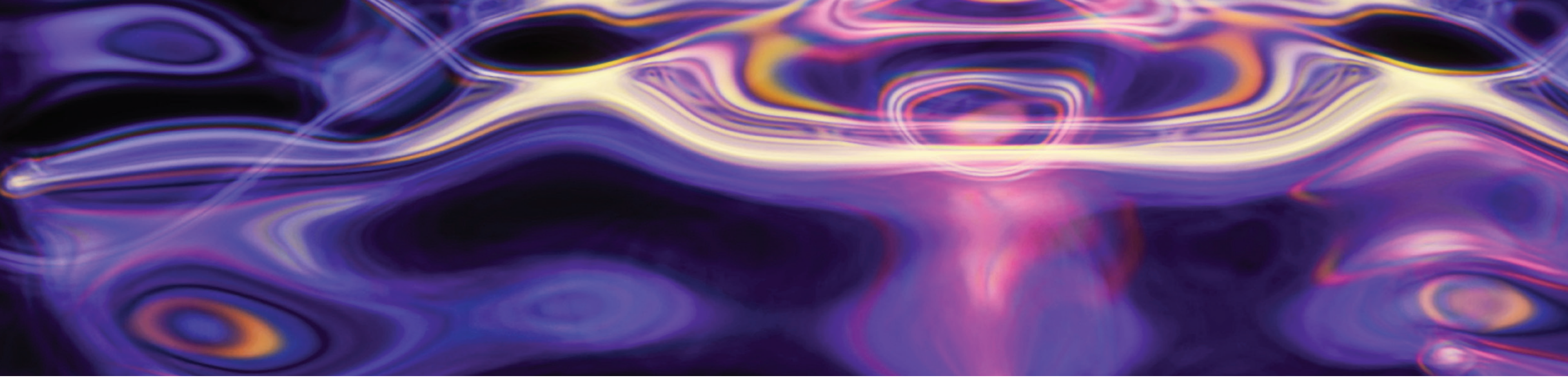
LUBES'N'GREASES

EV Lubricant Technology

From *LUBES'N'GREASES PERSPECTIVE ON ELECTRIC VEHICLES*



Welcome to *EV Lubricant Technology*

We are delighted to bring you *EV Lubricant Technology*, an invaluable free guide that will give you a deeper understanding of the impact electric vehicles are having and are expected to have on lubricant performance demands.

This guide has been compiled using extracts from *Lubes'n'Greases Perspective on Electric Vehicles*, a new, comprehensive annual report, supplemented by quarterly news, that keeps you up to date with the impact on and outlook for the lubricants market. Visit www.LubesnGreases.com/electric-vehicles for more information.

In this guide we look at the ways in which lubricant performance demands will change due to the design differences between EVs and vehicles powered just by internal combustion engines.

If you are looking for more in-depth information and regular updates on EVs, then now is the time to subscribe to *Lubes'n'Greases Perspective on Electric Vehicles*. To view a full table of contents and sample content pages click here.

The full annual report provides a comprehensive view of EV sales trends and forecasts for the future; an overview of models available today and their electrification strategies; a thorough look at evolving EV lubricant technology; a summary of nine key EV markets worldwide; and a discussion of threats and opportunities for the global lubricant industry.

The publication also includes quarterly reports with news about EVs, including sales trends, designs and regulations, as well as the evolving outlook for lubricants.

Subscribe today and get access to independent, comprehensive and trusted information on EVs. An individual subscription is US$2,500, and enterprise licenses are also available. Visit www.LubesnGreases.com/electric-vehicles.

