Fuel Economy: An important outlook

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The automobile industry's rapid growth and innovation were fueled by the contribution of friction, a key factor in improving performance. However, modern cars' safety features and the competition to provide the best features to consumers have led to a significant increase in car weight, resulting in an increase in fuel consumption and friction. Between 1990 and 2005, fuel consumption in cars increased by 37%, with road transportation contributing 75-89% of total CO_2 emissions in the transportation sector and approximately 20% of global emissions [1,2].

As concerns over carbon emissions are on the rise, especially after regulations such as the Safe Affordable Fuel-Efficient (SAFE) Vehicles Rules have been implemented, the need for sustainable practices is more necessary than ever. Tribologists have proposed the use of low-viscosity lubricants to improve fuel economy and reduce carbon footprint. However, using low-viscosity lubricants can also increase wear and tear on vehicles, making it important to find the optimal concentration of lubricating oil to balance fuel economy, friction, and wear. This paper aims to explore current research on lubricating oils and shed light on this issue.

The effectiveness of lubricating oil depends on the type of lubricant regime involved (e.g., boundary lubrication, mixed lubrication, hydrodynamic lubrication, and elastohydrodynamic lubrication). Low-viscosity engine oils are designed to reduce viscous drag during hydrodynamic or elastohydrodynamic lubrication conditions, where the oil film thickness is large enough to separate the two sliding surfaces completely. However, low-viscosity oils are more prone to shear thinning at high temperatures and thinning at lower temperatures, causing the lubricating film thickness to decrease. As the film thickness decreases, the lubrication regime shifts towards mixed and boundary lubrication, where the oil film cannot overcome the surface roughness [3].

Across North America, SAE 5W-30 has been the most popular oil grade for the existing automobile market since the 1980s, making up 40% of the total oil sold in the North American Market. However, it is gradually being replaced by SAE XW-20, a lower-viscosity oil grade. The implementation of ILSAC GF-6B allowed the introduction of new fuel economy viscosity grades below SAE 0W-20 to be introduced with their own certification mark. Figure 1 shows by 2025, SAE 0W-20 is expected to control 50% of the oil market share in the North American region [4].

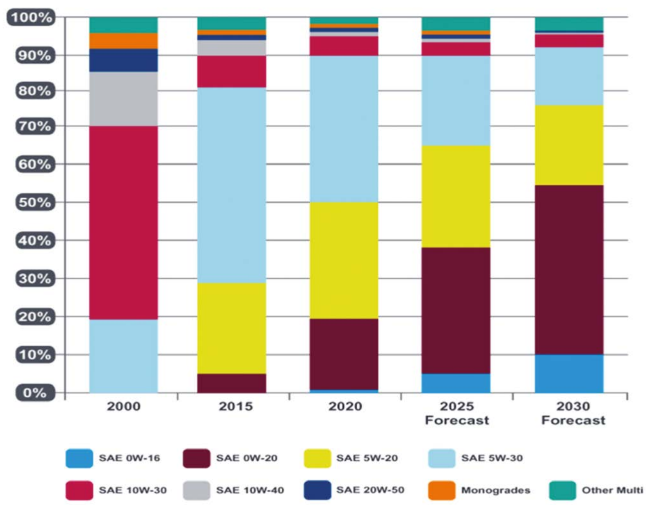

***Figure 1:** North American Viscosity Grade Trend [4]*

Over the years, heavy-duty diesel (HDD) saw a sharp rise in sales, and therefore, it is important to discuss the viscosity trend associated with these vehicles. Currently, there is a rise in SAE 15W-40's market share. However, it is predicted to decline to 30%, and SAE 10W-30 is all set to take over the market [4]. However, one of the main concerns associated with these low-viscosity oil grades is that they can lead to oil volatility and ruin and affect necessary characteristics.

