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Communication

Low Friction Powertrains: Current Advances in Lubricants and Coatings

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Abstract: Improving fuel economy and reducing emissions is nowadays more important than ever. Apart from powertrain electrification, automotive manufacturers have constantly been seeking to improve the efficiency of the internal combustion engine. Downsizing and boosting have become common practice in the internal combustion engine (ICE) design. Increased power density and torque output of modern boosted engines, in combination with the introduction of automatic stop-start systems and ultralow viscosity lubricants tends to stress the engine beyond the limits foreseen in the classical design. This leads to wear problems. Each engine component comes with a unique landscape of competing manufacturing technologies, among which advanced surface finishing and coating methods play an important role. This presentation provides an overview of different industrial trends related thereto. The role of lubricant on the engine tribology is studied for different engine designs. The importance of in-design "pairing" of low-viscosity motor oils with the engine characteristics is highlighted filling the gap in the understanding of complex interactions between the crankcase lubricant and engine mechanics.

Keywords: fuel economy; crankcase lubricant; motor oil; resource conserving; low friction coating; engine friction; engine tribology

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1. Introduction

New fuel economy standards for automobiles, changes in customer preferences driven by high fuel prices, and vehicle and carbon taxation have put increased pressure on car manufacturers. In the US, the National Highway Traffic Safety Administration (NHTSA) and the 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 and set a moving fuel economy target that will increase 1.5% in stringency from model years (MY) 2021 through 2026. Recognizing the realities of the marketplace, the expectations bar has been lowered to 40.4 mpg projected industry average required fuel economy in MY 2026, compared to 46.7 mpg projected requirement under the 2012 standards. The latter has been lowered from the initial 2025 EPA target of 62 mpg announced a decade ago and soon afterward reduced to 56 mpg. The overambitious targets may not be achieved without a solid technological foundation and powerful financial incentives.

The European Parliament and Council adopted Regulation [2] that 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. This corresponds to a fuel consumption of 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 level for new cars sold in EU is 120 g CO_2/km.

Japan's new fuel economy standards issued a year ago set a target for average fleet gasoline-equivalent fuel economy of 25.4 km/L (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 major 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, emphasis is placed on understanding tribological aspects of powertrain energy losses and current advancements in engine design and hardware, lubrication engineering and coatings to minimize those losses. To encourage eco-innovation, manufacturers are granted "emission credits" for innovative technologies that should result in reduced CO_2 emissions. Manufacturers are also granted "super credits" for zero- and low-emission cars such as battery and hybrid vehicles emitting less than 50 g CO_2/km.

In the past decades, engineering advancements in manufacturing have enabled approximately 40% reduction in CO_2 emissions. The average fuel economy for compact cars has increased from 30 mpg (7.8 L/100 km) in the 1980s to 50 mpg (4.7 L/100 km) because of the broad acceptance of fuel-stratified injection (FSI), direct injection technology, variable valve timing, variable compression ratio, cylinder deactivation, powertrain electrification and other efficiency-boosting solution, Figure 1.