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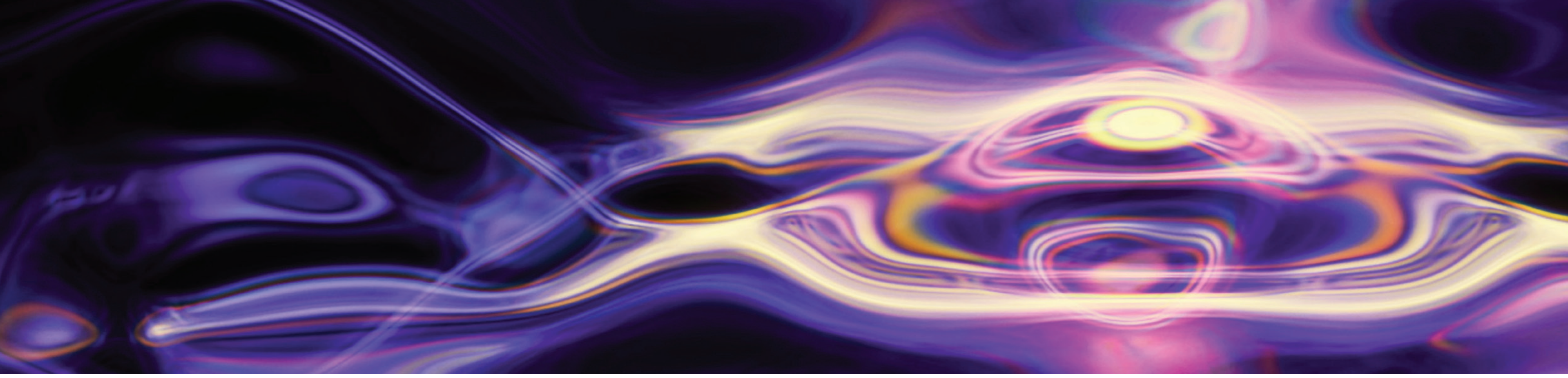


EV Lubricant Technology

Requirements for Crankcase Lubricants

The designs of EVs vary significantly and are still evolving a lot, and so their lubrication needs also vary and will change in the future. Moreover, the performance requirements of lubes in all EVs, mild and full hybrids, as well as BEVs, differ from ICEs – either because of the electrical aspects of their operation or because of changes in the way the ICE is used.

This section of our report examines the design differences between different types of EVs that are pertinent to lubrication and explains their implications for lubricant requirements: how hybrids still need crankcase fluids and create new and stiffer performance requirements for them; the starkly different requirements for fluids used in different powertrain configurations; the new requirements that greases will face – and how industry already has solutions for them.

The bottom line is that, while electrification will eventually mean that automobiles use lower volumes of lubricants, it will also mean that they require different lubricants, and this latter change will occur before the former. EV designs are still evolving, so performance requirements for their lubricants will continue to as well.

Mild Hybrids
With the ICE doing most of the work in a mild hybrid, the main concern for a lubricant is that the ICE operates for far less time at peak power than in ICE-only mode. The driving cycle, therefore, looks more like a series of stop-start or short "cruising" journeys for an ICE, with the associated earlier degradation of the lubricant.

Given that OEMs are very keen on what they refer to as platforms – modular design, engineering and production of several distinct models with shared internal and/or external features – mild hybrids over the next few years are likely to have the same ICE as another vehicle in the same branded range. Even in the PHEV arena, the Volvo XC90 T8 features the same 2-liter engine as the more powerful (of two) ICE-powered vehicles in the range.

So conceptually, a mild hybrid describes an extreme stop-start driving scenario for the ICE, and there is unlikely to be a need for a dedicated crankcase fluid for such vehicles.

Full and Plug-in Hybrids
The EMs do more work in full hybrids, which place different stresses on the crankcase fluid. A full hybrid can operate in three modes: battery-only, series and parallel. Some vehicles can switch between two or three of these modes.

Battery-only Mode
While a vehicle is in battery-only mode, the ICE and some parts of the transmission are not turning over. This means that they are subject to vibration without being powered. This could be a significant issue in PHEVs, which have a longer battery-only range. Honda's

> "All these exciting challenges are real opportunities for further enhancing the added value of lubricants and additives to the transport industry. As plug-in hybrids grow with larger battery capacities, we could see these focus areas and challenges become more prominent in the future. While clearly not all hybrids are the same and no one solution will fit them all, finding the right additive chemistry balance is more important than ever."
>
> — **JORGE PAIN** PASSENGER VEHICLE PORTFOLIO MANAGER, INFINEUM

senior chief engineer, Tomonori Niizato, reported in 2017 that Honda had begun studying a vibration test where an engine is placed on a vibrating table that can be programmed to produce real-world vibration patterns from actual driving cycles. He told the 2017 TTRF-TAIHO International Symposium on Automotive Tribology that, using this rig, Honda had been able to induce fretting corrosion in a bearing.

Fretting corrosion is a significant issue in wind turbines, which has partly been addressed by using power from the grid to move the blades and the nacelle in an attempt to eliminate the low amplitude rocking motion that can give rise to fretting. Formulators have to be careful of their use of extreme pressure additives to protect against fretting damage, as some are said to contribute to fretting-related failures.

