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Fuel economy for engine oils: the formulator's dilemma

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Introduction

New fuel economy standards for automobiles introduced by governments in the G20 major economies, changes in customer preferences driven by high fuel prices, and vehicle and carbon taxation have increased pressure on car manufacturers. In the USA, the National Highway Traffic Safety Administration (NHTSA) and Environmental Protection Agency (EPA) have recently issued (2018) the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule [1] that sets tough fuel economy and carbon dioxide standards. These standards apply to passenger cars and light trucks, setting a moving fuel economy target that is increasing 1.5% in stringency each year from model years 2021 through 2026.

In Europe, the European Parliament and Council adopted Regulation [2] sets Carbon Dioxide (CO_2) emission standards for new passenger cars and vans for 2025 and 2030. From 2021, the EU fleet-wide average emission target for new cars is set at 95 g CO_2/km, corresponding to a fuel consumption of around 4.1 l/100 km (57.4 mpg) of petrol or 3.6 l/100 km (65.3 mpg) of diesel. Today's average CO_2 emissions for new cars sold in the EU is around 120 g CO_2/km. Car manufacturers pay a per vehicle penalty of €95 for each g/km in excess of the target.

Japan's new fuel economy standards issued a year ago set a target for average fleet gasoline-equivalent fuel economy of 25.4 kilometers per litre (59.8 mpg) by 2030, some 30% improvement over today's fleet average [3].

These political and economic factors intensify research and development efforts taken by OEMs in their pursuit for better fuel efficiency. Apart from concerted efforts on powertrain electrification and the use of alternative energy sources to reduce greenhouse gas (GHG) emissions, a big emphasis is made on understanding tribological aspects of energy losses in powertrains and utilising current advancements in engine design, lubrication engineering and coatings to minimise those losses.

To encourage such eco-innovation, manufacturers are granted "emission credits" for deployment of innovative technologies that should – based on independently verified data – result in reduced CO_2 emissions, even though the test procedure used for vehicle type approval fails to demonstrate the effect. Manufacturers are also granted "super credits" for bringing to market zero- and low-emission cars such as battery and hybrid vehicles emitting less than 50 g CO_2/km.

Effect of motor oil on fuel economy

A significant portion of the energy losses in internal combustion engines comes from the shearing of the engine oil. Hence a continuing trend toward lower viscosity oils [4]. However, whereas the use of low viscosity oil helps reduce friction losses, it increases the tribological stresses on engine components. This necessitates wider use of friction modifiers (FM) and antiwear (AW) additives in lubricant formulations to help protect the engine from wear [5]. The development of balanced formulations is not as straightforward as it appears, and numerous pitfalls may be encountered due to additive interactions. Figure 1 explains how "fuel economy" motor oil works: on the left-hand side is shown the actual torque curve of a typical production 1.6L gasoline direct injection (GDI) engine, and on the right-hand side is shown the friction torque loss for the same engine measured using a motored rig (an engine run by an external motor, with no fuel supplied to the engine during the motored test). Friction "eats up" around 1/10th of the useful torque the engine can produce. Below 2000 rpm, where the contribution of mixed and boundary lubrication is significant, friction can be reduced by using FMs or low friction coatings. Above 2000 rpm, when the hydrodynamic lubrication prevails, friction can be reduced by using lower viscosity lubricants.

Various engine drive cycles have been developed and are used to compare fuel economy between different vehicles. In Europe there is the New European Driving Cycle (NEDC), in the US the EPA has several cycles for city and highway and in Japan the JC08 is used. In an attempt to harmonise the cycles, the Worldwide Light Vehicle harmonised Testing Procedure (WLTP) has also been developed.

For passenger cars, a change from legacy SAE 15W-40 grade to SAE 0W-20 brings on average 3-4% improvement in fuel economy under the NEDC or EPA conditions, and the subsequent migration to 0W-8 can bring an additional 2-3%, provided that engine hardware can safely handle such low viscosity. Under more gentle driving in the JC08 cycle, lower viscosity oils may produce even larger effect, up to 5%. On the contrary, for the more aggressive WLTP cycle, the effect is usually reduced by 0.3 to 0.6% compared to the NEDC.

