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A Review on Tribological Considerations in the Transition from IC Engines to Electric Vehicles

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Review Article

Abstract

The shift from internal combustion (IC) engines to electric vehicles (EVs) marks a significant transformation in the automotive industry, prompting a comprehensive reassessment of various engineering considerations. Among these, tribological factors play a critical role in ensuring the performance, reliability, and longevity of vehicle components. This review examines the tribological challenges and opportunities posed by the transition to EVs, focusing on key components such as bearings, gears, and braking systems, which face unique operating conditions in electric powertrains compared to their IC counterparts. The paper addresses how electric vehicles encounter distinct tribological scenarios, such as lower operating temperatures but higher torque loads, which demand new materials and lubrication strategies. It also explores how the near absence of internal combustion in EVs affects component wear and the mechanisms of friction reduction. Additionally, the tribological challenges in IC engines are revisited to provide a comparative understanding of how they differ from those in EVs, particularly regarding energy efficiency and frictional losses. This review emphasizes the importance of minimizing wear and friction to maximize energy efficiency, which is crucial for extending vehicle range and improving performance in EVs. By synthesizing the latest research findings and industry advancements, the review offers valuable insights for researchers and engineers involved in the design and optimization of tribological systems for the next generation of electric vehicles.

Keywords: Electric vehicles; Energy efficiency; Internal combustion engines; Lubrication; Tribology

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1. Introduction

Vehicles with internal combustion (IC) engines and electric vehicles (EVs) differ in their propulsion systems and operational processes, which lead to tribological differences between the two types of vehicles. The production of conventional cars with internal combustion engines (ICE) is increasingly being replaced by less carbon-intensive drive technologies, such as entirely battery-electric and hybrid electric vehicles [1-7].

The latter mix smaller internal combustion engines with electric engines. Significant changes in the automobile and other industries are implied by this transition. Certain outdated technology will become less significant when new ones become necessary. For instance, battery-electric vehicles (BEVs) no longer require some of the fundamental technologies of conventional cars, such as internal combustion engines and gearboxes, but they do require new generations of strong batteries, elec-tric motors, and inverters. It is now necessary to develop new methods of thermo-management be-cause there is no longer a combustion process that produces heat that can be used for heating or cooling [8].

Internal combustion engine vehicles have been the technological answer that has dominated the automobile industry and shaped global transportation networks. However, alternative powertrain technologies are already acquiring economic benefits, and businesses need to adapt given the pressing need to decarbonize the global economy. Significant investments are made in hybrid and completely electric drivetrains as well as in novel mobility concepts and services that operate at the intersection of the energy and transportation systems. One of the most crucial features of the new mobility concepts is taking the tribological aspects into account and paying close attention to them [9].

The tribological characteristics of passenger cars, namely those with internal combustion engines and battery electricity, are the primary focus of this study. BEVs, PHEVs, and REEVs (range-extended electric vehicles) are some examples of electric vehicles. It does not include hybrid electric vehicles (HEV) that use a combustion engine as their primary power source but feature an electric motor and a small battery as a supplemental power source. Additionally, it doesn't include other carbon-efficient drivetrain options like fuel-cell electric cars (FCEV).

The future of transportation is electric vehicles. Their reliance on electricity, compared to gas or combustion engines, results in increased efficiency and less harmful to the environment [10]. Even while conventional vehicles currently rule the market, electric vehicles are growing in favor as more people become aware of their advantages. The fact that electric automobiles emit no pollutants when in motion is one of their main advantages. This indicates that they don't add to air pollution, which has the potential to be hazardous to both the environment and human health. On the other hand, toxic gasses such particulate matter, nitrogen oxides, and carbon monoxide are released by conventional cars. The fact that operating an electric car is less expensive than a conventional one is another advantage. Compared to gasoline or diesel fuel, electricity is less expensive per kilowatt-hour (kWh) [11]. Additionally, because electric vehicles have fewer moving parts than conventional combustion engines, their maintenance costs are lower.

1.1 Fundamentals of Tribology

The multidisciplinary scientific and engineering area of tribology studies how surfaces interact when moving relative to one another. It includes the investigation of wear, lubrication, and frictional processes that take place at the interface between interacting materials [12]. In order to raise the effectiveness, dependability, and performance of mechanical systems and components, tribology attempts to recognize, predict, and handle these interactions. Improvements in tribology will play a major role in the engineering of more energy-efficient systems. Research can lead to such developments. Because there are so many mechanical systems in the world, even small reductions in friction and energy consumption would have a big impact [13]. At its fundamental level, tribology is the study of managing wear and friction. When appropriate, lubricants are used to help control the contact between interacting surfaces.

1.1.1 Friction

The resistance to relative motion is known as friction [14]. The coefficient of friction can be stated mathematically as follows:

$$\mu=\frac{F}{W} \tag{1}$$

where W is the normal force, F is the frictional force, and μ is the coefficient of friction.

Both interacting surfaces and non-solid lubricants that originate from fluid shear can cause friction. There are two types of coefficient of friction that emerge from contacting surfaces: kinetic friction (μ_k) and static friction (μ_s). Kinetic friction is the frictional force needed to maintain sliding conditions, whereas static friction is the initial frictional force needed to create sliding conditions.

1.1.2 Wear

Material loss from interacting surfaces is referred to as wear. A number of factors, including the degree of lubrication failure, pressures, mechanical damage, temperature, kind of surface contact, and chemical reactions, can affect how severe wear is. Wear is therefore an extremely complicated process, much like friction. In general, wear is expressed as a wear rate and is quantified as volume per unit distance. The Archard wear equation is a popular and basic model for sliding wear [15].

$$Q=\frac{KW}{H} \tag{2}$$

Here, W represents the usual load, Q the volume worn per unit sliding distance, K the wear coefficient, and H the hardness of the softer body.

1.1.3 Lubricant

The purpose of lubricants is to keep mechanical systems lubricated. A lubricant's primary method of action is to create a layer between interacting surfaces in order to lower shear strength, or the shear stress needed to start and continue sliding. The lubricating layer, also known as the film thickness, comes in different thicknesses. Friction and interface wear are determined by the lubricant's film thickness. As a lubricant, a variety of materials, including liquid, semisolid, solid, and gas, can be utilized. For instance, hydrocarbon compounds that are both biological and non-biological can be the source of liquid lubricants like oils. Lubricating oils typically consist of 75–95% base oil and 5–25% additives [16].

