lubricants

Review

Common Properties of Lubricants that Affect Vehicle Fuel Efficiency: A North American Historical Perspective

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Abstract: The development of advanced lubricants to improve vehicle fuel efficiency can appear to be as simple as lowering the viscosity and frictional properties of a fluid. However, applied research studies have shown that it is quite difficult to quantify the fuel efficiency properties of advanced lubricants in vehicles. A review of the historical research predominantly performed in North America in this area reveals that there are many factors to consider in order to demonstrate the effectiveness of advanced lubricants. First, the methodology used to measure vehicle fuel efficiency will impact the results since there are many factors not related to the lubricant which will influence vehicle fuel efficiency. Second, developing advanced fuel-efficient lubricants under well controlled conditions overlooks the issue that lubricant properties such as viscosity and friction affect the operating conditions encountered by the lubricant in the vehicle. Finally, the physical properties of lubricants that historically control fuel economy do not have the same effect on fuel efficiency in all vehicles. The proper vehicle or system level test needs to be selected to properly assess the benefits of new advanced lubricants.

Keywords: fuel efficiency; lubricants; viscosity; friction

1. Introduction

Worldwide government regulations describing vehicle fuel efficiency and exhaust emissions requirements are major technical drivers for improvements to all automotive lubricants. For example, in 1980 in the US, the minimum corporate average fuel economy (CAFE) for a passenger car and light duty truck was approximately 23 MPG. In 2010, this CAFE minimum was approximately 30 MPG and is projected to be over 50 MPG by 2025. For heavy-duty trucks, particulate emission and NOx reductions have been the focus of US regulations. In 1998, the maximum allowed NOx and particulate emissions were 14.4 g/kW-h and 0.8 g/kW-h, respectively. In 2015, these maximum emissions were 0.27 g/kW-h of NOx and 0.013 g/kW-h of particulates. For passenger cars and light duty trucks, there is now a focus on reducing particulate emissions since vehicles equipped with turbocharged gasoline direct injection engines (TGDI), which can improve fuel efficiency, emit exhaust soot. For heavy-duty trucks, reducing CO_2 emissions is becoming a priority by requiring annual increases in fuel economy of between 2.0% and 2.5% from 2018 until 2027 [1,2].

The increased need for advanced lubricants to improve fuel efficiency is reflected in the increase in research related to fuel efficiency lubricants. Figure 1 shows the number of technical papers related to lubricant derived fuel economy published by the Society of Automotive Engineers (SAE) from the 1960s through the 2000s. The number of publications has steadily increased over this time frame, with most research focused on engine oils. A steady increase in publications related to transmission fluids and gear oils also occurred since it is becoming necessary to extract fuel economy performance throughout the drivetrain. When summarizing lubricant technical trends, review papers often focus on future looking technologies. For example, Victor Wong and Simon Tung have written an excellent review of the current state of engine oil lubricant technology to reduce friction and improve fuel efficiency [3]. These reviews and discussions in trade journals often describe future technologies that may have special lubrication needs [3–5]. There are also excellent discussions of how current and new lubricant additive technology affects friction and thus fuel efficiency [6–9]. However, we often do not look back to remind us what past research efforts have already taught us regarding (1) measurement of lubricant properties on fuel economy; (2) the common lubricant properties identified previously and (3) that in all applications, these lubricant properties do not always have the same relative effects.

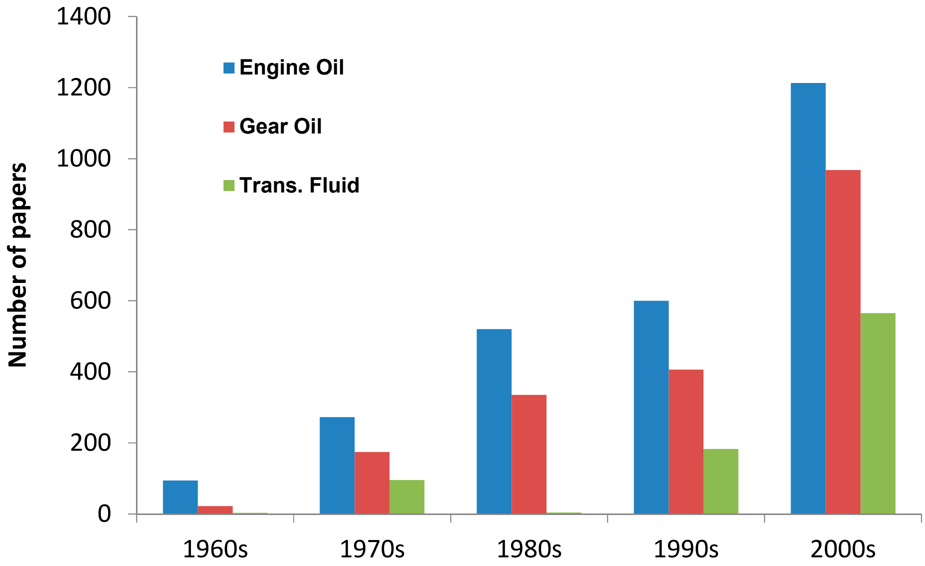

Figure 1. Society of Automotive Engineers (SAE) papers related to fuel economy and lubricants.