Since the fuel economy performance of an oil depends largely on the engine design, vehicle type,

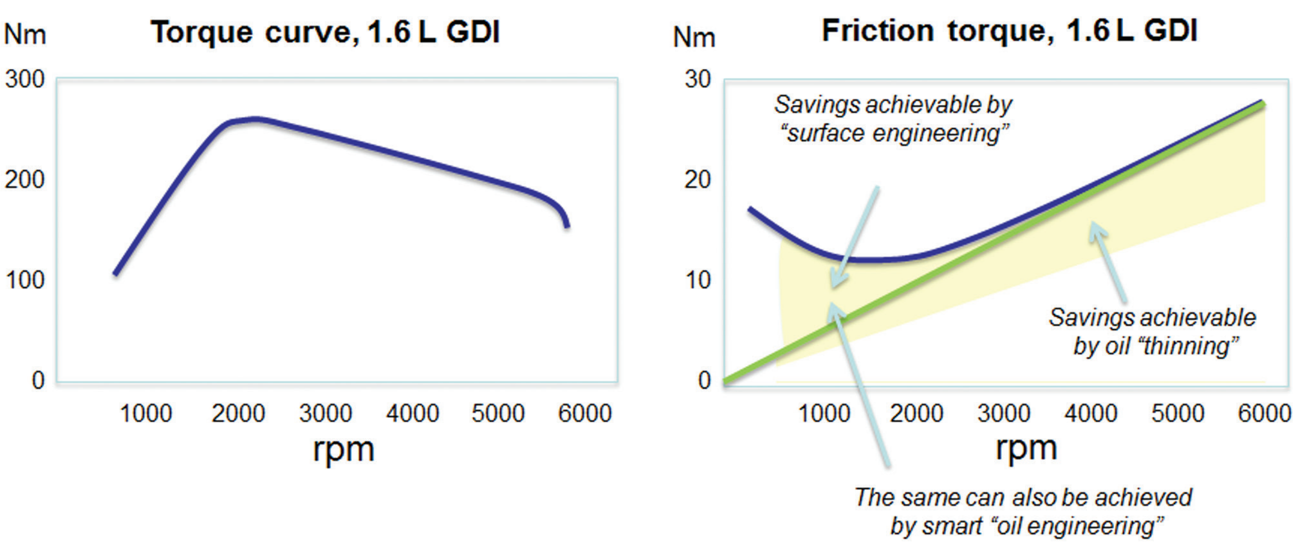


Figure 1: *The torque curve and the friction torque for a production 1.6L i4 GDI engine. The primary engineering strategies for friction reduction are also shown [6]*

and driving conditions it is essential to compare oil in a 'like-for-like' test. One commonly used standard for this is called the Sequence VI. Two current standards, Sequences VIE and VIF (as per ASTM D8114 and D8226) use a 2012 3.6L General Motors engine that is run under well-defined operating conditions on a test stand. A standard non-friction modified SAE 20W-30 mineral oil is used as a baseline. Fuel economy at two different ageing stages is determined: FEI1 after 16 hours (fresh oil) and FEI2 after 109 hours (aged oil). This procedure is essential to discriminate between different types of FMs since some are readily oxidised and can quickly lose their activity. Different test limits are set for different oil viscosity grades, see Table 1.

Fuel efficiency		Test limit, %
Sequence VI E (ASTM D8114)		
0W-20, 5W-20	FEI2 FEI1+FEI2	1.8 3.8
0W-30, 5W-30	FEI2 FEI1+FEI2	1.5 3.1
10W-30	FEI2 FEI1+FEI2	1.3 2.8
Sequence VI F (ASTM D8226)		
0W-16	FEI 2 FEI1+FEI2	1.9 4.1

Table 1: *Sequence VIE and VIF Test Limits*

Actual Sequence engine test results have a lot of scatter since fuel economy of fully formulated oils is driven by both the base oil viscosity and the additive package [4-6]. Some higher viscosity oils can achieve much better fuel economy values than their lower viscosity counterparts. However, statistically, based on tests run at SwRI®, Fuel Economy improvement becomes larger with decreasing viscosity until SAE 0W-8 oils are used, when a decrease in fuel economy is observed. The reason for this effect is clearly demonstrated in Figure 2. This data was obtained using a firing (i.e.: running due to fuel combustion) single cylinder gasoline engine instrumented to measure engine component friction. The continued reduction of viscosity results in continued reduction of bearing friction, whereas the lowest viscosity lubricant results in an overall increase in engine friction due to the greatly increased friction in the valvetrain and piston assembly. One should realise, therefore, that many engines are not designed to work with low viscosity oil. For such engines, any talk about the use of low viscosity oil is largely irrelevant.

