IN POSTERUM FOR AUTOMOTIVE LUBRICANTS:

MAXIMISING FUEL ECONOMY BY THINNING LUBRICATING OILS

The automotive industry has always had numerous concerns with respect to its impact on the environment. While there has been an increasing amount of research to improve fuel emissions and efficiency, such as synthetic fuel and biofuels, as well as refining engine design to improve fuel efficiency, another important area of research is lubricating oils. Lubricating oils are vital to the optimal operation of any engine. Increasing the efficiency of lubricating oils allows for a more efficient engine, thus requiring less energy and decreasing the environmental effects of automobiles.

According to the U.S. EPA, in 2017 the largest source of greenhouse gas (GHG) emissions in the United States was the transportation sector, making up 29% of all GHG emissions [1]. Although lubricating oils provide only a marginal ~1 % increase in fuel economy [2] by SAE grade, with an estimated 135 million passenger vehicles in the US alone there is great potential to reduce GHG emissions. However, engine oil is something the typical motorist rarely thinks about and, when they do, it is usually during their 1-2 oil changes per year. Many drivers are also unaware of what type of oil is put into their engine during these oil changes.

The main purpose of any lubricating oil is to reduce the friction between moving parts of an engine, to prevent failures and reduce wear. The reduction of friction is related to the lubrication regimes:

a. Under mixed/boundary lubrication, additives (friction modifiers (FM)) are effective, whereas

b. Under hydrodynamic lubrication, the viscosity and the viscosity index determine the friction.

All formulation strategies must consider both lubrication regimes. The reduction of friction is possible due to the viscosity of the oil and especially under transient operations, by the viscosity index, a quantity for the retention of viscosity over temperature. In simple terms, the viscosity of lubricating oil is a measure of the oil's resistance to being squeezed from two pressed surfaces in relative motion to each other, for example, a piston ring and a cylinder. While lubrication is vital for the engine, lubricating oils also provide numerous other benefits. Lubricating oils clean the engine by capturing contaminants (soot and wear particles) and keeping particulates in suspension until filtered or removed, cool the engine by absorbing and distributing heat until it is eventually dispersed, and protect the engine by preventing corrosion and oxidation caused by organic acids formed within the engine [3]. The problem with these beneficial properties of lubricating oils is that they vary with both the viscosity and the thickness of the oil film. For instance, lowering the viscosity reduces viscous drag and improves lubrication, yet thins the oil film, decreasing the cleaning, cooling, and protective ability of the lubricating oil against wear and scuffing. Thus, it is salient to balance the properties of lubricating oils such that the maximum fuel efficiency is achieved, and the integrity of the engine is maintained. For the average automobile, a lower viscosity lubricating oil will improve the efficiency of the engine while also exhibiting very little adverse effects to the engine; however, for harsher conditions such as overloading, overheating, fuel dilution, dusty conditions, or difficult terrain, a thicker lubricating oil will provide greater protection for the engine despite the decreased fuel efficiency. As such, the proper categorisation of lubricating oils is vital to appropriately and efficiently allocate lubricating oils to various automobiles.

Modern engine oil is rated with two numbers and is known as multi-grade oil. These oils are rated for their viscosities at their operating temperature and at a very cold temperature denoted with a W that stands for "winter" viscosity, resulting in ratings such as 0W-20, 10W-40, and 5W-30. In the case of 5W-30, the engine oil has a cold rating of 5 (as noted by the W) and a hot rating of 30. Engine oils with lower cold ratings are thinner than oils with higher cold ratings, so a 20W-50 oil is much thicker than a 5W-20 engine oil [6]. The number following the "W" is measured from the minimum kinematic viscosity at 100°C and denotes how much the oil will resist thinning at high temperatures. The higher this number the greater the oil is resistant to thinning at high temperatures [5].