This retrospective discussion of fuel efficiency will focus on research performed at Afton Chemical Corporation and predominantly covers research related to North American fuel economy concerns [10–57]. Papers from other research groups are listed in the reference section to show the commonality between observations throughout the industry [58–94]. Some of the studies cited included vehicles, driving cycles or engines of interest to researchers in Japan, Europe and South America [12,19,26,27,32,42,58,61,65,69,70,73,76,77,86]. Therefore, this review may be applicable to a global understanding of fuel economy. It is critical to distinguish between research efforts where lubricants have a direct impact on fuel efficiency versus research where lubricants ensure that mechanical systems designed to improve fuel efficiency operate properly [47–56]. For example, when operating engines at low speeds in order to improve the conversion of chemical to mechanical energy, pre-ignition events (LSPI) can occur that cause damage to the engine. Preventing LSPI enables the operation of engines under more efficient conditions so that fuel economy is improved [51–56]. There are engine oil additives that affect LSPI and fuel efficiency, and those will be discussed in Section 4. The focus in this review will be on lubricant properties that have a direct impact on fuel efficiency.

It is critical to point out that energy balance analyses have shown that the amount of energy to operate a vehicle is approximately 40% of the energy created from combusting fuel [3,4]. Energy loss due to friction in the engine, transmission and axles accounts for approximately 5–15% of the energy created from combusting fuel. Therefore, 45–55% of the energy is lost due to non-frictional inefficiencies in the vehicle, including inefficient conversion of chemical to mechanical energy. A majority of the forty years of lubricant research has focused on recapturing the 5–15% of energy lost due to friction.

Future lubricant advancements to enable mechanical devices that improve powertrain and drivetrain efficiency will help recapture a larger amount of the lost energy.

2. Difficulties with Measuring the Effect of Lubricants on Fuel Economy

Government fuel economy regulations are based on measuring fuel economy in vehicles. Tests to measure the fuel efficiency properties of lubricants can also be performed in fired and motored engine tests, as well as system level efficiency tests for automatic transmission fluids or axle oils. Therefore, before discussing lubricant properties that affect fuel economy, the issues that can arise in measuring fuel economy in vehicles versus isolated systems needs to be explored.

In vehicle fuel economy testing, vehicles are driven under different driving cycles such as those shown in Figure 2 (US06 and the New European Driving Cycle (NEDC) refer to driving cycles required by the US Environmental Protection Agency (EPA) and European Union, respectively). That is, there are accelerations and decelerations as well as steady-state speed conditions. These changes in engine operating conditions will result in changes in the temperature, pressure and shear conditions that a lubricant experiences. These changes in physical conditions will affect the rheological and frictional properties of lubricants and will be discussed in more detail in Sections 3–5.

Human or robot drivers are used to follow the specific driving cycles and the drivers must match the speed versus time profiles within specific tolerances. However, there is an inherent imprecision in following these profiles when control is through the gas and brake pedals. For example, during the development of the Sequence VID fuel economy test, a consortium of companies reviewed automaker-submitted data from more than 600 vehicle tests [94]. The conclusions were that changes in lubricant properties were too subtle to statistically determine in the vehicle tests. Multiple drivers were used in this study and the effect of the driver may well have overwhelmed the results. As a result, vehicle fuel economy procedures have been developed with better control of the driving cycle and lubricant effects can be observed [26]. Even with vehicle testing improvements, the cycles shown do not always reflect real world driving conditions, and in real world conditions, the effect of lubricants may be too small to statistically quantify [94].