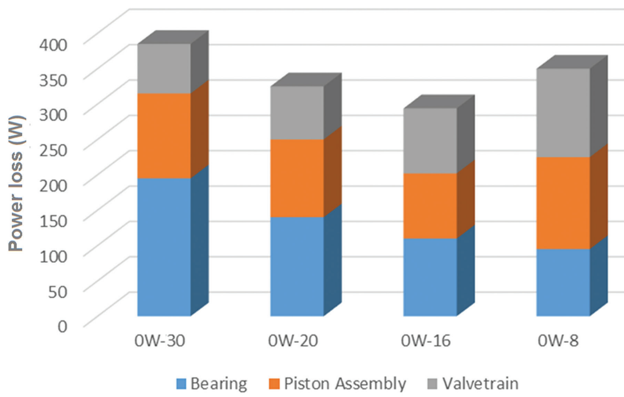


Figure 2: *Firing gasoline single cylinder engine friction measurements (Source: SwRI®)*

In Japan, a new Japanese Automotive Standards Organization (JASO) Fuel Economy Test – known as JASO M364:2019 – has been developed and may help lay the groundwork for how the next version of the Sequence VI test will look like in the future International Lubricants Standardization and Approvals Committee (ILSAC) GF-7 specification. The corresponding oil specification – JASO GLV-1 – was approved for use in Japan in 2019 [7]. For the fuel economy test, either the fired Toyota 2ZR-FXE 1.8L engine or motored Nissan MR20DD 2.0L engine can be used. The proposed fuel economy limits for the new JASO GLV-1 specification are >1.1% (firing) and >2.0% (motored) compared to SAE 0W-16 reference oil. ILSAC GF-7 is not likely to come before 2025 – if it comes at all, taking into account all the hurdles, delays, exorbitant costs, and challenges associated with the development of the ILSAC GF-6 category.

The downsides of lower viscosity

The primary obstacle to continually lowering

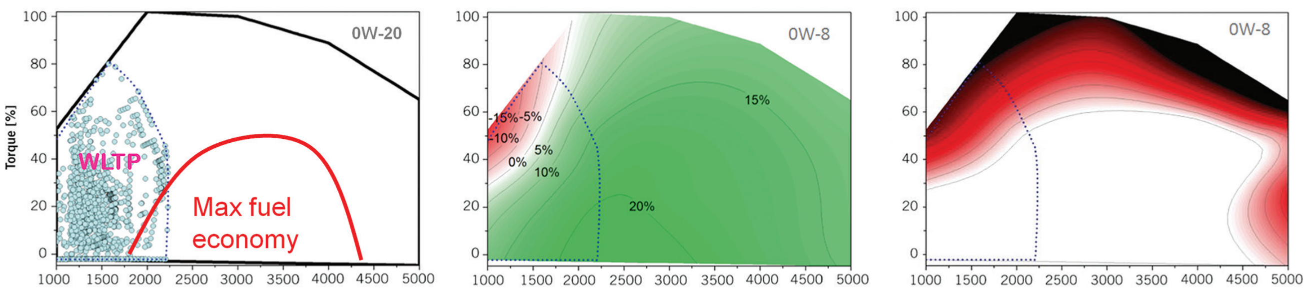


Figure 3: *Simulated ΔBSFC and bearing health maps for a modern passenger car engine [11]*

lubricant viscosity is increased engine wear [8-15]. The hydrodynamic lubricant film thickness is directly proportional to lubricant viscosity. Therefore, to maintain hydrodynamic lubrication, substantial modifications in the engine hardware are often required including surface finish specifications, bearings, filtration systems, and oil pump, galleries and squirters. Without that the risk of excessive wear is real and cannot be ignored.

Figure 3 shows the simulated brake-specific fuel consumption (ΔBSFC) map for a modern passenger car engine and simulated bearing health map for the same. In the middle, the change in BSFC on changing from SAE 0W-20 (left hand side graph) to SAE 0W-8 (middle graph) is shown, the green area corresponding to improved fuel economy, the red area to degraded fuel economy. Up to 20% reduction in BSFC is feasible. Unfortunately, the maximum effect is restricted to medium-to-high engine speeds and low load. Such conditions apply if the engine is revved in neutral. Close to the engine "sweet spot" – the area around 3000 rpm and 60% load where the engine reaches the lowest specific fuel consumption – the effect is reduced significantly. However, the most troublesome observation is the red area at low rpm and high engine load, since this does not only signify a degraded fuel economy but also an elevated risk of wear as confirmed by the main bearing health simulation (right hand side graph).