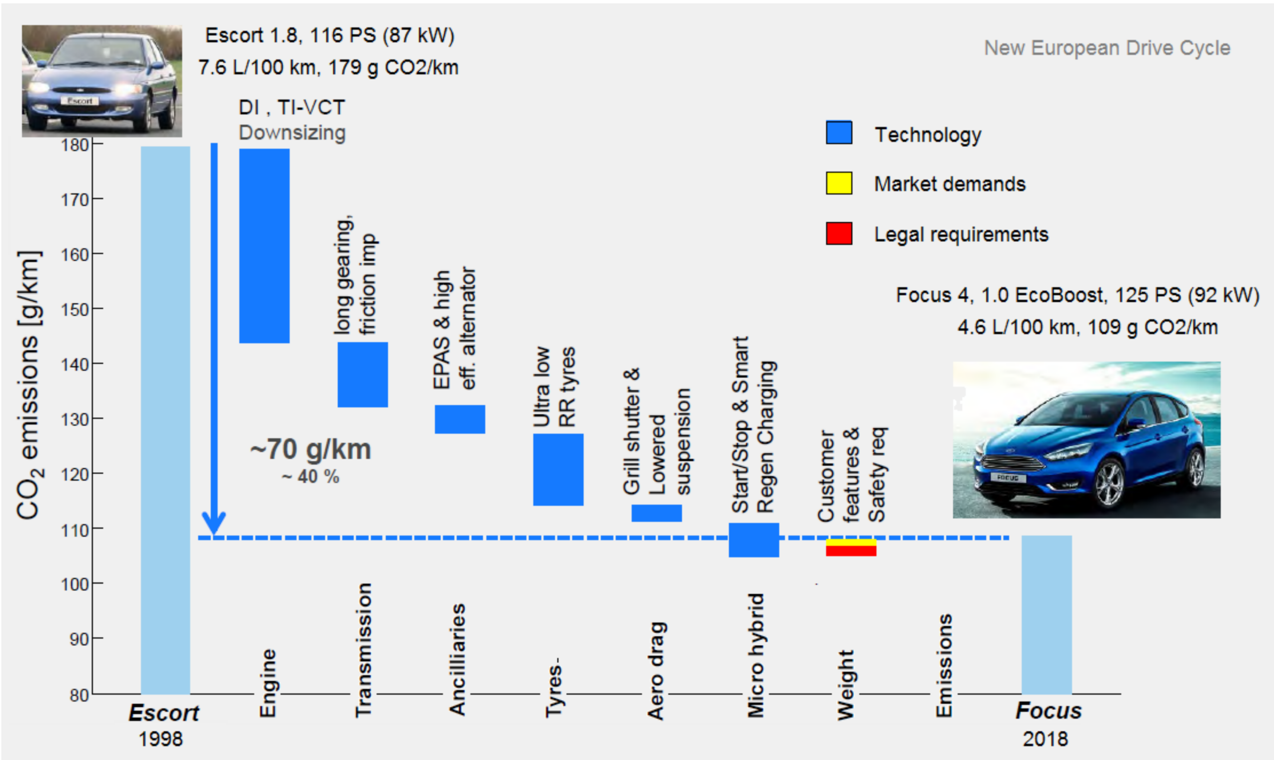

Figure 1. Reduction in GHG emissions through the progress in the powertrain technology over the past two decades (Source: Kramer et.al. [4]).

Lightweight materials are another important technology that helps improve passenger vehicle fuel efficiency, with 6–8% saving achieved by 10% weight reduction [5] and manufacturers are increasingly using new materials such as advanced ultrahigh strength steel (A-UHSS), aluminum, and even carbon fiber in the luxury segment, to push vehicle weight down.

In an internal combustion engine, around 10 to 20% of energy is lost due to friction. This can be further subdivided, in a proportion ~9:1, into viscous losses due to lubricant flow and frictional losses due to boundary contact primarily in piston ring/cylinder bore, cranktrain and valvetrain systems. The dissipative losses can be reduced by using lower-viscosity oils and smaller displacement volumes. The frictional losses can be reduced by using antifriction coatings on performance-critical parts, as well as by deploying special friction-reducing additives in engine oil, Figure 2.