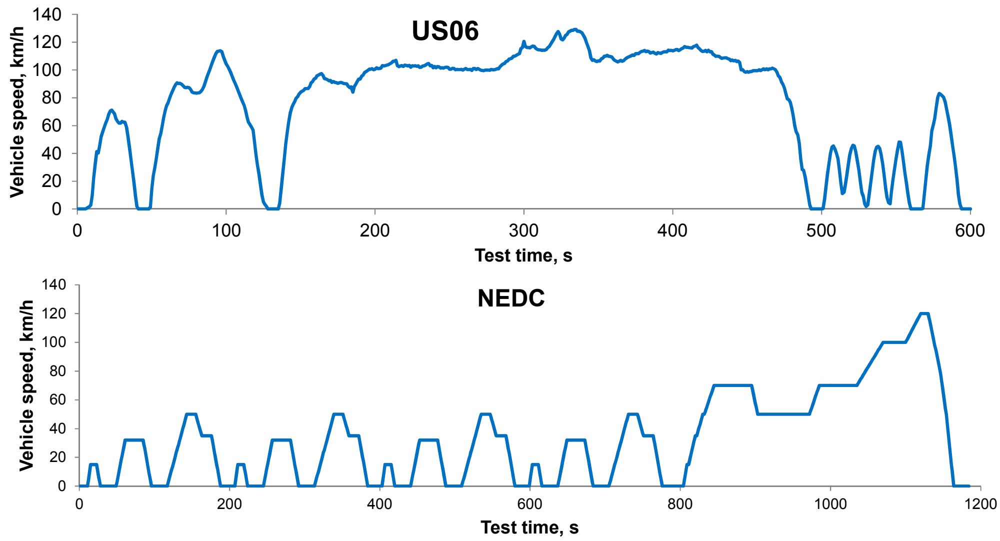

Figure 2. Driving cycles used to measure vehicle fuel economy. NEDC = New European Driving Cycle.

In fired engine or system level tests, fuel efficiency is typically measured under a variety of steady state conditions that are computer controlled to very tight tolerances. Table 1 shows the steady state operating conditions for the Sequence VID engine test (ASTM D7589) which is used to measure the fuel economy performance of passenger car motor oils. Steady state Sequence VID operating conditions are based on six conditions that represent a 2006 Buick LaCrosse being driven using the US EPA Federal Test Procedure and Highway Fuel Economy cycles. In addition, fuel economy is measured for up to 30 min under each Sequence VID steady state condition, so there is plenty of time for the system to stabilize. This improves the precision of the system level tests versus the vehicle tests. However, in these system level tests, fuel economy is not measured during transient operating conditions where a significant amount of fuel is consumed.

Table 1. Steady state conditions used to measure fuel economy in the Sequence VID engine test.

Parameter	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
Speed, r/min	2000 ± 5	2000 ± 5	1500 ± 5	695 ± 5	695 ± 5	695 ± 5
Load Cell, N·m	105.0 ± 0.1	105.0 ± 0.1	105.0 ± 0.1	20.0 ± 0.1	20.0 ± 0.1	40.0 ± 0.1
Oil Gallery, °C	115 ± 2	65 ± 2	115 ± 2	115 ± 2	35 ± 2	115 ± 2

Fuel consumption in vehicle tests is usually determined from measurements of vehicle emissions. Using physical properties of the fuel, such as density and fuel heating capacity, the amount of fuel consumed is calculated. Environmental conditions affect the fuel combustion process and emissions. In vehicle fuel economy testing, there are methodologies that are described to correct for these environmental conditions. These corrections are not always perfect and can skew fuel economy measurements in vehicle tests. In system level tests and vehicle tests, the amount of fuel consumed can be directly measured. This measurement can be a more accurate way to determine the fuel efficiency properties of lubricants. System level tests in motored engines, transmissions and axles have also been designed to measure lubricant efficiency by tracking the torque into and out of the mechanical device of interest. This is a more precise way to track the ability of lubricants to reduce friction and improve efficiency. However, these tests are a further step away from the "real world" measurement of vehicle fuel efficiency required by government regulations.

In vehicle and fired engine tests, the fuel efficiency of candidate lubricants is compared to that of baseline lubricants. The intent is to calculate the percent fuel economy improvement (%FEI) of the candidate lubricant versus the baseline lubricant. For example, Figure 3 shows the fuel economy performance measured for a baseline engine oil in a vehicle over time (blue line). In between tests with the baseline oil, candidate oils are tested. The fuel economy performance of the baseline oil improves as the vehicle is aged and this occurs rapidly at lower vehicle miles and more slowly at higher vehicle miles. Running-in conditions affect fuel economy since parts are worn or tribofilms form on the surfaces of engine parts (see Section 5). These effects also vary with the engine oils in use during these running-in time frames.

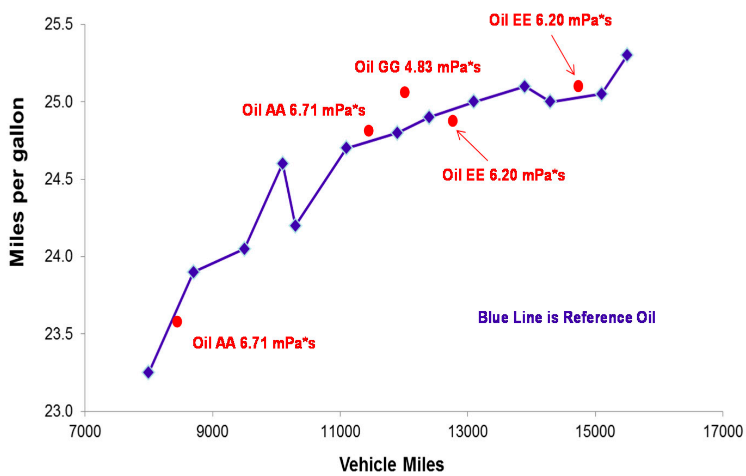

Figure 3. Effect of vehicle age on fuel economy.