With growing concern over greenhouse gas emissions as well as the environmental problems associated with the transportation and automotive industries, nearly all countries in the world have set fuel economy regulations in order to reduce the consumption of fuel as well as emissions. For example, in the United States, the Corporate Average Fuel Economy (CAFÉ) standards first enacted in 1975 regulates the fuel economy of cars and light trucks [6] until replaced by the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rules effective June 29, 2020. The new SAFE Vehicles Rules are similar to the updated 2012 version of the CAFÉ standards; however, for the model years 2021-2026, the Safe Vehicles Rules reduce the 5% increase in stringency from CAFÉ standards to a 1.5% increase per year [7]. The European Parliament and Council has also adopted a similar regulation focused specifically on carbon dioxide emission reduction named Regulation (EU) 2019/631. The European regulation aims to reduce greenhouse gas emissions from the transportation sector by 23% in 2030 with respect to benchmarks from 2005 [8]. These regulations have thus culminated towards the development of International Lubricants Standardization and Approval Committee (ILSAC) GF-6 as a new engine oil category for the United States and Japan. The ILSAC GF-6 specifications have begun to spread as equivalent specifications are being developed in Europe by the European Automobile Manufacturer's Association (www.ACEA.be). These new specifications bring about a new low viscosity oil standard during a period of time where it is greatly needed.

The increasing regulations and deadlines have pushed the automotive industry to make swift decisions to reduce carbon dioxide emissions. Thus, researchers have found a simple means to improve fuel efficiency via the optimisation of lubricating oils. CO_2 emissions in internal combustion engines (ICE) can be reduced by lower viscosity oils or by using fuels from biomass. It is then possible to improve the fuel economy of precedent models without replacing its engine, but retrofitting options are limited. The SAE J300 standard added a lower viscosity grade SAE 16 with High Temperature High Shear (HTHS) viscosity > 2.3 mPas in 2013. Following SAE 16, viscosity grades SAE 12 (HTHS viscosity> 2.0 mPas) and SAE 8 (HTHS viscosity> 1.7 mPas) were added in 2015. The main driving force for lower viscosity engine oils is to reduce hydrodynamic friction and ultimately improving the average fuel economy of automobiles.

Recently the new oil grade SAE 4 with an HTHS viscosity > 1.4 mPas has been proposed. Yet, how much can the viscosity of engine oils be lowered? As an indication, the dynamic viscosity of water at 20°C is 1 mPas. The fluidity of ultralow viscosity engine oils at 150°C is now inching closer to that of water at 20°C. It has to be reminded, that the oil film thickness depends on the viscosity and the pressure-viscosity coefficient of which the latter has a greater influence on hydrocarbons, esters, and PAGs by a factor of ten as compared to water. Another drawback of low viscosity oils is their NOACK volatility [9] because the molar mass of the base oil backbone lowers with reduced viscosity the evaporation loss of the lubricating oil increases.

A study by Ishikawa et al. [10] compared SAE 0W-20 and SAE 0W-16 lubricating oils created from a group-III base stock and three sets of additive technologies made up of a GF-5 additive package, an appropriate viscosity index improver and pour point depressants. The study utilises the Sequence VID (ASTM D7589) method to test each of the lubricating oils fuel economy improvement (FEI) compared with the baseline oil SAE 20W-30 before and after an oil aging phase. The results (Figure 1) showed that prior to oil aging the SAE 0W-20 oils

Table 1: Rheological characteristics of oils used in Tormos et al. Study [11]

Oil Designation	R	C1	C2	C3	C4	C5
SAE Grade	10W-30	10W-40	10W-30	5W-30	5W-30	5W-20
Kinematic Viscosity 40°C [mm²/s]	75.23	86.71	56.45	70.60	70.15	43.72
Kinematic Viscosity 100°C [mm²/s]	12.05	13.34	9.607	11.85	12.08	7.992
High Temperature-High Shear 150°C [cP]	3.67	3.85	3.17	3.61	3.61	2.7
SAPS Level	Medium	Medium	Medium	Low	Medium	Medium
API Base Oil Group	III	III	III	III + IV	III	III
API Category	CK-4	CI-4	FA-4	CJ-4	CK-4	FA-4
Friction Modifier	–	–	–	Mo-DTC	Mo-DTC	–

