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Innovative Advances in Electric Vehicle-Driveline Lubrication: Optimizing Lubricants for Enhanced Efficiency and Sustainability

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The global reduction of CO2 emissions, including from the transportation sector, is critical for addressing climate change. New electric vehicles (NEVs) are pivotal in this effort, with battery electric vehicles (BEVs) being a primary focus, due to their potential for significantly reducing emissions. This study investigates the efficiency of selected lubricants in the context of an electric axle (E-axle) drivetrain, a key component in BEVs. Compared with conventional vehicles, driveline efficiency may be viewed as even more essential for the BEV. Here, all aspects of efficiency are essential to improve delivery from the main drive battery capacity, reduce vehicle weight, and improve overall performance. By testing different fluids and formulations, this research identifies significant efficiency gains from the E-axle, which directly contribute to enhancing the range, whilst reducing the operational costs. Using a typical E-axle, the study practically demonstrates that the targeted selection and optimization of lubricant can achieve worthwhile efficiency improvements. It is expected that efficiency gains are possible with other motors and drivetrains. However, each system requires individual optimization to realize such benefits. This research demonstrates the importance of customizing lubricant solutions to the specific demands of each drivetrain, thereby supporting the broader adoption of more efficient and sustainable electric vehicle technologies. [DOI: 10.1115/1.4067976]

Keywords: fluid friction, friction, gears, lubricant additives, lubricants, tribological systems, viscosity

1 Introduction

It is now widely recognized that climate change is caused by CO2 emissions and that these need to be significantly reduced in order to meet global emission targets and slow down climate change. Since around 23% of global CO2 emissions are generated by the transportation sector and a significant proportion of this is due to road transport/traffic, it is imperative to reduce emissions from vehicles [1]. In order to achieve this goal, the automotive industry is developing new electric vehicles (NEVs) [2]. The broad term NEV includes all types of vehicles that do not run exclusively on diesel or gasoline. Typical representatives are battery electric vehicles (BEV), plug-in hybrids (PHEV), hybrids (HEV), mild hybrids (MHEV), and fuel cell electric vehicles (FCEV). A factor which all these have in common is at least one electric motor [3]. This publication is not intended to compare individual NEVs with each other or with conventional combustion engines. For this, there is, for example, the review by Gröger et al. [4] in which BEVs and FCEVs are compared, or Richard Butcher et al. [5] in which PHEVs are compared to MHEVs and combustion engines.

This article will discuss the special requirements of drivetrains in BEVs. However, it is first important to clarify that there is no such thing as “the one standard electric car.” In the passenger car sector, for example, there are vehicles with masses from 766 to 3370 kg, power from 5 to 575 kW, battery capacities from 10 to 100 kWh and a consumption of 4.9–29.3 kWh/100 km according to World Light-duty Transient Cycle (WLTC) [6].

In addition to the wide range of vehicle parameters, various motor technologies are currently being developed, all of which have their own requirements. If you look at current car models, for example, you will find induction motors, permanent magnets, DC motors, and switch reluctance motors, which can be installed either alone or in combination with another type [7]. Each of the different motor types uses different materials, has different sizes, and generates different torque maps and resulting temperatures. All these factors result in very different requirements for the lubricant in the drivetrain. The biggest challenge in oil development for electric cars currently is therefore adapting and tuning the oil precisely to the conditions of the chosen powertrain [8].

Electric vehicle driveline efficiency is increasingly important; for example, the energy content of a large, long-range passenger car EV drive battery ∼100 kWh is considerably less than a conventional internal combustion engine (ICE) fuel tank, and 66 liters of diesel contains 700 kWh, which at 25% ICE efficiency gives 175 kWh into the driveline, or at 30% efficiency gives 210 kWh, along

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Table 1 Weight comparison of BMW models based on the same platform

Vehicle	Year	Motor	Weight (kg)	Comparison
BMW 330i	2020–2024	Combustion (petrol)	1525	Baseline
BMW 430i	2021–2024	Combustion (petrol)	1620	+6.2%
BMW 330e (11.15 kWh)	2020–2024	PHEV (petrol/ electric)	1845	+21%
BMW 330e (19.5 kWh)	2024–	PHEV (petrol/ electric)	1910	+25%
BMW i4 eDrive 40	2021–	Electric	2125	+39%

Note: For simplicity, only the weights of the sedans and coupés were compared.

with free demisting and full compartment heating from the waste heat.

The battery is the single most expensive component in today's BEVs. So improved efficiency is important to enable a BEV with a smaller, cheaper battery, to compete with a baseline larger battery. Further, a BEV with a longer range and the same battery size can help acceptance among customers/end users.

The three main situational barriers to not purchasing electric cars are range anxiety, compounded by charger access and the costs (purchase and insurance) of BEVs [9,10]. All three of these reasons can be combated with higher efficiency.