The issue is determining which result for the baseline oil needs to be compared to the result for the candidate oil. In Figure 3, straight lines are drawn between each baseline oil fuel economy result. Fuel economy for candidate oils is then compared to the baseline oil result on the point of the line at which the candidate oils are tested. For example, candidate oil AA was tested twice in this vehicle. In one case, the measured fuel economy is above the line between adjacent baseline results, and in another case, the measured fuel economy is below the line between adjacent baseline results. Furthermore, the result for the test with AA at approximately 8500 miles is in between two baseline oils that differ by a large amount (~0.7 MPG). It is not clear which result for AA is correct. Similar shifts in baseline oil results are observed in fired engine tests. More sophisticated treatments of the changes in baseline oil results have been used to improve the precision of fuel economy testing.

Overall, it is very critical to be aware of the methodology used to measure fuel efficiency when interpreting the fuel economy performance of lubricants. The balance is between improvement in the precision of the test and determining fuel efficiency performance that is relevant to the actual operation of a vehicle. This discussion is not meant to judge which methodology is the best for achieving this balance. There are many ways that researchers have used to achieve the proper balance. Instead, when summarizing the common properties of lubricants that affect fuel efficiency, the overall trends in lubricant performance need to be considered since fuel efficiency results from separate studies are influenced by many factors that are not related to the lubricant.

3. Effect of Viscosity on Fuel Economy

It is generally agreed that fuel economy is improved when a lower viscosity lubricant is used in place of a higher viscosity lubricant. This is reflected in engine oil performance and viscosity specifications as well as the general trend for the need for lower viscosity transmission and axle oils. For example, Table 2 shows key differences between the SAE J300 engine oil viscosity specifications in 2009 and 2015 for selective viscosity grades. The low temperature cranking (Cold Cranking Simulator CCS: ASTM D5293) and pumping viscosity (mini-rotor viscometer (MRV): D4684) limits describe the tradeoff between being able to start an engine and the ability for the oil to be pumped around an engine, respectively. These low temperature performance specifications have not changed between 2009 and 2015.

Table 2. Selected SAE J300 engine oil viscosity classification specifications: 2009 vs. 2015.

SAE Viscosity Grade	Low T Cranking Viscosity (mPa·s) ASTM D5293	Low T Pumping Viscosity (mPa·s) ASTM D4684	Kinematic Viscosity at 100 °C (mm^2/s) ASTM D445 or D7042	High Shear Viscosity at 150 °C (mPa·s) ASTM D4683, D4741 or D5481
2009				
0 W	<6200 at −35 °C	<60,000 at −40 °C	>3.8	
5 W	<6600 at −30 °C	<60,000 at −35 °C	>3.8	
20			6.9–9.3	>2.6
30			9.2–12.5	>2.9
2015				
0 W	<6200 at −35 °C	<60,000 at −40 °C	>3.8	
5 W	<6600 at −30 °C	<60,000 at −35 °C	>3.8	
8			4.0–6.1	>1.7
12			5.0–7.1	>2.0
16			6.1–8.2	>2.3
20			6.9–9.3	>2.6
30			9.2–12.5	>2.9

High shear viscosity (HSV), which can be measured using several ASTM methods (D4683, D4741 or D5481) is the critical rheological property that influences fuel economy. In the past five years, several new high temperature viscosity categories (8, 12 and 16) have been introduced. The limits on HSV at 150 °C are >1.7 mPa·s, >2.0 mPa·s and >2.3 mPa·s, respectively, for these three viscosity grades. Today, many engine manufacturers recommend engines oils that meet the SAE 0W20 and SAE 5W20 viscosity specifications, and a few engine manufacturers recommend engine oils that meet the SAE 0W16 and 0W8 viscosity specifications. Engine oils that meet the 8 and 12 viscosity specifications are not yet on the market, but clearly engine oils with these lower HSVs could be recommended to further improve fuel economy.

In previous correlations between viscosity and fuel efficiency, viscosity under conditions other than those at high shear and 150 °C have been measured. Kinematic viscosity at 40 °C, viscosity index and even CCS viscosity at low temperature have been used in correlations to fuel efficiency. These properties are easy to measure using ASTM methods. ASTM has also created methods to measure the high shear viscosity of engine oils at temperatures lower than 150 °C (for example, D6616). While these ASTM methods make it easy to measure the rheological properties of lubricants at specific conditions, Table 1 shows that fuel economy is measured at temperatures that are not specifically described in ASTM methods.

