Heavy-duty vehicle fleets and fuel economy

Examining the correlation between rheological profiles with fuel economy performance of low-viscosity oils for heavy-duty vehicle fleets

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Introduction

Heavy-duty engine original equipment manufacturers (OEMs) in Europe, North America and Asia are working rapidly to meet ambitious fuel economy and CO_2 emission goals coming into effect over the next decade. While specific targets and timelines vary from region to region, heavy-duty vehicle manufacturers face equally complex challenges globally. In the EU, heavy duty trucks must comply with requirements to achieve fuel consumption and emission reductions of 15% by 2025 and 30% by 2030 relative to the 2019/2020 baseline. The numbers are even more aggressive in the US and Canada, seeking a 45% reduction by 2030. The standards are quite stringent, and manufacturers will face financial penalties in the thousands of euros or dollars per vehicle if their engines exceed the prescribed CO_2 limits by as little as 1%.

OEMs have begun making significant changes to the vehicle and engine hardware design and technology to comply with these requirements. Regarding engines, these changes include, amongst others, the move from aluminium pistons to steel pistons, which allow higher combustion pressures and temperatures, improving total efficiency. Consequently, engine parts are subjected to greater thermal stress and a higher risk of moving parts running into a boundary lubrication regime which induces a risk of higher wear levels.

However, we cannot ignore the hydrodynamic and mixed lubrication regimes. Along with optimising the performance of newer engines, low-viscosity oils directly affect fuel economy: the lower the viscosity (down to a minimum dependent on engine design) the greater the fuel economy potential. Low-viscosity oils cannot compromise on durability or protection that fleet operators are accustomed to from the previous generation of thicker oils. That is where additives play a critical role in ensuring oxidation stability, wear control, and thermal stress protection in low-viscosity lubricant formulations.

Work is being done in close collaboration with heavy duty OEMs and lubricant marketers to help them meet fuel consumption and greenhouse gas (GHG) goals of engine design and engine oil formulation. The relationship between lower viscosity grades and fuel economy has been closely studied, as have the ways in which certain additive types, such as viscosity modifiers and friction modifiers, can help optimise a lubricant's fuel economy performance in the full lubrication regimes ranging from hydrodynamic to mixed to boundary regimes.

This article will present how a rheology-based methodology can correlate with the fuel economy improvement of oils in engines and driving cycles with dominant hydrodynamic lubrication regime.

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Trend toward lower viscosity heavy-duty engine oils

The trend toward lower viscosity oils is not new. In December 2016, the industry introduced two new heavy-duty engine oil categories: API CK-4 and FA-4. CK-4 oils were intended as the replacement for the CJ-4 category, introduced a decade earlier; they address the new fuel economy and emission requirements of newer engines but are also backward compatible with older engines using higher viscosity oils, for example, SAE 15W-40. The FA-4 standard specifies thinner oils, 10W-30 and 5W-30, for heavy-duty applications. These lower viscosity oils are formulated specifically for newer engines designed to comply with stricter standards for fuel efficiency and greenhouse gas emissions.

While approval and adoption of FA-4 oils have been slow, it has begun picking up in the past two years. Major European heavy-duty OEMs have started using 0W-20 or 5W-20 as their factory fill oils as pressure mounts to increase fuel economy and reduce emissions. To advance the widespread adoption of lower viscosity oils, heavy-duty OEMs and their lubrication industry partners need to understand the actual fuel economy benefits that could be achieved without compromising engine performance and durability.

Fuel economy improvement

As noted earlier, lower viscosity translates to lower fuel consumption. In the industry, the viscosity of oils is specified at different temperatures and shear rates, such as kinematic viscosity at 100 °C or high-temperature high shear at 150 °C. In an engine, oils are subjected to different temperatures and shear rates, where the traditionally measured viscosities will not represent the real operating conditions. Therefore, these viscosities cannot efficiently predict the fuel economy performance of oils in different driving conditions. To overcome this issue, Chevron Oronite has developed a rheological testing protocol. It generates a rheological profile of the lubricating oil that can be used to predict the relative fuel economy benefits achievable at various viscosity grades and with different additive systems.

To generate rheological profiles, viscosity of the lubricating oil is measured at different temperatures across a wide range of shear rates using a rotational rheometer and an ultra-shear viscometer. Applying the Time-Temperature Superposition principle[1] and fitting a rheological model to the experimental data, a rheological profile of an oil can be generated.

The rheological profiles of various fully-formulated multi-grade oils, ranging from a low viscosity grade of SAE 0W-12 to a high viscosity grade of SAE 10W-40 at 110 °C, are summarised in Figure 1. One can notice that the viscosity is constant in oil at low shear rates, demonstrating a Newtonian behaviour. As the shear rate increases, the oil viscosity decreases as it transitions to a shear-thinning behaviour, followed by a terminal Newtonian plateau at higher shear rates. As expected, the heavier-grade oils (10W-40 and 10W-30) show the highest viscosity at all shear rates compared to lower-grade oils (0W-xx).