Cooler Operation

The main issue is that the ICE will, on average, operate cooler and less frequently than in a mild hybrid. This raises risks of significant condensation and fuel dilution of the crankcase lubricant, both of which could lead to sludge. For example, in a PHEV in parallel mode, the ICE kicks in to drive the wheels when the battery charge is low. This will usually happen when the car is moving, so the ICE warms up gently. Even if the ICE comes into operation while the car is driving around town, it is just like starting from cold. Usually, the ICE is active for a short distance, meaning that it rarely runs hot.

While it is possible that an engineering approach will be taken to warm up the lubricant and the ICE engine block, this could require dedicated oil heaters if the EM (the most obvious source of heat in the moving vehicle) is at the opposite end of the car. Until that engineering solution appears, the onus is on the lubricant to cope with running colder on average.

In series mode, such as in range-extended vehicles like the BMW i3, the ICE is a generator charging the battery. The ICE is expected to deliver maximum power output instantly when the battery charge falls below a certain level. Rapid delivery of high power is a wider issue for crankcase lubricants in HEVs.

Formulators will face fresh challenges in ensuring engine durability. High power demand at start-up requires a cold ICE to deliver instantly significant torque. Getting lubricant in all critical contact points as quickly as possible and building up a protective film will be instrumental for engine durability.[1]

Change or No Change?

Taken in full, this means that a crankcase lubricant for an HEV where the ICE can operate in either series or parallel mode may have to be formulated to address condensation (additional corrosion protection and possible demulsification), sludge formation (antioxidants and dispersants) and wear (more or different antiwear additives and friction modifiers). That said, experts in the field seem less concerned about lubricating ICEs in hybrid vehicles than their counterparts in transmissions.

HEV lubrication will present ongoing challenges for formulators and may lead to HEV oil specifications even though operating at both ends of a wide temperature spectrum is not new to the industry.

Demands on crankcase lubricants for future hybrids could lead to greater use of higher quality base fluids. Wear, engine cleanliness, fuel efficiency and compatibility with after-treatment devices will all remain challenges to crankcase lubricants for HEVs, but the nature and prevalence of these challenges could differ from today's ICE powertrain.[2]

Transmission Fluids

Mild Hybrids
The future for mild hybrids can be described as a scenario where all technology will be a derivative of a technology already developed for other applications: ICEs will be those created in ICE-only developments, and transmission/axle fluids will be derived from those developed for ICE-only vehicles, full hybrids or BEVs.

Although an exaggerated representation, this scenario is useful for the following section as it allows emphasis of the similarities of transmission fluids' requirements in other hybrids and BEVs, where significant technological change is required.

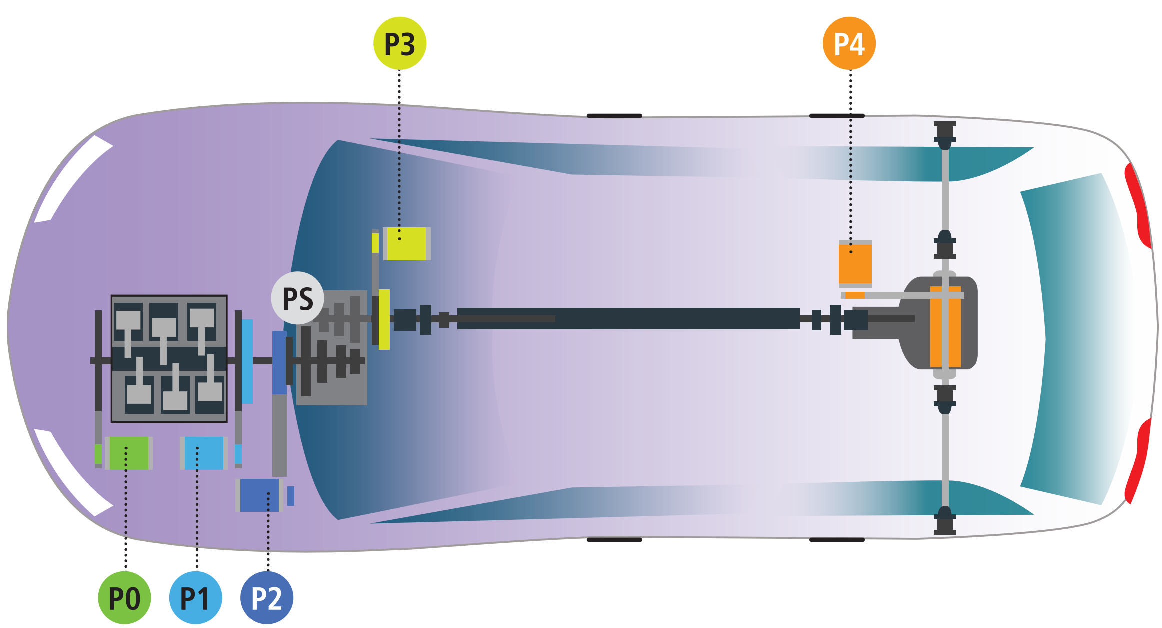
Despite the likelihood of mild hybrids being the largest part of the EV market in the short-term future, it is possible to project the requirements on any fluids that interact with the EMs as being driven by – or at least being common with – the full hybrid or BEV market.

