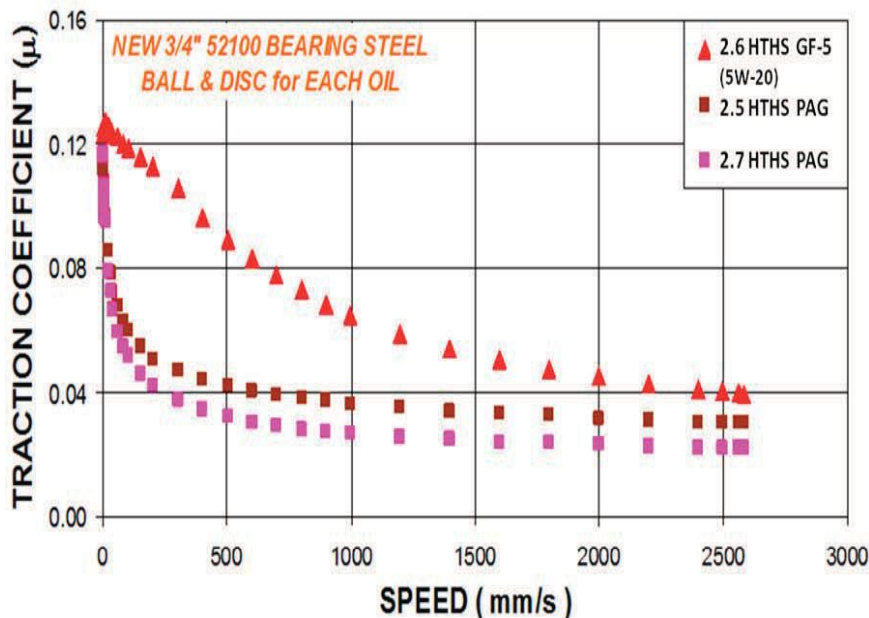


Figure 6 | MTM ($T = 100\text{ C}$; $F_N = 50\text{ N}$, $SRR = 150\text{ percent}$, 12th repeat) traction curves for PAG-based prototype passenger car engine oils are benchmarked against a typical 5W-20 GF-5 formulation. (Courtesy of The Dow Chemical Co.)

But Sztenderowicz cautions that continuing to reduce engine oil viscosity will not lead to further fuel economy benefits without friction modifiers. He says, “For prototype oils of viscosity below 0W-20, Sequence VID engine test results flatten out. Due to this, friction modifiers become increasingly important for low-viscosity oils, and, in fact, enable further fuel economy improvements when continuing to reduce viscosity.”

Bell agrees that engine oil viscosity will, in general, more effectively improve fuel economy. He says, “The impact of a viscosity grade change is typically four to five times larger than the maximum one might expect from a friction modifier in a typical test. However, friction modifiers still play a part in lubricants. First, there is a limit (or indeed several limits) to how low one might drive viscosity. Second, the friction modifiers allow the formulator to tune performance (boost) within the range of the viscosity grade.”

Mark Rees, global business manager-passenger car engine oil additives for The Lubrizol Corp. in Wickliffe, Ohio, indicates that engine oil formulations have evolved over the past 20 years, showing a progressive improve-

ment in fuel economy from GF-2 to GF-6A, as shown in Figure 5. “Formulating engine oils is a balance between engine durability, which is paramount, emission system durability and fuel efficiency. Optimizing fuel efficiency is much more than just adding friction modifier and switching to a lighter viscosity grade,” Rees says. “The core formulation must be built from the ground up in order to properly balance the many components, including the friction modifier that act together to maintain durability while also reducing overall friction.”

STLE-member Dr. Kaustav Sinha, associate scientist for The Dow Chemical Co. in Midland, Mich., expressed concern that reducing the engine oil viscosity to reduce friction in the hydrodynamic region may lead to a premature transition to the boundary/mixed regime that could lead to frictional losses and wear, if the right combination of friction modifier/extreme pressure/antiwear components are not used. He believes there are opportunities to improve fuel economy, particularly for heavy-duty diesel engine oils that use the 15W-40 viscosity grade and mostly operate in the hydrodynamic region.

“One possible option for friction reduction would be through the introduction of polyalkylene glycols (PAGs) as an additive/co-basestock in a fully-formulated fluid,” Sinha says. “Due to their oxygen polarity, PAGs have solvent properties different from those of hydrocarbons. The polarity of PAGs, including oil-soluble versions, further enhances their affinity for metal surfaces, forming a durable, low-friction lubricating film.”