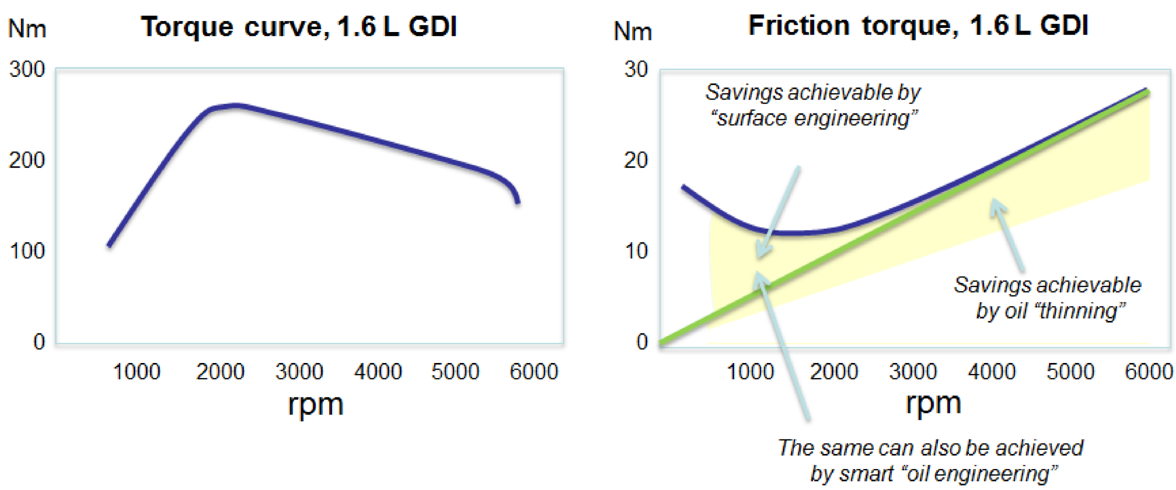

Figure 2. The torque curve (l.h.s.) and the friction torque (r.h.s.) for a production 1.6L i4 GDI engine. The primary engineering strategies for friction reduction are also shown [6].

In order to reduce boundary friction and to improve longevity of performance critical parts, various coatings are used, Figure 3. Classical methods used for enhancing the tribological properties of various automotive components are chrome plating, nitrocarburazing and phosphating/parkerizing. Newer technologies, such as electrodeposited (Nikasil), hypereutectic aluminium-silicon (Alusil®, Silitec®, Albond®) and thermally sprayed (PTWA, TWAS, APS) coatings are used for reinforcement of cylinder bore walls and improved oil film retention. Low friction polymeric and polymer-bonded coatings (TriArmor, EcoTough) can be found on bearings and pistons. Hard antiwear coatings such as diamond-like carbon (DLC) and chromium nitride (CrN) are used for piston rings, valvetrain elements, etc.

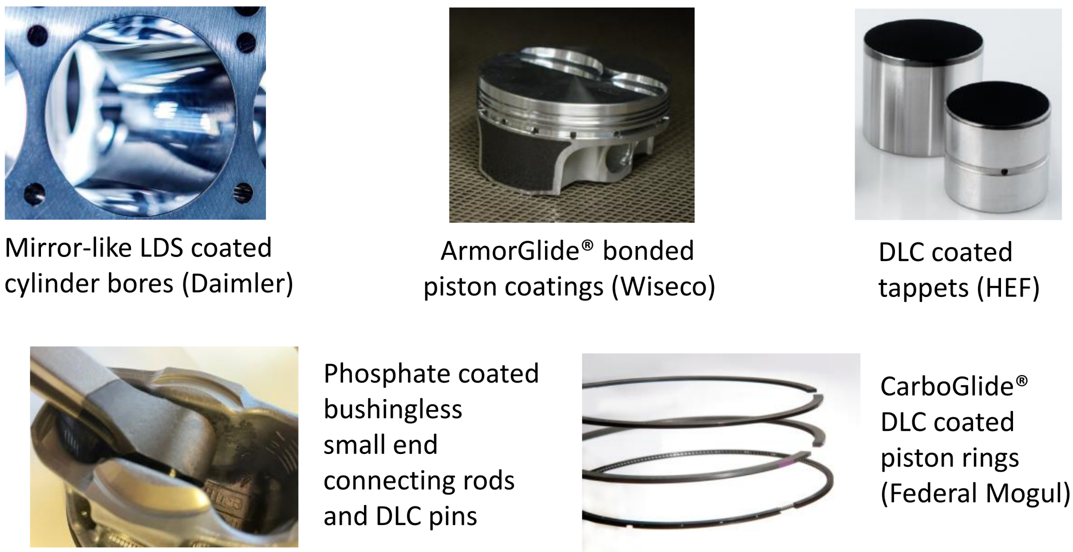

Figure 3. Examples of tribological coatings used in the automotive industry. All images are copyright to their respective owners.

For instance, it has been reported that the use of piston rings with the TiSiCN coating developed by SwRI® allows one to reduce piston/bore friction (see Figure 4) leading to some 0.5% improvement in fuel economy as well as a substantial reduction in ring and liner wear [7].