48 Volts
A caveat to the above is the move by many OEMs toward 48-volt architecture, which is the main reason why mild hybrids may dominate the market for the next few years. This volt architecture allows OEMs to introduce technologies that reduce emissions at lower cost per vehicle. Moving from 12 volts to 48 volts also allows the OEM to include power-hungry functional auxiliaries, such as an electric compressor to replace a turbocharger, or up-rate personal comfort auxiliaries, such as in-vehicle climate control. (See the section on electrical properties for further information.)

Full and Plug-in Hybrids
The requirements placed on driveline fluids are similar for full hybrids and PHEVs and reflect the position of the electric motor or motors relative to the ICE. These relative positions are often referred to as P0, P1, P2, P3 and P4 (see Figure 1). However, there are no industry-agreed references, so other terminology is in use.

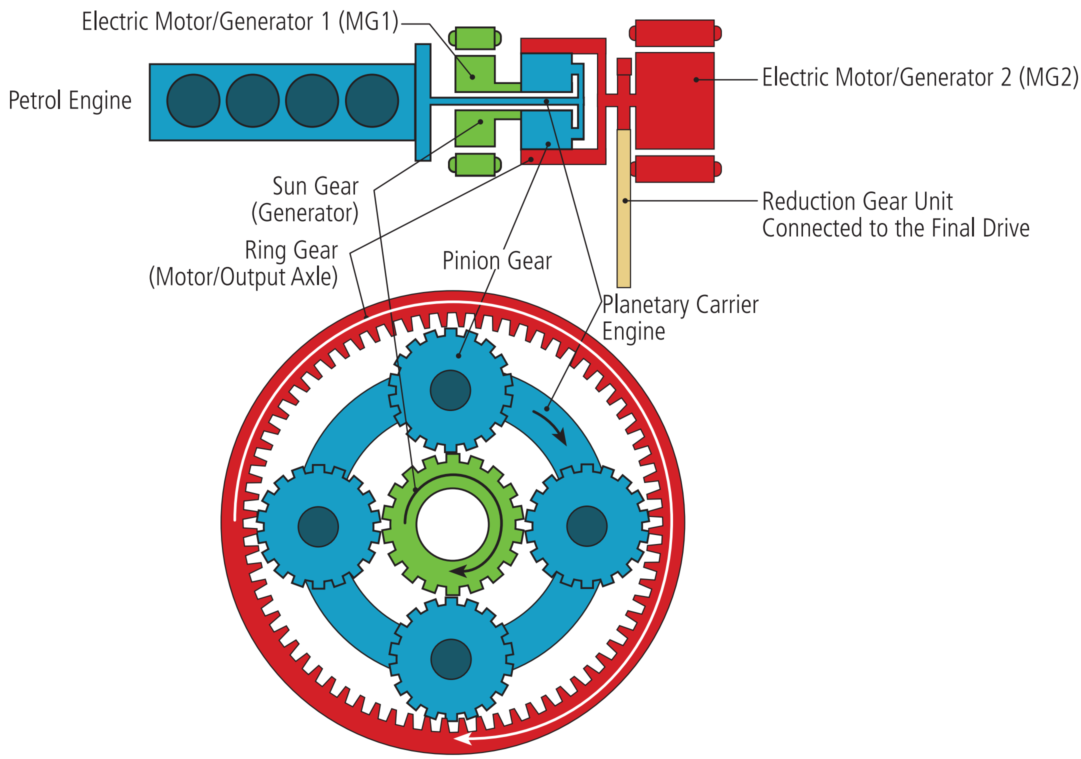
P0 and P1 refer to the EM sitting before or after the ICE, respectively, and physically separated from the transmission. In both cases, the EM drives the existing transmission, boosting the ICE, so little change is anticipated for the transmission fluid. EMs can act as motors and generators, but in these positions, they do not interact with the transmission fluids.