Figure 6 shows the friction reduction benefit of two prototype, PAG-based PCMO formulations in MTM studies.

David Gray, technical service manager for Evonik Oil Additives USA, Inc. in Horsham, Pa., observes, “The question can be very difficult to answer for a variety of reasons. First, the majority of published data available uses fully formulated lubricants, which are highly likely to contain friction modifiers so the impact of lowering viscosity along is difficult to determine. Second, different engine or bench tests used to generate the data may respond more strongly to either reducing viscosity or changes in friction modification than can be seen in the field. As such, it would be fair to say both are critical, but the art is determining the balance.”

‘An engine is a very complex system that at any one time can have multiple frictional regimes occurring simultaneously.’

**– David Gray,
Evonik Oil Additives USA Inc.**

Gray continues, “An engine is a very complex system that at any one time can have multiple frictional regimes occurring simultaneously. Addressing one frictional regime alone while ignoring others will not maximize all potential gains that are possible. As such one should look at specific viscosity measurements such as High Temperature High Shear (HTHS) viscosity, which can be directly correlated to improvements in fuel economy.”

DeBlase also believes that friction modifiers will be needed with the low-viscosity GF-6B engine oils. He says, “The higher FEI expected for GF-6B will no doubt also require sufficient, durable friction-modifier additives in their formulation to overcome increased boundary layer asperity friction from the SAE-16 lower viscosity oils.”

For heavy-duty diesel oils, viscosity reduction will be very important, according to DeBlase. He says, “Reducing oil viscosity reduces mixed and hydrodynamic losses, which, if significant, can improve fuel economy.”

HOW LOW CAN THE VISCOSITY BE REDUCED?

Most respondents consider the answer to this question to be more a matter of how effective OEMs are in developing new engine technology that will be compatible with the new SAE 16 grade and even lower viscosity oils. Bell says, “This is a critical question that essentially cannot be answered in isolation. It is possible to develop an effective lubricant at viscosities well below those used today and well below 0W-16. However, it necessitates the co-development of hardware to accommodate that fluid. This is the direction that we believe the industry will need to move toward in the future to truly access extreme fuel economy benefits.”

Bell continues, “We are beginning to see these hardware limitations become evident. The fact that not all OEMs will use 0W-16 oils and not all will use 5W-20 oils means there are limitations in the current hardware and engine configurations preventing the use of lower viscosity fluids.”

DeBlase stresses that friction modifiers will be instrumental as engine oil viscosity continues to be reduced. “Besides viscosity, other key parameters to consider when reducing friction are the load and the speed of moving parts in contact. Lowering engine oil viscosity without reducing boundary friction provides little improvement (especially at high loads),” DeBlase says. “To achieve lower boundary friction, either friction modifiers or modification

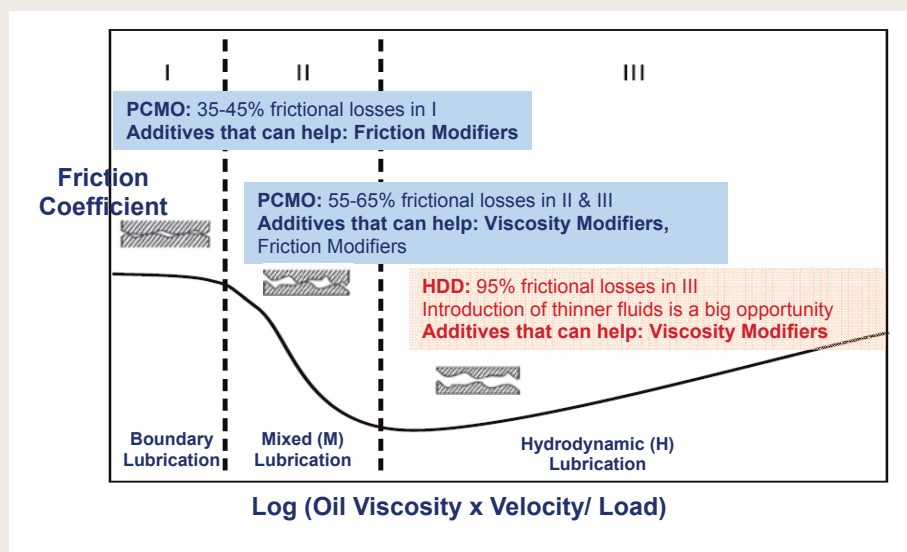


Figure 7 | VI improvers and friction modifiers can be used in a complementary fashion in properly formulated engine oils to reduce friction because they operate in different lubrication regimes, as noted in the Stribeck Curve. (Courtesy of Infineum USA LP)

of the engine metallurgy and surfaces through coatings such as diamond-like carbon or other alloys, working in concert with friction modifiers, may be needed.”