Some systems may not have lubricants that are completely capable of separating surfaces at the interface, enabling some asperity contact, depending on the tribological conditions. Thus, different lubrication regimes will be established based on the level of lubrication at the interface. Three primary lubrication regimes exist. These three regimes (full film lubrication, mixed lubrication, and border lubrication) are best shown on the Stribeck curve. The Stribeck curve can be expressed as the coefficient of friction versus the Hersey number (speed × viscosity / pressure) or as the lambda (λ) ratio of (layer thickness /surface roughness). Surface interaction and lubrication at the interface are shown in Figure. 1.

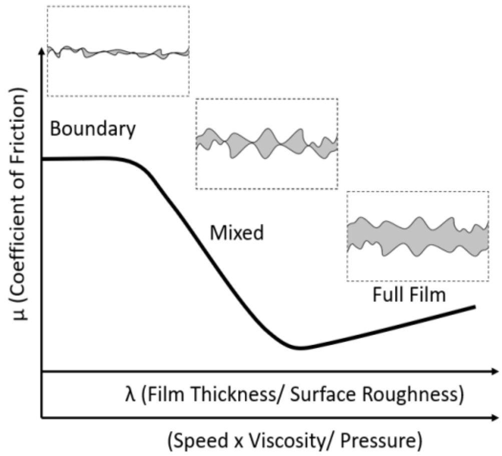

Fig. 1. Typical Stribeck curve behavior depicting the main lubrication regimes in terms of coefficient of friction and λ ratio [17, 18]

This review study aims to provide an in-depth review of the important features of tribology (friction, wear, and lubrication) in the context of shifting vehicle propulsion systems from IC engines to EVs. With major implications for sustainability, efficiency, and design, this shift marks a turning point for the automotive sector. The purpose of this paper is to clarify the special tribological possibilities and challenges that EVs present. Some of these opportunities include the effects of regenerative braking systems, the development of effective lubrication strategies suited to electric propulsion systems, and the optimization of bearing materials for electric drivetrains. The review attempts to provide useful insights for engineers, researchers, and policymakers involved in the advancement of electric mobility by synthesizing existing research and identifying knowledge gaps, ultimately contributing to the development of more reliable, effective, and environmentally sustainable transportation solutions.

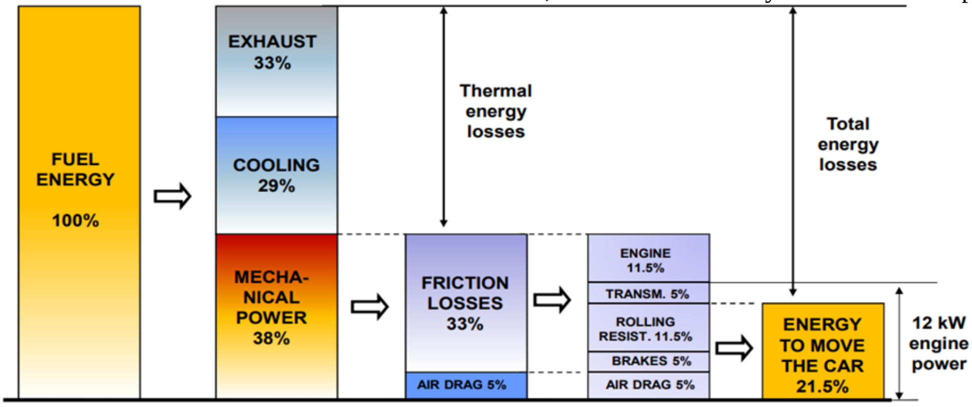

Fig. 2. Breakdown of energy use for ICE driven passenger cars [19]

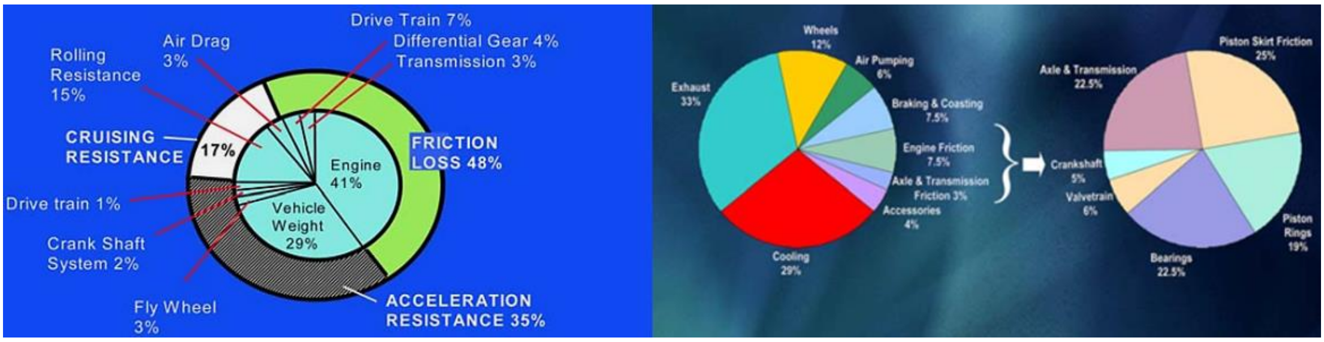

Fig. 3. Energy consumption and distribution with in internal combustion (IC) engines [13, 18]

2. Tribological Challenges in IC Engines

Modern transportation and power generation rely heavily on internal combustion engines (IC engines), which are essential to many industries including aerospace, automobile, marine, and stationary power plants. Tribological challenges still provide serious obstacles to the effective and dependable functioning of internal combustion engines, notwithstanding developments in lubrication and material technology. One of the big challenges in ICE is loss of power. The majority of transportation vehicles today use internal combustion engines (ICEs) as their primary power source. Figure 2 illustrates that in a normal passenger car, only 21.5% of the fuel is used for propulsion and the rest 78.5% is spent for energy losses [19].

The high-speed reciprocating motion of different components, the harsh working circumstances, and the requirement for effective power transmission produce a number of tribological issues associated with internal combustion (IC) engines.