Coating durability is critical for the effect retenion. Wear, flaking or corrosion of coatings may lead to catastrophic engine failures. Before an engine is launched onto the market, it must go through a number of endurance tests to guarantee adequate performance.

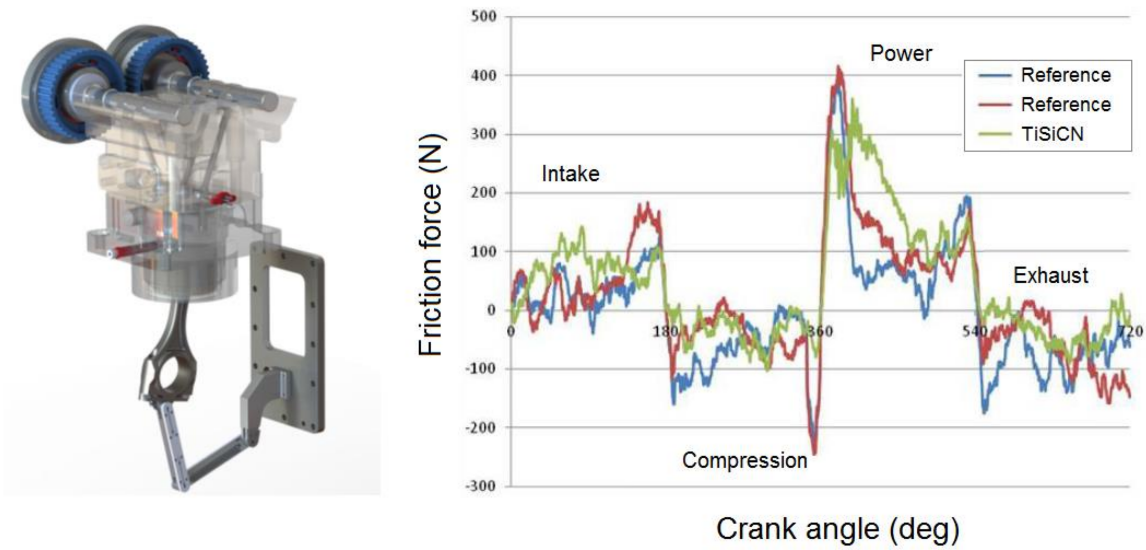

Figure 4. Reduction in piston/bore friction achieved on switching to TiSiCN coated top and second ring [7].

In this connection, advances in surface finishing technology should also be mentioned. These include abrasive finishing, burnishing, laser texturing and mechanochemical finishing methods [8–12].

2. Effect of Motor Oil on Fuel Economy

For passenger cars, a change from the legacy SAE 15W-40 grade to SAE 0W-20 brings on average 3 to 4% improvement in fuel economy under the NEDC or EPA conditions, and the subsequent migration to 0W-8 can bring an additional 2 to 3% [13–16]. Under more gentle driving in the JC08 cycle, lower viscosity oils may produce 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 oil depends so much on engine design, vehicle type and driving conditions, it is essential to compare oil in a 'like-for-like' test. One commonly used standard is Sequence VI. Two current standards, Sequences VIE and VIF (per ASTM D8114 and D8226), use a 2012 3.6L GM engine 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 aging stages is determined: FEI1 after 16 h (fresh oil) and FEI2 after 109 h (aged oil). This procedure discriminates between types of friction modifiers with age, and different test limits are set for the different oil viscosity grades (Table 1).

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 [6,13]. 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.

A new Japanese Automotive Standards Organization Fuel Economy Test, JASO M364:2019, may help lay the groundwork for the next version of the Sequence VI test 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 2019 [14]. For the fuel economy test, either the firing Toyota 2ZR-FXE 1.8L engine (JASO M366) or the motored Nissan MR20DD 2.0L engine (JASO M365) can be used. The set 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. Whereas ILSAC GF-7 is not likely to come before 2025, taking into account the cost and challenges associated with development of the

ILSAC GF-6 category, the new fuel economy test (JASO FE M366) using Toyota 2ZR-FXE engine has been included in the recently released ACEA 2021 European Oil Sequences, with first allowable use from 1 May 2021.

Table 1. Sequence VIE and VIF Test Limits.