Bansal speculates about how far the viscosity can be reduced without major adverse consequences. “It is generally believed that at a sufficiently low viscosity, the boundary losses will begin to wipe out any benefits gained from the reduced hydrodynamic losses,” Bansal says. “However, we feel that other factors such as oil volatility will be potential barriers to going too low in viscosity, well before the point of diminishing returns on energy efficiency is reached. Input will be needed from the basestock manufacturers on this issue.”

STLE-member John Cuthbert, principal research scientist for The Dow Chemical Co., says, “At low viscosities (such as 0W-20), there are significant formulation challenges with limited basestock options (with controlled Noack volatility) and little or no room for VI improvers. In order to push the envelope, the lubricant industry has to look into novel antiwear chemistries, friction modifiers and alternative co-basestocks.”

Gray states that while the current trend is to reduce viscosity in order to

improve fuel economy, some OEMs believe the fuel economy benefit seen with lower-viscosity oils will be more than offset by the cost needed to ensure durability. He says, “How low the viscosity can be reduced depends to a large extent on engine design, and bigger bearings may be more tolerant of lower viscosity. However, at least one OEM has stated that the added cost to ensure durability may more than offset the fuel economy benefit that can be realized.”

Gary adds, “Newer engine designs have been developed using lower viscosity fluids and have greater flexibility in the range of viscosities that can be safely used without impacting durability, but we must be mindful of protecting the engines currently in use.”

Sztenderowicz says, “Various OEMs have different opinions on how low engine oil viscosity can drop. Increased wear, especially in highly-stressed contacts like the valve train, have been noted for oils below 0W-20 using industry standard tests such as the Sequence IVA. But there are now OEMs that use oils below 0W-20 as their factory fill in some vehicles. The bottom line is that both engines and oils continue to improve and, when designed together as a system, using oils of SAE 0W-16 and lower without negative impacts is possible.”

Donaghy says, “Reducing the HTHS viscosity too far can have a negative effect on fuel economy. Too low a HTHS viscosity results in not having a sufficient film to support the increases in load and friction. Some polymeric friction modifiers that form thick, low traction films show potential to reduce HTHS beyond the current limits.”

Esche cautions that thin oils are not a problem when used in the correct engine. He says, “The problem arises when thin oils are used in older technology engines that were not designed to use a thin oil. If this were to happen, then it would not be unreasonable to expect friction and wear to increase, as the engine would tend to spend more time operating in the boundary lubrication regime.”

EFFECTIVENESS OF VI IMPROVERS

In looking at the Stribeck Curve (see Figure 7 on page 22), VI improvers can reduce frictional losses in the mixed and hydrodynamic lubrication regimes. This is in contrast to friction modifiers, which provide benefits in the boundary lubrication and mixed regimes. If properly formulated, VI improvers and friction modifiers can work in a complementary fashion.

Rees believes that VI improvers are an important element in improving fuel economy. He says, “VI improver use can result in a lower bulk oil viscosity under the actual operating conditions of the vehicle, and thereby lower viscous pumping losses for any given viscosity grade. Testing through a variety of protocols, including dynamometer testing under various drive cycles, and in the Japanese FTT Fuel Economy Test has demonstrated the fuel economy improvements of VI improver-containing formulations.”

