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Tribology of electric vehicles: A review of critical components, current state and future improvement trends

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A B S T R A C T

Considering the growing interest in substituting internal combustion engine vehicles with highly efficient electric vehicles around the world, this paper aims to contribute with a literature review about the current state and future improvement trends for optimization of critical tribological components used in passenger electric vehicles. The review gives an understanding of the most recent achievements in terms of tribological solutions applied to the critical components and the identification of research gaps for further developments and efficiency improvements for EVs through novel component designs, materials and lubricant technologies.

1. Introduction

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 [1,2]. 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 [3]. So, the main challenge in auto-industry is to develop advanced battery systems; that complements the technology the most. Other energy infrastructure components required can be hydrogen fuel cells, hydrogen storage systems, supercapacitors, photovoltaic cells, automotive thermoelectric generators, regenerative breaking systems, charging technology for energy storages, etc. [3]. According to such required technology, the cost of an EV can be expected to be higher than ICEVs currently since most of such technology has not been efficiently developed and commercially available. Nonetheless, EVs generate lower operating costs in comparison to ICEVs. For instance, the cost of an EV, in terms of energy cost, is about 2 cent/mile while an ICEV (gasoline powered) is around 12 cents/mile [3]. In addition, according to the recent reports of Holmberg et al. [4,5], about only 21.5% from the total fuel energy supplied to an ICEV is used to move the vehicle in contrast to EVs (passenger vehicles powered by battery), which use around 77% from the total grid electric energy supplied. It suggests that EVs are about 3.6 times more efficient than ICEVs.

The growing interest in employing EVs, not only as passenger cars, but also as heavy-duty vehicles and buses has given potential to carry out different developments and research topics based on energy storage, hydrogen cells, electric motors (EMs), micro-electro-mechanical systems (MEMSs) and sensors, autonomous driving, thermal and electric efficiency increase, etc. In conjunction with a series of multi-disciplinary efforts, the challenge is to consolidate this technology as totally viable and efficient for the transportation sector.

Although EVs present a substantial high efficiency in terms of energy consumption, there is a challenge to increase it even more. It can be achieved by reducing energy losses produced in EMs and power electronic devices, charging and discharging of battery, cabin heating and ventilation, air dragging and friction. The last source of loss being potentially decreased via tribological solutions. In line with the recent report of Holmberg and Erdemir [5], about 57% of the total electric energy supplied to an EV (powered by lithium ion batteries and moved by using an EM working also as generator to recover energy from breaking) is used to overcome friction losses. The total friction losses considered in the report are distributed as follows: 1% in the EM with a capacity of 75 kW, 3% in the transmission (one step mechanical transmission), 41% in the rolling resistance, and 12% in brakes. Since ICEVs tyre technology is being applied similarly in current EVs and considering that EVs are expected to operate under similar rolling conditions to ICEVs, the rolling resistance losses in EVs can approach similar values to ICEVs. Other friction losses should be considered since commercial passenger EVs involve other tribological components which can increase friction losses affecting negatively efficiency and durability.

The most common tribological components required in EVs to operate as similar as possible to ICEVs can be seen in Fig. 1. For the analysis in this paper, they were classified into: motor, transmission, steering system, tyres, wheel bearings, constant-velocity joints,

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Abbreviations

ACS	Air conditioning system
AMT	Automated manual transmission
AT	Automatic transmission
BM	Boundary lubrication
CM	Coreless machine
CR	Chloroprene rubber
CVT	Continuous variable transmission
DCM	Direct current motor
DCT	Dual clutch transmission
EM	Electric motor
EPASS	Electric power assisted steering system
EPDM	Ethylene-propylene-diene monomer
EV	Electric vehicle
FKM	Fluorelastomer
HPASS	Hydraulic power assisted steering system
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
IM	Induction motor
IWM	In-wheel motor
KERS	Kinematic energy recovery system
MEMS	Micro-electro-mechanical system
MSS	Mechanical steering system
NBR	Nitrile-butadiene rubber
PEEK	Polyetheretherketone
PI	Polyamide
PTFE	Polytetrafluoroethylene
RM	Reluctance motor
SBM	Synchronous brush motor
SPM	Synchronous permanent-magnet motor
VMQ	vinyl-methyl silicone

kinematic energy recovery system (KERS), comfort and safety devices, suspension and MEMS. Each component employing different tribological elements which together produce a considerable amount of friction losses in the vehicle.

This paper aims to address a literature survey on the current state and future improvement trends for critical tribological components in EVs with regards to the friction loss reduction and durability enhancement. The review gives an understanding of the most recent achievements in terms of tribological solutions applied to the components and the identification of research gaps for further work and developments according to the improvement of efficiency of EVs.

2. Critical tribological components in electrical vehicles (EVs)

2.1. Motor

Although ICEVs use various EMs for different secondary operating functions, namely, engine running, fuel pumping, steering, etc., EVs use EMs for propulsion primarily. The efficiency of EMs is about three times superior to ICEs. As a reference, it can be considered the simplest and least efficient EM (direct current motor (DCM)). It reaches 78% efficiency between 40 and 50 kW [6]. Another of the most remarkable advantages of EMs in comparison to ICEs is that they do not produce soot through their operation. It contributes to the environmental care and no-contamination of lubricating oil with soot, which may extend the oil service life and avoid increase of oil viscosity. More than 100 different topologies of EMs can be found in the configuration of modern vehicles [7], the most popular being, by means of rotor topology, the DCM, the induction motor (IM), the synchronous permanent-magnet motor (SPM), the reluctance motor (RM) and synchronous brushed motor (SBM), while by means of stator topology, the coreless machine (CM), multiple phases power systems and the in-wheel motor (IWM) [8].

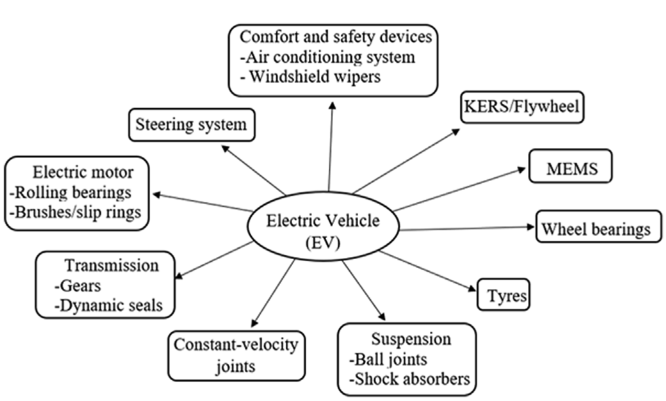

Fig. 1. Classification of critical tribological components in a common electric vehicle (EV).

