THE NEED FOR DEDICATED LUBRICANTS FOLLOWING HEIGHTENED DEMAND FOR ELECTRIC VEHICLES

Incentives from governments and car makers for electric vehicles (EVs) fuel global sales with the aim to cover the additional costs for batteries. Electric vehicles are considered to be zero emission and the combustion of hydrogen or conversion of hydrogen in fuel cells to electricity will be a focus for the future.

Electrified drivelines, both as batteries or fuel cells, must reduce costs, improve lifetime (number of charging cycles), and improve reliability. Fluids that cool the batteries and lubricants in the driveline to extend the range by reducing friction play a key role. This leads to the creation of dedicated lubricants that will conform to those electrical components while maintaining thermal cooling and corrosion prevention properties. The lubricants must also be adapted to high-speed reduction gears. Tribological performance testing for EVs will aid to evaluate and further understand the characteristics of these advanced lubricants [1]. In this paper, we will discuss the development of dedicated lubricants for EVs and mention some recent advancements.

The electrification of the drivetrain brings new challenges regarding the development of dedicated greases and lubricants. With the inclusion of an electric motor, dedicated lubricants need to fulfill different requirements for properties such as noise, efficiency (low friction), dielectric properties, and compatibility with the electrical components. Electric motors are small and operate at elevated temperatures so cooling properties in lubricants are essential for safe operation, as well as the ability to interact safely with electrostatic fields [2].

Currently, several OEMs have presented their first lines of dedicated EV fluids and lubricants. Despite the increased stringency required for lubrication standards in EVs, the significant reduction of multiple moving components allows for EVs to remove the need for conventional engine oils, but hybrid vehicles still use internal combustion engine lubes by "engine oils". The issue of lubrication is shifted onto internal components such as roller bearings, gears, and the driveline [1]. Apart from gears, these components call for greases.

Roller bearings are preferably lubricated by greases or by lubricating oils in gears. The distinction between a lubricating oil and a grease lies in the differences in consistency (or viscosity) and their sealing capabilities. In order to decrease the friction within a roller bearing, especially during hydrodynamic lubrication, it is necessary to reduce the viscosity of the applied lubricant [3]. Thus, lubricating oils allow for a greater reduction in friction due to their lower viscosity in comparison to greases. Also, hydrodynamically lubricated sliding contact provides effective noise reduction from the fluid film. Contrarily, the higher viscosity of greases allows for the lubricant to remain in the bearing without significant leakage; as such, 80-90% of roller bearings are lubricated with greases [3]. Furthermore, current low viscosity oil technologies were found to promote micro-pitting within rolling contact surfaces as a result of ZnDTP additives [4]. While it is unknown if greases display the same behavior as these lubricating oils, due to the increased viscosity of greases as well as their ability to form a thicker film than its original base oil on account of a thickener, research into wear characteristics of greases for rolling contacts should be conducted.

Frictional work lost to gears has been attributed to approximately 8% of total frictional work loss of the average passenger vehicle in 2012 [5]. Therefore, reducing the friction of gears can improve the efficiency and range of EVs. Currently, most gears in EVs are lubricated utilizing gear oils, which have been modified to have increased oxidative stability, anti-corrosion protection, copper compatibility, and good seal compatibility [6]. Additives, along with reducing the viscosity of gear oils, are important factors for reducing a large amount of friction. The very high speeds of electric motors of up to 20,000 rpm represent another driver for reduced oil viscosities. Hydrolubes, a mixture of water thickened by polyalkylene glycols (PAGs), were shown to offer high load carrying capacities and low friction for the gears [7]. Such a monofluid concept in the vehicle enables simultaneous cooling of batteries and lubrication of gears.

Most notably, nano-particle additives of multi-walled carbon nanotubes have been shown to improve the friction and wear of mineral gear oils, particularly at concentrations of 0.5 wt% [8], but these new approaches stay in functional-cost competition with the traditional chemical- driven additive concepts.

The lubrication of an EV's driveline is nearly identical to a corresponding driveline of the average ICE passenger vehicle; however, EVs require the lubricant to reduce the corrosion of wiring elements such as copper and electronic components and improve its electrical properties, in addition to keeping viscosity low [1]. As such, conventional mineral or synthetic lubricants may be altered to fit the needs of EVs through the use of additives.

There are different types of lubricant tests that check to see if specifications are met. Oil viscosity is developed according to load, speed, and operating temperature of the application [2]. Viscosity can be difficult to balance because it should be low enough to reduce loss of energy from friction, but it should not be too low to where durability is sacrificed and the lubricant leaks out from the bearings. In extreme temperature applications, dropping point and oxidation properties should be considered. Additives are included to modify and enhance these properties, but some may shorten the life span of the grease. The lubricant must also maintain electrical properties such as volume resistivity, dissipation factor, and dielectric strength to avoid electrical losses in the system [2]. Overall, the lubricant must balance all these requirements. Table 1 depicts specific properties that must be tested today.