Gray feels that significant fuel economy improvements are possible with the use of VI improvers by raising the viscosity index of an oil. “Selection of the correct VI improvers for the application will allow an oil marketer to meet the minimum HTHS viscosity while lower kinematic viscosity,” Gray

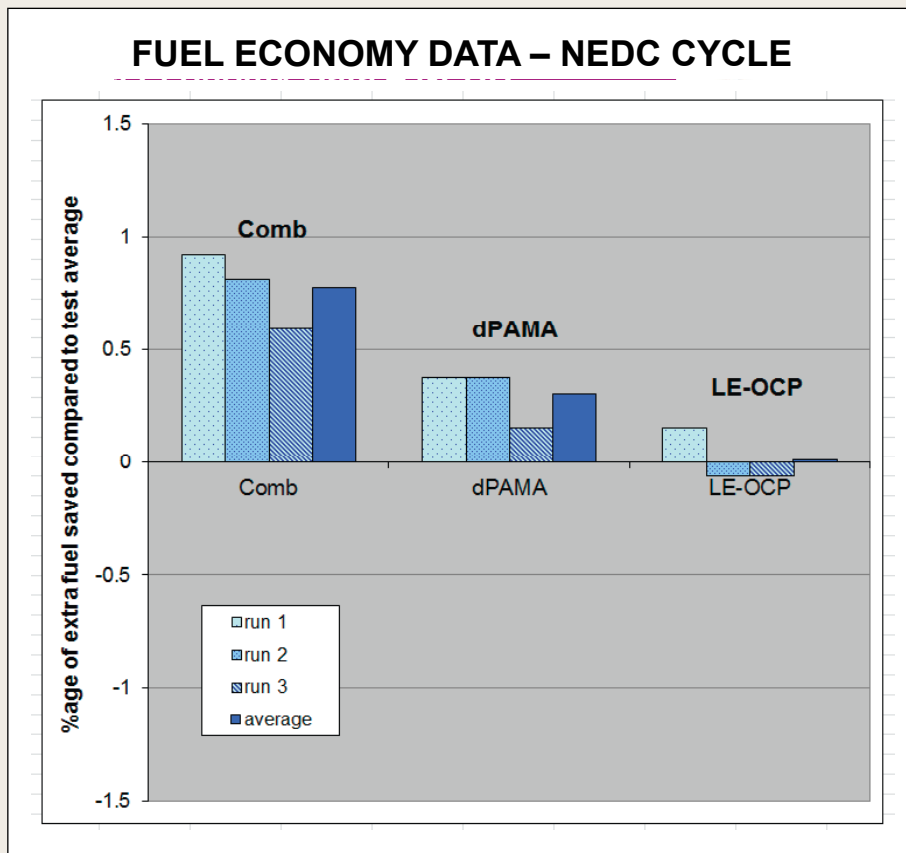


Figure 8 | Evaluation of three VI improvers by the new European driving cycle (NEDC) test showed that a comb type poly alkyl methacrylate polymer and a dispersant poly alkyl methacrylate polymer display fuel economy improvements as compared to a baseline low ethylene olefin copolymer. (Courtesy of Evonik Oil Additives USA, Inc.)

says. “Furthermore, VI improvers with specific chemistry and unique architecture can be utilized to optimize viscosity across a much wider range of temperature and shear regimes. This would allow a marketer to further lower the kinematic viscosity at critical temperatures, while ensuring engine durability by maintaining the critical minimum level of HTHS viscosity.”

In a study using the new European driving cycle test, engine oils were formulated with 4 cSt group III base oil using the same DI package.⁴ Three different types of VI improvers were used at a HTHS 150 C level of 3.5 mPas. The results in Figure 8 (over three runs that are averaged) show that a comb type poly alkyl methacrylate (comb) polymer displayed superior fuel economy improvement over the baseline low ethylene olefin copolymer (LE-OCP). Fuel economy improvements were also seen with a dispersant poly alkyl meth-

acrylate (dPAMA) polymer as compared to the baseline.

Gray summarized by saying, “Combining friction modifiers with the correct VI improver has been proven to make engine oils a very effective tool in improving overall vehicle efficiency.”

Bell notes that VI improvers have an important role to play in improving fuel economy, mainly through the use of new polymers that can enable formulators to access specific viscometric properties not allowed with current ones. He adds, “As engines get smaller and more powerful, there will be increased thermal stress on the lubricant, so the industry will need effective VI improvers that minimize polymer loading. Specific dispersant-VI improvers could be very helpful in reducing soot agglomeration in the emerging gasoline direct-injection engines and their inherent wear benefits should be useful in lower viscosity engine oils.

One potentially important area will be HDDEOs as the industry moves to lower viscosity lubricants for PC-11.”