The rate of efficiency from 1 to 5 for different EM topologies is given in Table 1 [8]. It suggests that SPMs present the highest efficiency while DCMs the lowest. Thus, considering other advantages, namely, high-power density, compact size, reliability, very low noise and minimum maintenance requirements [9,10], SPMs are the best current option for the traction in most modern EVs as considered by most automotive industries and researchers around the world [11]. In general, the losses occurring in EVs can be divided into electrical, magnetic, mechanical and stray losses. Electrical and magnetic losses are the largest sources of loss [12]. As a reference, Lukaszczyk [13] reported the percentage distribution of the above losses occurring in a modern IM. Electrical losses being around 64.1%, magnetic losses around 26.7%, mechanical losses above 3.53% and stray losses (including harmonic losses) being around 5.58%. Although mechanical losses only contribute slightly, they can be reduced even more to improve the efficiency and durability of EMs. Even a small improvement in mechanical losses could be significant if all EMs used in an EV were considered. Besides, considering the total amount of EVs expected to replace all ICEVs in the world, even the smallest reduction of mechanical losses could represent significant energy savings and financial losses over the world. Mechanical losses in EMs mainly surge from friction generated in the rotor bearings and/or by sliding of brushes with slip rings, in the case of EMs working with brushes, and from windage or cooling [8,13]. The friction losses are proportional to the rotor speed generating heat, vibrations and wear. A significant effort to improve the maintenance of EMs has been carried out specifically in rolling bearing lubrication since about 40–60% of all early motor failures are ascribed to the bearings. Most bearing failures are a consequence of improper lubrication with the wrong grease or missing relubrication [14]. Hence, the rotor rolling bearings and the brushes/slip rings can be considered as the critical tribological elements in EMs to be optimized further.

2.1.1. Rolling bearings

Typically, two kinds of rolling bearings (ball and roller bearings) are used to allow rotation and relative motion of mechanical elements by producing minimal friction in ICEV's components [15], but also, they are being transferred to the architecture of EVs taking advantage of the

Table 1
Rated efficiency from 1 to 5 for different EMs [8].

Motor	SPM	SBM	RM	IM	DC
Rate	5	4	4	3.5	2

advances achieved in automotive rolling bearing technology. Most of literature about automotive rolling bearings is focused on ICEV applications. In a common ICEV, nearly 100 rolling bearings are used, mainly tapered roller bearings, thrust needle bearings and wheel bearing hubs [16]. Although the friction loss occurring in a single rolling bearing is considered as minimal, even a slight reduction of such friction can represent a decrease in energy consumption if the amount of the total bearings is considered [17].

Friction loss of rolling bearings is expressed in terms of the torque required for rotating it. It is the sum of the torque generated by churning, sliding, rolling and/or seal sliding friction [16]. Churning friction loss may occur only in the churning phase. It is expected to be minimal for a good channelling grease. Sliding friction is related to the viscous shear of the lubricant if it is capable to generate a full lubricant film. In the case that full film cannot be generated, boundary lubrication (BL) conditions may be present, but they are expected to be as low as possible. The rolling friction is very large sometimes. It is the result of the non-symmetric elasto-hydrodynamic lubricant pressure distribution and will vanish in the absence of lubrication. The friction loss by rolling resistance can be reduced considerably by using low viscosity oils or greases. Nevertheless, it promotes a decrease of bearing life due to reduction of the lubricant film and achieving BL conditions [16], which could be minimized by means of lubricant additive technology.

The friction loss distribution in some rolling bearings (a tapered roller bearing supporting a pinion shaft of a rear differential of an automobile lubricated with gear oil with high viscosity [18], a thrust needle bearing used in an automatic transmission of a passenger car lubricated with an ATF [19] and a wheel bearing hub lubricated with enclosed grease [20]) can be seen in Fig. 2. In the first case, the largest source of friction loss is the rolling/viscous shear. This is ascribed to the large viscosity of gear oil. The second case exhibits the sliding as the largest source of friction loss. It is associated with the sliding occurred between rollers and the cage in this kind of bearings. The rolling/viscous shear is lower due to the low viscosity of ATFs. In the last case, the largest source of friction corresponds to that produced by sliding. Since the complete hub unit was considered for this case, it was found that the friction generated by the sliding of the dynamic seal was the largest source of loss. Also, the rolling/viscous shear represents considerable friction losses due to the high viscosity of grease.

Technically, three methods can be carried out to reduce friction loss in rolling bearings. One is by changing the design of the bearing without changing the main dimensions. The second one is by downsizing the bearing to decrease torque and weight meanwhile the third one is by optimizing lubrication in terms of the lubricant and/or bearing materials [17]. One example of a successful achievement for reducing friction losses in bearings has been reported in Ref. [21]. The bearings developed reduced friction losses by at least 30% compared to standard bearings. They were designed for light-to-normal load applications such as EMs, pumps, gearboxes and conveyors.

Further improvements in rolling bearing life and friction loss can be achieved by implementing advanced coatings [4] and lubricant technologies [4,16]. Coatings play a role to be protective layers to reduce friction coefficient and increase wear resistance. Coated rolling bearings have been reported to have a ten-fold increase in fatigue lifetime and a seven-fold decrease in wear [22,23]. Different coatings are being considered for decreasing friction and wear, the most popular being physical vapour deposition (PVD) and diamond-like carbon (DLC) coatings [24–26]. However, other options, namely, coatings of Cr–N, TiN, Ni–SiC, AlMgB14, MoS2, WC/Co, TiAlN, W–C:H, AlMgB14–TiB2; composite coatings with TiN, TiC, or TiB2 particles embedded in Si3N4 or SiC ceramic matrix, and various nanostructured coatings could be also effectively applied to increase life time [4,27–36]. The advances in grease and lubricant technology can be found in the following Sections 2.1.3 and 2.2.2, respectively.

2.1.2. Brushes/slip ring assembly

The brush/slip ring assembly is the most conventional system used in DCMs for conduction of electrical power or signals between stationary and moving parts through a sliding electrical contact. This sliding contact comprises a complex combination of parameters that influence the tribological behaviour [37–39]. The efficiency of a brush/slip ring assembly depends on the material properties and geometry of both the brush and slip ring, surface boundary film and environmental and operating conditions. High wear resistance, good electrical and heat conductivities, low electrical contact resistance and low friction can enable efficient, reliable and long-term operation of this tribosystem. The brush/slip ring assembly is considered as one of the most critical tribological parts of DCMs [40].