Furthermore, in vehicle efficiency tests and some system level tests, the temperature of the lubricant is not controlled, and the lubricant may encounter different shear and pressure regimes. Shear can reduce the viscosity of the lubricant and pressure can increase the viscosity of the lubricant, which would affect fuel efficiency. Therefore, lubricant rheological properties at multiple operating conditions need to be determined in order to get a true measure of the effect of lubricant rheology on fuel efficiency. Table 3 shows the operating temperatures for a series of axle oils tested in an axle efficiency rig. The HSVs of these gear oils (GOs) were measured at 100 °C. The HSVs of the gear oils at the measured operating temperatures are also shown in Table 3. GO 18 and GO 19 have the highest 100 °C HSVs so we would expect these to have the poorest efficiency results. However, at operating temperature GO 18 has the lowest high shear viscosity. It is critical to measure viscosity at the correct operating conditions to observe the true effect of lubricant viscosity on fuel economy.

Table 3. Viscosities and operating temperatures for gears oil in an axle efficiency rig. GO = gear oil.

Oil	Kinematic Viscosity at 100 °C (cSt)	HSV at 100 °C (mPa·s)	Operating Temperature (°C)	HSV at Operating Temperature (mPa·s)
GO17	14.92	11.91	104	7.72
GO14	15.41	12.52	120	7.52
GO13	15.79	13.02	116	7.30
GO16	16.21	13.07	119	8.10
GO15	16.40	13.09	117	8.38
GO20	17.66	13.94	118	12.45
GO18	16.79	14.10	116	7.30
GO19	17.11	14.15	129	9.24

4. Balance of Viscosity and Elastohydrodynamic Film Thickness

While lower viscosity fluids clearly provide improved fuel efficiency it is also well known that lower viscosity fluids form thinner elastohydrodynamic (EHD) films. This is illustrated in Figure 4 where the film thickness of several gear oils and transmission fluids are shown as a function of temperature. For the gear oils, the 100 °C kinematic viscosities are all ~15.0 cSt, and for the transmission fluids, the 100 °C kinematic viscosities are all ~7.5 cSt. Film thickness was measured using an optical interferometer at an entrainment speed of 1 m/s and at 35 N. Of course, this is a very familiar graph to tribologists.

Other familiar graphs are shown in Figures 5 and 6 where friction as a function of film thickness is shown. The data in Figure 5 is for a series of different base oils (designated by their American Petroleum Institute (API) classification) and the data in Figure 6 is for a base oil with different anti-wear additives. For the base oils shown in Figure 5, the 100 °C kinematic viscosities are all ~4.0 cSt. For the lubricants shown in Figure 6, the 100 °C kinematic viscosities are all ~4.0 cSt. In both graphs, friction was measured using a Mini-Traction Machine (MTM) at 100 °C, 20% slide-to-roll ratio and 35 N on steel surfaces with similar surface roughness. Typically, MTM friction curves are plotted as friction versus speed. The EHD film thicknesses of the fluids shown in Figures 5 and 6 were measured as a function of speed under the same load and temperature conditions as friction measurements in the MTM. Therefore, MTM friction can be plotted as a function of speed.

As film thickness decreases (or if rougher surfaces are used), the surfaces start to come into contact and friction increases. Again, this is not surprising. It should be noted that in Figure 6, the black line shows an anti-wear additive that results in a reduction in friction at low EHD film thickness (compared to the blue line) but causes friction to increase at higher film thickness. Detergents that are known to influence LSPI also have an effect on friction measured in the MTM (100 °C, 20% slide-to-roll ratio, 35 N and 100 mm/s) [8,53]. Oils containing Ca-based detergents have lower friction coefficients (~0.040) than oils containing Mg-based detergents (~0.070). In developing new lubricant technology, data (such as that seen in Figures 4–6) is generated under very tightly controlled conditions. However, in a vehicle, engine, transmission or axle, different well-designed lubricants do not always operate under the same conditions. This means that while there is ample evidence that reducing viscosity improves efficiency, if viscosity is reduced too much, the effect of viscosity on efficiency may not be evident.

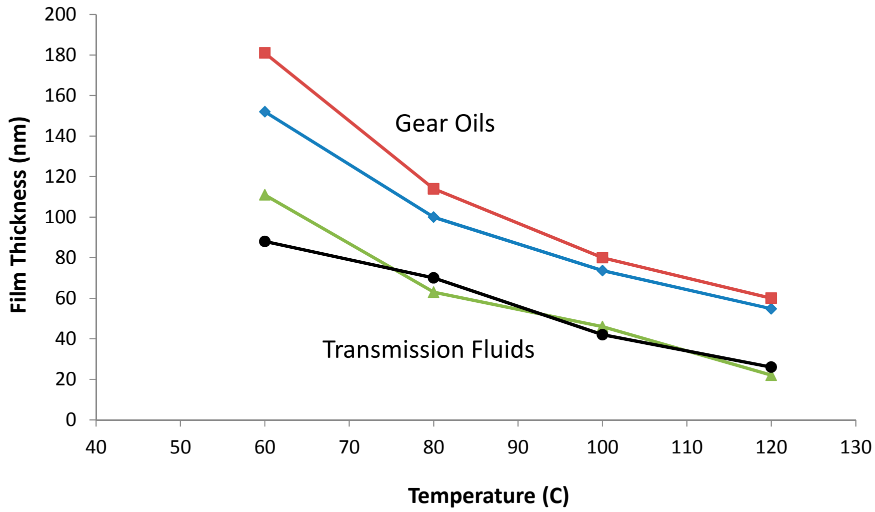

Figure 4. Effect of temperature on film thickness for two different gear oils and two different transmission fluids.