When it comes to engine energy consumption challenges, as Fig. 3 illustrates, the majority (48%) of the energy created in an engine is lost through friction [18]. The remaining percentages are the cruising resistance (17%) and the acceleration resistance (35%). The engine friction loss, which includes piston skirt friction, piston rings, and bearings, makes up 66% of the overall friction loss when we examine the complete part as seen in the right pie chart of Figure 3. The remaining 34% is made up of the valve train, crankshaft, transmission, and gears. Sliding of the piston rings and piston skirt against the cylinder wall is definitely the biggest contributor to powertrain friction loss alone.

In internal combustion engines, a few of the major tribological challenges are discussed below.

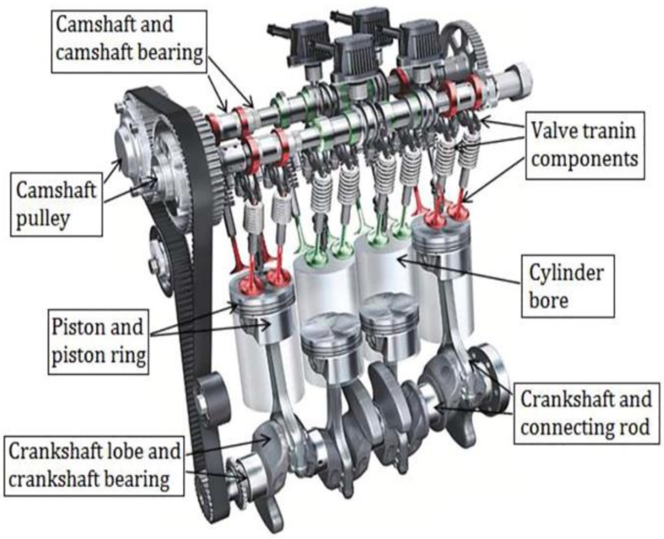

Fig. 4. Components affecting the friction loss of internal combustion engine [20]

2.1 Challenges include minimizing frictional losses

It has been demonstrated that energy loss due to mechanical friction is one of the big challenges in IC engine which, accounts for between 4% and 15% of the fuel energy in a typical IC engine [17]. Figure 4 illustrates that the sources of friction loss are primarily focused on three components: the piston-ring-liner system, the crankshaft and bearing system, and the valve-train system. The friction losses induced by them account for 50%–68%, 25%–35%, and 10%–20% of the total friction loss, respectively [20].

2.2 Challenges of wear on Piston Rings

When it comes to tribological challenges of wear, piston rings are the most sophisticated parts of an IC engine. At the piston-ring interface, there is a rapid change in temperature, load, speed, and lubrication supply. In a single IC engine stroke, piston rings can operate in a variety of lubrication regimes, including boundary, mixed elasto-hydrodynamic, and hydrodynamic regimes [17]. The piston's position (upstream, downstream, top dead center, and bottom dead center) determines the lubrication regimes. A hydrodynamic lubrication regime may occur when the piston is at bottom dead center because the rings may be flooded with lubricating oil at the lowest possible temperature, appropriate gas load, and speed (at the end of the expansion stroke and the start of the compression stroke). The thickness of the lubricating oil coating and the piston rings' surface roughness can also affect the lubrication regime. Wear and friction at the piston ring–liner interface are influenced by the asperity to asperity contact between the cylinder liner and the piston rings.

2.3 Challenges of wear on engine bearings

Crankshaft, connecting rod, and camshaft are supported by spinning journal bearings in a functioning engine. After a first running-in period, bearing wear is minimal if the bearings are properly lubricated. On the other hand, excessive wear may result from shaft misalignment or lubrication supply particulate contamination. Bearing corrosion is another mechanism of failure. Journal bearing tribology is complicated by factors like the availability of lubrication, heat effects, dynamic loads, and the elasticity of the bounding solids [18].

Research on tribological difficulties is still important for creating IC engines that are more robust, effective, and environmentally friendly. Materials scientists, lubrication engineers, and automakers must work together multidisciplinary to address problems including friction and wear, high-temperature lubrication, oil deterioration, and tribo-corrosion. In order to overcome these challenges and clear the path for the development of the next generation of IC engines with enhanced performance, durability, and sustainability, researchers aim to make use of modern materials, lubrication technologies, and surface treatments.

2.4 High-Temperature Lubrication and Oil Degradation

High temperatures and pressures are common operating conditions in internal combustion engines (IC engines), demanding the use of lubricants that can survive harsh conditions while continuing to function as lubricants. New lubricant additives, such as organic friction modifiers and nanoparticles, have been investigated in research to improve the anti-wear and thermal stability of engine oils at high temperatures. Maintaining lubricant performance over longer service intervals is challenging due to engine oil degradation caused by heat breakdown, oxidation, and contamination by combustion byproducts. The goal of recent developments in oil formulation technologies is to increase oil stability and resistance to deterioration, extending engine life and preserving peak performance [10].

Due to the tribological challenges discussed above as well as numerous others Figure 5 depicts the typical energy flow for an internal combustion engine (ICE). In general, heat loss from the fuel's total energy and friction on a moving part are the manner in which internal combustion engines lose energy. Hence, an ICE vehicle need regular maintenance [21].

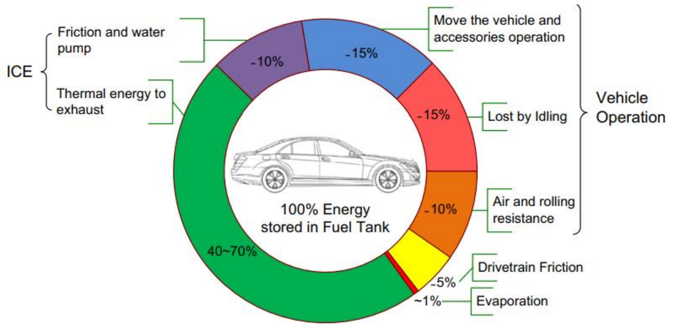

Fig. 5. The typical energy flow of conventional internal combustion engine vehicle [21]

3. Tribological Considerations in Electric Vehicles

With the goal to reduce environmental issues and minimize the transportation industry's dependency on fossil fuels, electric vehicles (EVs) offer a possible option. But just like internal combustion engines, EVs have tribological issues that affect their reliability, durability, and performance. One of The focus of this paper is to examine the tribological aspects of significant components found in electric vehicles, emphasizing the difficulties and new developments in the field of reducing wear, friction, and other associated problems.