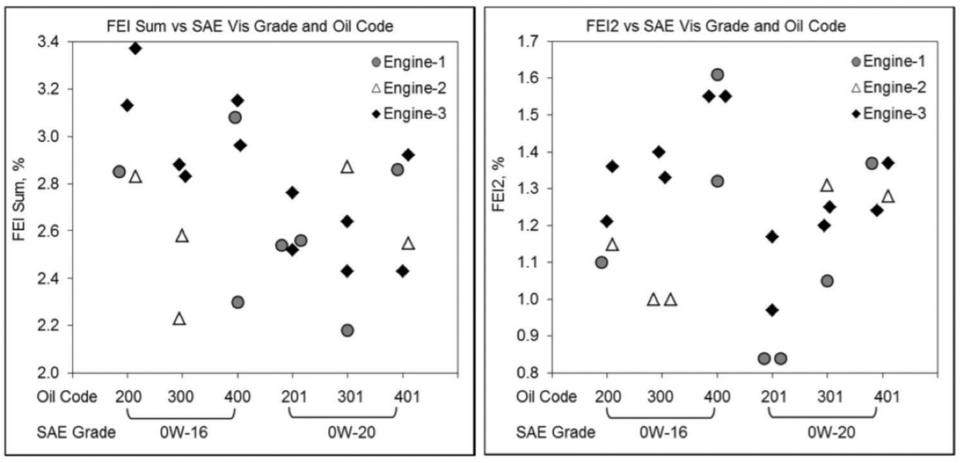

Figure 1: Left: FEI Sum vs SAE Viscosity Grades before oil aging [10] Right: FEI Sum vs SAE Viscosity Grades after oil aging [10]

showed a 2.57% FEI sum, passing the ILSAC GF-5 requirement of the highest minimum FEI of 2.6%. After the oil aging phase, while the SAE 0W-20 oils showed a 1.13% FEI sum, which did not pass the 1.12% highest minimum ILSAC GF-5 requirement, more than half of the test passed the requirement, proving these lubricating oil mixtures meet the base requirement with a minimum 50% probability. The study further shows that the SAE 0W-16 oils improved the FEI sum before oil aging by 0.24% and the FEI sum after oil aging by 0.14%. This improvement demonstrates that with current research a minimum increase of 2.81% FEI sum before oil aging and 1.27% FEI sum after oil aging is possible by simply lowering the viscosity of the lubricating oil to the new SAE 0W-16 low viscosity oil grade. In consequence, the retention of fuel economy will be a development item in the future.

While there is a clear correlation between oil viscosity and fuel economy during laboratory experiments, it is also necessary to observe the performance of vehicles in a real-world setting. Thus, a study by Tormos et al. [11] attempts to verify the fuel economy improvement of vehicles under stationary and real driving conditions with decreasing oil viscosity. The study of a stationary 3 litre diesel engine comprised of five lubricating oil formulations labelled C1-5 shown in Table 1 compared to a reference lubricating oil, labelled R, at 17 different test points covering different working zones at four engine speeds and one test point for idle conditions.

Utilising the stationary engine, it was found that fuel consumption dropped as a result of lower HTHS viscosity and all oil formulations with lower HTHS viscosity than the reference oil showed lower fuel consumption (Figure 2). These tests clearly illustrate that the effects of viscous drag within an engine degrade when shifting from hydrodynamic lubrication to mixed or boundary lubrication as well as the benefits low HTHS viscosity provides by minimising viscous drag during hydrodynamic lubrication conditions. Oil formula C2 was graded the same as the reference oil; yet, due to its lower HTHS viscosity oil formula C2 showed a maximum reduction of 2.7% at idle conditions and 1.2% at low loads across all engine speeds, which then decreased with load increase. Furthermore, oil formula C5 had the lowest HTHS viscosity of all the oil formulations exhibiting a maximum fuel consumption reduction of 5.3% at an engine speed of 2000 rpm and a load of 70 Nm and averaging a 4% reduction at low loads across all speeds, which decreased with increasing load. While the oil formulation with the greatest HTHS viscosity, C1, showed an overall increase in fuel consumption at low to medium loads and medium engine speeds.