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	FEI2 FEI1+FEI2	1.9 4.1

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

3. The Downsides of Lower Viscosity

The primary obstacle to continually lowering lubricant viscosity is increased engine wear [15–22]. 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, see Figure 5.

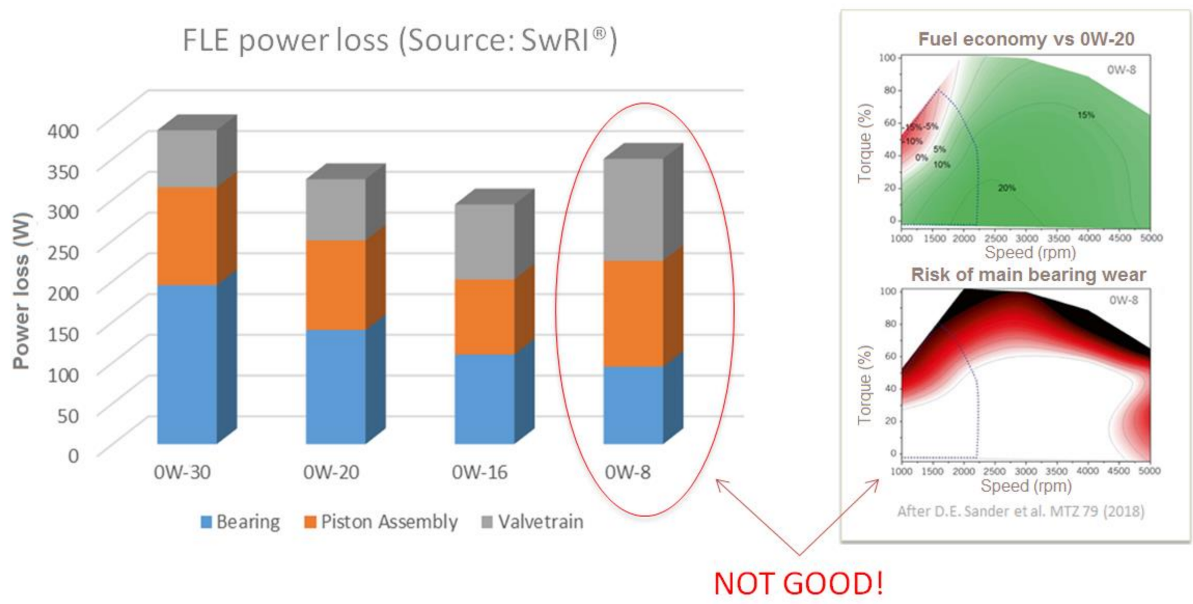

Figure 5. Friction power loss measured for different engine subsystems in a firing engine using different oil viscosities (l.h.s.) and simulated fuel economy and bearing health maps for SAE 0W-8 oil in a modern passenger car engine (r.h.s.).

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 realize, 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.

As Figure 5 shows, a change from SAE 0W-20 to SAE 0W-8 can result in up to 20% reduction in BSFC. 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.

These examples show that it is under low speed−high load conditions that lubricant film may fail. Problems at high speed are associated with inadequate oil pump capacity and can be addressed by using variable pumps. At high engine speeds, inertial forces acting on the reciprocating piston assembly and connecting rod and cavitation effects also increase wear and may cause problems with the connecting rod/wrist pin interface and bearings. However, 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 low viscosity lubricants are further aggravated due to automatic start-stop technology. Use of electric oil pumps and roller bearings for the camshaft and balancer shaft helps mitigate the issue. Roller-bearing-supported crankshafts have been 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 recognized, however, that there becomes 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.

The importance of "fuel efficient" lubricants for reducing GHG emissions has historically been too narrow a focus 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 tons CO_2-eq., which is 20 to 30% of lifetime CO_2 emissions. By changing to fuel economy oil, we can reduce the emissions by a few percent. But if by doing so we shorten the vehicle life, we do more harm than good for the climate. This is where new surface and coating technology comes into play, prolonging the vehicle life.