Electric vehicles (EVs) powered either by battery, fuel cell or full cell hybrid systems have gained great attention over the past few years around the world as a viable solution to decrease greenhouse gas emissions and to maintain a clean and healthy environment curtailing the adverse effect produced by using internal combustion engines (ICEs) in the transportation and energy production sectors [11, 32]. In comparison to internal combustion engine vehicles (ICEVs), EVs require new components and energy infrastructure to operate efficiently, which implies additional manufacturing and maintenance costs. For example, in the case of EVs powered by battery, 45.3% of the EV's cost corresponds to the cost of battery [10]. So, the main challenge in auto-industry is to develop advanced battery systems; that complements the EVs technology.

Even though EVs have a very high energy consumption efficiency, increasing it further is a big challenge. It can be accomplished by lowering the energy losses generated by electric motors (EMs) and power electronics, battery charging and discharging, cabin heating and ventilation, air drag, and friction. Tribological solutions could potentially reduce the most serious cause of loss [32].

Figure 6 illustrates that 77% of the energy is really utilized to move the car, with the remaining 23% going toward compensating for various energy losses. Inertial energy is used for acceleration, where electrochemical energy is converted into kinetic energy, and the energy required for the basic action of moving the car is used to overcome air drag and rolling friction on the wheels. The braking energy and the inertial energy are equivalent. Frictional thermal energy loss occurs as a result of the kinetic energy being converted back into electrochemical energy by regenerative braking. This is represented as an extra 6% energy input on top of the 100% electric energy obtained from the grid, meaning that 106% of the energy will be used by the vehicle.

Table 1. Review of Tribological solutions for Challenges in Internal Combustion Engines

Paper Title	Authors	Methods Used	Year	Summary	Ref.
Microstructure and wear characterization of AA2124/4wt.%B4C nano-composite coating on Ti−6Al−4V alloy	Esther, I. et al.	using friction surfacing techniques	2019	Advanced nano-composite coatings effectively reduce friction and wear in critical IC engine components.	[22]
Adsorption of organic friction modifier additives	Benjamin, M. et al.	Lubricant formulation and testing	2020	Organic friction modifiers enhance thermal stability and anti-wear properties of engine oils under high-temperature conditions.	[23]
Corrosion assessment of metals in bioethanol-gasoline blends using electrochemical impedance spectroscopy	Libia, M. et al.	Tribocorrosion testing	2021	Austenitic stainless steels exhibit significant tribocorrosion resistance in ethanol-blended gasoline environments.	[24]
The effects of laser surface texture applied to internal combustion engine journal bearing shells	Chen, L. et al.	Surface texturing and experimental testing	2019	Surface texturing reduces friction and wear in IC engine components, potentially improving energy efficiency.	[25]
Self-healing anti-icing coatings prepared from PDMS polyuria	Xuewei, Z. et al.	Formulation and characterization of additives	2021	Self-healing lubricant additives repair micro cracks in engine components, leading to improved durability and longer service intervals.	[26]
Nano-enhanced lubricants for improved IC engine performance	AlTarawneh ,M. et al.	Nano-lubricant formulation and testing	2023	Nano-enhanced lubricants significantly reduce friction and wear, enhancing overall IC engine performance and efficiency.	[27]
High-temperature tribological behavior of ceramic coatings in IC engines	Devarajan, DK. et al.	High-temperature tribological testing	2023	Ceramic coatings exhibit superior wear resistance and friction reduction under high-temperature conditions in IC engines.	[28]
Development of eco-friendly lubricants with reduced carbon footprint for IC engines	Taylor, RI. et al.	Formulation and environmental impact assessment	2024	Eco-friendly lubricants reduce friction and wear in IC engines while minimizing environmental impact and carbon footprint.	[29]
Advances in bio-lubricants for sustainable IC engine applications	Opia, AC. et al.	Bio-lubricant development and testing	2024	Bio-lubricants derived from renewable sources offer excellent tribological properties and sustainability benefits for IC engines.	[30]

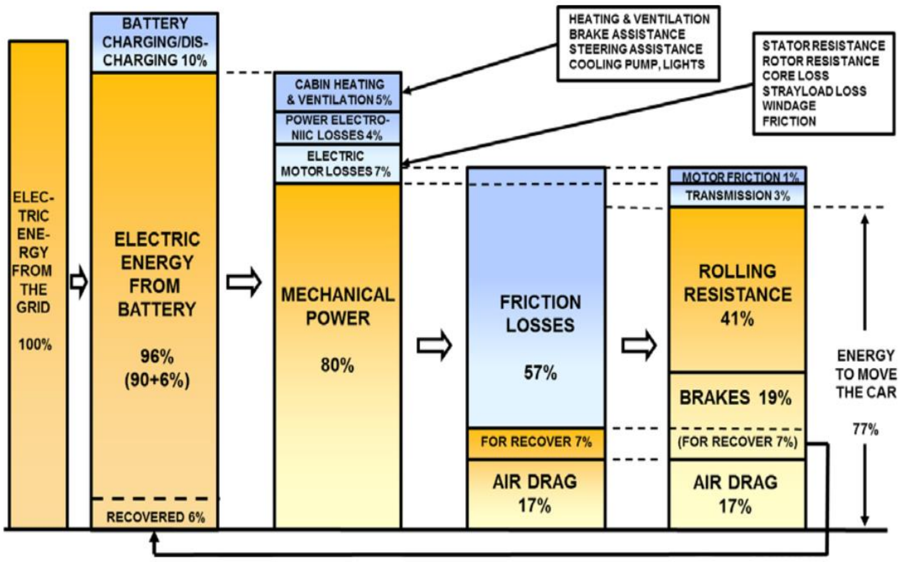

Fig. 6. Breakdown of the energy use in a battery electric passenger car, grid-to-wheel calculations [19]