In order to properly recreate real driving conditions, three driving cycles representative of medium-duty freight transportation vehicles were tested: an urban route in Valencia, Spain (10.4 km); an urban route in Romsey, UK (2.1 km); and a rural route between the municipalities of Canals and Quesa of Valencia, Spain (26.6 km). When comparing the different routes, the uneven topography of the urban route in Romsey, UK and the rural route in Spain lends to creating greater load conditions thereby decreasing the effectiveness of the low HTHS viscosity oils. As such the greatest reduction in fuel consumption was 8.84% utilising oil formulation C5 with the urban route in Valencia, Spain due to its even terrain. Therefore, while decreasing oil viscosity is necessary to improve fuel economy, it is also vital to create a synergistic effect between the driving conditions of the vehicle as well as the lubricating oil to further maximise fuel economy reduction.

Yet, it is not possible to recreate favourable conditions as modifying infrastructure and terrain is not economically or socially viable such as in largely populated urban cities. Thus, certain additives are added to lubricating oils to augment their properties. Friction modifiers (FM) are additives used as a means to reduce friction and wear between surfaces particularly during boundary lubrication. For example, molybdenum dialkyldithiocarbamate (MoDTC) is a well-known friction modifier, which reduces friction between two surfaces by creating a molybdenum disulphide tribofilm. Glyceryl mono-oleate (GMO) as an organic friction modifier reduces the interaction between surfaces due to its linear alkyl radical and strong adsorption sites inhibiting tribofilm formation from zinc dialkyldithiophosphate (ZnDTP) that can increase friction, and polymer type friction modifiers (PFM), which reduce friction as they can be created to adsorb specifically to polar surfaces [12,13]. Comparing the different FMs, Yamamoto et al. [12] proved that all of the FMs performed better than an identical oil without FM, but most notably, the MoDTC FM performed the best throughout all tests, even with low oil temperature. Although low viscosity lubricating oils excel during hydrodynamic lubrication conditions, they suffer immense friction during boundary lubrication, so the addition of FMs can improve the lubricating oil tremendously. Thus, the movement towards thinner lubricating oils must also drive the development of proper additives to maximise efficiency.

Currently the creation of efficient lubricating oils is necessary to reduce GHG emissions; yet, it is vital to analyse the potential fuel economy improvement with respect to both viscosity and a life-cycle CO_2 emission analysis of the lubricating oil in order to determine the benefits of lubricating oils. Ishizaki et al. [15] correlated in Figure 4 the fuel efficiencies of engine oils from literature with the kinematic viscosity at 100°C. The improvements in Figure 4 of the fuel efficiency of ultra-low viscosity (ULV) engine oils was related to SAE 0W-16 engine oil and the rates of improvement of the vehicle fuel economy of ULV-Mineral and ULV-PAO were estimated to be 0.6 and 1.1%, respectively, or ~0,75% FEI per mm²/s at 100°C. While ULV-PAO has a greater FEI than that of ULV-Mineral one must note the production costs of the oil's base stock is also greater in terms of cost and emissions. At an equivalent oil drainage interval of 7,500 km ULV-PAO shows 0.1% reduction in life cycle CO_2 emissions compared to ULV-Mineral, yet when the oil drainage interval of ULV-PAO is doubled it is possible to achieve 0.7% reduction of life cycle CO_2 emissions. Thus, it is necessary to lower the NOACK volatility to increase intervals between oil drainage and improve the life cycle CO_2 emissions of lubricating oils.