Figure 1: Possible EM Positions in a Hybrid Passenger Car



Source: Lubrizol

Figure 2: Planetary Gear Assembly



Source: New Emerging Automobile Technologies

P2 and P3 have the EM either immediately before or immediately after the transmission. In both cases, the EM could be inside the transmission housing. If it is, then the EM is in contact with the transmission fluid, so fluid formulators must consider electrical compatibility. The motor configuration of the Toyota Prius approximates to EMs at P2 and P3, although an alternative interpretation is that the P2 motor is part of the transmission.

The Toyota Prius configuration has led to the term "power split" (as denoted by PS in Figure 1). Toyota has also referred to this arrangement as an e-CVT, or electronic continuously variable transmission. This can cause confusion, as the well-established CVT used by many manufacturers has belts and pulleys. The Toyota e-CVT has no belts or pulleys but provides continuous and variable output from the transmission by use of a planetary gear set, which allows the ICE and both EMs to work in concert.

P4 has the EM driving the rear axle in Figure 1, but P4 could also describe a motor driving the front wheels. The key feature is that the EM is physically separated from the transmission and ICE. A motor at P4 can either drive the axle via a drive shaft and a conventional axle or be integrated within the axle assembly. Some BEVs have the motor integrated with the axle box, so the characteristics of some BEV motors are like those at P4 in a hybrid. This arrangement is often called an e-axle.

Electric Vehicles

Almost everything to do with EVs is driven by the three significant sources of customer concern: range anxiety, charging time and cost. The first and third impact the lubricants, while the second can impact coolants.

Conceptually, a full EV needs a very simple transmission. The efficient running speed of electric motors ranges between 3,000 and 10,000 rpm, so the simplest transmission is a step-down gear set, often called a reduction gear or e-axle, with a fixed ratio to convert the most efficient motor revolutions into just over 1,000 rpm at the wheel hub, given current sizes of wheels and tires. In the longer term, transmission OEMs are openly discussing motors running at more than 20,000 rpm.

The advantage of simplicity is offset by the fact that the EM operates for a great deal of its time outside its most efficient range, leading to reduced vehicle range, the most significant source of customer concern.

There are also issues relating to non-optimization of fluids with the simplest transmissions. The problems Tesla has had with its earlier models (reduction gear ratio of 9.73:1) could be related to wear due to high torque. Tesla has not responded to this or published any information about why more than 60 percent of early drivetrains were replaced within 96,500 kilometers. Due to the high torque, Tesla employs a limiter to constrain wheel spin. Some believe it is intended to protect the bearings and gearbox from wear.

Other OEMs have incorporated multi-gear transmissions into EVs to address range anxiety by allowing the motor to operate at maximum efficiency over a wider range of road speeds. One of the end-user benefits of this is that a small motor can still exert torque at higher road speeds, allowing acceleration at around 100 kilometers per hour. The drawbacks are additional weight and cost (the third obstacle), plus perception of a less smooth ride relative to an EV with a single reduction gear.

This leaves the picture regarding transmissions for EVs somewhat unclear: simplicity dictates a single-speed reduction gear, but range anxiety and/or performance requirements could push OEMs towards multi-speed gearboxes. Conventional wisdom is that many OEMs are planning to utilize both. This is possibly because there will be a technological divergence between luxury vehicles and economical city cars. At the luxury end, 2018 has seen Jaguar Land Rover, Audi, Volkswagen and Porsche either launch or announce EVs based on a multiple electric motors, each with a single reduction gear between the EM and the wheels. The larger EMs deployed in these vehicles are capable of powering the vehicle to speeds above 200 km/h without reaching maximum engine revolutions. The economical city car will likely bear strong resemblance to current ICE-powered city cars. With a smaller EM, these may require a multi-speed gearbox to achieve an attractive combination of acceleration, range and top speed.