Viscosity modifiers contribute to lubricant fuel efficiency primarily through shear thinning and viscosity-temperature properties. Since viscosity modifier technologies differ significantly in terms of these properties, they differ significantly in their relative contributions to lubricant fuel efficiency, according to Bansal. “All viscosity modifiers exhibit some amount of shear thinning, i.e., temporary loss of viscosity with the shear field applied by the engine operation. This temporary reduction in viscosity can translate into fuel economy benefits, especially in hydrodynamic and mixed lubrication operations,” Bansal says. “The extent of shear thinning depends on the degree to which the viscosity-modifier polymer coiling in the oil can align itself with the shear field. By suitably manipulating the chemical structure of the polymer backbone, the shear thinning response of a viscosity modifier can be enhanced.”

Bansal also points out that driving conditions impact the temperatures seen by the oil, which, in turn, makes the viscosity-temperature behavior of the oil an important property for the lubricant fuel efficiency. He says, “A lubricant in a vehicle driven mainly in short-haul drive (e.g., urban commuter traffic) would rarely operate at the kind of sump temperatures seen in long-haul highway driving. Therefore, a lubricant that exhibits lower viscosity at the moderate temperatures prevalent in short-haul drive cycles would offer fuel economy benefits over a higher viscosity lubricant under similar conditions. Recent advances in viscosity-modifier technology has made it possible to maximize the lubricant fuel efficiency in low temperature operations by minimizing the lubricant viscosity under such driving cycles.”

Alex Boffa, global viscosity index improver-technical team leader for Chevron Oronite Co. LLC, says, “VI improvers can be tailored to provide optimum temperature and shear re-

sponse for both fuel economy and engine durability benefits. Properly designed VI improvers support higher lubricant viscosities in the hotter engine operating environments for robust wear protection, while maintaining lower viscosities in moderate engine temperature environments, which provides fuel economy benefits.”

He continues, “Depending on the engine design and operating conditions, hydro- and elasto-hydrodynamic lubrication are predominant within the engine and, consequently, viscosity measurements such as HTHS show strong correlations with fuel economy. This is particularly important for state-of-the-art engines designed to mini-

‘However, we feel that other factors such as oil volatility will be potential barriers to going too low in viscosity, well before the point of diminishing returns on energy efficiency is reached.’

– Dr. Jai Bansal, Infineum USA LP

mize boundary and mixed friction with specialty features. As a result, VI improvers have a far greater role in today’s engine oils beyond their traditional thickening capabilities.”

DeBlase says, “VI improvers offer a compromise allowing effective viscosities to be low on cold start-up at low speeds but allow the viscosity to increase at warm temperatures so that boundary lubrication friction is not as severe a problem.”

The use of other synthetic basestocks that have high viscosity indexes may play a role in improving the effectiveness of VI improvers. Donaghy says, “The use of unconventional base oils such as esters may help to produce less viscosity drag at lower temperatures, while also reducing traction in the hydrodynamic regime.”

Cuthbert says, “The very broad product design space possible with polyalkylene glycols enables them to be potentially useful as a co-basestock for VI improvement.”

ENGINE WEAR

With the growing use of lower-viscosity oils, engine wear may become more of a problem. The contributors were asked to comment on whether VI improvers and other additives may be used to minimize this potential concern.

Boffa indicates that rheological response has a significant impact in controlling engine wear. He says, “Proper understanding of the full rheological response curve can mitigate the effects of seeing higher wear in lower viscosity oils. For instance, higher HTHS viscosity measured at 150 C (which is commonly reported given its inclusion in SAE J300), provides better wear protection and strong correlation with fuel economy at temperatures ranging from 40 C to 100 C.”

Boffa continues, “Certain OCP VI improvers provide a good balance of robust HTHS 150, which is important for low wear while having reduced viscosity contributions at lower temperatures important for fuel economy. Further, certain functionalized VI improvers can also help to reduce wear by forming a protective film on metal surfaces or finely dispersing soot to help minimize wear.”

Gray agrees that HTHS viscosity is critical for engine durability when using low and ultra-low viscosity oils. VI improver choice will be very important in minimizing wear and maximizing fuel economy. He says, “While some VI improvers can maintain or boost HTHS viscosity, many do it at the expense of low temperature viscosity potentially negating fuel economy gains. Additionally, some VI improvers have been shown to form very effective films at the surface, reducing friction and wear and improving efficiency.”