Traditionally, the European market has favoured slightly heavier oils compared to North America. In Europe, the dominant viscosity grades for engine oils have traditionally been above 3.5 centipoises (cP) in terms of high-temperature high-shear (HTHS) viscosity. This includes premium grades like 5W-40 and mid-tier grades like 10W-40. However, in recent times, there has been a shift towards lighter viscosity oils. The viscosity grade 5W-30, with an HTHS viscosity of 2.9 cP, has gained traction and witnessed significant growth in the European market. This shift can be attributed to the increasing pressure to reduce greenhouse gas emissions. In response to this demand, original equipment manufacturers (OEMs) are now moving towards even lighter lubricants with an HTHS viscosity of 2.6 cP or lower. The transition to lighter lubricants is driven by the aim to improve fuel efficiency and reduce emissions. By using lower-viscosity oils, engines can experience reduced internal friction, resulting in better overall performance and lower fuel consumption. This trend reflects the industry's ongoing efforts to meet stricter environmental regulations and promote sustainability in automotive applications.

However, there is a shift expected among German carmakers, including Daimler, BMW, and Volkswagen, who are anticipated to introduce original equipment manufacturer (OEM) specifications that include SAE 0W-16 and 0W-12 oils. SAE 0W-20 engine oils that meet ILSAC (International Lubricant Standardization and Approval Committee) standards can be formulated using conventional Group III base stocks with Noack volatility of up to 15%. However, as the industry moves towards lubricants that meet the performance requirements of both passenger car and diesel engine oils, such as those specified by the European Automobile Manufacturers Association (ACEA) or GM's dexos1, the allowed Noack volatility becomes more restricted. Both ACEA and dexos1 standards require oils to have a Noack volatility no higher than 13 percent. In some cases, original equipment manufacturer (OEM) specifications can be even more stringent, imposing stricter limits on oil volatility [5].

To improve the sustainability of commercial fuels and reduce friction, researchers have suggested decreasing their viscosity. However, research over the years shows that there is an inverse relation between oil viscosity and volatility which results in loss of oil during operation. Henceforth, to maintain steady performance, it is essential that both base oil and blend components have strong volatile properties, which can be assured through various volatility tests that meet API oil guidelines. Noack Volatility Test indicates that volatility >15% is too high and will most likely not pass crucial oxidation tests, including the IIIG engine test. Additionally, both General Motors and European Automobile Manufacturer's Association (ACEA) have their own specifications for the maximum Noack volatility, which should be followed. It is also worth noting that the volatility of engine oils is generally lower than the volatility of their base oils, and thus the Noack volatility of base oil is rated at 2% higher than the engine oil in Europe [6,7].

The addition of Polyalphaolefin (PAO) and esters in the original oil blend might be a viable option. PAO is a synthetic hydrocarbon (SHC) that is able to mimic the best hydrocarbon (branched) structure found in mineral oils. Due to its controlled structure, there is no small, volatile hydrocarbon present which decreases volatility and creates less hydrocarbon tailpipe emissions [8]. Dodecene-based PAOs, in particular, offer exceptional Noack volatilities; dodecane-based PAOs contain a 36-carbon atom component as the lightest material, which is about 6 carbon atoms heavier than traditional decene-based PAOs. Using dodecane-based PAOs or other low-volatility base oils can reduce oil loss due to volatilisation and maintain ideal viscosity, ultimately improving engine performance and efficiency.