The above example shows that it is under the low speed – high load conditions that lubricant film may fail. Problems at high speed are mostly associated with inadequate oil pump capacity and can be addressed by using variable speed pumps. At high engine speeds, inertial forces acting on the reciprocating piston assembly and connecting rod and cavitation effects also play an increased role in wear and this may cause problems with the small end of the connecting rod/wrist pin interface and bearings. However, in general, lower viscosity lubricants tend to be less prone to cavitation.

Since the hydrodynamic film collapses when there is no relative motion between the rubbing surfaces, wear problems associated with the introduction of low viscosity lubricants are further aggravated due to automatic stop-start technology. Use of electric oil pumps and roller bearings for camshaft and balancer shaft helps mitigate the issue. Roller bearing supported crankshafts were also tried but found to be impractical.

Crankcase lubricants are formulated to balance a large number of different properties, a conscious and unavoidable paradigm shift from "being best at something" to "being good enough at everything". Since fuel efficiency is viewed as an extremely important performance aspect – in fact, many OEM approvals explicitly demand it – the transition to lower viscosities will continue. It should be recognised, however, that there comes a point where fuel economy oils do not make much economic sense for the end consumer – we talk about a fuel saving of ~€100 compared to a risk of €1000 Euros if the oil is too thin and causes increased engine wear rates. However, the benefit of these oils accrues to the car manufacturers. If their vehicles can save 1-2% fuel by using a special fuel economy lubricant, then that OEM can drastically reduce the amount of fines they need to pay.

At the same time, the importance of "fuel efficient" lubricants for reducing Greenhouse Gas emissions is overhyped and more and more experts are turning to the life cycle analysis when discussing pros and cons of different technologies. Embodied CO_2 cannot be neglected: each new vehicle arrives with some 10 ton CO_2-eq., which is approx. 20-30% of vehicle's lifetime CO_2 emissions. By changing to fuel economy oil, we can reduce the emissions by a few percent only. However, if by doing so, we shorten the vehicle life, we do more harm than good for the climate.

Hence, it is not surprising that all engine oils are required to meet certain performance specifications for wear protection. The standardised tests – such as Sequence IVB (ASTM D8350) – designed by ASTM and included in API/ILSAC performance specifications are carried out using a single "typical" engine deemed to be representative of current engine technology, in this case port fuel injected. However, currently nearly 75% of new vehicles are powered by GDI engines. Different engine designs produce dissimilar results and as a consequence, a large number of OEM-specific tests and approvals have been introduced, thereby complicating the lubricant development process.

Table 2 shows wear measurements for a 2.0L GDI EcoBoost engine carried out by SwRI® using the Radionuclide Tracer Testing (RATT®) technique. Testing was conducted using SAE 5W-30 and SAE 0W-16

	Top Ring Face	**Top Ring Side**	**Second Ring Face**	**Liner**	**Main Bearing**
Cold Start	■	■	■	■	■
Turbo Transient		■			
Transient Load: Low Speed, Low-High Load				■	
Transient Load: High Speed, Low-High Load		■			
Transient Load: High Speed, High-Low Load		■	■		
Transient Speed: Low Load, Low-High Speed	■		■		■
Transient Speed: High Load, Low-High Speed	■	■	■	■	
Transient Speed: High Load, Low-High Speed, 115°C Oil		■	■		■
Trailer Tow					
Trailer Tow, 115°C Oil	■	■	■	■	■
Boundary Lubrication				■	■
Stop-Start, 4hr Hot Temp			■		
Stop-Start	■	■	■	■	■
Stop-Start, Very Cold	■	■	■	■	
Wide Open Throttle (WOT) Transient Cold	■	■	■		
WOT: Steady State, 2500rpm				■	
WOT: Steady State, 3500rpm					■
WOT: Steady State, 5000rpm					
WOT: 3500rpm, Max. Boost		■			
WOT: 5000rpm, Max. Boost					■

Table 2: *Engine Components with Measurable Wear during Different Engine Test Sequences*

dexos1™ Gen 2 oils containing the same additive package. The engine and oil was subjected to various severe conditions, including cold start, transient load, trailer tow, and stop-start sequences, and wear values for each irradiated engine part were compiled. Table 2 shows components that experienced noticeable wear (shaded boxes) [14,15]

Figures 4 and 5 show top ring and cylinder liner wear rates [14].