Rees feels that VI improvers will have a strong role in minimizing wear in low viscosity engine oils. “VI improvers have the capability to provide thicker lubricating films under certain operating conditions. A thicker lubricant film can protect metal surfaces, thereby minimizing wear,” Rees says. “As the use of lower viscosity engine oils increases, the role of VI improvers

to provide wear protection increases. The combination of a robust engine oil additive package, VI improver and base oil can optimize engine oil performance to ensure durability, emission system compatibility and optimize fuel efficiency.”

Besides seeing a need for viscometric balance, Bell believes that maximizing soot control and antiwear performance are important for low viscosity engine oils. He says, “Wear protection will need to be supported via soot control and inherent antiwear properties.”

‘Wear protection will need to be supported via soot control and inherent antiwear properties.’

– Ian Bell, Afton Chemical Corp.

DeBlase sees the use of VI improvers being very important in HDDEOs and agrees that minimizing soot formation will be very important in low temperature oils. “Since frictional losses in diesel engines are more heavily weighted toward hydrodynamic lubrication, it is expected that VI improvers can be useful in controlling the losses at low temperatures,” DeBlase says. “The impact of soot formation from burning diesel will be decreased by effective dispersants capable of reducing the viscosity impact from soot accumulation.”

Bansal says, “Viscosity modifiers can contribute to wear protection by providing thicker oil films under the shear conditions prevalent in the engine. However, the proper choice of the antiwear additive system is the most important factor in wear protection in low viscosity regimes. Indeed, some recent advances in antiwear technology have the potential to significantly reduce the viscosity sensitivity of engine wear.”

To date, no conclusive evidence has been presented to the industry showing this should be a problem, according to Esche. He says, “The current GF-5 antiwear technology will be sufficient to protect engines. However,

one cannot rule out the use of supplemental antiwear additives.”

HEAVY-DUTY DIESEL ENGINE OILS

The movement to improve fuel economy in heavy-duty diesel vehicles raises the questions about what additive technologies, in general, and whether friction modifiers and VI improvers, in particular, will have a role in formulating future engine oils in the two PC-11 categories under development. Feedback from most contributors indicates that VI improvers will play a significant role. But there is uncertainty about how much influence friction modifiers will have at this point.

Bansal says, “Our research in heavy-duty diesel fuel economy over the last six years indicates that lubricant viscosity is a much bigger factor than friction modifiers. These observations are further supported by our work on engine friction mapping, which shows that hydrodynamic and mixed lubrication regimes, and not the boundary regime, are the dominant modes of operation in modern heavy-duty diesel engines.”

Rees agrees that VI improvers will continue to have an important role in meeting the requirements of future fuel economy in HDDEOs. “For PC-11, the industry is considering the balance point between fuel efficiency and engine wear associated with the HTHS viscosity of the lubricant,” Rees says. “Daimler is sponsoring a scuffing wear test to assure that HDDEOs protect the engine from scuffing (adhesive) wear in traditional SAE 15W-40 viscosity grades, as well as at reduced oil viscosities such as SAE 10W-30 and 5W-30.⁵ VI improvers are the fundamental design component used in meeting the several viscometric requirements of modern HDDEOs.”

Sztenderowicz feels that friction modifiers will have a role in future HDDEOs. He explains, “We published data showing that friction modifiers also can provide a benefit in on-highway commercial diesel engines. Effective application of friction modifiers

improves fuel economy by several tenths of one percent (see Figure 4 on page 20). Additionally, other components such as detergents and dispersants can impact friction in an engine, while base oils and viscosity modifiers can be chosen to optimize viscometric properties.”

Bell considers friction modifiers to probably not be a factor for HDDEOs. He says, “It seems unlikely that friction modifiers will see mainstream use in HDDEOs. The technology is lagging behind PCMOs and as such there are far bigger gains to be had through the continued drive down in viscosity grade. As such, VI improvers will likely have a bigger part to play. Further, there are no current fuel economy tests for HDDEOs that would likely show an impact from friction modifiers.”

Sinha says, “We expect the data on fuel economy testing obtained from PCMOs will slowly trickle down to HDDEOs. An added stress will be the need to minimize soot induced wear, which is a major component of the HDDEO specification testing. Controlling soot induced wear will be a key factor, while lowering the viscosity in HDDEOs to achieve improved fuel economy.”