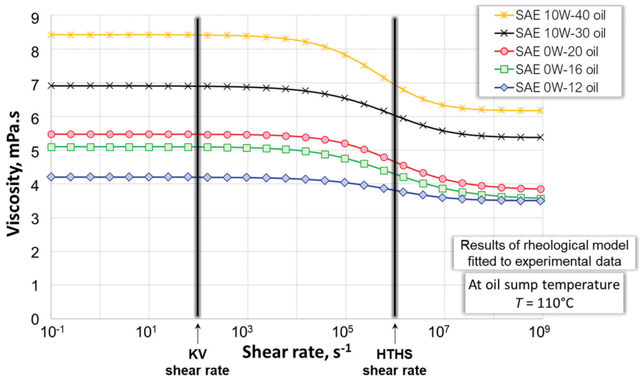

Figure 1: Viscosity profiles of different fully formulated multi-grade oils at 110 °C

The same finished oils were tested in the Detroit Diesel DD13 engine, at an oil sump temperature of 110 °C, in modal operating conditions to evaluate their fuel economy performance compared to an SAE 10W-30 oil as baseline oil. As Figure 2 illustrates, the lowest viscosity oil (SAE 0W-12) delivers the highest Fuel Economy Improvement (FEI) of 1.35% compared to the SAE 10W-30 baseline. The higher viscosity oils show lesser FEI relative to the 10W-30 baseline, with the worst being SAE 10W-40 with negative FEI.

The rheological profile of tested oils over a wide range of shear rates strongly correlates with their FEI obtained in the DD13 engine.

[1] Reference: Viscoelastic Properties of polymers, Author: John D. Ferry, Publisher: Wiley ISBN: 978-0-471-04894-7

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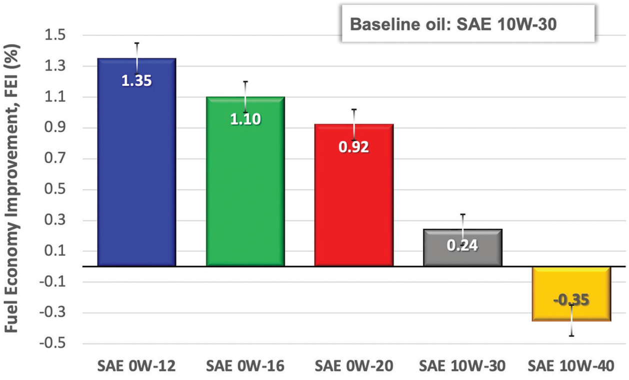

Figure 2: *Fuel Economy Improvement of oils tested in DD13 in steady state operation conditions*

Additive Effect on Fuel Economy

The above rheological approach can be used to rank FEI of different viscosity modifiers in different fuel economy engine tests. The primary purpose of a viscosity modifier is to stabilise the viscosity against temperature fluctuations so that the fluid does not thin out too much when the engine is running hot, nor does it thicken too much at low temperatures, in winter or at cold start conditions. In addition, viscosity modifiers bring unique polymer shear-thinning behavior, which might differ for polymers with different chemistries and architectures. A more shear-thinning oil shows a more temporary viscosity decrease at high shear rates, contributing to improved fuel economy performance. Rheological profiles of oils made with different viscosity modifier types can help identify those with the highest potential to improve fuel economy further.

This rheological methodology was used to investigate three SAE 0W-20 oils with the same viscosity at high-temperature, high-shear (HTHS) at 150 °C, each formulated with different viscosity modifiers. These three oils were tested in Daimler OM 501 LA in World Harmonised Transient Cycle (WHTC) driving cycles. Figure 3 shows the rheological profile of these oils at an average temperature of the first WHTC run (T = 82 °C) and their FEI obtained at the first WHTC run in OM 501LA. One can note that in the middle range of shear rate, the rheological profiles of these oils very much mirror their fuel economy performance. Oil C with lower viscosity at a shear rate lower than 10^7 s^{-1} shows the best FEI in WHTC driving cycle in OM 501 LA, and Oil A with the highest viscosity shows the lowest FEI. We should emphasise that using the viscosity at a single temperature and single shear rate, such as HTHS at 150 °C, does not show the complete rheological profile of oil and might not effectively be used to predict its fuel economy performance.

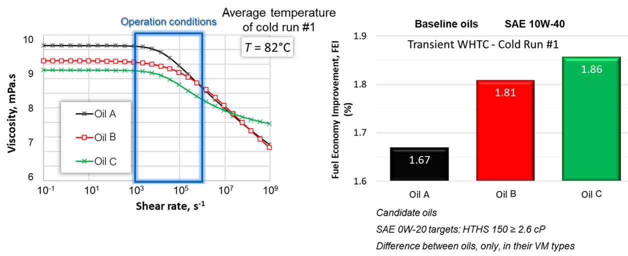

Figure 3: *Viscosity modifier additive fuel economy comparison – rheological profile vs. Fuel Economy engine testing in OM 501 LA – WHTC driving cycles*

In this paper, we saw how we could use the rheological profile of oils to predict and rank their relative fuel economy performance before going to the extra step of testing them in an actual engine. Lubrication engineers could save significant R&D time and expense in selecting effective fuel economy solutions.

Conclusion

These studies make a compelling case that rheology is an effective tool in developing engine oils that promote greater fuel efficiency. Rheological profiles can be used to describe different viscometric attributes of lubricants, mainly to rank and predict their relative fuel economy performance in an engine under actual driving conditions. In addition, the shear-thinning behavior of oils, mainly due to viscosity modifiers, is advantageous for FEI. However, one should note that the same oils might perform differently when tested in different engines and driving/operating conditions.

Chevron Oronite is actively engaged in research to optimise viscosity modifiers and additive solutions to further enhance the ability of low-viscosity lubricants to deliver fuel economy improvements. We continue working with our lubrication industry partners and heavy-duty engine manufacturers toward our shared goals of energy efficiency, emission reduction, and progressing lower carbon solutions.

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