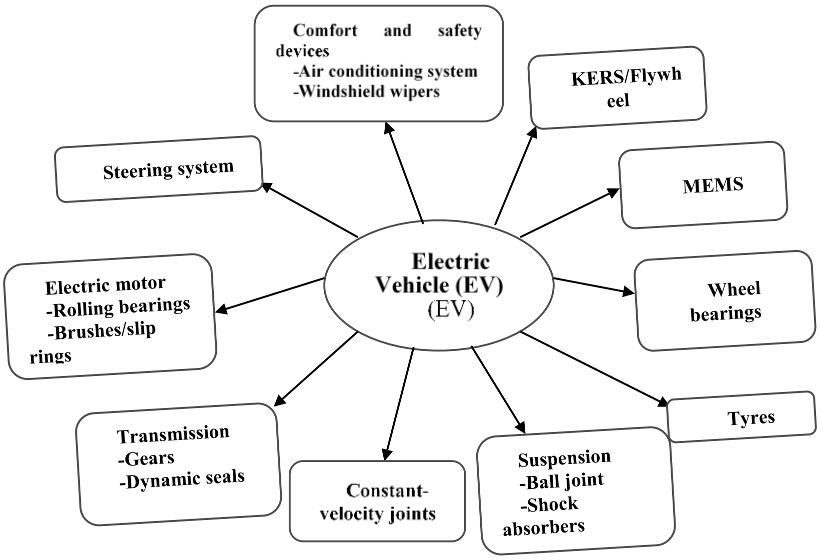

Fig. 7. Major Tribological components of EVs [33]

3.1 Tribological Components of EVs

The most common tribological components required in EVs to operate as similar as possible to ICE vehicles can be seen in Figure 7. Electric motor, transmission, steering system, tyre, wheel bearings, constant-velocity joints, kinematic energy recovery system, comfort and safety devices, suspension and Micro-electro-mechanical system. Each component employing different tribological elements which together produce a considerable amount of friction losses in the vehicle [33].

3.1.1 Battery system

The fundamental component of electric vehicles (EVs) are their battery systems, which store energy for auxiliary and propulsion purposes. The main causes of tribological problems in battery systems are interfacial friction, electrode degradation, and thermal control. Thermal interface materials, protective coatings, and innovative cell designs are the primary areas of research in an effort to increase battery system durability and safety by reducing wear and improving heat dissipation.

In electric vehicles, batteries serve as a system for energy storage. Whether an electric car is plug-in hybrid or all-electric, the type of battery used can differ. These days, batteries are made to endure a long time; they usually survive for eight years or 10,000 miles [11]. Making a determination based on table 2 types of batteries and their benefits; it goes without saying that the best option for an EV vehicle's primary battery must be lithium ion.

3.1.2 Electric traction motors

Traction motors are essential parts of electric vehicles (EVs) that transform electrical energy into mechanical energy for propulsion. Friction and wear in the bearings, shafts, and seals of traction motor are the tribological challenges. To improve the durability and efficiency of electric traction motors, novel approaches such enhanced lubrication systems, surface coatings, and sophisticated bearing materials are being developed.

Table 2. Classification of batteries used in electric vehicles [11]

	Lithium Ion	Nickel-Metal	Lead-Acid	Ultra capacitors
Easy Access / Inexpensive	yes	no	yes	yes
Energy Efficiency	yes	yes	yes	no
Temp. Performance	yes	no	no	yes
Weight	yes	yes	yes	no
Life Cycle	yes	no	no	yes

The majority of commercial solutions for the power traction system in BEVs include synchronous permanent magnet motors with dispersed stranded wire windings and incorporated rare-earth magnets, which is shown in Figure 8 [34]. Tesla S is one noticeable exception, using an induction motor with a dispersed stranded wire winding and a copper rotor cage.

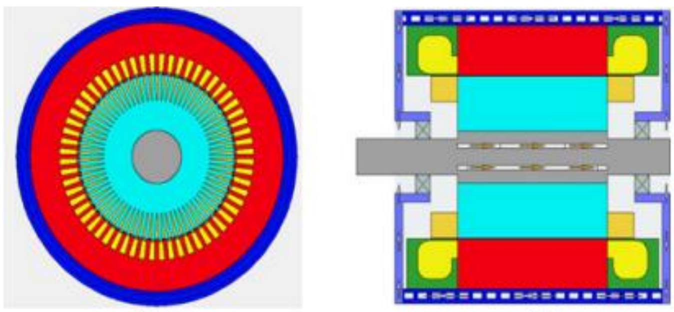

Fig. 8. Induction motor design for BEV.
(a) Radial view. (B) Axial view [34]

3.1.3 Regenerative braking systems

During braking, an electric vehicle's regenerative braking system recovers kinetic energy and transforms it into electrical energy to recharge the battery. Frictional losses in braking parts like brake pads, rotors, and calipers are one of the tribological problems in regenerative braking systems. To maximize energy recovery and reduce wear in braking systems, innovations including brake-by-wire systems, low-friction materials, and regenerative braking control algorithms are being investigated.

Regenerative braking is a special method used in electric vehicles (EVs) to recover energy from motion, or more specifically, kinetic energy that would have been lost during braking-related deceleration or stoppage. Calculating the amount of kinetic energy lost to braking involves measuring the vehicle's starting and final velocities. Since traffic control systems surround towns and cities, urban driving cycles contain a lot of acceleration and deceleration intervals. As a result, a lot of energy is lost during deceleration. Regenerative braking, on the other hand, makes it possible to capture this energy and use "waste" energy for driving the car [35].

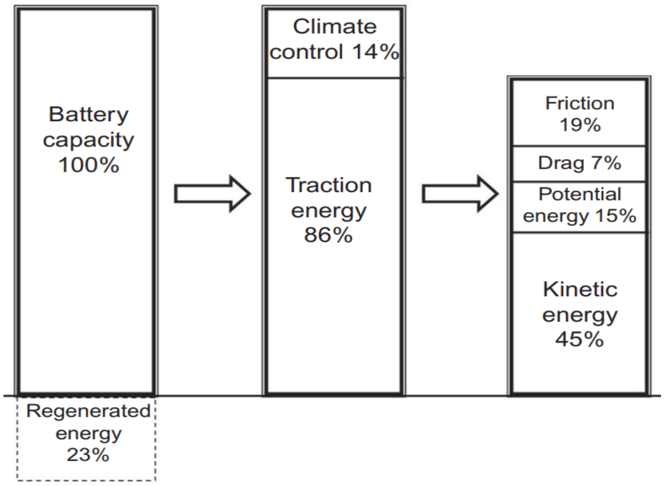

Fig. 9. Breakdown of a comparable passenger electric vehicle's energy use [35]

The breakdown of a comparable passenger electric vehicle's energy use in the winter, when cabin heating is necessary, is shown in Figure 9. Because there are fewer moving components in the EV, it has fewer mechanical losses and eliminates exhaust losses. Traction energy accounts for about 86% of the battery's energy.