The classic brush/slip ring assembly for EMs consists of stationary brushes made of graphite pressed against a metal rotating slip ring, typically made of copper or bronze [37,41]. Improvements in terms of contact-material combinations and design for increasing the assembly lifetime have had great attention and development in the last few decades [42,43]. However, longer lifetimes and lower friction are still required for new applications.

The most recent developments, presenting substantially enhanced tribological properties, comprise the application of new contact-material combinations for the brush/slip rings, such as: graphite/graphite [38,44] and brass fibre and coin-silver/Au plating [40]. Although there has been a significant progress in the performance of brushes/slip ring assembly, further research is still required to reduce friction and wear without compromising electrical conductivity in the electric sliding contact, and thus increase the efficiency of EMs.

2.1.3. Greases

A conventional grease used for lubrication of bearings, joints or gears is composed of a base oil (mineral or synthetic) and different additives ((molecules, polymers, or particles) used to promote grease thickening. In general, the selection of the base oil and thickener type is based on the required temperature operational range and compatibility with the polymeric elements to be lubricated. The main advantage of greases over oils is their consistency, which prevents the grease from leaking out from the mechanical component. So, the lubrication of bearings and gears with grease is easier than with oils. Thus, about 80–90% of rolling bearings are lubricated with grease [16]. However, the foremost disadvantage of greases is limited lubricity life compromising the prediction of the combined performance of the grease and the lubricated mechanical element. The lubrication mechanisms with grease become much more complex than those using oils.

The evolution of grease development can be seen in Fig. 3. A calcium grease consisting on a combination of lime (calcium carbonate) and olive oil or animal fats were the first greases used by humanity (Egyptians and Romans) to lubricate plain bearings for carriages. The

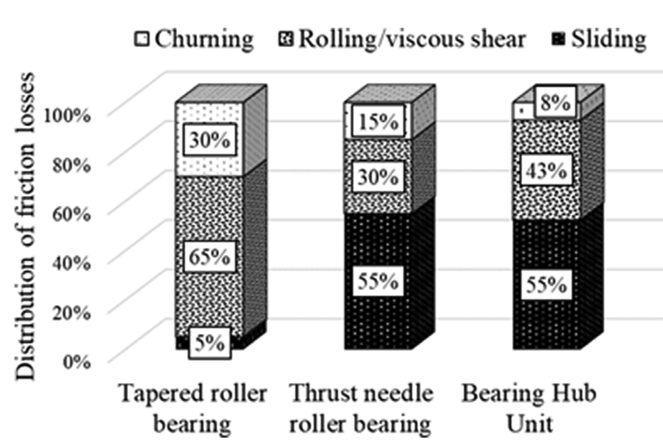

Fig. 2. Friction losses distribution for different automotive rolling bearings.

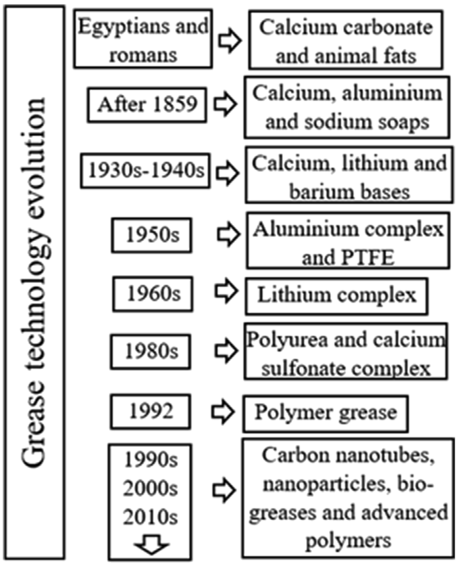

Fig. 3. Evolution of grease technology.

first modern greases based on mineral oil were calcium soaps. Then, aluminium and sodium soaps replaced those greases because they could resist higher temperatures. New greases based on calcium, lithium and barium were developed in the 1930–1940s [45], lithium-based grease being the most widely used today [16]. The following grease advancements were between the 1950s and 1990s, developing greases in the following order: Aluminium complex and PTFE-based, lithium complex-based, polyurea and calcium sulfonate (complex)-based, and polymer grease.

The optimization of grease performance is based on the variation of the bleed rate, consistency, mechanical stability, base oil viscosity and oxidation performance to improve both grease and mechanical component life times, to reduce friction and noise, and to resist higher or lower temperatures. Currently, the challenge in tribology research is focused on the fundamental understanding of the lubrication mechanisms by using greases. Besides, the creation of new greases capable to resist more severe lubrication conditions (extreme low and high temperature and shear rates), the development of more accurate predictive tools for grease and lubricated component performance, and the optimization of the grease flow in mechanical components are strategies in progress to enhance the performance of greased tribological components [46].

Recently, the trend of grease research is based on applying nanotechnology (carbon nanotubes and nano-particles) as reinforcement for different greases since lubricity and grease life has demonstrated noteworthy improvements [47–50]. The use of synthetic base oils [51] and titanium complex thickeners [52] have been other effective solutions given to generate lower friction torque and higher service life and to resist higher temperatures.

The development of biodegradable or eco-friendly greases is another current research trend topic due to increasing demands for environmental protection [53]. Different research works have addressed developments in this matter [53–56]. Although these greases have demonstrated better lubricity properties than greases based on mineral or synthetic oils, thermal stability is their principal drawback, but it can be improved by using different types of nano-particles or chemical modifications applied to the biodegradable base oil, as explained in Section 2.2.2 [57].

Greases reinforced with different advanced polymers such as rubber [58], polypropylene [16] and methylpentene [59] have also demonstrated upgraded properties, in particular, for high speed bearings application [16]. Overall, the most successful additives for greases are the MoS_2 (typically 3%), graphite, polarized-graphite, poly-isobutylenes, non-toxic bismuth and calcium sulfonate complex [16].

All the above solutions could be potentially applied for developing more efficient greases for lubrication of components either for ICEVs or EVs. In a recent report for electric driveline challenges [60], tackiness of grease has been remarked as the most important property to be improved. Tackiness is a lubricant property that allows sticking and formation of long threads between two separating surfaces while grease redistributes itself between the surfaces. It provides the grease the ability of traveling from one surface to another and sticking appropriately to work efficiently in sliding applications.