Impact on the Fluids

With so many arrangements of hardware, there are many potential and different requirements on the lubricant. Current lubricants are not optimum, but with the small volumes required, OEMs are likely to use an off-the-shelf fluid. However, optimization is ongoing as EV volumes rise.

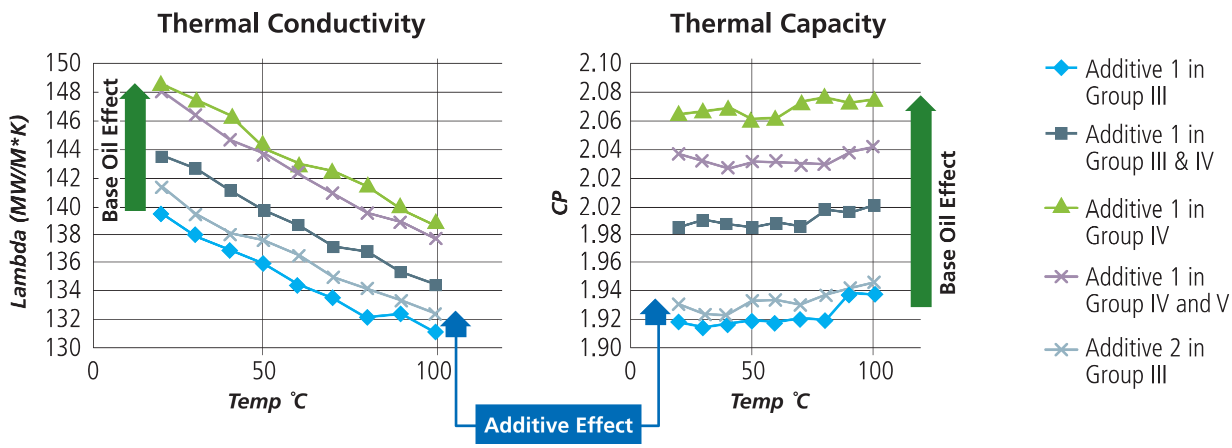
A vehicle with EMs at the P0 and P1 positions (see Figure 1) would have little requirement for a novel transmission fluid.

If motors at P2 or P3 are integrated with the transmission, the transmission fluid will be in contact with the motor. Some additives used to modify the frictional properties of the transmission fluid are said to have electrical compatibility issues, which could mean re-formulation when the fluid is also required to cool the electric motor.

An EM at P2 could be integrated with a dual-clutch transmission or the transmission itself. A DCT requires traction from the fluid, as the plates and discs of the clutch packs engage. This is a significantly different frictional situation compared to a conventional ATF, which has no requirement for traction. Therefore, different fluids are required, depending on the mechanical hardware deployed.

An EM at P4 in a hybrid will have many of the same requirements placed on it as an EM driving the rear axle in a BEV.

Figure 3: Thermal Properties of E-transmission Fluids



Source: Afton Chemical

As noted above, this is often referred to as an e-axle and could describe an electric motor driving the front axle. The recently released Chevrolet Bolt features an integrated EM driving the front axle, for example.

An e-axle requires enhanced gear protection when the axle and motor are used as an electronic brake, converting motion into electrical power to recharge the battery. This is also called regenerative braking. 2018 e-axle designs from companies such as Ricardo, GKN and McLaren Applied Technologies all point to smaller units with higher power density. These units will run hotter than before, and the fluid will experience greater churn, which will probably lead to much more air in the fluid.

Overarching all of this is the quest for greater efficiency. With an electric motor being around 90 percent efficient in energy conversion, compared with an ICE at around 40 percent, improvements in the transmission have a greater effect on overall efficiency in EVs. This drives the development of smaller and faster running electric motors, smaller transmissions with a smaller sump and faster meshing gears, plus greater regenerative braking, all of which must be cooled, lubricated and protected by transmission fluids.

What to Formulate for: P2, an e-DCT or e-ATF?