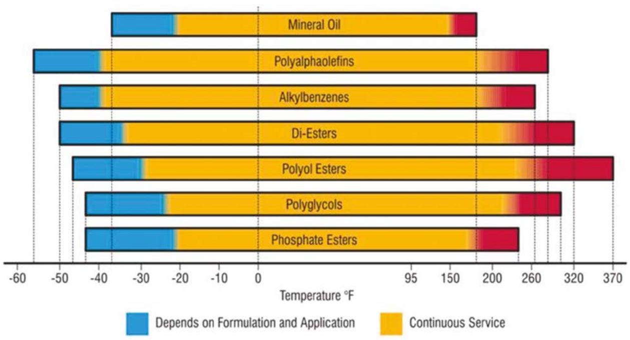

Figure 2: *Stability of PAO [7]*

One of the other proposed solutions includes esters which are a monolithic class of Group V base oils with exceptional properties like high oxidative stability and low volatility. Group V base oils (esters) can be formed from byproducts of Group IV base oils, with esters having dynamic viscosities ranging from around 5 Pa·s to around 0.001 Pa·s as the temperature increases. However, only esters derived from an oct-1-ene dimer could serve as potential Group V base oils due to volatility concerns with other esters at certain temperatures. Esters also aid additive solubility and elastomer seal swell, which can counteract seal shrinking present in Group III and IV base oils. Blending options with these and other materials can provide low-viscosity and low-volatility options for engine oils. Friction reduction and fuel economy are the major concerns of Original Equipment Manufacturers (OEM) across the world, and the study found that the oxidative stability of base oils significantly impacts fuel economy and engine cleanliness. Base oils with poor oxidative stability cause more sludge and varnish deposits and reduce engine efficiency. The use of ester base oils, such as TruVis™ A130, TruVis™ P3020, and TruVis™ P3121, can improve deposit performance and reduce friction, thereby improving fuel economy. TruVis™ P3121 was found to reduce friction at all treatment rates. Esters have higher VI and lower volatility compared to traditional base oils, exhibit good deposit control, and can reduce the friction of finished engine oils. It also enables the solubilisation of advanced additives, which can be helpful in meeting the goal of minimising carbon footprint around the world [9].

A study conducted by Macian et al. studied the effect of low-viscosity engine oil (LVO) in a real fleet to understand the effect on internal combustion engines' (ICE) wear and oil performance. Traditionally, the kinematic viscosity of engine oils was measured at standard temperatures of 40°C-100°C. However, to make the temperature replicate the inner environment of the engines, the viscosity was measured at 150°C, and 10^{-6} s^{-1} was used. In diesel technology, candidate oils showed negligible variation in High Temperature-High Shear viscosity (HTHS) during the ODI (Oil Drain Interval), while the baseline oil showed a slight increase; this can be attributed to efforts by oil formulators to ensure good fuel economy performance in LVO products. In CNG technology, a mild increase in HTHS viscosity value is observed, possibly caused by higher thermal stress and oxidation. However, the viscosity gap between baseline and candidate oils is maintained during the ODI, ensuring that the fuel economy effects are the same for both oil types. There is also a relationship reported between wear rate and oil consumption. The iron rates were similar for engines with lower mechanical stress and higher for engines with higher break mean effective pressure (BMEP) values. The use of LVO had no significant difference in iron rates for lower-stressed engines but substantially increased iron rates for EURO V engines. The valve distribution system based on OHV with cam follower steel without heat treatment was identified as a possible cause of increased wear rate in EURO V engines due to adverse lubrication regimes. The study also couldn't find any