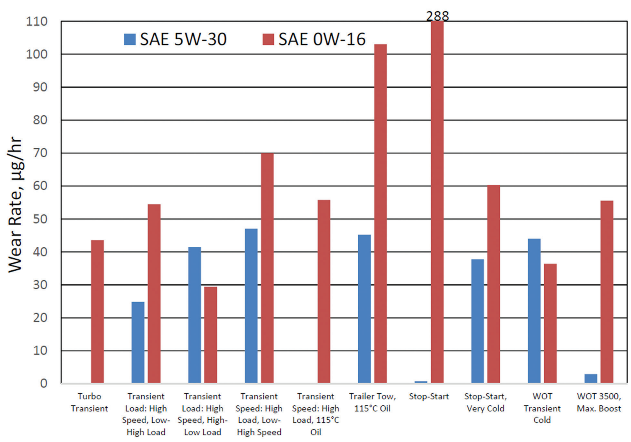


Figure 4: *Top ring wear rates for different engine test sequences*

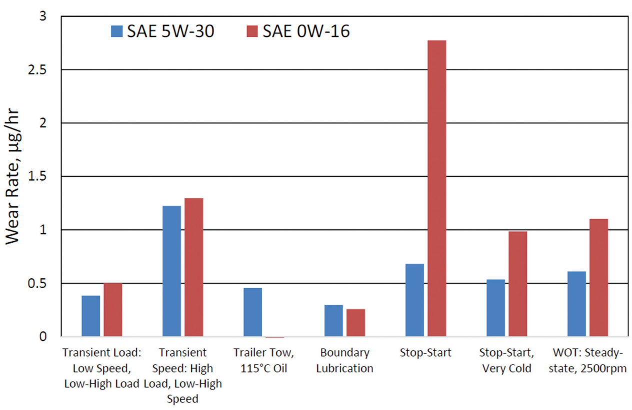


Figure 5: *Liner wear rates for different engine test sequences*

As can be seen, lower viscosity lubricant resulted in higher wear across roughly two thirds of the engine operating conditions!

Motored engine rigs are very useful to study the effect of motor oil on engine friction [16]. Figures 6 and 7 show friction torque data for two different gasoline engines. Used but functional production 2L i4 engines were used to build the rigs: Ford Duratec and Mercedes Benz M133. The main difference between the engines was the cylinder bore surface: honed cast iron vs thermally sprayed, and the valve train type: direct-acting mechanical bucket (DAMB) vs roller finger follower (RFF). The rigs were motored and run non-pressurised, using an external electric oil pump to supply engine lubricant.

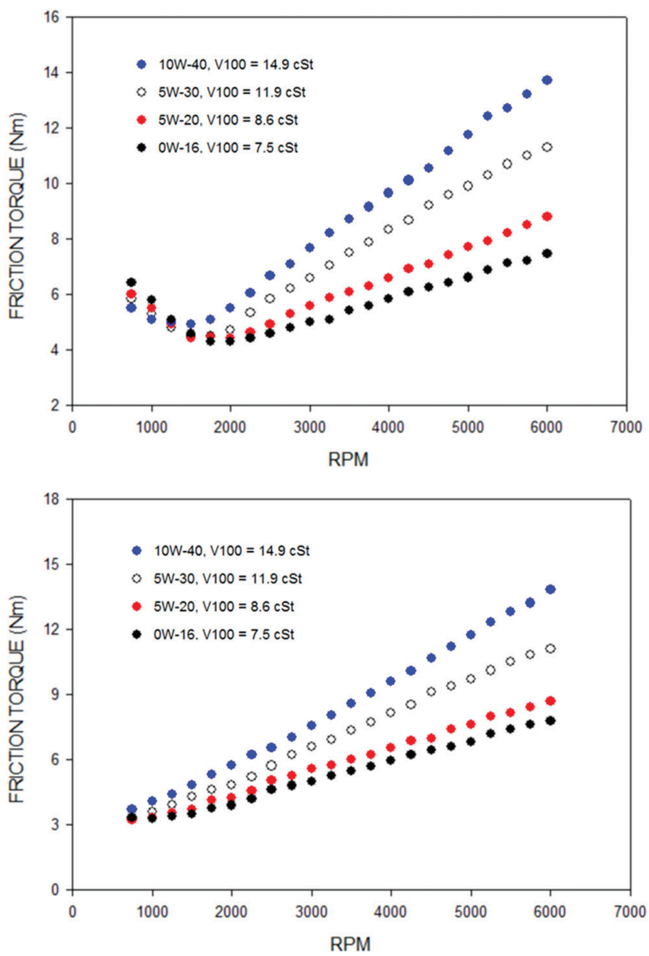
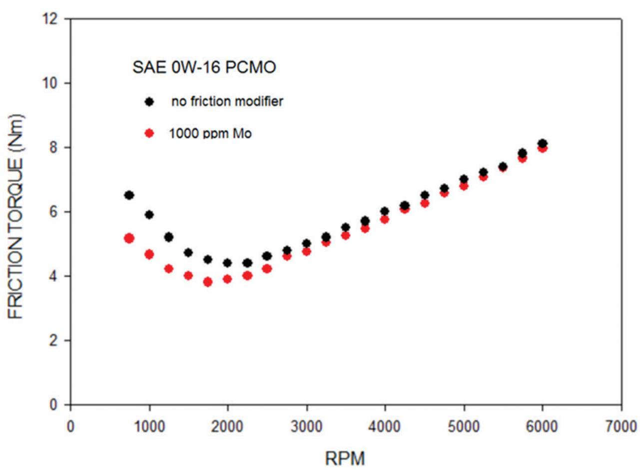