3.1.4 Power transmission system

EV configurations are mostly based on the three distinct drivetrain systems depicted in Figure 10. These are the central motor with a single-speed transmission, the central motor with a multi-speed transmission, and the in-wheel motor (IWM) system. Since there are fewer moving components in the IWM form, there are less rotational inertia and friction losses in the gear and differential mechanism are avoided, leading to improved efficiency and reduced mass [31]. IWM systems, however, need high torque traction motors to accelerate the car from a stop, which lowers efficiency because of heat loss from the high current flow required for that [32]. The high tyre wear and usage brought on by tyre slippage is another drawback of this kind of powertrain system. Tyre slip is caused by control inaccuracy when the EV's wheels are not moving at the same speed during curves.

For electric vehicles, the most popular and economical setup involves a central motor drive coupled to a single-speed transmission that serves as a differential. It lowers the overall weight, losses, volume, and cost of the drivetrain. Even if they are not required in terms of dynamic performance, various research groups have shown that the use of multispeed gearboxes and differentials in electric vehicles (EVs) can increase the powertrain's overall efficiency [11]. Potentially, the multi-speed transmission could allow the EM to function in places with higher efficiency.

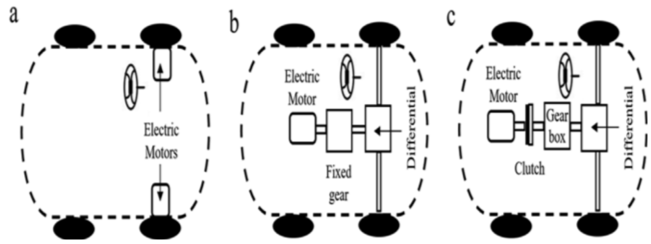

Fig. 10. a) IWM system; b) central motor equipped with a single-speed transmission; c) central motor equipped with a multi-speed transmission [32]

3.1.5 Gears or gear box

An EV is made up of a number of geared components, such as the steering system, transmission, MEMS, etc. In electric vehicles, the biggest causes of friction losses may be the gears in the transmission. For comparison, an ICEV with a manual transmission uses roughly 2.75% of its energy supply to overcome the friction in its gears, which accounts for nearly 8% of the vehicle's overall friction losses [36]. Therefore, improving the efficiency of an electric vehicle (EV) may be possible by lowering friction losses in the gears of geared devices, namely in the transmission.

Recent research has shown that adding spherical alumina nanoparticles and carbon and graphene nanoparticles to gears can significantly improve friction and reduce wear. Additional lubricating oil advances are detailed in Table 4. Additionally, gears showing significant improvements have been made using coating technology and laser surface texturing [37, 38].

3.1.6 Tyre

The rolling friction of tires consumes a substantial amount of the energy given to a vehicle. Approximately 41% of the electric energy provided to the EV is needed to counteract rolling friction in the tyre-road contact caused by hysteresis in the elastomeric tyre during driving, according to the study on friction losses in EVs developed by Holmberg and Erdemir [19]. Hence, by lowering rolling friction force—which can be accomplished by optimizing tyre design, operating settings, and materials—vehicles—both internal combustion engine and electric vehicle (ICEV) efficiency might be greatly increased.

Currently, various reinforcing particles are utilized in rubber compounds for tyre in a variety of ways that compounding engineers and scientists have particularly developed as new instruments to improve the dynamic qualities of these compounds. The new techniques can improve other performances or even raise rolling resistance performance without sacrificing them. Furthermore, nanoparticle technology can be implemented and researched as a novel means of lowering energy consumption through rolling resistance, as well as by lowering tyre weight and wear [39]. Rubber nanoparticles, silica carbide, core/shell polymer nanoparticles, poly(alkylbenzene)-poly(diene) nanoparticles, polyhedral oligomeric silsesquioxanes, carbon nanotubes, graphene, aerogels, nano-diamond, and fullerenes are some of the most effective nanotechnologies used to improve tires.

4. Advances in Tribological Solutions for Electric Vehicles

Tribological solution can help in overcoming the special issues posed by electric vehicles. Tribology can help with a wide range of challenges, including the requirement for specialized cooling, regenerative braking, and the generation of high torque at low speeds. Tribology, the science of friction, wear, and lubrication, contributes to the continuous development of electric vehicles (EVs) as a sustainable form of transportation by improving EV durability, reliability, and efficiency.

Although EVs are believed to have higher energy efficiency than ICEVs, efforts are being made for further enhancement of this efficiency. Comfort systems, air drag and friction (related wear), power electronics, electric motors, and battery losses are possible areas for advancement. Tribological advancements may be able to minimize the losses resulting from air drag and friction. The majority of EV tire technology is derived from ICEVs, which experience similar losses. Because of the numerous tribological components in the vehicle that affect its efficiency and durability, frictional losses are the primary source of energy dissipation [40].

4.1 Artificial Intelligence in Tribology

The tribological community has taken notice of artificial intelligence and, more specifically, machine learning techniques because of its capacity to forecast characteristics that are relevant to tribology, like the oil film thickness or coefficient of friction [41]. Through the optimization of frictional interactions between moving parts and the development of predictive maintenance strategies catered specifically to the needs of electric vehicle drivetrains, the integration of AI into tribology research and applications holds significant promise for improving the performance, reliability, and sustainability of electric vehicles. To improve efficiency, sustainability, and reliability in EVs, artificial intelligence (AI) is being used more and more into tribology research and applications. In the domain of EVs, tribology uses AI in the following ways:

Predictive maintenance: Future breakdowns or performance degradation can be anticipated by using AI algorithms to evaluate real-time data from sensors installed in electric vehicle (EV) components including bearings, gears, and lubricants. By keeping an eye on variables like temperature, vibration, and friction, artificial intelligence (AI) can spot trends that point to potential problems and initiate repairs before they break, reducing downtime and extending the life of EV components [42].

Optimized Lubrication Systems: AI can identify the best lubrication plan for particular EV components by evaluating surface features, operating conditions, and lubricant qualities. Reduced friction, increased energy efficiency, and longer component life are possible outcomes of this optimization [43].

Material Design and Surface Engineering: Advanced materials and surface coatings customized for tribological applications in electric vehicles (EVs) can be designed with the use of AI-driven computational models. Artificial Intelligence (AI) has the potential to improve the efficiency and durability of electric vehicle (EV) components by assisting in the creation of materials with increased wear resistance, decreased friction coefficients, and improved thermal stability by modeling and evaluating the interactions between surfaces at the nanoscale [44].