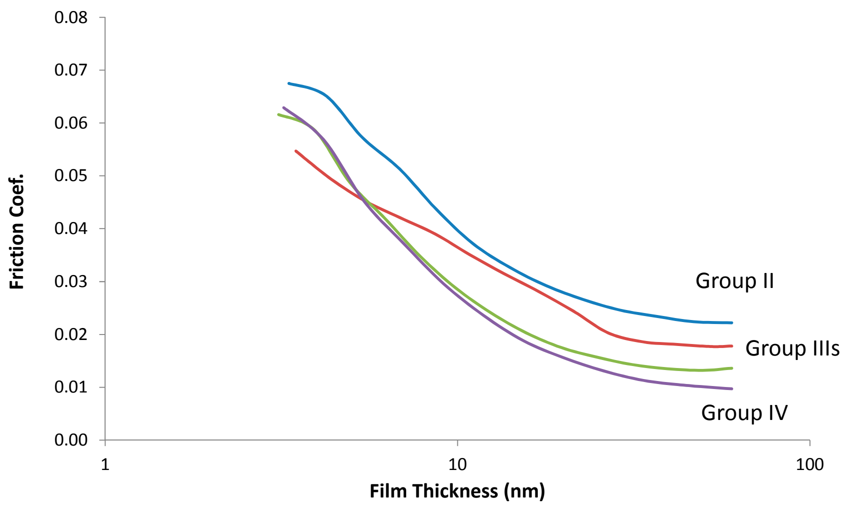

Figure 5. Friction versus film thickness for four different base oils.

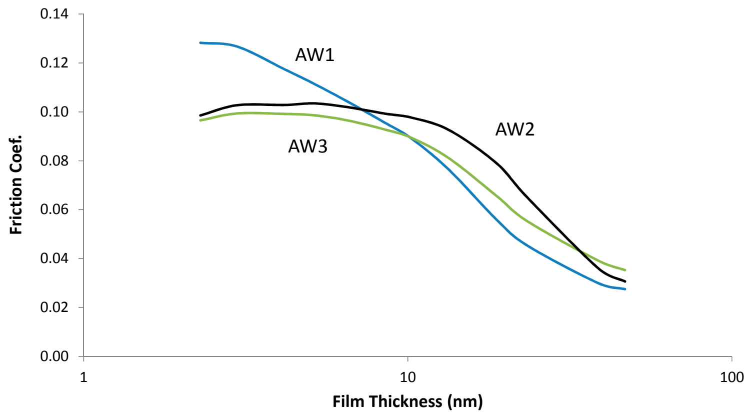

Figure 6. Friction versus film thickness for lubricants with different anti-wear (AW) additives.

The question is whether this shift in lubrication regimes and subsequent increase in friction is observed in fuel efficiency testing. Figure 7 shows the fuel economy properties of engine oils with different 150 °C HSVs measured in four vehicles with 2.3 L, 3.1 L, 3.8 L and 5.7 L engines [45,88]. These engine oils all contain the same additive systems and friction control agents. For all of these fluids, the boundary friction coefficients measured in a High Frequency Reciprocating Rig at 100 °C and 130 °C and 4 N load are ~0.130. The 100 °C kinematic viscosities and high shear viscosities for these fluids varied in a similar fashion with the kinematic viscosities varying from ~13.0 to ~5.5 cSt. The high shear viscosities are shown in Figure 7. For the three vehicles with 2.3 L, 3.1 L and 3.8 L engines, as the viscosity of the engine oils is reduced, fuel economy measured under city driving conditions increases, as does combined city and highway fuel economy (COMFE). The standard deviation in the measurement of vehicle fuel economy is ~0.2%. Fuel economy measured under highway conditions also increases as viscosity decreases, except when viscosity is less than 2.7 mPa·s. For the vehicle with the 5.7 L engine, a reduction in viscosity has no effect on fuel economy. Therefore, depending on the vehicle or operating conditions, a reduction in viscosity can improve fuel efficiency, but there is a limit to how much viscosity can be reduced before there is no effect of viscosity on fuel economy.