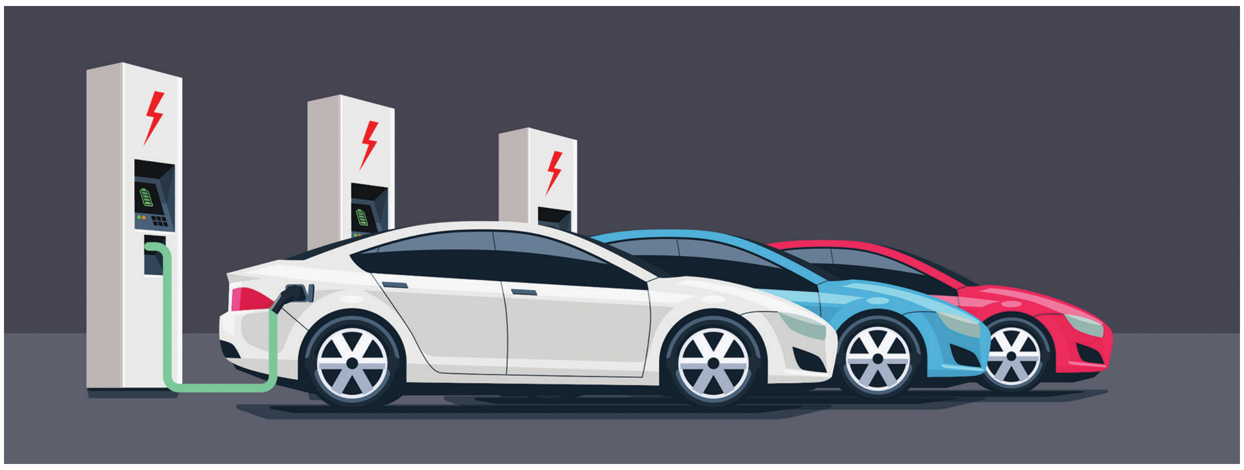
Vehicle noise derives in part from the combustion process in internal combustion engine (ICE) vehicles at low speed, whereas tires and wind dominate at high speeds. Excessive traffic noise can cause hearing damage and even cardiovascular diseases [9]. Electric motors are steadier and produce less noise than ICEs but nonetheless, they require an appropriate grease to mitigate this issue, especially at speeds of 20,000 rpm. There have not been many recent advancements in lubricants that specifically aid in noise reduction and a large issue is that there are no standardization practices for noise testing in EVs [2].

Table 2 compiles existing test methods for electrical and dielectric properties of fluids. Basically, no dedicated test methods exist for determining the electrical and dielectric properties of lubricants and greases for EVs. The test methods in Table 2 focus on transformer oils and fuels. Standardization bodies are underway to set-up working groups for this purpose.

Efficiency is another area of focus and correlates directly to the torque properties of EVs. Increasing useful torque by decreasing friction in the powertrain will push EVs to dominance in the auto industry [2]. There have been approaches to making changes with gears, such as enhancing them with nanoparticles made from alumina, carbon, and graphene. Coatings on gears made by thermo-chemical treatment, like double glow plasma alloying with tungsten-molybdenum and plasma nitriding or thin film coatings, like tungsten doped diamond-like carbon (DLC) and tungsten doped diamond-like carbon (DLC) deposited on chromium nitride (CrNx) or molybdenum nitride (MoNx) have been applied as well, all of which have shown improvements in reducing friction and wear [1].

Additionally, one study reported a lubricating grease containing a silicon dioxide nano-particle additive at 0.3 wt% that had a very low coefficient of friction and can help to reduce wear [10]. Additives containing magnesium, phosphorus, and sulfur synergistically acting together also showed a reduced friction coefficient [11].

Other than for performance purposes, the developing lubricant must be compatible with the electrical components such as electric modules, polymeric insulations, sensors, and circuits [12]. The



Test specifications	Required characteristics
DIN 51819 FAG FE8 (wear of rollers)	Superior wear properties under accelerated rolling contact fatigue
DIN 51821 FAG FE9	Grease life/oxidation stability
ASTM D217 Worked Cone Penetration (100Kx)	Mechanical/work stability
ASTM D1264 Water wash out	Water resistance
ASTM D1478 Col start torque	Low-temperature torque
ASTM D1831 Grease roll stability	Resistance to physical degradation
ASTM D2265 Dropping Point	High operating temperatures
ASTM D2266, D2596, D7421, D5706	Extreme pressure (EP) properties
ASTM D4170, D7594 Fretting	Fretting wear resistance and low friction
ASTM D4289 Elastomer compatibility	Seal compatibility
ASTM D4950 NLGI Grade	Consistency
ASTM D6138 Anti-Rust Test	Corrosion resistance
IP 121, ASTM D1742, ASTM D6184	Excellent oil release properties
SNR FEB2 (company test)	False brinelling test
Courtesy of Kuldeep Mistry and The Timken Co.	