Another factor to highlight how higher efficiency is important for BEVs is to recognize that they are significantly heavier than their combustion engine relatives. To illustrate this, we compare the weight of the BMW 330i, 330e, 430i, and i4 in Table 1. These vehicles are based on the same platform and have comparable performance and equipment. A PHEV is around 300–400 kg heavier than its combustion counterpart, while the BEV is even 500 kg heavier. However, the general trend also applies to other cars that have their own platforms for BEVs (e.g., VW's Modularer Elektro Antreibs Baukasten, Modular E-drive toolkit (MEB) versus Modular Querbaukasten, Modular Transverse Matrix (MQB)).

1.1 Results and Discussion. Various requirements and challenges must be considered for the development of a modern gear oil. Some of the typical ones are shown in Fig. 1. This paper focuses on the aspect of efficiency, but it is important to note that the candidates also meet all these standard requirements typical of Original Equipment Manufacturer (OEMs). For example, an efficient oil that does not offer sufficient mechanical protection would have very limited value.

2 Efficiency Characterization

To determine the lubricant effect on the electric drive unit (EDU) efficiency performance maps were measured, using a complete drive unit including gearbox, E-motor, and inverter. This drive unit is from a current production vehicle available worldwide. The efficiency was calculated using the electrical input power (voltage and current) and the mechanical output power (torque and speed). To minimize contamination effects from the previous oil, the drive unit was drained and flushed twice. After each oil fill, 11 speed/load reference test points were run to circulate the oil. Then, the oil was drained and replaced with fresh oil, and the main test procedure was run. The Reference fluid was tested regularly, for every four candidates.

The test procedure includes ten different torques that were run at fourteen speeds. The efficiency was determined by comparing input power with output power and then typically expressed as a percentage. For example, 50 Nm torque was applied from 1000 to 17,000 rev/min. Not all speed and torque points can be displayed, as electric motors typically do not deliver high torques and speeds at the same time. High torque at low speeds, or low torque at high speeds, or moderate torque at moderate speeds is possible. In Fig. 2, for a better overview, the individual values are color-coded according to efficiency. All efficiency values shown here are the average of five individual measurements. At the limiting edges of the motor range, fewer points were recorded, and this was to reduce the thermal effects of continued operation at the edge of the motor performance envelope.

From Fig. 2, it can be seen that the motor runs most efficiently between 50 and 150 Nm, at speeds from 4000 to 9000 rev/min. If the motor is in either drive or recuperation, the trends are the same, torque +ve or −ve. The reference oil was the OEM's first fill oil, at that time. For comparison, this fluid was then replaced with a candidate fluid. Here, Candidate 1 was chosen, as it is a comparable viscosity grade (SAE Grade 70), with an optimized additive technology. It shows that the general trend regarding the efficiency of the drivetrain is similar for both lubricant oils; it depends primarily on the transmission and engine components installed.

A common formulation approach within the industry is to lower the lubricant viscosity as far as possible and to achieve an efficiency increase. To investigate this approach, we replaced the reference oil