2.2. Transmission

Power transmissions have been widely investigated and enhanced for the best performance of ICEVs. However, they are being currently optimized for enhancing performance of EVs. Typically, EVs are being basically configured according to the three different drivetrain systems showed in Fig. 4. They are the IWM system, the central motor equipped with a single-speed transmission and the central motor equipped with a multi-speed transmission [1,2,61]. The first configuration presents higher efficiency and lower mass due to less moving parts generating lower rotational inertia and avoiding friction losses in gear and differential mechanism [2,8]. However, IWM systems require high torque traction motors for accelerating the vehicle from zero speed, which reduces efficiency due to heat loss by high current flow needed for that purpose [62–65]. Also, since IWMs have a low and limited top speed, they are preferred to be used in applications where performance in stop-and-run driving is prioritized over comfort, such as in-city driving and sport cars [1,2]. For example, it is considered as the unbeatable configuration for solar car competitions [66]. Another disadvantage of this type of drivetrain system is the excessive tyre wear and overuse produced due to tyre slip. Tyre slip is generated by the control inaccuracy to compensate the speed difference of the EV's wheels in curves [67].

In a similar way to ICEs, the efficiency of EMs depends on torque and speed of working, having an optimum working condition and decay of efficiency out of the optimum condition. It depends on the type of EM involving design, structure, materials, weight, etc. Therefore, one approach to increase the vehicle driving range and top speed is by

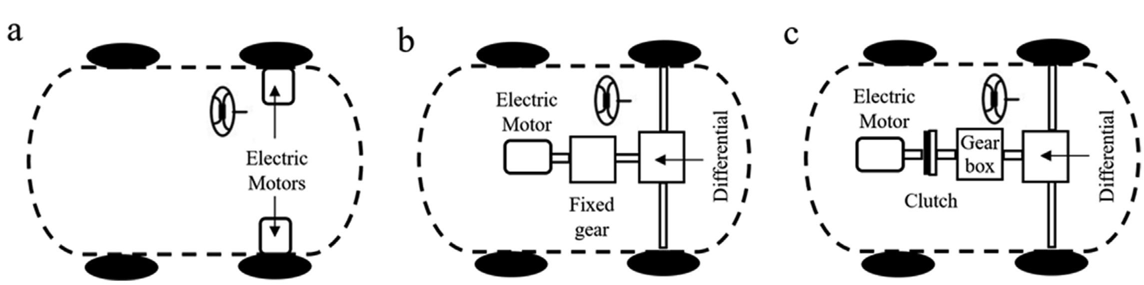

Fig. 4. Examples of common EV powertrain configurations: a) IWM system; b) central motor equipped with a single-speed transmission; c) central motor equipped with a multi-speed transmission.

modifying the vehicle powertrain by incorporating a reduction gear box/differential [68]. It provides the EV with the capacity to run at a reduced single-speed or at multi-speed for driving in both city and highway. However, it has a negative effect on the EV efficiency due to more moving parts producing higher friction loses and rotational inertia in the powertrain. The single-speed transmission has been demonstrated to be capable of providing a satisfied dynamic performance [69–71]. The most common cost-effective solution given for EVs is the configuration comprising a central motor drive adapted to a single-speed transmission acting also as differential. It reduces the drivetrain volume, mass, losses and cost [8,72]. Nonetheless, the use of multi-speed transmissions/differential in EVs have been demonstrated by different research groups [73–75] to improve the overall efficiency of the powertrain although it is not necessary in terms of dynamic performance. The multi-speed transmission may enable the EM to operate in higher efficiency regions reducing energy consumption.

There are different commercial options of multi-speed transmissions, namely, automated manual transmission (AMT) [69,76,77], automatic transmission (AT) [78-80], dual clutch transmission (DCT) [81–83] and continuous variable transmission (CVT) [81,84–87], which has been investigated to be implemented in EVs with expectation to become autonomous in a future.

Considering the above transmission options for EVs, the 2-speed transmissions for all the cases have shown the best balance between the advantages of a multiple-speed transmission system and the simplicity of a compact and lightweight drivetrain [61]. On the other hand, strategies by using dual motor input powertrains either coupled to planetary gear transmission or coupled to a parallel axle transmission can provide higher overall efficiency than EVs equipped with a single motor input powertrain [61].

Currently, different options of structure and components for the drivetrain of EVs are being investigated and developed till reaching the best efficiency and performance. Discarding the IWM drivetrains, the rest of drivetrains use a transmission either a single-speed or multi-speed, which represent higher energy consumption due to higher friction losses. Tribological research solutions can be potentially addressed to reduce deficiencies in such transmissions by improving the tribological behaviour of the mechanical elements, such as rolling bearings, gears, synchronizers, dry or wet clutches, lubricating oils, etc., involved in each type of transmission.

2.2.1. Gears

There are various geared devices comprised in an EV, for example, the transmission, steering system, MEMS, etc. The gears in the transmission can represent the largest sources of friction losses in EVs. As a reference, about 2.75% of the energy supplied in an ICEV equipped with a manual transmission is used to overcome friction produced in gears generating around 8% from the total friction losses in the vehicle [4]. Hence, reducing friction losses in gears of geared devices, in the transmission particularly, the efficiency of an EV could possibly benefited.

It is well known that low friction in gears is achieved by using lower viscosity gear oils and efficient additives [88,89]. The common gear oil additives themselves are based on sulphur and phosphorus chemistry, but other chemicals are introduced into the additive package to provide oxidation stability, anti-corrosion protection, copper compatibility and good seal compatibility. Boron compounds have been shown to improve the antiwear and extreme-pressure properties of gear oils, as well as oxidation stability, thermal stability and detergency for gears [90].

Recent developments have demonstrated remarkable enhancements in friction and wear reduction for gears by adding spherical alumina nanoparticles [91] and carbon and graphene nanoparticles [92]. More advancements in lubricating oils are given in Section 2.2.2. In addition, laser surface texturing [93] and coating technology have been applied in gears exhibiting considerable improvement. Coatings made of double-glow plasma surface alloying W–Mo [94], WC/C, WC/C–CrN, DC and plasma nitriding [95,96] are the most recent research works reporting on substantial improvement on tribological behaviour of gears.

Therefore, further friction and wear reduction in gears for EVs could be reached by developing more advancements on each part of the gear tribo-system, namely, lubricants, additives, surface textures or coatings. However, it may have a larger impact if all those advancements are implemented and improved together.