The fluid for a hybrid transmission that integrates an electric motor at P2 (see Figure 1) will be significantly different from previous fluids, such as those for DCTs or more conventional ATFs. An e-DCT fluid or e-ATF should protect against copper corrosion, have low electrical conductivity, excellent oxidation and sludge control and protect seals, all in addition to the appropriate frictional properties. The new fluids will have to achieve better performance in copper corrosion, oxidation protection, sludge control and seals compatibility, as well as address new issues regarding electrical compatibility.[3]

Reducing copper corrosion in the presence of an electrical current is probably the most significant formulating challenge. As described in the section on electrical compatibility, the way forward for formulators is not necessarily to remove sulfur, but to understand the processes by which copper corrodes components and then modify the formulations.

Electrically induced copper corrosion is an element of electrical compatibility. There are other factors – electrical conductivity and breakdown voltage. These are strongly influenced by the base fluid, but Afton Chemical and Lubrizol both claim to be able to modify conductivity by additive and base oils effects. These effects must persist throughout the lifetime of the fluid; it would be potentially catastrophic for a fluid to become dramatically more conducting over time, for example.

Additional oxidation and sludge control may be achieved by existing additive technologies that have been used for many years in industrial and crankcase lubricants. However, as the presence of an EM means that hybrid transmissions will run hotter than conventional transmissions, the thermal and oxidative stability of some long-established additives could rule them out.

Currently, materials compatibility appears to be an issue of lower concern, but this could change as OEMs introduce new materials.

Power Split: A Dedicated Hybrid Transmission Fluid (DHT)
As power splits have been around for a long time, dedicated hybrid transmission fluids exist. The DHTF should also have very good heat transfer and foaming performance, in addition to the parameters required for an EM at P2.[4]

Efficient heat transfer away from the transmission component depends on the thermal conductivity and heat capacity of the fluid. In both cases, some PAOs have better performance than some Group III base oils when the same additive package is used. The additive effect on the thermal parameters of the fluid appears small in Figure 3, but some additives can have a significant effect.[5]

P4/E-axle
When considering an e-axle, efficiency, durability at low viscosity, copper corrosion protection, oxidative stability, electrical conductivity and foam suppression are key parameters.[6] High efficiency hints at lower-viscosity fluids than conventional axle oils. However, these fluids will also get hotter than conventional axle fluids, so a high viscosity index would be required to maintain viscosity at higher operating temperatures. Higher temperatures indicate that thermal stability is also key. As with the power split fluid, these requirements probably push the formulator towards more synthetic base fluids.

With an EM incorporated into the driving axle, the thermal and oxidative stability of some long-established additives could rule them out. This could be a challenge, especially when extreme pressure protection is required for regenerative braking. Foam suppression as e-axles get smaller will almost certainly require novel additives that are either new or not yet commercialized.

Successful Formulating?
Successful formulations are already in the field. The Toyota Prius power split has been successfully lubricated over the past 20 years through several generations of vehicle through modifications to the driveline. One additive supplier has offerings for e-DCT fluids and e-ATFs, including one completely new additive, relative to previous axle oil packages.

Greases

Technical Challenges
The technical challenges for greases will be electrical, thermal and energy-saving, but most developments are likely to be evolutionary. This is because there is immense experience in the industry in formulating greases for most, if not all, the technical issues that could arise during vehicle electrification.

48 Volts
Motors, pumps and other engine accessories are subject to the likely migration of vehicles from 12- to 48-volt operation, so formulators will have to pay more attention to electrical compatibility. There is a long-established market for greases for motors, bushes and bearings in automotive applications that can operate at 48 volts in traditionally electrically driven vehicles like golf carts. There are also many industrial motor and pump applications that operate at greater than 48 volts. Experience in selecting appropriate base fluids, thickeners and additives for these applications will drive future developments.

If current industrial EM greases are considered as a starting point for automotive applications, the voltage issue has already been addressed and the formulating challenge is around the different mechanical environment of the EM. Industrial EM greases are often based on polyurea or lithium complex thickeners, due to their higher mechanical stability, which ensures the grease stays in the bearings and doesn't migrate to the windings.

Electric motors for automotive applications will operate at higher rotational speeds than most industrial applications, leading to higher shear and higher temperatures in the bearings. The viscosity of the base fluid will have to be low to reduce energy losses due to friction or drag in all parts of the drivetrain but high enough to maintain an oil film under all anticipated operating conditions. All these factors drive formulators towards synthetic and lower-viscosity base fluids. Stop-start operation is likely to be more prevalent in EVs than in most industrial applications, so formulators will have to ensure their greases can cope with more frequent shock loads.