Energy Efficiency Optimization: To reduce energy losses from friction in EV drivetrain components, AI-based optimization methods can be used. Artificial Intelligence (AI) can enhance energy efficiency and range of electric vehicles while minimizing wear and tear on tribological surfaces by continuously modifying operating factors including torque distribution, gear ratios, and regenerative braking systems [45].

4.2 Surface Engineering and Coatings

Surface engineering methods, such as surface treatments and coatings, are essential for reducing wear and friction in the parts of electric vehicles. The efficiency and durability of electric powertrain systems are increased by advanced coatings such diamond-like carbon (DLC) coatings and nanostructured coatings, which provide improved wear resistance and reduced friction properties. These coatings can be used to reduce energy losses and increase the lifespan of crucial parts including slide contacts, bearings, and gears. A wider range of coating technologies are being recognized as suitable to meet the unique technical requirements of various automotive applications. These technologies include thermal spray (wire arc, plasma, high velocity oxy-fuel, detonation spray), laser deposition, electrolytic methods (electrodeposition, electroless deposition, pulsed electrodeposition, micro arc oxidation/plasma electrolytic oxidation), and vapor based techniques (physical and chemical vapor deposition, plasma nitriding, nitrocarburizing).

4.3 Advancements in Lubricant Technology

A new era of automotive technology has been brought about by electric vehicles (EVs), but they also present special lubrication issues. Electric motors, which produce substantially less heat when in operation, are the power source for EVs, in contrast to conventional internal combustion engines. Because of this decrease in heat, EVs have very different lubrication requirements because they need specific lubricants to continue operating at peak efficiency and lifetime. One such invention is high-temperature grease, which was created to mitigate the intense heat produced by the high-speed, high-torque electric motors present in electric vehicles (EVs) [32]. By keeping the motor and transmission's parts sufficiently lubricated, these greases guard against overheating and excessive wear. Furthermore, increasing EV battery longevity is critical to both their overall effectiveness and affordability. By reducing friction and energy losses in the drivetrain, extending battery life, and eventually improving the sustainability and attraction of electric vehicles in the contemporary automotive sector, lubrication plays a critical part in accomplishing this goal [46].

Greases: Grease's primary benefit over oils is that it's more consistent, meaning that grease is unlikely to leak out of mechanical components. Thus, it is simpler to lubricate bearings and gears with grease than with oils. However, the primary drawback of greases is their limited lubricity life, which makes it difficult to forecast how well the grease and the lubricated mechanical element will work together. Since lubricity and grease life have experienced noteworthy advances, the current trend in grease research is based on employing nanotechnology (carbon nanotubes and nanoparticles) as reinforcement for various greases [47]. Using titanium complex thickeners and synthetic base oils have been suggested as further efficient ways to resist higher temperatures, produce less friction torque, and extend service life [48].

The enhanced qualities of greases reinforced with various modern polymers, like rubber, polypropylene, and methylpentene, have also been demonstrated, particularly for high speed bearing applications. All things considered, the most effective grease additives are the non-toxic bismuth, calcium sulfonate complex, graphite, polarized graphite, poly-isobutylenes, and moS2 (usually 3%). All of the techniques mentioned above may be used to create greases that are more effective in lubricating EV components [49].

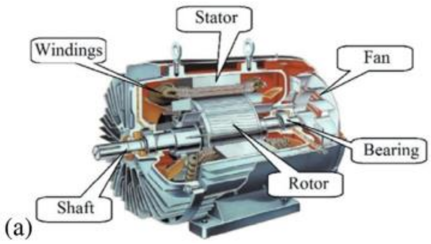

Fig. 11. Schematic of an electric motor emphasizing points of interest for grease lubrication [50]

Figure 11depicts a schematic of an electric motor emphasizing points of interest for grease lubrication would typically highlight the key areas where lubrication is crucial.

Solid Lubricant Coatings: Solid lubricant coatings, including graphene, molybdenum disulfide (MoS2), and diamond-like carbon (DLC) coatings, are utilized in critical electric vehicle (EV) components like sliding contacts, gears, and bearings to reduce wear and friction. These coatings increase the longevity and effectiveness of EV drivetrains by offering a low-friction interface, high load-bearing capability, and resilience to adverse operating circumstances [51].

Lubricating oils: Similar to ICEVs, an EV has a number of parts that need to be lubricated with oils, with the driveline being the most crucial. Unlike the oils needed for ICEV drivelines, EV drivelines need additional essential characteristics in order to function properly. Three crucial factors which aren't included by the ICEV driveline oil standards are being taken into account for the development of innovative EV driveline lubricants: The first concerns the oil's capacity to prevent copper components, primarily copper wiring from corrosion and its compatibility with polymers used in electrical and electronic components, such as sensors, resins, contacts, and so forth. It also entails the creation of industry-standard techniques for assessing these attributes in high-temperature, realistic EV driveline operating situations. Achieving extremely low viscosity is the second factor, and improving electric characteristics is the third [32].

Table 3. Advantages and recent advancements in each type of solid lubricant commonly used in electric vehicles [43, 44]

Solid Lubricant	Advantages	Advancements
Molybdenum Disulfide (MoS2)	- Lamellar structure providing low shear strength - Widely available and cost-effective	- Improved deposition techniques (PVD, CVD) - Nanostructuring for enhanced properties
Graphene	- Exceptional mechanical strength - High surface area and lubricating properties	- Development of graphene oxide (GO) and reduced graphene oxide (rGO) coatings - Functionalization for tailored properties
Diamond-Like Carbon (DLC)	- Combines hardness with low friction - Excellent wear resistance	- Optimization of deposition processes (PECVD, PLD) - Doping for enhanced properties
Boron Nitride (BN)	- Hexagonal crystal structure with low shear strength - Chemical inertness	- Development of nanocomposite coatings - Hybrid coatings for tailored properties
Tungsten Disulfide (WS2)	- Similar to MoS2 with higher temperature stability - Resistant to oxidation	- Nanostructured or multilayer coatings - Surface modification for enhanced durability

Table 4. Summary of few tribological components of electric vehicle including mechanisms of loss of energy and lubricants to be used to overcome the losses [18, 31-34, 39]