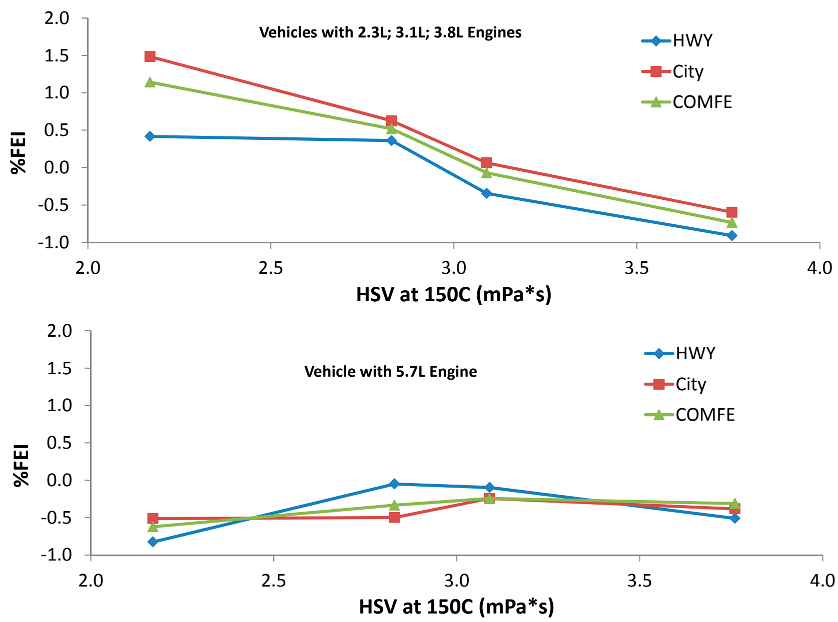

Figure 7. Effect of viscosity on fuel economy measured in vehicles. %FEI = percent fuel economy improvement. HWY = highway. COMFE = combined city and highway fuel economy.

5. Lubricant Effects on Boundary and EHD Friction

Fuel economy improvements are not dependent just upon a reduction in lubricant viscosity. There has been over forty years of research to understand friction reduction in the various lubrication regimes shown in Figures 5 and 6. Hugh Spikes has written several excellent discussions describing the effect of lubricant additive technologies on friction [6–9]. The review of friction modifier technology includes the effects of traditional surfactants, Molybdenum-containing additives, as well as polymers and nanoparticles. These are additives that the industry has used and is beginning to use (nanoparticles) to improve fuel economy. As shown in Figure 5, it is also well known that changes in base oil structure can reduce friction and improve fuel economy. What we often overlook is the effect of other surface-active agents such as anti-wear additives and detergents on friction. Figure 6 shows that by choosing the proper anti-wear additives, friction can be controlled as film thickness decreases.

Friction control by anti-wear additives and detergents is related to the formation of chemical tribofilms on surfaces [7,8,10,11]. Figure 8 shows the effect of the formation of surface tribofilms on friction in the boundary lubrication regime [11]. As the thickness of the Zinc dithiodiphosphate (ZDDP) film grows, friction increases. The film is then worn away and friction decreases. The growth and wearing away of the tribofilm is accompanied by a change in the morphology and composition of the film. These two factors affect friction. Tribofilms formed by metal-free anti-wear additives and detergents have similar effects on friction. Furthermore, the temperature, pressure and shear stress encountered by a lubricant affect tribofilm formation, as do the metallurgy and surface roughness of the materials on which the tribofilms form [7,8,10,11].

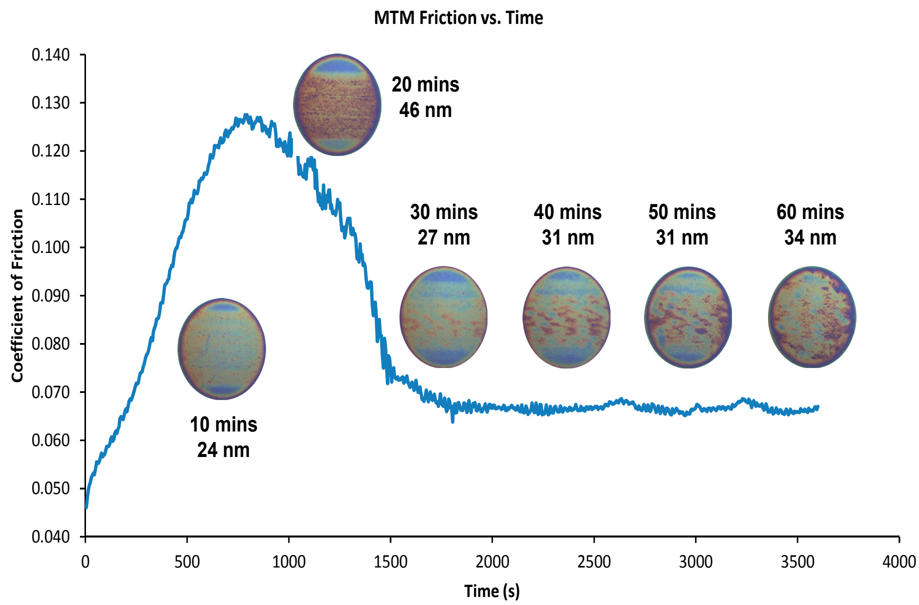

Figure 8. Changes in Mini-Traction Machine (MTM) friction as tribofilms form.