2.2.2. Lubricating oils

An EV has different components similar to ICEVs which are required to be lubricated with oils; the driveline being the most important. In contrast to oils required for drivelines from ICEVs, those for EV driveline require other critical properties to operate effectively. There are three essential aspects being considered for development of novel EV driveline oils which have not been included in current ICEV driveline oil standards [60]: the first involves the ability of the oil to limit corrosion of copper elements, mainly copper wiring, and to be compatible with polymers used in electric and electronic components, namely, sensors, resins, contacts, etc. It also includes the development of standard methods to evaluate such properties in realistic EV driveline operating environments at high temperatures. The second aspect is to achieve extreme low viscosity meanwhile the third one is the improvement of electric properties. Hence, an effective oil for EV driveline will be expected to provide high performance in electrical compatibility, at extreme low viscosities, at speeds higher than 20 000 RPMs in an operating condition of sustained excursions at high temperatures [60].

The best traditional lubricants used for ICEVs with the possibility to be employed in EV automotive components are made of mineral-based oils formulated with different additives to meet stringent requirements. Currently, lubricants made of synthetic-based oils have a great acceptance due to better lubricity and thermal and oxidative stability than mineral-based oils, promoting a more prolonged life. There is a huge published literature about further optimization of lubricating oils for different applications. The most notable achievements have been done by research focused on low-viscosity oils, vapour phase lubrication, ionic liquids, and nanotechnology-based anti-friction and anti-wear additives [5,97–107].

The growing concern over environmental protection has aroused a global widespread alarm on substituting mineral-based products with eco-friendly goods obtained from alternative renewable sources. Thus, bio-lubricants made of different sources, namely, animal fats and vegetable oils have been subject of numerous investigations [108,109]. Vegetable oils have been demonstrated as the most promising alternatives to substitute automotive mineral-based lubricants since they have wide arrays of physicochemical properties meeting with the most of current requirements for engine lubricants, hydraulic fluids, compressor oils and gear oils, even exhibiting very low friction coefficients. The prospects being considered for future automotive bio-based lubricants are those produced from non-edible oil seed crops, namely, *Jatropha curcas*, *Calophyllum inophyllum*, *Pongamia pinnata* (karanja), *Hevea brasiliensis* (rubber seed), *Ricinus communis* L. (castor), and *Simmondsia chinensis* (Jojoba). Microalgae which is considered as the third-generation feedstock, has become the latest potential source of bio-based lubricant [109].

The greatest advantages of bio-lubricants are renewability, biodegradability and better lubricity than mineral-based oils meanwhile the principal drawbacks are low oxidative stability and poor low temperature characteristics which limit their full potential for wide-scale usage. Nonetheless, the addition of additives (antioxidants and pour point depressant), nano-additives, emulsification, and chemical modification (transterification, estolide formation, epoxidation, etc.) have been recently demonstrated to diminish up those deficiencies [109]. However, it still the subject of further research, in particular, for EV driveline application.

Bio-based ionic liquids are also one of the most recent progresses. For example, ionic liquids derived from environmental-friendly and halogen free sources and synthesized from various sources of bio-polymers such as proteins (amino acids) and carboxylic acids have gained great attention for development of bio-lubricants [110,111].

2.2.3. Dynamic seals

Dynamic seals, either reciprocating or rotary seals, are used in different components of EVs, for instance, transmission, steering gear box, wheel bearings, actuators, etc. Their function is to generate an elasto-hydrodynamic lubricating film between the seal and shaft surfaces with relative motion while a pumping action from one-side toward the other-side of the seal is formed to prevent fluid (oil, grease, coolant, water, etc.) leakages [112]. Different types of dynamic seals made of different materials are commercially available for automotive applications. Rubber, ethylene-propylene-diene monomer (EPDM), nitrile-butadiene rubber (NBR), neoprene (poly-chloroprene or chloroprene rubber, CR), fluorelastomer (FKM), silicone rubber (vinyl-methyl silicone, VMQ), Polytetrafluoroethylene (PTFE) are the most common materials employed to manufacture seals at present [113].

The efficiency of a seal is mainly determined by wear resistance, low friction and sealing capacity with the short and long-term use under a wide range of temperatures. The performance is dependent of the compatibility existing between the seal and the lubricant involved [114,115]. A poor compatibility generates swelling and degradation of the seal with time. Thus, both seal and lubricant should be selected or developed primarily by considering compatibility.

Reducing friction in the sealing gap without compromising sealing capacity and durability of dynamic seals could be an important achievement for energy consumption in EVs. However, optimizations have been barely achieved perhaps due to the complexity of different parameters involved, namely, non-linear viscoelastic properties of the seal material, swelling and changes in the seal properties, and long time-consuming performance tests.

Recently, the most outstanding optimizations in performance of dynamic seals have been obtained by applying surface texturing techniques either to shafts [116] or seals [117]. The seal materials exhibiting the lowest friction coefficients are PTFE, polyimide (PI), and polyetheretherketone (PEEK), PTFE presenting the lowest friction coefficient values [118,119]. These materials could be considered for development of new seals options for components in EVs.

Overall, reduction of friction and increase in durability of seals can be achieved by modifying surfaces texture, developing novel composite materials for seals and advanced lubricants. However, studies of compatibility under realistic working environments should be considered primarily in the case of developing new seal materials or lubricants.

2.3. Steering system

The function of the steering system is to convert the turning movement applied to the steering wheel by the driver into a change in the steering angle of the steered wheels. Simultaneously, it informs the driver, by means of the haptic feedback, of the current driving situation and the road conditions [120]. In EVs, the steering system cannot be considered as a source of electric energy consumption since it can be operated by human energy (driver's energy) by using pure mechanical steering systems (MSSs), which could be optimized in terms of comfort and durability by decreasing friction and wear of the sliding components involved in the system. However, considering the future trend of EVs to become autonomous, electric power assisted steering systems (EPASSs) will be required. The IWM systems do not need an additional steering system since they are capable to control vehicle's steering by controlling the speed of each wheel independently enabling the steered wheels to turn by the difference of speed in each wheel. In contrast, the EVs having the other drivetrain systems mentioned above, EPASSs are the best option in terms of efficiency due to its on-demand system feature, which allow an operation only when the steered wheels are required to be turned [121,122]. Besides, it consumes about 5% of the vehicle's energy [123] in comparison to the hydraulic power assisted steering systems (HPASs) that consumes almost 15% of the total vehicle energy by the continuous action of pumping even if the system is not used [124]. Other advantages of EPASSs are the reduction of steering torque and the return-to-centre performance of the steering wheel when it is steered, giving accuracy, comfort and steering road feeling for driving [125]. According to the research works reported in Refs. [126,127], the efficiency of EPASSs in terms of energy consumption can be enhanced further by implementing advanced control techniques.