Figure 6: *The effect of oil viscosity grade on engine friction at 90°C: l.h.s. - Ford Duratec, r.h.s. - M.B. M133*

Figure 6 shows the effect of oil viscosity grade at 90°C. Moving from the legacy SAE 10W-40 grade to SAE 0W-16 allows nearly twofold reduction in engine friction at high rpm. Both viscosity grades were formulated using the same additive package and had identical chemical limits. However, the effect gets progressively smaller when going to lower rpm. It is interesting that for the older Ford engine featuring conventional cast iron cylinder bores and a DAMB valvetrain, the lowest viscosity oil gives the highest friction in the low rpm end. Once again, this shows the hydrodynamic lubricant film collapse may be a real problem. For the newer Mercedes Benz engine featuring spray-coated bores and RFF valvetrain, the friction torque is nearly linearly dependent on engine speed. This shows the new design effectively avoids boundary friction.



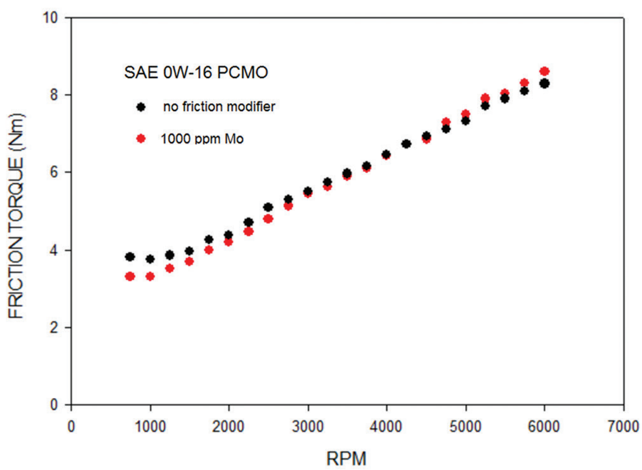


Figure 7: *The effect of molybdenum friction modifier on engine friction: l.h.s. - Ford Duratec, r.h.s. – M.B. M133*

Figure 7 shows how engine friction responds to the use of a FM in the lubricant formulation. One can see that the engine with a DAMB valvetrain and conventional cast iron cylinder bores gains more benefit from the use of FMs than the engine with an RFF valvetrain and thermally sprayed bores. This shows that the use of friction modifiers is only beneficial when there is a substantial contribution of boundary friction to the total energy loss.

It is important to understand that different FMs may compete with each other for vacant surface sites, and they may also compete with detergents – another important class of additives invariably present in crankcase lubricants. Therefore two different formulations with identical viscometrics may still have different fuel economy properties, although variations rarely exceed 1 percent.