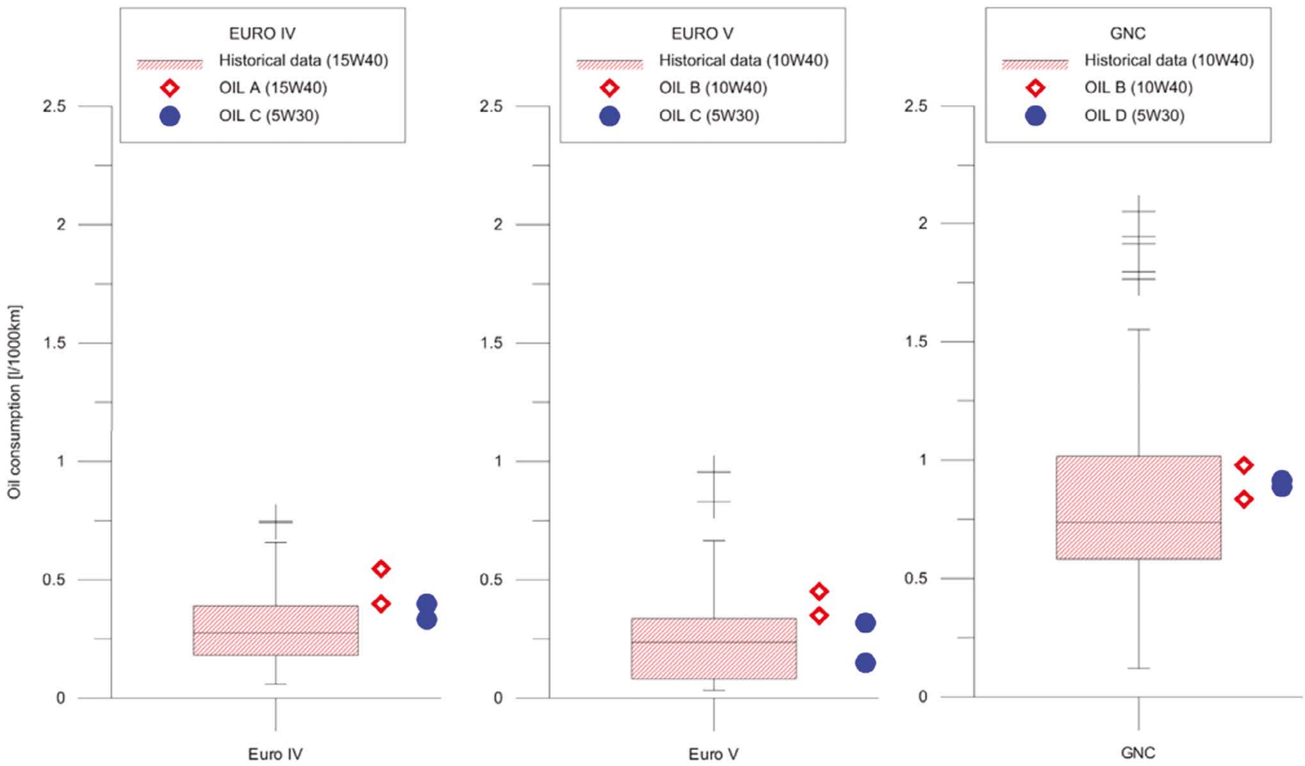

Figure 3: *Oil consumption measurement for each engine technology: EURO IV (left), EURO V (center) and CNG (right) [9]*

evidence that oil consumption increases because of LVO usage (Figure 3). The study concluded that the use of LVO does not lead to increased wear in EURO IV and CNG engines, as both candidate-low viscosity oils used in these engines showed similar wear performance to baseline oils [10].

However, it is important to keep in mind that Europe has been following the EURO VI standard, and EURO VII is already in the development phase. EURO VI CO permissible emission standard from EURO V but severely cut back on adequate NOx emission by the heavy-duty engines. Therefore, it is important to perform similar studies on EURO VI/VII engines to verify these claims. The adoption of advanced lubricants for heavy-duty diesel engines depends on OEM developments and field testing, with a more conservative approach due to durability concerns. The market penetration of lower-viscosity lubricants in the heavy-duty diesel segment may take longer compared to passenger car motor oils. Factors such as alternative fuels and advancements in electric vehicle technology also impact the future landscape for large diesel engines [5].

Another study led by Carden et al. found that baseline oil with the highest viscosity resulted in the least wear, and the amount of wear increased as the viscosity was decreased in the other oils. They used three different test oils in an IVECO Cursor 13 Euro V engine: a baseline 5W-30 oil with a kinematic viscosity of 12.28 mm2s-1 at 100 °C and compared them with low viscosity oil with a kinematic viscosity of 6.53 mm2s-1, and 4.82 mm2s-1. The lower viscosity oil caused micro-pitting, which was attributed to the ZnDTP additives used to protect against wear. The study mentioned that these micro pitting could be reduced by decreasing the concentration of ZnDTP in the oil or reducing the oil's viscosity. Adding friction modifiers and blending PAO oil into the oil containing ZnDTP was also observed to mitigate the micro-pitting [11,12]. Another option would be the inclusion of high-viscosity mPAO base oils as a viscosity modifier since this has been beneficial in racing applications [13].

Another study led by Tamura et al. suggested that friction modifier (FM) is essential as viscosity modification for next-generation engine oils to achieve better fuel economy. They studied several FMs, including molybdenum dithiocarbamate (MoDTC) and nonmetallic fatty compounds, to modify the boundary lubrication performance of engine oils. The addition of (FMs) reduces the friction coefficient, with MoDTC showing the lowest friction coefficient among the FMs tested. However, MoDTC requires high temperatures to generate low-friction tribo-films based on MoS2, resulting in a temperature-dependent friction coefficient. Organic FMs show relatively small temperature dependence and statistical variation of friction coefficient compared to MoDTC, possibly because of the dynamic stability of adsorbed layers of organic FM molecules on the interfacial surfaces. The adsorption of organic FM molecules might be kinetically faster than the generation and growth of MoDTC-based tribo-films [14].