This creates a quandary when new lubricant technologies are developed to control friction and improve fuel economy. Different parts in a mechanical device (engine, transmission and axle) are made from different materials, as well as having different surface finishes. These conditions would all change the tribofilms formed on surfaces and the frictional properties of the tribofilm. In an even more complicated feed-back loop, friction affects surface temperatures which would control tribofilm formation and friction, which would again change surface temperatures [38,40,57]. All of this suggests that developing new lubricant technology to improve vehicle fuel efficiency would be very difficult. However, as long as all aspects of tribology are considered when new technology is developed, and these properties are measured under multiple relevant conditions, progress can be made. The development of new inorganic nanoparticles to improve fuel efficiency is an excellent example of this process [36].

6. Relative Effect of Viscosity, Boundary and EHD Friction on Fuel Economy

In choosing the engine, transmission or axle in which to test new lubricant technology, it is important to make sure the system is responsive to the tribological properties that are being improved. As shown in Figure 7, there are cases where viscosity has no effect on fuel efficiency. For many years, researchers have tried to determine the relative effect of viscosity, boundary friction and EHD friction on efficiency in engines, transmissions and axles [42,45,88–93]. In these research efforts, a series of lubricants with different tribological properties are developed. The fuel economy improvements as a result of using these lubricants are measured. Finally, correlations between changes in viscosity, boundary friction, EHD friction and fuel economy are determined. These correlations are often in the form of multi-linear regression equations. From these equations, the general effect of changes in tribological properties on fuel economy can be calculated.

Table 4 shows several examples of the output from these analyses for engine oil effects on fuel economy. The effects of a 20% reduction in viscosity, boundary friction or EHD friction on %FEI are listed. These values are calculated from correlations between these lubricant properties and %FEI measured in various fuel economy tests. The higher the %FEI, as a result of a 20% reduction in each physical property, indicates a greater benefit of that physical property. The effect of each physical property is not the same in each test. Viscosity has the greatest effect in the Sequence VIB test. Boundary friction has the greatest effect on combined city and highway fuel economy (COMFE) in vehicles with 5.7 L engines and EHD friction has the greatest effect in the COMFE test in vehicles with 2.3 L, 3.1 L and 3.8 L engines. Perhaps more importantly, if new additives are designed that optimize viscosity or EHD friction, there is no point in testing them in the vehicle with the 5.7 L engine because this test does not respond to these physical properties.

Table 4. Relative effect of lubricant properties on fuel economy.

Fuel Economy Test	%FEI That Results from 20% Reduction in Viscosity	%FEI That Results from 20% Reduction in Boundary Friction	%FEI That Results from 20% Reduction in EHD Friction
COMFE Vehicles with 2.3 L, 3.1 L and 3.8 L engines	1.2%	0.4%	0.5%
COMFE Vehicle with 5.7 L engine	0.0	0.6	0.0
Sequence VIB	2.0	0.3	0.4
Sequence VID	0.2	0.3	0.2

7. Conclusions

The development of advanced lubricants to improve vehicle fuel efficiency can appear to be as simple as lowering the viscosity and frictional properties of a fluid. However, applied research studies have shown that it is quite difficult to quantify the fuel efficiency properties of advanced lubricants in vehicles. The methodology used to measure vehicle or system level fuel efficiency will impact the interpretation of results. This means that driving cycles, vehicle condition and control systems need to be closely monitored. Measurement of fuel efficiency under real world driving conditions includes many factors that are not related to the lubricant. This makes it difficult to determine the effect of the lubricants unless all of the non-lubricant factors are taken into consideration (see Figures 2 and 3).

To improve correlations between fuel efficiency and the rheological or tribological properties of advanced lubricants, these properties need to be measured under relevant conditions. This means that the effect of temperature, shear and pressure on lubricant properties needs to be considered. This may be complicated since lubricant properties such as friction and tribofilm formation will affect the operating conditions that the lubricant encounters (see Tables 1 and 3). Advanced lubricants intended to control a single rheological or tribological property can affect other properties. For example, the formation of tribofilms may result in a reduction in friction under one set of conditions and an increase in friction under a different set of conditions (See Figure 6).

Finally, advanced lubricants need to be evaluated in "real world" systems to confirm their beneficial performance. However, all "real world" systems do not respond to all physical properties that historically control fuel economy. The proper vehicle or system level test needs to be selected to properly assess the benefits of new advanced lubricants (see Table 4).

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