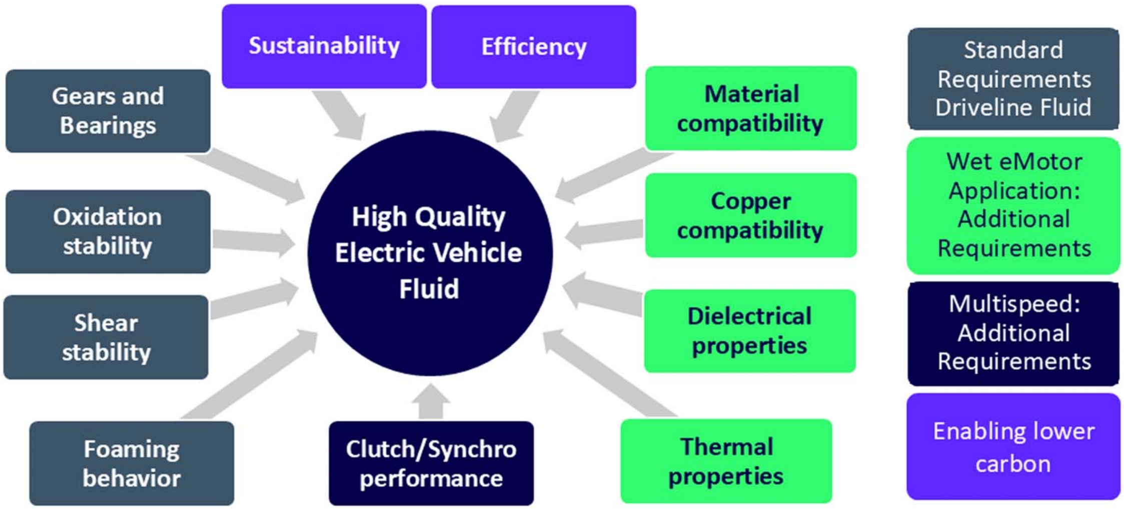
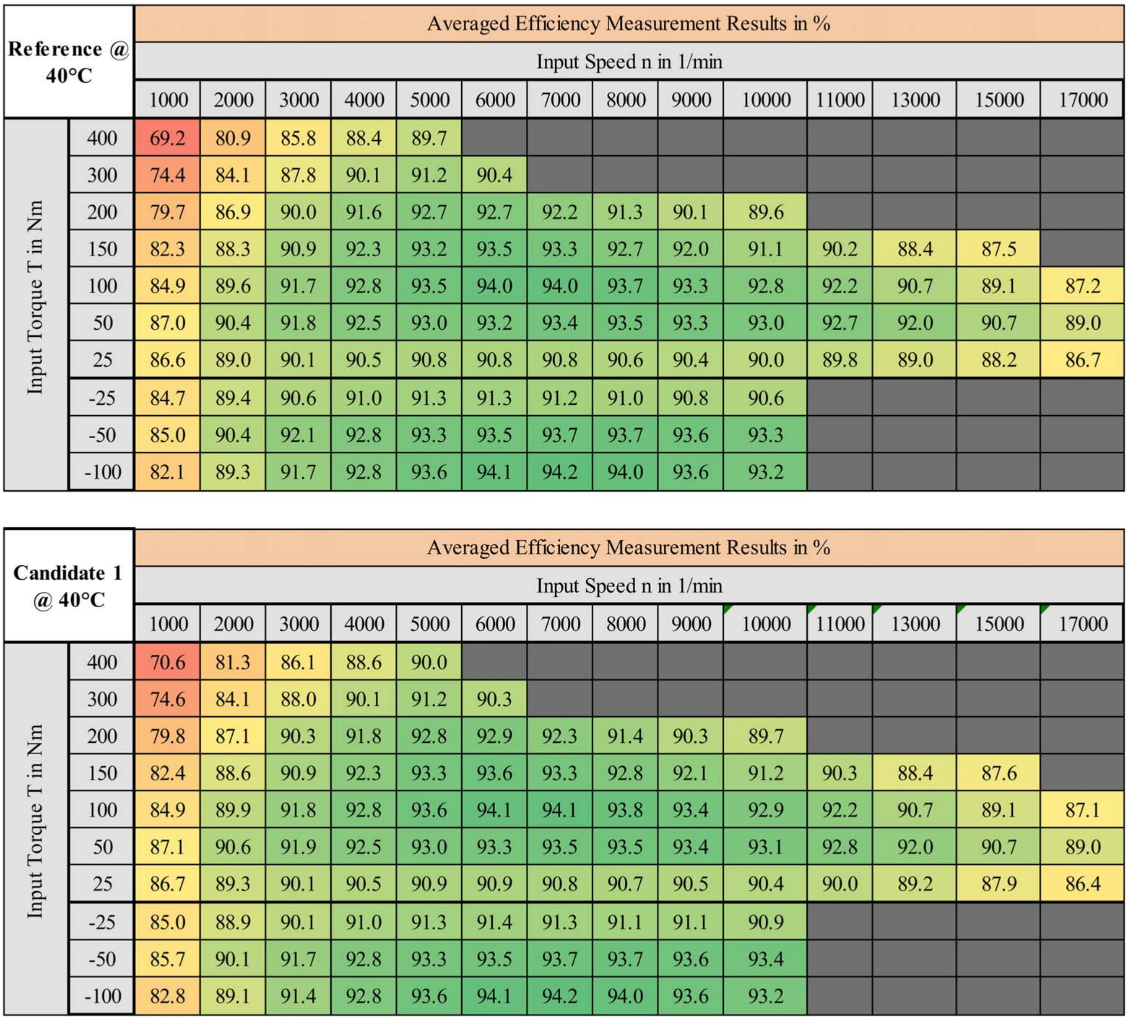


Fig. 1 Typical requirements for the development of transmission fluids



Reference @ 40°C		Averaged Efficiency Measurement Results in %													
		Input Speed n in 1/min													
		1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	13000	15000	17000
Input Torque T in Nm	400	69.2	80.9	85.8	88.4	89.7									
	300	74.4	84.1	87.8	90.1	91.2	90.4								
	200	79.7	86.9	90.0	91.6	92.7	92.7	92.2	91.3	90.1	89.6				
	150	82.3	88.3	90.9	92.3	93.2	93.5	93.3	92.7	92.0	91.1	90.2	88.4	87.5	
	100	84.9	89.6	91.7	92.8	93.5	94.0	94.0	93.7	93.3	92.8	92.2	90.7	89.1	87.2
	50	87.0	90.4	91.8	92.5	93.0	93.2	93.4	93.5	93.3	93.0	92.7	92.0	90.7	89.0
	25	86.6	89.0	90.1	90.5	90.8	90.8	90.8	90.6	90.4	90.0	89.8	89.0	88.2	86.7
	-25	84.7	89.4	90.6	91.0	91.3	91.3	91.2	91.0	90.8	90.6				
	-50	85.0	90.4	92.1	92.8	93.3	93.5	93.7	93.7	93.6	93.3				
	-100	82.1	89.3	91.7	92.8	93.6	94.1	94.2	94.0	93.6	93.2				