Component	Tribological Challenges	Energy Loss Considerations	Lubricants
Electric Motors	Friction and wear in bearings, shafts, and seals	Frictional losses during operation; regenerative braking reduces energy loss during deceleration	Synthetic oils, greases; solid lubricants; polymer-based coatings
Battery Systems	Thermal management, electrode wear, interfacial friction	Heat dissipation during charging/discharging; frictional losses during thermal cycling	Thermal interface materials; protective coatings; dry film lubricants
Regenerative Braking Systems	Frictional losses in brake pads, rotors, and calipers	Energy recovery during deceleration reduces overall energy loss; optimization of regenerative braking control	Low-friction brake pad materials; regenerative braking algorithms
Power Electronics	Thermal cycling, electrical contacts, interconnections	Heat dissipation during operation; minimize contact resistance to reduce energy loss; improve reliability	Thermal interface materials; electrical contact lubricants; advanced coatings
Bearings	Wear, fatigue, and lubrication challenges	Energy dissipation due to frictional losses; efficient lubrication systems can minimize losses	High-performance oils, greases; solid lubricants; advanced bearing materials
Gears	Wear, pitting, and micro pitting	Energy losses due to friction and tooth meshing; optimization of gear design and lubrication reduces losses	Gear oils, lubricating greases; anti-wear additives

5. Future Directions and Conclusions

In this review, which included into consideration the most relevant published research, the present state and challenges in tribological optimizations for the important components indicated for EVs were addressed and generally reviewed. However, more in-depth and specialized examination work would be necessary for a more precise identification and quantification of research gaps and quality for each tribological element for EVs. This work would be very helpful and complementing to specific study topics.

5.1 Future Directions of Tribology for EVs

Tribology for EVs will see a concentrated effort in the future to improve sustainability, dependability, and efficiency. This path requires cutting-edge developments in coatings and materials designed to reduce wear and friction in major drivetrain parts. The optimization of component designs and lubrication strategies will be guided by computational tribology, which will be crucial in modeling and simulating frictional processes. Sensor and AI technologies will be used by smart lubrication systems to provide adaptive lubricant management and real-time monitoring. Innovations in motor design and bearing technologies will be driven by the goal of lowering friction losses in electric motors. Eco-friendly lubricants and materials will be used to prioritize environmental sustainability while standardized testing techniques will guarantee the reliability and efficacy of EV components. Integrating with car electronics will promote comprehensive system optimization by enabling advanced monitoring and predictive maintenance features. Together, such efforts will advance EV tribology in the direction of future electric vehicle performance, longevity, and environmental responsibility.

6. Conclusions

This work addresses the fundamentals of tribology, tribological challenges in IC engines, tribological considerations in electric vehicles, tribological components of EVs, and advances in tribological solutions for electric vehicles intended to eliminate or minimize energy losses due to many tribological components and future directions of tribology for EVs are discussed.

In order to improve efficiency and reliability, tribological developments in EVs concentrate on lowering friction, wear, and energy losses. EVs have lower friction losses than conventional automobiles since they have fewer moving components, especially since they don't have complicated gearboxes. Enhancing efficiency and prolonging the life of vital components requires advanced lubrication systems along with customized lubricants. In order to reduce friction losses, electric motor designs are constantly evolving and now include temperature management systems and optimized bearing materials. Tires with low rolling resistance and cutting-edge materials and coatings also help to increase efficiency by lowering friction at different points of contact. Predictive maintenance is made possible by real-time monitoring and control systems, which guarantee the durability and best possible performance of EV components. The overall goal of these tribological developments is to increase the electric vehicle's sustainability, efficiency, and range.

The conclusions drawn from the review of academic literature that gives a general overview on tribological considerations in the transition from IC engines to electric vehicles are as follows.

- ➢ Since they don't have complicated mechanical parts like pistons, crankshafts, and camshafts, EVs often have less wear and friction than ICE vehicles.
- ➢ Tribological factors in electric vehicles (EVs) consist of battery materials and their interplay, in addition to conventional mechanical components. In order to improve battery system longevity and performance, wear and friction mitigation strategies are essential.
- ➢ To improve the durability and efficiency of electric traction motors, novel approaches such enhanced lubrication systems, surface coatings, and sophisticated bearing materials are being developed.
- ➢ One typical characteristic of EVs is regenerative braking, which adds more tribological challenges, especially in the braking system. Innovative friction materials and thermal management techniques are required because frictional interactions between brake pads and rotors during regenerative braking cycles can affect efficiency and wear rates.
- ➢ Compared to traditional ICE vehicles, EV drivetrains have different lubricating needs. For electric motors, gearboxes, and other components, optimizing lubrication systems is crucial to minimizing energy losses, cutting wear, and prolonging component life.

Opportunities for multidisciplinary research at the intersection of materials science, mechanical engineering, and environmental science are opened up by the transition from ICE to EVs. Through integrating knowledge from several domains, scientists can create novel approaches to improve the tribological efficiency of electric vehicles and advance environmentally friendly transportation.

These review paper emphasize the significance of tribological factors in the transition to electric vehicles and point to areas that could use more investigation and technological advancement in this rapidly developing industry.

Nomenclature

AI	: Artificial Intelligence
BEVs	: Battery-Electric Vehicles
CVD	: Chemical Vapor Deposition
DLC	: Diamond-Like Carbon
EMs	: Electric Motors
EVs	: Electric Vehicles
FCEV	: Fuel-Cell Electric Vehicles
GO	: Graphene Oxide
HEV	: Hybrid Electric Vehicles
ICE	: Internal Combustion
ICEVs	: Internal Combustion Engine Vehicles
IC	: Internal Combustion Engines
MoS2	: Molybdenum Disulfide
PHEVs	: Plug-in Hybrid Electric Vehicles
PLD	: Pulsed Laser Deposition
PVD	: Physical Vapor Deposition
rGO	: Reduced Graphene Oxide
REEVs	: Range-Extended Electric Vehicles
WS2	: Tungsten Disulfide

Conflict of Interest Statement

The authors have no relevant financial or nonfinancial interests to disclose.

CRediT Author Statement

Biniyam Ayele Abebe: Original draft writing, conceptualization, methodology, and data collection.
Samet Çelebi: Teaching and supervision, structure – assessment & editing.
Recep Kiliç: Conceptualization, Supervision

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