The most common mechanical configurations used for EPASSs in vehicles with independent suspensions of the front axle, which is the case of most of passenger EVs, are the rack-and-pinion gear and the worm gear, having mainly some of the configurations illustrated in Fig. 5, due to lower steering elasticity, less need for space, less weight of the full steering system and lower production costs [128,129]. Conventional standard EPASSs developed for modern cars are based on a dependable mechanical coupling between the steering wheel and the steered wheels comprising electromechanical components that consume energy and reduce the overall EV efficiency. In general, the steering column unit (involving the steering wheel, the torsion bar and universal joints), the servo unit (comprising the torque sensor, the assist electric motor, the controller and the reduction mechanism (pinion-and-rack or worm gear)) and the tie rods are the key components in these systems.

Different designs and concepts have been proposed and developed by vehicle manufacturers to improve performance of EPASSs in terms of energy consumption, comfort and safety. For example, EPASSs by means of elliptical wave train engine, belt driven rack, epicyclical gear and by wire, well known as steering-by-wire. The last being the most recent advancement for modern vehicles [129]. It can provide a much better power steering feel, quieter wheel steering, and steering on-demand by eliminating mechanical connection between the steering

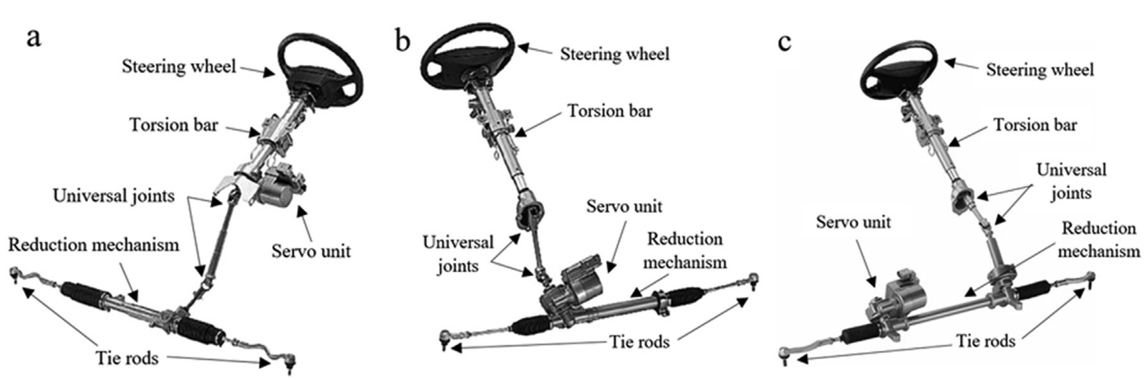

Fig. 5. Common electric power assisted steering system (EPASS) configurations: a) Column type; b) pinion-type; c) dual pinion-type.

wheel and the rack. It makes it simpler and more efficient, so it is being highly considered for the development of a new generation of autonomous EVs [130].

In general, the components generating energy losses by friction in EPASSs are the steering column comprising tribological elements such as rolling bearings and universal joints, the electric motor comprising also rolling bearings and brushes/slip rings (in the case of brushed type motors), the reduction/transmission mechanism involving the pinion and rack gear, the rack guide yoke, the rack bushings, dynamic seals, belt and pulleys (in the case of belt driven rack systems) and tie rods. If steer-by-wire systems are considered, universal joints from the column are discarded. Hence, the efficiency improvement in terms of friction losses in steering systems could be focused on reducing friction and improving durability of the elements mentioned above or by implementing either IWM or steering by wire systems in EVs.

2.4. Tyres

A considerable part of the energy supplied to a vehicle is consumed due to rolling friction of tyres. As stated in the study developed by Holmberg and Erdemir [5] on friction losses in EVs, about 41% from the total electric energy supplied to the EV is used to overcome rolling friction in the tyre-road contact due to hysteresis in the elastomeric tyre during driving. Thus, the efficiency of vehicles, either ICEVs or EVs, could be significantly furthered by reducing rolling friction force, which can be achieved by optimizing the tyre design, operating parameters and materials.

There are different reviews dealing with the reduction of rolling resistance of tyres [4,131–134]. One of the most effective and classic strategy to reduce rolling friction in tyres is increasing air pressure [135] and monitoring it [4]. However, reducing rolling friction in tyres can imply a decrease in time of acceleration and breaking due to increase in tyre slippage, which is negative in terms of comfort and safety. Therefore, the goal is to achieve low rolling friction, but high traction and breaking friction, which can be reached by modifying the viscoelastic modulus of the tyre material [136–138].

Different approaches to reduce hysteresis loss of rubber compounds have been conducted broadly [134]. They include optimizations in elastomers, reinforcing particles, and curative packages. The most significant results have been presented by reducing the loading level of reinforcing particles. Nevertheless, the treadwear, traction, and handling performance of tyres is negatively affected. The use of elastomers with low Tg has been effective to reduce the hysteresis of rubber compounds at high temperatures at the expense of wet grip performance. Also, functionalized polymers can provide the flexibility of enhancing the rolling resistance performance of tyres without compromising wet and dry traction.

Nowadays, the dynamic properties of rubber compounds used for tyres is being improved by using different reinforcing particles through a variety of methods developed specifically as new tools for compounding engineers and scientists. The new methods can increase the rolling resistance performance without compromising, or even by improving, other performances. In addition, nanoparticle technology can be adopted and investigated also as a new tool to reduce energy consumption by rolling friction and reducing weight and wear of tyres [134]. Some of the most successful nanotechnologies applied for the improvement of tyres are based on rubber nanoparticles, silica carbide, core/shell polymer nanoparticles, poly(alkylbenzene)-poly(diene) nano-particles, polyhedral oligomeric silsesquioxanes, carbon nanotubes, graphene, aerogels, nano-diamond and fullerenes [139]. Although these technologies have demonstrated noteworthy progresses, barriers, namely, high cost, unreliable production techniques and uncertainty over environment, health and safety risks limit the use of nanotechnology in the production of commercial tyres, which are future challenges for research.

2.5. Wheel bearings

Conventional rolling bearings are used in the road wheel hubs, which are unavoidable components in any vehicle moved by wheels. They permit reduce rotational friction and support radial and axial loads caused by the wheels rotation. Although the wheel hub bearing has changed a great deal with the development of the automobile itself, it is still a source of friction losses and a component that is susceptible to wear and rolling contact fatigue, decreasing durability. Those friction losses and durability can be a key factor for the overall performance and efficiency of EVs. The improvements of these components have been mostly focused on ICEV applications. Nevertheless, considering the great advances raised in ICEV's wheel bearings and the EVs architecture, which is similar to ICEVs, the wheel bearing technology achieved till now is being transferred and adapted to EVs.