As such the proper optimisation of lubricating oil properties can allow for far greater improvements when carried out correctly. For instance, a study by Kocsis et al. [16] optimised a lubricating oil from observing the properties of lubricating oils of varying viscosities from 10W-40 to 0W-16 and lubricating oils of consistent viscosity but varying FM levels. The optimised lubricating oil was graded as a 0W-20 oil with medium FM levels and performs well in both boundary lubrication and hydrodynamic lubrication conditions. According to an engine dynamometer (ASTM Sequence VIE) fuel economy test, the optimised oil achieved an FEI of approximately 2.5% and 2.1% with respect to the industry-standard baseline before and after oil aging, corresponding to an increase in FEI of 1.25% and 0.75% compared to 0W-16 lubricating oil, respectively. This study indicates the importance of properly examining the properties of lubricating oils as well as the benefits of properly developing all aspects of a lubricating oil.

Furthermore, the impact of viscosity on fuel economy can also be seen for heavy-duty Diesel engines in Figure 5. The figure shows the average over all test modes measured in the 12 mode steady state and 13 mode European Stationary Cycle (ESC) tests. The test modes and the test engines may differ, but the trend regarding fuel economy as a function of HTHS viscosity is clear, especially considering both test modes operate utilising warm engines. Moreover, the increasing trend of fuel economy vs. HTHS viscosity utilising polyalkylene glycol (PAG) denoted in red compared to the hydrocarbon-based formulations denoted in black illuminates the action of PAGs as a FM. An important observation considering a base oil acting as a FM cannot be consumed and retains its function over drain cycles. With these factors in mind, previous research concerning low viscosity lubricating oils in passenger or medium-duty vehicles may be applied to heavy-duty vehicles after modifications considering end-use specifications.

These technological advancements are great for reducing emissions and increasing fuel economy of ICEs, but manufacturers also have another trick up their sleeve: hybrid vehicles, as evidenced by the rapid development and perfection of hybrid technology. If you wanted to own a hybrid in 2001, your only options were to buy a Toyota Prius or a Honda Insight, while Audi also sold a few Duo III's, mainly to the European market. In 2020, the selection of hybrids is magnitudes greater than it was at the turn of the century. These last 20 years alone have built up virtually all the hype around hybrids and, when coupled with stricter fuel economy and emissions standards, hybrids are rapidly becoming the vehicle of choice for consumers [18]. Hybrid technology is also improving greatly, with decreasing motor sizes, better battery packs, and more refined systems [19]. Hybrid or range extenders generally operate at lower oil temperatures, because they run periodically and/or more on stationary revolutions when compared to