Further viscosity reductions can make a significant impact more recently due to the rise of diesel fuel prices. The retail price of Diesel, according to **www.eia.gov** is $4.21/gallon as of March 2023. The savings for moving to lower viscosity engine oils for Class 8 over-the-road fleets is estimated to be "0.5% - 1.5% by switching from 15W-40 to 5W/10W-30" according to Barrie Masters from Lubrizol [15], and this claim was sourced from Trucking Efficiency Confidence Report: Low-Viscosity Engine Lubricants from the North American Council for Freight Efficiency and Carbon War Room [16]. The 0.5% to 1.5% of fuel economy from viscosity changes applied to a fleet will have substantial energy cost reduction. According to the ATA, there are currently 4.06 million Class 8 trucks in operation in 2021 and 38.9 million trucks registered for business purposes covering 302.14 billion miles and consuming 44.8 billion gallons of fuel [17]. Saving 0.5% of the 35.5 billion gallons of diesel at the March average cost would be approximately $747 million in addition to the CO_2 saved through the increased efficiency. So even though the percentage of savings seems small, those numbers are by no means small when applied to just what is used here in the US.

The trend of reducing engine oil viscosity has resulted in decreased lubricating film thickness and increased risk of engine damage. Additives, such as friction modifiers (FMs), have been developed to address these issues. MoDTC, in particular, has shown a significant reduction in friction compared to other FMs. It is important for research to continue to address friction and wear risks, even as technology and regulations evolve.

Biographies

Dr. Raj Shah is a Director at Koehler Instrument Company in New York, where he has worked for the last 28 years. He is an elected Fellow by his peers at IChemE, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute and The Royal Society of Chemistry. An ASTM Eagle award recipient, Dr. Shah recently coedited the bestseller, "Fuels and Lubricants handbook", details of which are available at ASTM's Long-Awaited Fuels and Lubricants Handbook 2nd Edition Now Available (https://bit.ly/3u2e6GY).He earned his doctorate in Chemical Engineering from The Pennsylvania State University and is a Fellow from The Chartered Management Institute, London. Dr. Shah is also a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute and a Chartered Engineer with the Engineering council, UK. Dr. Shah was recently granted the honourific of "Eminent engineer" with Tau beta Pi, the largest engineering society in the USA. He is on the Advisory board of directors at Farmingdale university (Mechanical Technology), Auburn Univ (Tribology), SUNY, Farmingdale, (Engineering Management) and State university of NY, Stony Brook (Chemical engineering/ Material Science and engineering). An Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical engineering, Raj also has over 575 publications and has been active in the energy industry for over 3 decades. More information on Raj can be found at https://bit.ly/3QvfaLX

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Ms. Mrinaleni Das is part of a thriving internship program at Koehler Instrument company in Holtsville, and a student of Chemical Engineering at Stony Brook university, Long island, where Dr. Shah is the current chair of the external advisory board of directors.

Ken Hope graduated with a Ph.D. in physical chemistry from the University of Alabama at Birmingham in 1988.

Ken has over 30 years of experience in the lubricant industry. His research interests have been primarily focused in the area of polyalphaolefins and the use of synthetic lubricants. Currently, he is the Global PAO Technical Services Manager with Chevron Phillips. Prior to this, he was a Research Fellow and Team Leader for NAO and PAO Research and Technology responsible for the product development, process improvement and technical service for NAO and PAO product lines.

Industry Activities: Ken is the currently the immediate Past-President of STLE. He served on the Board of Directors of STLE from 2006 – 2017, STLE's Treasurer, Secretary, Vice-President and President (2021-2022). He has instructed the synthetics part of the Basic Lubes course at the Annual Meeting for the last 20 years. He holds a CLS (Certified Lubrication Specialist) and has served on the Editorial Board of the Journal of Lubrication Science and as a Technical Editor for Tribology & Lubrication Technology. He has also presented over 70 technical papers at STLE, NLGI, AICHE, ELGI, UNITI, ACS and SAE meetings and holds 21 US patents.

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