Table 1: Laboratory test specifications for current wheel bearing lubricants [2]

Test specifications	Required characteristics
ASTM D149	Dielectric Strength
ASTM D1169	Specific Resistance (Resistivity) of Electrical Insulating Liquids
ASTM D257	DC Resistance or Conductance
ASTM D1816	Dielectric Breakdown Voltage of Insulating Liquids
IEC 60156	Dielectric breakdown voltage of insulating liquids
ASTM D2624	Electrical Conductivity of Aviation and Distillate Fuels
ASTM D4308	Electrical Conductivity of Liquid Hydrocarbons
ASTM D924	Dissipation Factor (or Power Factor) and relative permittivity (dielectric constant) of electrical insulating liquids
IEC 60247	Relative permittivity, dielectric dissipation factor (tan) and d.c. resistivity of liquids
To be developed	Loss tangent tan δ (greases)
To be developed	Relative permittivity (greases)
ASTM D6138 Anti-Rust Test	Corrosion resistance
IP 121, ASTM D1742, ASTM D6184	Excellent oil release properties
SNR FEB2 (company test)	False brinelling test

Table 2: Laboratory tests for electrical properties

electric motor generates heat and inductive currents that must be insulated from the electric modules. Conductivity is another property like viscosity in that it must be very carefully balanced for the most effective operation. Electrostatic charges can build up if the conductivity of the fluid is too low, and this can cause degradation in the fluid by sparks. The very dangerous situation of current leaking can arise if the conductivity is too high. The oxidation products in oils were also known to increase the electrical conductivity [13].

Many mineral oil-based lubricants popular today in ICE vehicles suffer from low thermal and oxidative stability. Improved oxidative stability is gained with the use of synthetic-based oils, made from molecules like polyalphaolefins (PAOs), esters, and polyalkylene glycol (PAG). Incorporating boron compounds into gear oils has also improved thermal and oxidative stability [1]. These types of base oils and additives are very promising for their use in EVs, but more investigation is needed into how they will interact with the electric components.

With growing concerns over the environment and sustainability, biodegradability and reduced toxicity will become a very important characteristic for dedicated lubricants. Bio-lubricants can be formulated based on base oils synthesized from renewable resources, like animal fats or vegetable oils or any biomass. Biomass sources can include forestry, sugar, or lignocellulose. The polarities in the molecular backbones of most bio-lubricants (esters and PAGs) have been shown to display better lubricity properties over mineral or synthetic hydrocarbon oils [1].

The issue of thermal and oxidative stability can be alleviated through the addition of electrically conductive nanoparticles or advanced polymers such as rubber, polypropylene, and methyl¬pentene, which all showed promising results in high speed applications [1]. Additives such as antioxidants and pour point depressants and chemical modifications such as trans¬esterifi¬cation and epoxidation have also contributed to alleviate those issues [1]. Graphite and 3% MoS2 are very effective additives for greases now. Renewable resources, like microalgae and hydroxy-fatty acids from Jatropha curcas, Calophyllum inophyllum, Pongamia pinnata, Hevea brasiliensis (rubber seed), Ricinus communis L. (castor), and Simmondsia chinensis all show promise for future applications in bio-lubricants [14].

EVs will become more ubiquitous over time as we focus on the development of environmentally friendly solutions. The global number of electric vehicle (BEV/PHEV) sales reached a peak in 2019 at 2,264,400 units sold, which represents an increase of only 9% over 2018. By the end of 2019, ~7.5 million BEVs/PHEVs were running around the world [15]. The increase in demand for EVs and electrified drivelines illuminates the need to develop more dedicated lubricants. There have been advancements to increase the efficiency of these systems and therefore broaden the possible range of EVs, which include incorporating nanoparticles and various other metals into gear coatings and also using additives such as silicon dioxide in lubricating greases. Implementing synthetic-based oils and boron compounds into gear oil has been shown to increase thermal and oxidative stability, which are very important after the introduction of an electric motor. Advancements have also been made in the bio-lubricant area that provide these lubricants with thermal and oxidative stability. All these advancements have worked specifically for ICE vehicles and show much potential for application in EV systems. However, there is still much testing needed to determine their electric properties and how they will interact with the electric motor or battery in EVs. After dedicated EV lubricants are perfected, they will allow for the widespread use of EVs as viable options for transportation and as a way to help keep the environment cleaner.

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