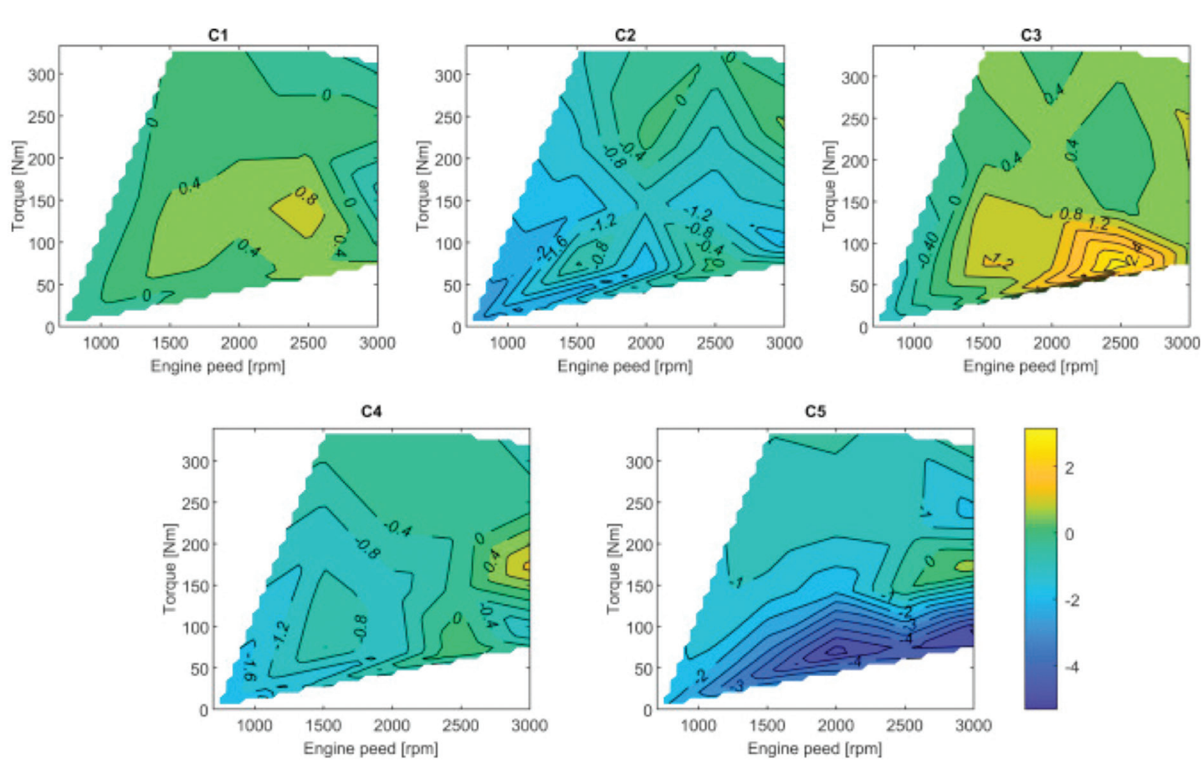

Figure 2: Differences in fuel consumption by percent between candidate and reference oils [11]

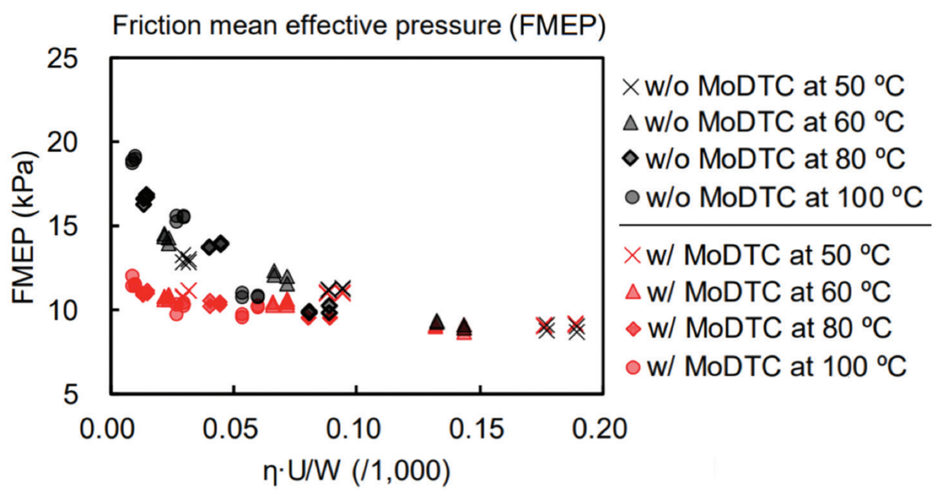

Figure 3: Effect of Viscosity and Velocity on MoDTC Friction Reduction [12]