Esche says, “One thing is for certain given the lubricant industry’s push for improving diesel engine oil fuel economy is that you can be certain that formulators will select the best VI improvers, friction modifiers, antioxidants and any other additives they think are necessary to maximize the fuel economy performance of their engine oils.”

DeBlase cautions that the friction modifiers used in HDDEOs will need to be compatible with dispersants. He says, “The use of friction modifiers should help the effort to reduce the viscosity to a greater extent by protecting boundary lubricant friction increases. In addition, the impact of the accumulation of soot and dispersant use to counteract this potential problem will require friction modifiers that will avoid negative interactions with dispersants.”

'VI improvers can be tailored to provide optimum temperature and shear response for both fuel economy and engine durability benefits.'

– Alex Boffa, Chevron Oronite Co. LLC

Donaghy says, "Friction modifiers will come into their own as (and when) oil viscosity is reduced to improve fuel efficiency. Much will depend on whether heavy-duty diesel engines run in the mixed or hydrodynamic lubrication regime. If principally hydrodynamic, then viscosity, base fluid and VI improver technologies will have the greatest impact."

Gray says, "Fuel economy will be extremely important in heavy-duty diesel vehicles. How it will be defined and how much can be achieved by friction modifiers and how much can be achieved by reduced viscosity will likely be quite different than in a gasoline engine."

PC-11

Most respondents feel that fuel economy benefits in HDDEOs will be realized by using lower viscosity oils.

DeBlase notes that the higher viscosity oils needed for the backward compatible PC-11 subcategory will mean that higher treat rates of friction modifiers may be needed to begin to make an impact on the fuel economy improvement. He says, "The improvements in HDDEOs by PC-11 will be more likely targeted for newly designed heavy-duty diesel engines designed for lower viscosity lubricants. In effect, the PC-11 category may have to compromise on fuel economy improvement in order to keep the other required performance characteristics."

Bell says, "The fuel economy focus for PC-11 will manifest itself in areas other than fuel economy. The fuel economy benefit will be realized through a shift in viscosity grade, so the technical challenge will manifest in durability (wear). Also, the use of lower viscosity basestocks may have a secondary impact on oxidation and cleanliness."

Gray says, "At this time, the Engine Manufacturers Association has determined that no specific fuel economy test is recommended for PC-11. Instead, a viscosity specification specifically reducing the HTHS viscosity of the fluid will be used to impact and improve fuel economy."

"In a similar fashion to gasoline engine OEMs, the primary concern of diesel engine OEMs when reducing HTHS viscosity is durability," Gray continues. "Accordingly, the OEMs have adopted a fairly modest reduction in the minimum requirements for PC-11, which they believe will still afford measurable and significant fuel economy improvements."

They are, however, working on a split specification with a second, higher and more traditional HTHS limit in order to protect heritage equipment still in use in the field, which is less tolerant of lower viscosity fluids.

Bansal draws a parallel between the current PC-11 category and the work done to improve the fuel economy of PCMOs. "Fuel economy is one of the major reasons for the introduction of the PC-11 category," Bansal says. "We believe this is the beginning of a long march to low-viscosity lubricants for the heavy-duty diesel segment, much as the introduction of the SAE 5W-30 grade was for light-duty vehicles in the early 1980s."

"It will take some time for the market to warm up to low viscosity grades, but the benefits of such lighter grades over the current SAE 15W-40 lubricants is not in question," Bansal continues. "OEMs and end-users will need to be convinced that these lighter viscosity grades will not compromise engine durability before large scale migration to these viscosity grades takes place."

Sztenderowicz sees the need for field testing to demonstrate both better fuel economy and durability with PC-11 engine oils. "For PC-11, there will be much greater emphasis on developing fuel-efficient, low-viscosity oils such as 5W-30 and 10W-30 compared with any previous API heavy-duty category," Sztenderowicz says.

"This will require extensive additional work to develop oils that provide the needed performance and durability at lower viscosities. Since there is no proposed industry fuel economy test for PC-11, field testing will be highly desired to demonstrate both the fuel consumption benefits as well as real-world durability."

Now that fuel economy has become a focal point for the lubricant industry, undoubtedly, a good deal of attention will be paid to what additives will be needed for both PCMO and HDDEOs. The end result at this point is uncertain, but it appears that both VI improvers and friction modifiers will be involved in the development of engine oil lubricants with even better fuel economy characteristics. **TLT**

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