Some insights regarding hybrid powertrains

Hybrid powertrains bring new challenges for oil formulators: since the ICE is not permanently firing during the vehicle's use, it may fail to reach working temperate. Oil viscosity changes significantly with temperature, resulting in cold engines having higher friction losses. Furthermore, low oil temperature creates conditions for water condensation on power cylinder walls resulting in water accumulation in the crankcase. Cold engines also experience increased fuel dilution in the sump. While dispersants help to solubilise water and drive it away from the crankcase, their effect is limited, and in extreme cases, oil may turn into a "mayonnaise" like substance failing to efficiently lubricate the engine. The only practical solution currently available is to program powertrain control electronics to engage the ICE at intervals to heat up the oil and evaporate excess water and fuel.

Hybrids tend to use low SAE 0W-20 (Volvo, Mercedes) and ultralow SAE 0W-8 (Honda) viscosity lubricants. Ultralow viscosity lubricants depend heavily on friction modifiers and extreme pressure/AW additives to improve fuel economy in the low speed-high load limit that lies closer to the engine sweet spot, whereas oil viscosity has the dominant effect on fuel economy in the high speed-low load limit.

Concluding remarks

Motor oil is a critical element in the development of low friction powertrains and using low viscosity motor oil is an efficient way to reduce friction losses in internal combustion engines. However, low viscosity oil tends to compromise wear protection if hardware technology remains stagnant, necessitating the use of FMs and AW additives in crankcase lubricants. Together with a broader adoption of synthetic base oils, FMs are expected to play an increasingly important role in future engine lubricant blends.

References

1. *Environmental Protection Agency, The Safer Affordable Fuel Efficient (SAFE) Vehicles Final Rule for Model Years 2021-2026, Docket Number EPA-HQ-OAR-2018-0283, published 2018.*
2. *European Environment Agency, Regulation (EU) 2019/631, published 2019.*
3. *Z. Yang, D. Rutherford, Japan 2030 fuel economy standards. ICCT, September 2019.*
4. *B. Zhmud, Current advances in crankcase lubricants. European Base Oil & Lubricants Summit, Rotterdam, The Netherlands, Nov. 20-21, 2019.*
5. *B. Zhmud, A. Coen, K. Zitouni, Fuel Economy Engine Oils: Scientific Rationale and Controversies, Frontiers Mech. Eng. (submitted)*
6. *B. Zhmud, Superlubricity in the Real Automotive World, 2nd International Workshop, Brazil, 2018.*
7. *S. Yoshida, K. Yamamori, S. Hirano, T. Sagawa, et al., The development of JASO GLV-1 next generation low viscosity automotive gasoline engine oils specification. SAE Technical Paper 2020-01-1426.*
8. *B. Zhmud, Engine tribology: a thorny way from lab to field, Lube 154 (2019) 20.*
9. *R.I. Taylor, R.C. Coy, Improved fuel efficiency by lubricant design: A review, Proc. Inst. Mech. Eng. 214 (1999) 1.*
10. *B. Zhmud, E. Tomanik, "Optimizing the piston/bore tribology: The role of surface specifications, ring pack, and lubricant." International Colloquium Tribology, Esslingen, Germany, January 28-30, 2020.*
11. *D.E. Sander, H. Allmaier, C. Knauder, F. Strömstedt, Potentials and risks of reducing friction with future ultra-low-viscosity engine oils. MTZ Worldwide 79 (2018) 21.*
12. *G. Lechner, A. Knafl, D. Assanis, S. Tseregounis, M. McMillan, S. Tung, P. Mulawa, E. Bardasz, S. Cowling, Engine oil effects on the friction and emissions of a light-duty, 2.2L direct-injection diesel engine, Part 1 - Engine test results. SAE Technical Papers 2002-01-2681.*
13. *S. Tung, M. McMillan, G. Hong, E. Bardasz, Engine oil effects on friction and wear using 2.2L direct injection diesel engine components for bench testing, Part 2: Tribology bench test results and surface analyses. SAE Technical Papers 2004-01-2005.*
14. *P. Lee, M. Lochte, Gasoline direct injection (GDI) engine wear test development, CRC Project No. AVFL-28, SwRI, San Antonio, Texas, October 9, 2017.*
15. *P. Lee, M. Lochte, Gasoline direct injection (GDI) engine wear test development Phase II, CRC Project No. AVFL-28, SwRI, San Antonio, Texas, September 12, 2019.*
16. *R.I. Taylor, N. Morgan, R. Mainwaring, T. Davenport, How much mixed/boundary friction is there in an engine - and where is it? Proc IMechE Part J: J. Engineering Tribology 234 (2020) 1563.*

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