It is not surprising that all engine oils are required to meet certain performance specifications for wear protection. The standardized tests—such as Sequence IVB (ASTM D8350) for low temperature valvetrain wear—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. Currently nearly 75% of new vehicles are powered by gasoline direct injection (GDI) engines. Different engine designs produce dissimilar results. 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 dexos1™ Gen 2 oil and SAE 0W-16 oil 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) [21,22].

Table 2. Engine Components with Measurable Wear during Different Engine Test Sequences.

	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, 4 h Hot Temp			■		
Stop-Start	■	■	■	■	■
Stop-Start, Very Cold	■	■	■	■	
Wide Open Throttle (WOT) Transient Cold	■	■	■		
WOT: Steady State, 2500 rpm				■	
WOT: Steady State, 3500 rpm					■
WOT: Steady State, 5000 rpm					
WOT: 3500 rpm, Max. Boost		■			
WOT: 5000 rpm, Max. Boost					■

Figures 6 and 7 show top ring and cylinder liner wear rates [21].

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 [23]. Figures 8 and 9 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 valvetrain type: direct-acting mechanical bucket (DAMB) vs. roller finger follower (RFF). The rigs were motored and run non-pressurized, using an external electric oil pump to supply engine lubricant.

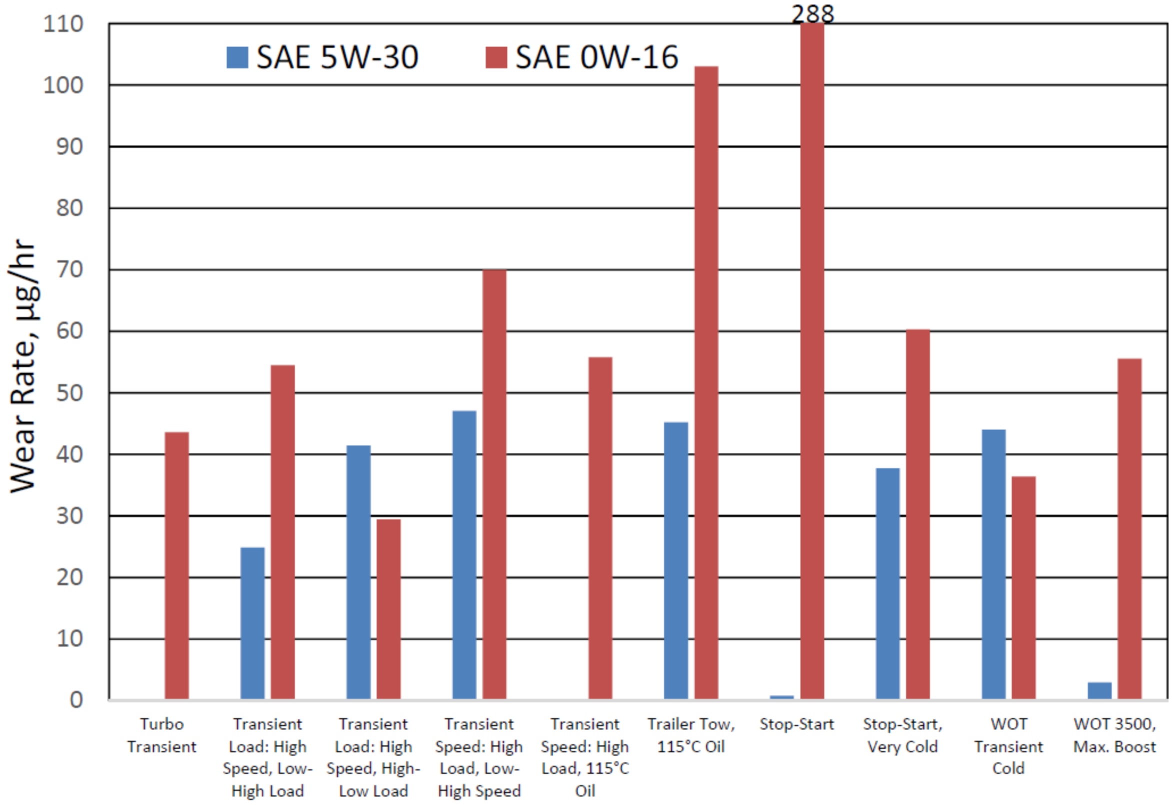

Figure 6. Top ring wear rates for different engine test sequences.