Candidate 1 @ 40°C		Averaged Efficiency Measurement Results in %													
		Input Speed n in 1/min													
		1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	13000	15000	17000
Input Torque T in Nm	400	70.6	81.3	86.1	88.6	90.0									
	300	74.6	84.1	88.0	90.1	91.2	90.3								
	200	79.8	87.1	90.3	91.8	92.8	92.9	92.3	91.4	90.3	89.7				
	150	82.4	88.6	90.9	92.3	93.3	93.6	93.3	92.8	92.1	91.2	90.3	88.4	87.6	
	100	84.9	89.9	91.8	92.8	93.6	94.1	94.1	93.8	93.4	92.9	92.2	90.7	89.1	87.1
	50	87.1	90.6	91.9	92.5	93.0	93.3	93.5	93.5	93.4	93.1	92.8	92.0	90.7	89.0
	25	86.7	89.3	90.1	90.5	90.9	90.9	90.8	90.7	90.5	90.4	90.0	89.2	87.9	86.4
	-25	85.0	88.9	90.1	91.0	91.3	91.4	91.3	91.1	91.1	90.9				
	-50	85.7	90.1	91.7	92.8	93.3	93.5	93.7	93.7	93.6	93.4				
	-100	82.8	89.1	91.4	92.8	93.6	94.1	94.2	94.0	93.6	93.2				

Fig. 2 Performance curves of the tested drivetrain for the reference oil and Candidate 1 at 40 °C oil temperature. Ascending speeds are plotted in rev/min horizontally. Torques in Nm are plotted vertically. Negative torques represent recuperation. Greyed-out data fields could not be displayed due to structural and/or thermal limitations of the drive train. The individual fields indicate the efficiency in %. Coloured from red = lower efficiency, to green = higher efficiency.

with a Castrol Ultra Low Viscosity Oil (Candidate 2) at KV100 <3.0 cSt. For a clearer representation, the difference of candidate 2 from the reference was calculated and plotted in Fig. 3; positive (green) values show an improvement compared to the reference, while negative (red) values are a decrease.

On initial inspection, this approach looks useful. The data show at 0 °C that Candidate 2 is more efficient than the reference oil, over the map. The average improvement is 1.4% with a maximum benefit of 4.9% at 3000 rev/min, 25 Nm.

However, at 40 °C, the picture is more complex. Below 4000 rev/min, the reference shows better efficiency, whereas above 5000 rev/min, Candidate 2 is more efficient. There are multiple different possible explanations for this behavior. However, in this paper, we are focusing on the effect of this on overall efficiency. The unweighted average is +0.2%, which leads to the questions: can an ultra-low viscosity fluid really help to improve the drivetrain efficiency? and how does this reflect typical EV driveline operation?

3 WLTC Simulations

The WLTC vehicle transient drive-cycle is based on worldwide measurements of many recordings of typical vehicle operations shown in Fig. 4. More details on the cycle development can be found in Refs. [11,12].

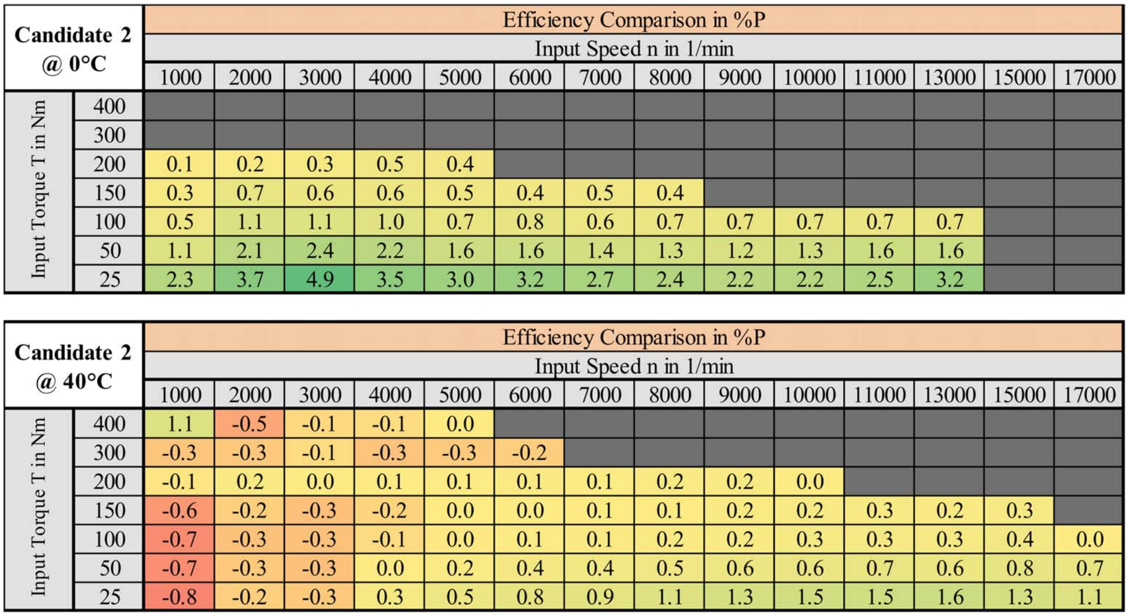
Using some typical, current, electric vehicle data, the torque and speeds required for the motor to drive WLTC can be calculated. Of course, this example applies to this vehicle only; however, this methodology can be adapted to other electric vehicle types.