There are two kinds of automotive hub bearings with different configuration and characteristics used nowadays: double-row tapered roller bearing and double-row angular contact ball bearing. The first is primarily used in the United States while the second is commonly implemented in vehicles from Japan and European countries [88]. The bearings are installed in hubs packed with a specific grease on assembly and sealed with elastomeric lip seals [140]. The development trend of these components is based on a flexible compact structure, convenient maintenance, weight, endurance at high temperatures and speeds, sealing capacity of the seal, reducing fretting and resisting rolling contact fatigue. The advances in the lubrication technology of the bearing hub is also a key parameter to improve performance. The challenges for development of bearing hub greases are based on requirements, such as reducing degradation (extend the useful life of grease), resisting high temperatures and shear stresses, water and leakage resistance, compatibility with elastomeric seals and reducing wear and friction. The advances in rolling bearings and grease technology are mentioned in above Sections 2.1.1 and 2.1.3, respectively.

2.6. Constant-velocity joints

Constant-velocity joints are designed and used to transmit power between two shafts with some degree of axial misalignment [141]. Overall, they are used to transmit power from the main driveshaft to the wheels in modern vehicles, including most of EVs. Most developments and advances of these elements for automotive application has been based on ICEVs operating conditions. So, there is a lack of literature about the performance and improvement of these elements under EV operating conditions. These joints consist of an array of rolling elements held by a retaining cage between two raceways. The entire assembly is packed with grease and sealed inside a rubber boot. The rolling elements that can be balls, needles or rollers, the raceway grooves and the cage interact by contact between each other to operate. If the shafts are aligned, the rolling elements are stationary. Otherwise, the rolling elements undergo a low oscillation reciprocating motion producing a high load on the ball race contact and a low velocity. It may be dominated by BL regime. The consequence of these operating parameters are relatively high friction and failures due to contact fatigue and wear of both rolling elements and raceway [142]. However, the most common cause of failure in these mechanical elements is damage to the boot promoting loss of grease and starving the rolling elements from lubrication [140].

The reduction of friction and increase of service-life of constant-velocity joints can be directly achieved by optimization of the rolling elements, lubricity and service-life of grease, but mostly by improving the durability of the boot [143].

2.7. Kinematic energy recovery system (KERS)/Flywheels

Generally, the kinetic energy of moving vehicles is dissipated in terms of friction, wear and heat of breaking materials to deaccelerate or stop the vehicle. Instead of dissipating such energy, it can be recovered to be used further in the vehicle, generating much higher energy consumption efficiency. KERSs, also known as regenerative brakes, are the most effective way to recover kinetic energy from breaking. Basically, they recover the kinetic energy of the vehicle and store it for using it on-demand, mainly, in the acceleration stage, in which much energy is needed. It is an element particularly used in most of EVs and hybrid vehicles for enhancing their energy consumption performance.

The best option for energy storage from regenerative brakes is the flywheel [142]. A flywheel stores energy in kinetic form in a rotating mass. The energy stored in a flywheel is proportional to the product of its moment of inertia times the square of its angular velocity. The energy stored per unit mass can be increased by increasing the angular velocity of the flywheel. Flywheels, as storage devices, have many advantages (high power/energy density, availability of output energy directly in mechanical form and high efficiency) in comparison to other energy storage options, such as: batteries, compressed air, hydrogen and super-capacitators [144,145]. Flywheels were first developed to recover the braking energy in race cars, but now they are being used for buses and some passenger cars, in particular, hybrid and EVs [146,147].

Flywheel devices are commonly coupled to the mechanical transmission through a clutch system allowing regenerative braking and power augmentation. Examples of two typical driveline configurations including CVTs and flywheels can be seen in Fig. 6. Those configurations must be capable of accepting power during braking and/or from the primary power source, as well as delivering power to the vehicle for traction and/or auxiliary power loads by engaging or disengaging the clutch, respectively [146]. The energy recovery, storage and delivering efficiency depends strongly on the efficiency of power transmission of the clutch system and friction losses in the flywheel bearings that allow the rotation of the mass. The flywheel systems have recently re-emerged as a promising application for energy storage and KERS due to significant improvements in materials and technology, such as composites [145,148], low-friction bearings [149], magnetic bearings [150], and power electronics and control techniques [151]. However, reduction of friction losses in bearings and the increase of power transmission efficiency in the clutch are the current challenges in terms of tribological solutions.

Superconducting magnetic bearings have been developed and implemented to reach zero values of friction losses in the rotation of flywheels for high energy storage applications, for example, renewable energy plants [150]. However, the operating conditions, namely, cryogenic temperatures and vacuum, required for achieving superconductivity can be a restriction to implement magnetic bearings in automotive flywheels due to the complexity of devices, maintenance and cost.

2.8. Comfort and safety devices

2.8.1. Air conditioning system

Vehicle air conditioning systems (ACSs) have achieved numerous improvements since the 1940′s. Many changes have been made to accommodate new vehicle designs, improve fuel efficiency, gain environmental acceptability, enhance passenger comfort, provide health benefits and increase passenger safety. Since the entrainment of EVs to the passenger vehicles market, ACSs were required to be implemented in commercial passenger EVs. Thus, the most efficient ACSs developed for ICEVs are being transferred and implemented in modern EVs. Currently, the most common used types of compressors for ACSs are based on configurations such as rotary piston, scroll and variable displacement (reciprocating). The last configuration being the most popular for automotive applications. Scroll compressors are quickly becoming as popular as reciprocating compressors because they do not have as many moving parts and are therefore more reliable. The performance improvement of ACSs has been majorly focused in the compressor configuration [152–154] and development of more efficient refrigerant and lubricants [155–158].

The refrigeration industry has moved away from chlorofluorocarbon-based refrigerants such as R12 and R22 to more eco-friendly refrigerants such as the hydrofluorocarbon-based refrigerants R134A, R410A and isobutene R600a. Moreover, the use of CO_2 as refrigerant to replace harmful chorofluorocarbon and hydrofluorocarbon refrigerants has gained great interest in the last decade. Nevertheless, the tribology in CO_2 environments is not yet very well understood and advances in this area are highly required. The compressor lubricants mainly employed are synthetic polyolester and polyalkylene glycol due to miscibility issues with refrigerants [158]. Recently, nanotechnology has been applied to reinforce compressor lubricants. For instance, the addition of Al_2O_3 [156] and CuO [155] nanoparticles in compressor lubricants have demonstrated considerable improvements at certain concentrations.