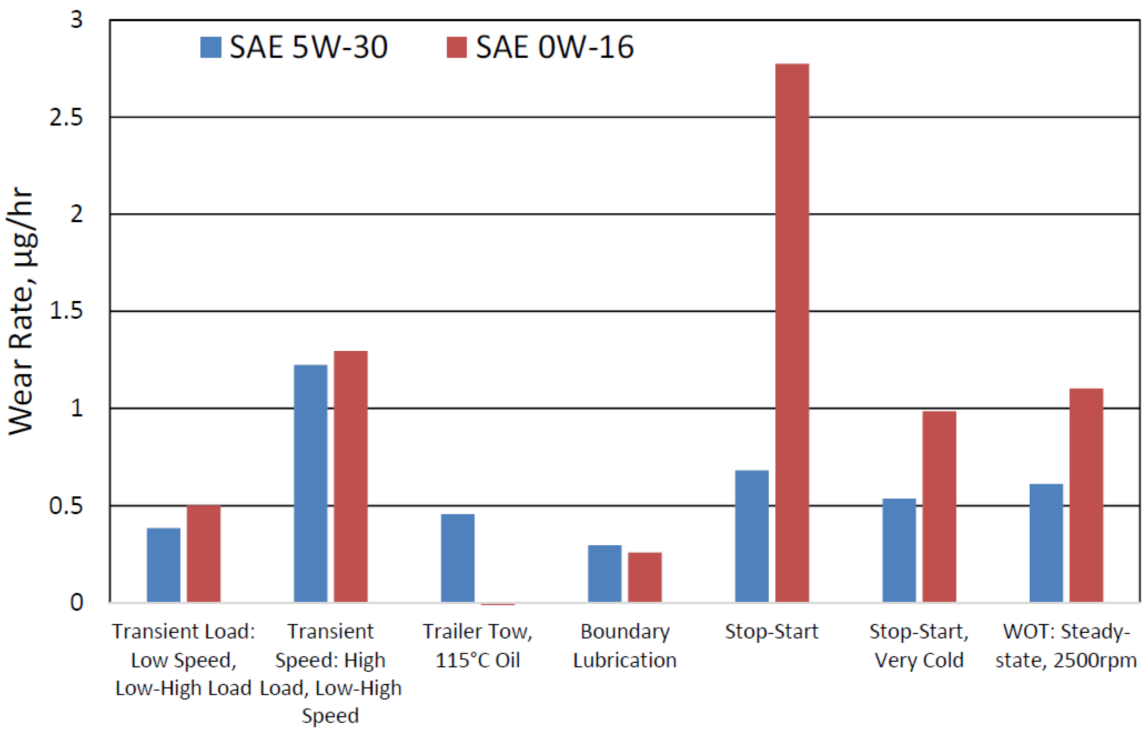

Figure 7. Liner wear rates for different engine test sequences.