To investigate how this relates to the motor efficiency tables, these WLTC points were compared with the motor efficiency maps in Fig. 5. The vehicle operation points are shown in blue.

In particular, the maximum motor torques, and speeds are not reached during WLTC. Specifically, the peak torque is ∼130 Nm, peak speed is ∼12,000 rev/min. For the urban/inner city operation, the motor speed does not exceed 6500 rev/min. It is also noticeable that the WLTC running points are mainly outside the high-efficiency range of the drive train.

Combining the efficiency maps and the WLTC operating points enables the calculation of weighted efficiency values for the lubricants of interest, for the three temperatures tested, 0, 40, and 80 °C. These three temperatures were selected to represent typical ambient and drive modes, as shown in Table 2 below.

Here, 40 °C represents the typical temperature of a drivetrain at an ambient temperature of 15–25 °C; 0 °C in the transmission can be reached if, for example, very low ambient temperatures of −20 to −10 °C prevail or if the vehicle is only used for a short distance at near 0 °C (e.g., commuting in rush-hour traffic); 80 °C, on the other hand, can be reached in the transmission when ambient temperatures of 40 °C and above prevail, but especially on long



Candidate 2 @ 0°C		Efficiency Comparison in %P													
		Input Speed n in 1/min													
		1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	13000	15000	17000
Input Torque T in Nm	400														
	300														
	200	0.1	0.2	0.3	0.5	0.4									
	150	0.3	0.7	0.6	0.6	0.5	0.4	0.5	0.4						
	100	0.5	1.1	1.1	1.0	0.7	0.8	0.6	0.7	0.7	0.7	0.7	0.7		
	50	1.1	2.1	2.4	2.2	1.6	1.6	1.4	1.3	1.2	1.3	1.6	1.6		
	25	2.3	3.7	4.9	3.5	3.0	3.2	2.7	2.4	2.2	2.2	2.5	3.2		

Candidate 2 @ 40°C		Efficiency Comparison in %P													
		Input Speed n in 1/min													
		1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	13000	15000	17000
Input Torque T in Nm	400	1.1	-0.5	-0.1	-0.1	0.0									
	300	-0.3	-0.3	-0.1	-0.3	-0.3	-0.2								
	200	-0.1	0.2	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.0				
	150	-0.6	-0.2	-0.3	-0.2	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.2	0.3	
	100	-0.7	-0.3	-0.3	-0.1	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.4	0.0
	50	-0.7	-0.3	-0.3	0.0	0.2	0.4	0.4	0.5	0.6	0.6	0.7	0.6	0.8	0.7
	25	-0.8	-0.2	-0.3	0.3	0.5	0.8	0.9	1.1	1.3	1.5	1.5	1.6	1.3	1.1

Fig. 3 Comparison of Candidate 2 and the reference oil at 0 °C (top) and 40 °C (bottom) sump temperature. The individual fields show the change in efficiency in percentage points through the use of Candidate 1 compared with the reference oil. The individual fields indicate the change in efficiency in %. For the sake of clarity, only the data from the motor in drive mode are shown here, with no recuperation data.