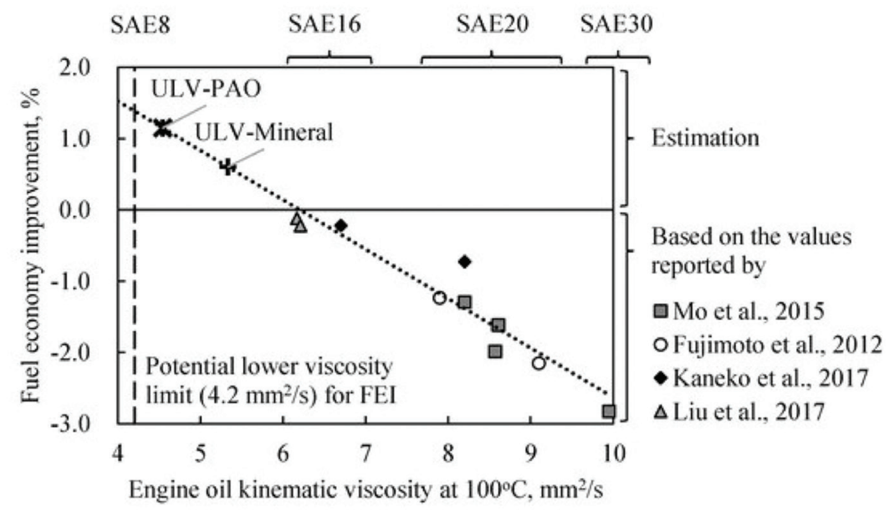

Figure 4: The correlation between the kinematic viscosity at 100 °C and fuel efficiency improvement (FEI) in NEDC mode using 1.5–1.8 L gasoline engines [15]

transient and dynamic operations of a typical ICE. The reduction in oil sump temperature increases the oil viscosity and compensates for the loss in oil film thickness.

Many automakers already on the quest to produce more fuel-efficient vehicles have adapted the use of thinner engine oils and combining this with their rapid introduction of more hybrid vehicles amplifies this trend. Thinner oils are to be anticipated in main ICEs as well as the application of thin film coatings and enhanced bearing and ring materials. Thus, the combination of low viscosity oils and hybrid vehicles will vastly improve fuel economy and CO_2 emissions as hybrid vehicles increasingly supplant previous ICE vehicles on the road.

Currently, the thinning of lubricating oils has been driven by the necessity to improve interactions between humans and the environment. While lubricating oils may seem trivial in comparison to completely removing fossil fuels such as gasoline with renewable alternatives, these lubricating oils are vital even beyond the eventual transition from fossil fuels due to their immense applications and usage in reducing friction and wear between moving components. The current research on lubricating oils has unanimously agreed to the benefits provided by reducing lubricating oil viscosity and by high-performance friction modifiers. However, the single-minded pursuit of simply lowering viscosity will not efficiently improve fuel economy and GHG emissions. Instead, it is salient that research continues to analyse all facets of lubricating oil that may be improved and properly synergise the benefits provided by a reduction in viscosity, the advantages different additives may contribute, as well as improving energy and fuel use of automobiles.

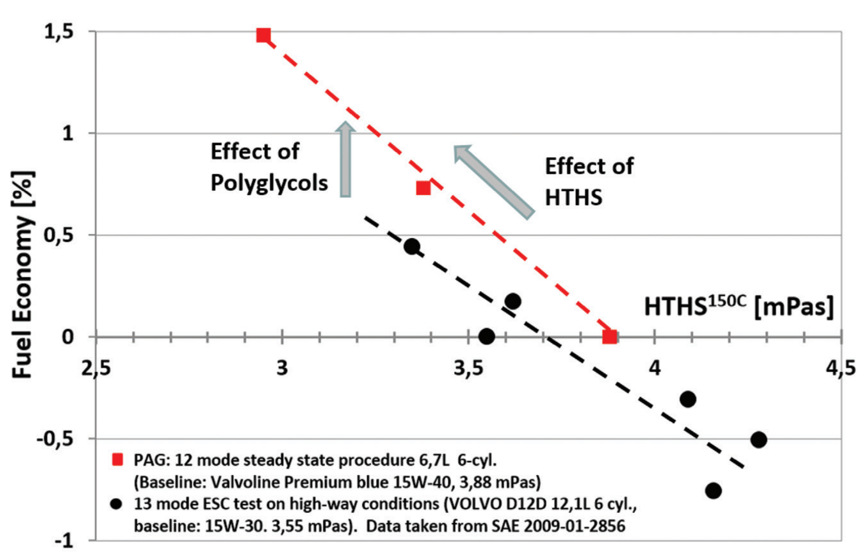

Figure 5: Specific fuel consumption improvements versus high temperature high shear viscosity [17]

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The authors with to thanks Ms. Melissa Quinn from BP (UK) , and Dr. Mathias Woydt (Germany) for their insightful comments and suggestions.

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