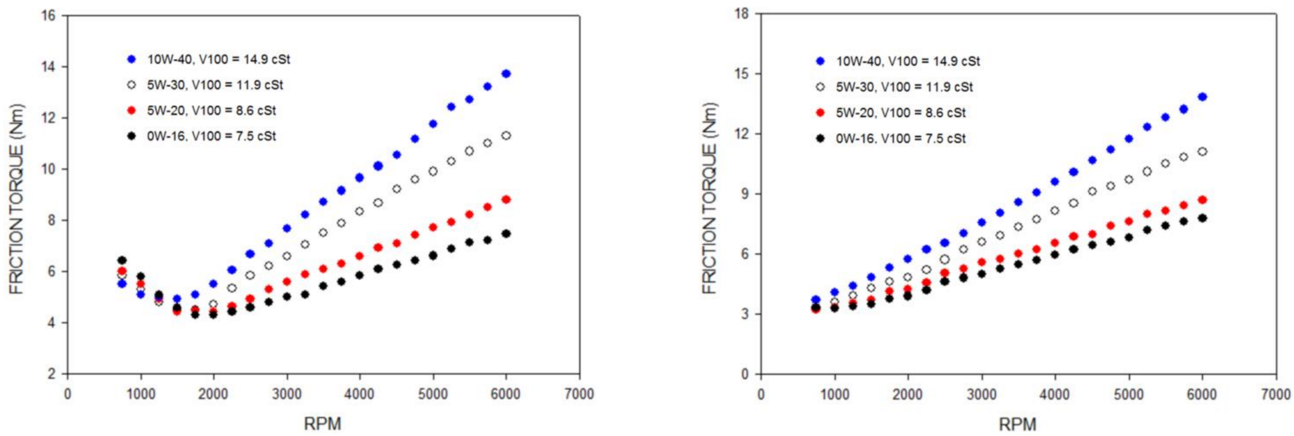

Figure 8. The effect of oil viscosity grade on engine friction at 90 °C: l.h.s.—Ford Duratec, r.h.s.—M.B. M133.

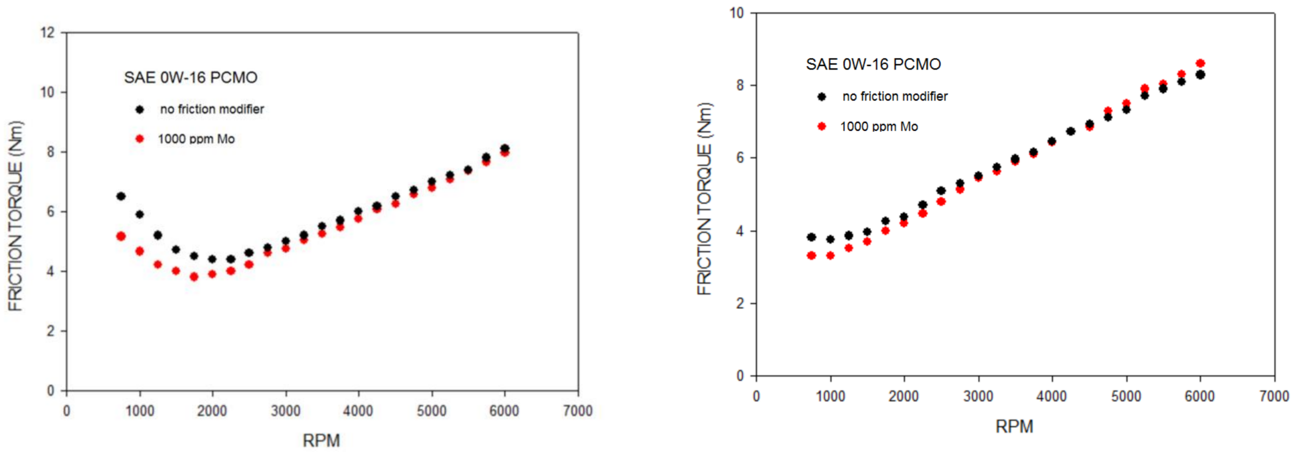

Figure 9. The effect of molybdenum friction modifier on engine friction: l.h.s.—Ford Duratec, r.h.s.—M.B. M133.

Figure 8 shows the effect of oil viscosity grade at 90 °C. Moving from SAE 10W-40 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. The effect gets progressively smaller when going to lower rpm. 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, proving that hydrodynamic lubricant film collapse may be a problem. For the newer Mercedes Benz engine featuring spray-coated bores and an RFF valvetrain, the friction torque is nearly linearly dependent on engine speed, showing that the new design can effectively avert boundary friction.

Figure 9 shows how engine friction responds to the use of a friction modifier in the lubricant formulation. The Ford engine gains more benefit from deployment of friction modifiers than the Mercedes Benz engine. This shows that the deployment of friction modifiers only makes sense when there is a substantial contribution of boundary friction in 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.

4. 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 solubilize 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 EP/AW additives as well as novel coating and finishing technologies 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.

5. Concluding Remarks

Engine lubricant and hardware development are critical elements in the development of low friction powertrains. 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 in older vehicles or if hardware technology remains stagnant, necessitating the use of FMs and EP/AW additives in crankcase lubricants. Continued improvement in fuel economy is expected through the use of coatings and finishes in modern engines combined with FMs and a broader adoption of synthetic base oils for both modern and older engines.

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