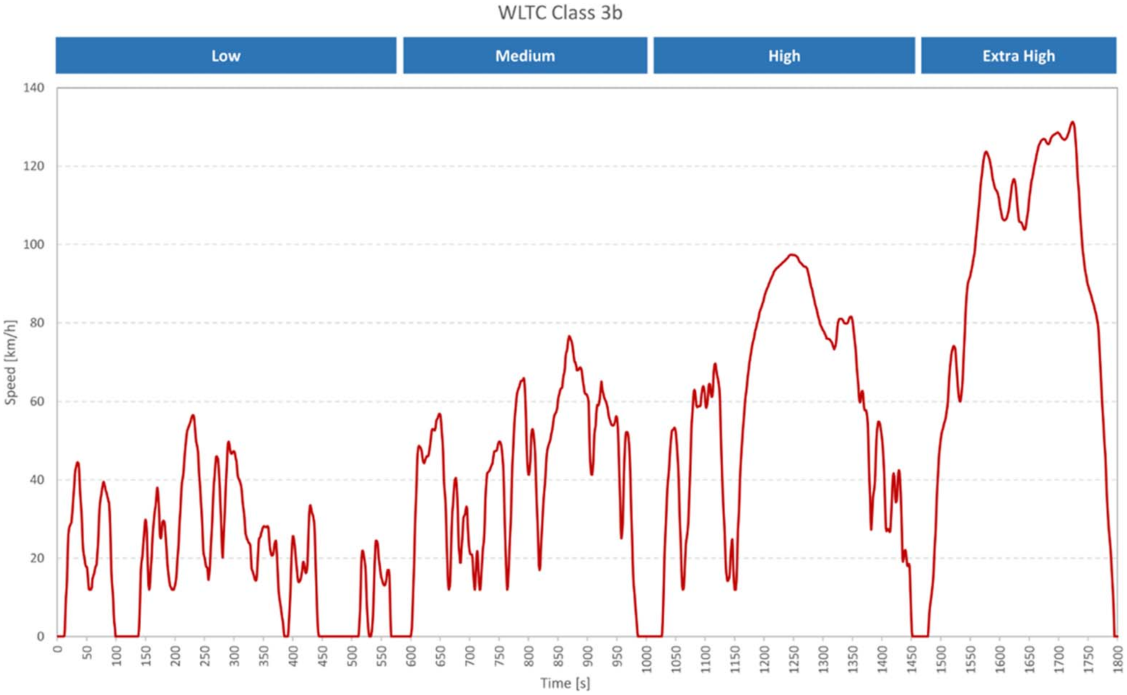


Fig. 4 The WLTC transient vehicle, showing the Low, Medium, High, and Extra High-speed phases [5,6]

journeys with high speeds, e.g., on freeways, highways, or the German Autobahn.

Comparison data of the three oils, the Reference Oil, Candidate 1, and Candidate 2 now show a different ranking (Fig. 6). Specifically, Candidate 1 is 0.51% more efficient than the reference, at 0 °C. At 40 °C, the benefit is 0.06%; at 80 °C, the data ar similar, 0.02%. For Candidate 2, there is a 2.48% benefit at 0 °C. At 40 °C, the benefit is 0.2%; however, there is a reduction of efficiency by 0.18% at 80 °C. To provide further context, for an annual mileage of 12,000 miles or ~19,300 km, 2.48% corresponds to a saving of approximately 116 kWh.

This shows that the approach of reducing viscosity has a limited benefit for this drivetrain. The thinner oil does show a benefit for the urban commute, but in the longer run, the efficiency is reduced. As range anxiety is often associated with longer journeys and higher driveline temperatures, an ultra-low viscosity oil such as Candidate

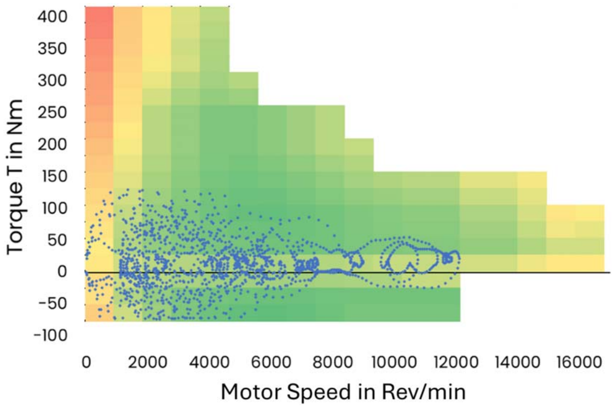


Fig. 5 Performance maps of the drivetrain with vehicle load point during the WLTC

Table 2 Comparison of drivetrain oil temperatures at different ambient temperatures and conditions

Drivetrain oil temperature	0 °C	40 °C	80 °C
Ambient Temperature	−20 to −10 °C	15–25 °C	~40 °C
Typical conditions	Short time/urban commute at low temps.	Short time/ urban commute	High speed Freeway/ autobahn
Other aspects	EV range is reduced by low ambient temperatures		

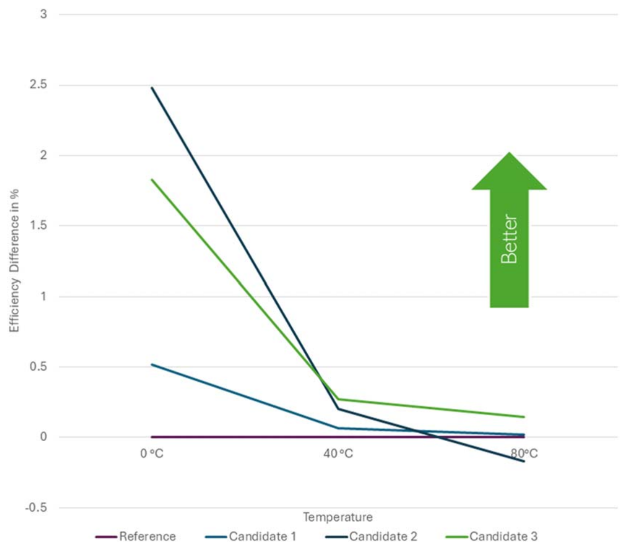


Fig. 6 Efficiency comparison of Candidates 1, 2, and 3 with the reference oil, over three temperatures. 0% is the Reference data line.

2 may not help with the transition of customers to electric vehicles, in this case.

For comparison, in the internal combustion engine sector, the engine oil can be optimized for the conditions. For example, light-duty vehicle engines may use a thinner 0 W–16 or 0 W–20 for normal duty cycles and cooler conditions, whereas for hot or very demanding conditions, heavier grades such as a 5 W–30 or 10 W–40 are often used; it is for the customer to choose. However, as drivetrains in electric vehicles are generally fill-for-life, and therefore, no oil change is planned; this approach is not practical.