Power Electronics

Greases that lubricate parts of the power electronics, such as actuators, will see voltages of hundreds of volts on par with industrial systems. The move to smaller componentry will mean smaller tolerances and consequent increased induced currents, magnetic fields and temperatures. Electrically, this could mean a higher possibility of short circuiting due to smaller gaps.

This could be exacerbated by the general need to increase both power density and specific power of the whole traction drive system in the pursuit of extended range, which could bring greased components into the same housings as the power electronics. While this would probably happen to optimize the layout of the cooling system, a consequence could be higher induced voltages than those parts see in present-day vehicles.

Integrated Motor/Inverters

This is one area of hardware where mild hybrids are taking the lead, as their lower power requirements (5 to 15 kW) than other hybrids or EVs make them the starting point for integrating power converters into the electric motor housing. One design from Continental, used in the Volkswagen Golf TSI, incorporates the inverter as part of the motor housing at the opposite end from the shaft with a bearing between it and the main electric motor. This bearing could therefore see high temperatures and induced voltages but is already being greased in a vehicle that is on the market. The challenge for grease formulators will therefore be to lower the costs of the greases in use and/or ensure that the grease for these bearings is the same as for other bearings in the vehicle.

Thermal Demands

The possible migration from coolants to thermal control fluids could bring change to the greases for coolant pumps. Fluids that are required to regulate the battery temperature (warm it during cold conditions and cool it during charging) as well as cool the motors and inverters could have significantly different physical characteristics from water/glycol mixtures used in current vehicles, including the likes of the Tesla Model S. Therefore, greases could see greater loads and much more cold operation.

Bearings

When most people think of greases and electric vehicles, the drive and wheel bearings come to mind first, as they are the greased components in a vehicle where it is perceived most energy savings could be made. The overarching mantra is energy efficiency, but within the context of changes to the hardware in which the grease must operate. While OEMs and bearing manufacturers are looking to extract even more efficiency from existing components – including the grease – they are also introducing new bearing designs and/or new materials for the rolling elements, raceways and cages.

Stop-start activity, which brings high shock loads to bearings, is already a common aspect of most modern ICE designs. Therefore, accommodation of this requirement into hybrid and EV designs is a further example of evolution.

Section References

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3 Interview, Scott Halley, Lubrizol, 2018
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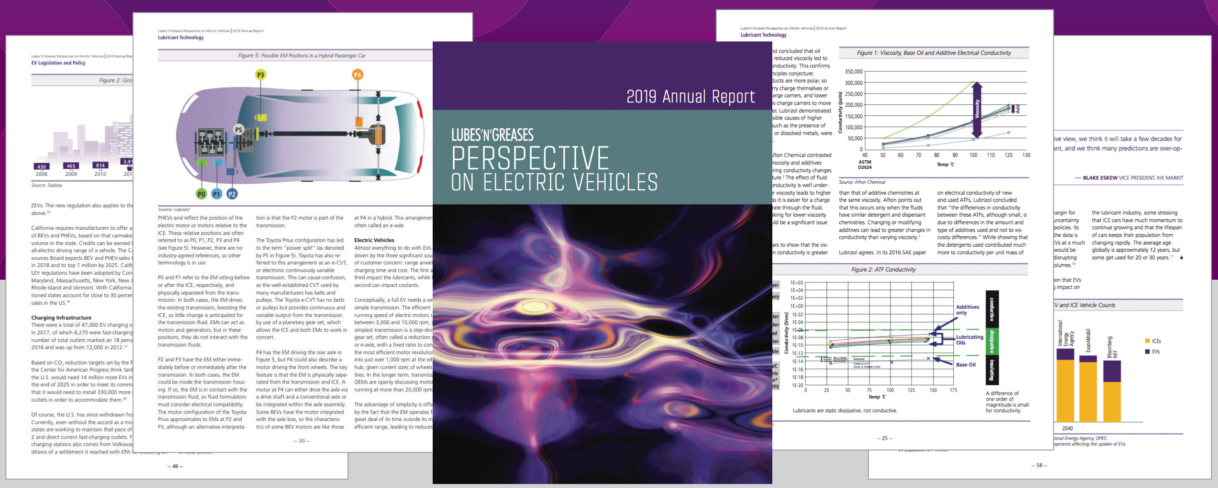
What impact will EVs have on the lubricants market?



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