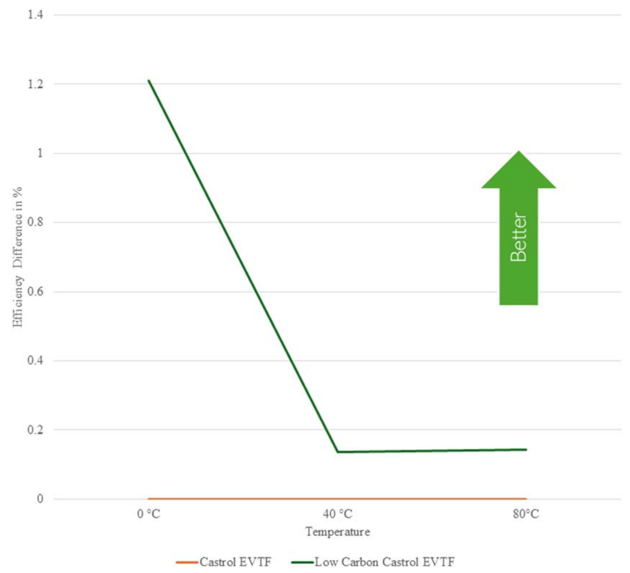


Fig. 7 Efficiency improvement of low carbon Castrol EVTF over Castrol ETVF, at three temperatures. 0% is the Castrol ETVF data line.

To solve this dilemma, a new oil which is optimized for the requirements of this drivetrain was developed. This has significantly increased viscosity compared with Candidate 2, to SAE 65 grade and adapted the additive technology precisely to the drivetrain, resulting in Candidate 3. At a temperature of 0 °C, this oil shows a significant improvement of 1.83% compared with the reference. At 40 °C, there is still a 0.27% benefit, and at 80 °C an improvement of 0.14%. Consequently, with Candidate 3 we have succeeded in formulating an oil which offers a significant efficiency gain over the reference oil, not only on short distances but also on long distances and during "typical" WLTC driving.

Potentially, end users could even consider changing their original oil. For an example comparison, in Germany for the case described here: if the customer changed their oil, they could save up to ~USD $71 or 64€ per year, when charging at public AC charging stations. Or up to ~USD$85 or 77€ per year if using DC charging, also by using a different oil with the associated increase in efficiency of the drivetrain. (Based on the price per kWh of AC: 55 EURO cents, DC: 66 EURO cents [13].)

4 RRBO Versus Virgin base Oil

Sustainability is increasingly becoming the focus of both society and the automotive industry [14] in all areas of life. For example, Jaguar Land Rover (JLR) is aiming to reduce CO_2 emissions of their vehicles by 54 percent by 2030 and be carbon neutral by 2039 [15] and Ford aims to reduce the Scope 1 and 2 Green House Gas emissions by 2023 by 76% and be carbon neutral by 2050 [16]. BMW is also focusing on circularity and the circular economy. Not only are raw materials recycled or bio-based materials used, but care is also taken to ensure that the vehicles built can be dismantled and recycled at the end of their service life. For example, BMW was able to reduce the global warming potential of an i5 by 20% from 21.3 t CO_2e to 17.0 CO_2e during production [17].

Even if the share of CO_2 emissions from the oil in the drivetrain only accounts for approximately 0.1% of total emissions during production, sustainable or circular solutions should of course not be overlooked. A well-known sustainable oil product group is re-refined base oils (RRBOs), which are produced by recycling used oils. RRBOs are currently typically used in small quantities for conventional engines and transmissions, in order to reduce their carbon intensity.

As far as the authors are aware, currently electric cars are rarely supplied with RRBO-based transmission oil as standard. This is mainly due to the availability of high-quality RRBOs in the last decade. Transmission fluids for E-axles require a high-quality base oil (API group II, or group III base oil with high viscosity index, low sulfur content, and good cold flow properties) to fulfil the increased fluid requirements for EV-Fluids. Due to the high technical requirements coupled with high-performance, high-speed motors within modern electric cars, there is little room to compromise performance, protective properties, or efficiency. To ensure this, a transmission oil based on conventional oil was initially developed (Castrol EVTF), with which all the OEM's requirements could be achieved.

The findings of this development were then used to develop an RRBO alternative for the same drivetrain (Low-Carbon Castrol EVTF). The low-carbon variant has exactly the same KV100 as the EVTF.

The efficiency of these was tested back to back in the same drivetrain as described earlier. As Fig. 7 demonstrates, the efficiency of Castrol EVTF was not only achieved by the low-carbon variant but even exceeded. At a temperature of 0 °C, this oil shows a clear further improvement of 1.21% compared with the reference. At 40 °C, there is a further benefit of 0.13%, and at 80 °C, a further improvement of 0.14%. As the Low-Carbon Castrol EVTF was also successful in other aspects including wear protection, foaming behavior, and material compatibility, it was decided to use this technology for vehicle development. As a result, vehicles with the Low-Carbon Castrol EVTF will go into series production well before 2030.

5 Summary and Outlook

Overall, it was possible to show that it is extremely important for electric cars to have a good understanding of the vehicle parameters and driving conditions to develop and optimize the lubricating oil for the vehicle drivetrain.

We were able to show that the efficiency of the powertrain tested here can be increased by up to 2.48%, by precisely matching viscosity and additives for the demands of this vehicle system. Furthermore, we were able to show that the conventional opinion that thinner oil is always more efficient and therefore better may be successfully challenged.

We have also successfully developed and established a sustainable low-carbon variant of this oil for another powertrain.

However, to develop sustainable low-carbon variants of Candidate 3 and various other modern transmission oils based on RRBO or bio-based oils, there is still a shortage of other viscosities and qualities. The aim should not be to achieve the thinnest possible one-size-fits-all quality. Rather, it would really enable this initiative, if base oil manufacturers provided transmission engineers and lubricant formulators with a versatile toolkit through a broad portfolio in order to be able to optimally adapt the oil to the different requirements.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

References

[1] IEA, 2023, "CO2 Emissions in 2022." https://www.iea.org/reports/co2—emissions-in-2022, Accessed August 5, 2024.

[2] Faria, R., Moura, P., Delgado, J., and de Almeida, A. T., 2012, "A Sustainability Assessment of Electric Vehicles as a Personal Mobility System," Energy Convers. Manage., **61**(1), pp. 19–30.

[3] Su, C.-W., Yuan, X., Tao, R., and Umar, M., 2021, "Can New Energy Vehicles Help to Achieve Carbon Neutrality Targets?" J. Environ. Manage., **297**(1), p. 113348.

[4] Gröger, O., Gasteiger, H. A., and Suchsland, J.-P., 2015, "Review—Electromobility: Batteries or Fuel Cells?," J. Electrochem. Soc., **162**(14), p. 2605.

[5] Butcher, R., Bradley, N., Jamieson, M., and Chambers, T., 2024, "Aspects of Engine Lubricant Operating Conditions and Fuel Economy Differentiation; In-Vehicle Comparisons of Standard Internal Combustion Engine With Two Types of Hybrid Electric," SAE Technical Paper No. 2024-01-2824.

[6] Weiss, M., Cloos, K. C., and Helmers, E., 2020, "Energy Efficiency Trade-Offs in Small to Large Electric Vehicles," Environ. Sci. Eur., **32**(1), p. 46.

[7] Sun, X., Li, Z., Wang, X., and Li, C., 2020, "Technology Development of Electric Vehicles: A Review," Energies, **13**(1), p. 90.

[8] Zhmud, B., and Merelli, M., 2024, "Modern Tools for Tribological Optimization of EV Transmissions and e-Axles," SAE Technical Paper 2024-24-0013.

[9] Li, W., Long, R., Chen, H., and Geng, J., 2017, "A Review of Factors Influencing Consumer Intentions to Adopt Battery Electric Vehicles," Renewable Sustainable Energy Rev., **78**(1), pp. 318–328.

[10] Needell, Z. A., McNerney, J., Chang, M. T., and Trancik, J. E., 2016, "Potential for Widespread Electrification of Personal Vehicle Travel in the United States," Nat. Energy, **1**(9), p. 16112.

[11] "Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP), United Nations Economic Commission for Europe (UNECE)," Global Technical Regulation (GTR) No.15, ECE/TRANS/180/Add 15, Geneva 2014.

[12] Tutuianu, M., Bonnel, P., Ciuffo, B., Haniu, T., Ichikawa, N., Marotta, A., Pavlovic, J., and Steven, H., 2015, "Development of the World-Wide Harmonized Light Duty Test Cycle (WLTC)," Transp. Res. D: Transp. Environ., **40**(1), pp. 61–75.

[13] Statista, 2024, "Strompreise an Ladesäulen für Elektroautos in Deutschland nach ausgewählten Betreiber im Jahr 2024." https://de.statista.com/statistik/daten/studie/882563/umfrage/strompreise-an-e-auto-ladesaeulen-nach-betreiber-in-deutschland. Accessed August 05, 2024.

[14] Poligkeit, J., Fugger, T., and Herrmann, C., 2023, "Decarbonization in the Automotive Sector: A Holistic Status Quo Analysis of Original Equipment Manufacturer Strategies and Carbon Management Activities," Sustainability, **15**(22), p. 15753.

[15] castrol.com, 2023, "Use Less, Use longer, Use Again." https://www.castrol.com/en/global/corporate/about-castrol/newsroom/jaguar-tcs-racing-breakthrough.html, Accessed August 5, 2024.

[16] media.ford.com, 2021, "Integrated Sustainability and Financial Report 2021." https://media.ford.com/content/dam/fordmedia/North%20America/US/2021/03/31/Ford-Integrated-Report-2021.pdf. Accessed August 05, 2024.

[17] bmwgroup.com, 2023, "BMW i5 VEHICLE FOOTPRINT.". https://www.bmwgroup.com/content/dam/grpw/websites/bmwgroup_com/responsibility/downloads/de/2024/BMW_Vehicle_Footprint_i5_eDrive40_DE.pdf, Accessed August 5, 2024.