The introduction of alternative refrigerants and advanced lubricants to rise the energy efficiency of compressors has also claimed for the development or application of novel materials and coatings [158–163] in sliding components in the compressor. It allows withstanding severe operating conditions while reducing wear and friction caused by the tendency of using smaller clearances and increased speeds in advanced compressors. The most recent studies have been aimed in using coatings made of polymers [160,163], WC/C [153,161], TiN and TiAlN [153], and DLC [153,158] for sliding components.

The friction generated by the operation of the ACS generates a considerable amount of friction losses which contributes to higher energy consumption in EVs. Therefore, the enhancement of the ACS efficiency in terms of tribology can be a significant way to minimize energy consumption.

2.8.2. Windshield wipers

The windshield wipers are needed and required in both ICEVs and EVs to assure a better driver visibility. It is achieved by cleaning the frontal and rear window-glasses removing dirt particles under wiping action using a washer fluid (water or a chemical liquid). The wiper also helps to remove water excess and leaves a thin film of water on the windshield in case of raining [140].

Wipers have a slender strip of a rubber compound with carbon filler material (blade) supported by 4–8 clips in an arm. Typically, the arm

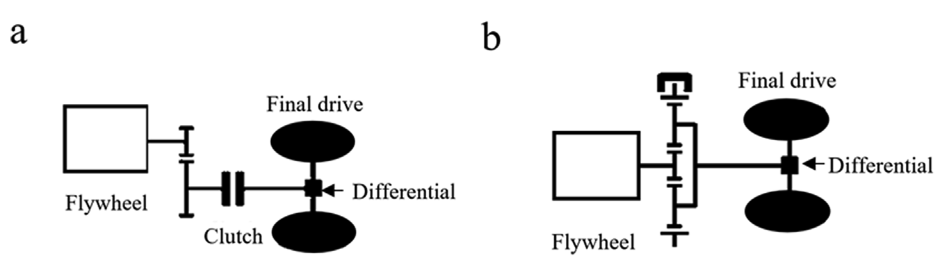

Fig. 6. Examples of typical CVT configurations comprising a flywheel for energy storing: a) slipping clutch transmission system; b) brake-controlled planetary gear set system.

applies a load from 10 to 20 N to the clip hinge centre being distributed almost uniformly along the blade. The speed can vary from 0.5 to 1 m/s generating friction coefficients about 1.4 in dry conditions while 0.15–0.2 in wet conditions (water or chemical liquid) [140]. The wiper blade, commonly made of rubber, is expected to work in three different environments: dry, wet and tacky. Dry is considered when glass is dry without any water. Wet condition corresponds to a lubricated condition with water or chemical liquid while tacky condition, also known as drying condition, corresponds to a transitory regime between wet and dry glass when the water is evaporated from the glass surface [164]. In general, during operation, wiper blades are subjected to sliding friction, stick–slip, wear, and different environmental effects [165], mainly, UV radiation, changes in temperature and unusually interaction with acids from acid rain.

Nowadays, there is a growing research interest in the lubrication of windscreen wipers. Considering the high levels of friction generated even in wet condition, it represents a considerable energy consumption source for EVs, which makes it an important issue for optimization. In some extent, the reports provided in Refs. [164–169] contribute with the understanding and optimization of the lubrication and contact phenomena existing in operation of wiper blades by proposing some parameters, materials and techniques to reduce friction, vibrations, noise and wear. Nevertheless, this topic is still scarcely investigated, so it is considered a subject of further research.

Moreover, the entire windshield wiper system involves two wiper blades attached to two arms, which are connected to a mechanism (typically two 4-bar linkages in series or parallel) being moved by an EM. In the mechanism, the bars are linked through rolling bearings or ball joints to allow rotation or oscillation producing low friction. An EV can comprise either one or two wiper systems for only the front or both front and rear screens, respectively. Additionally, a pumping system, commonly an EM pump, for the washer fluid is included. So, windshield wiper systems encompass various tribological elements producing friction losses which can be improved. Those elements are the wiper blades, rolling bearings (see Section 2.1.1) or ball joints (see Section 2.9.1), the EM (see Section 2.1), pump and the washer fluid's lubricity.

2.9. Suspension

2.9.1. Ball joints

Ball joints are the most commonly used type of joints in parallel manipulators for ICEVs, but friction force and clearance of this kind of joints affect considerably the functional performance of mechanisms. High performance suspension systems from ICEVs are being implemented into modern EVs to take advantage of the advances and developments achieved in suspension elements, namely, ball joints, shock absorbers, springs, etc.

The ball joints are used to allow the vertical motion of suspension system and the rotational motion of steering system simultaneously. Some aspects of handling, steering feel and ride-comfort of a passenger vehicle can be attributed to the tribological performance of the steering and suspension components, including the ball joints. High friction force is required in ball joints to inhibit vibration, fluttering and shimmy of the steering and suspension systems to a certain extent. However, high friction increases the torque required for the initiation of motion causing a heavy handling without smoothness, unpleasant steering feel and higher energy consumption. Both the low friction for smooth sliding initiation and the high friction for inhibiting vibration are required in ball joints [170]. A ball joint consists of a ball stud, a bearing, a bearing plug and housing, grease and a seal (rubber boot). The most followed route to obtain the friction required in ball joints has been attained by the improvement of lubricating greases. However, surface treatment and coatings solutions based on PTFE [171] and DLC [170] for the ball stud have been applied lately to extend service life and approach the appropriate friction in ball joints. The tribological performance of ball joints has been enhanced not only by modifying the ball stud, but also by modifying the bearing in terms of elasticity, surface roughness, resistance to temperature, and by increasing the durability of the boot [172].

2.9.2. Shock absorber

Shock absorbers play a crucial role in the driving quality and performance of an EV. A smooth and comfortable ride is provided by the attenuation of the energy transmitted from the wheels to the car body by the reciprocating work of shock absorbers that can be those passives, semi-actives or actives.

In EVs, the level of interior sound and vibrations are more evident than ICEVs because EMs produce much lower vibrations and sounds than ICEs. Besides, EMs generate other type of noises from electromagnetism and current. Although this sound pressure level can be considered low, the interior sound quality is reduced affecting negatively the passenger's psychology. In addition, the squeak noise

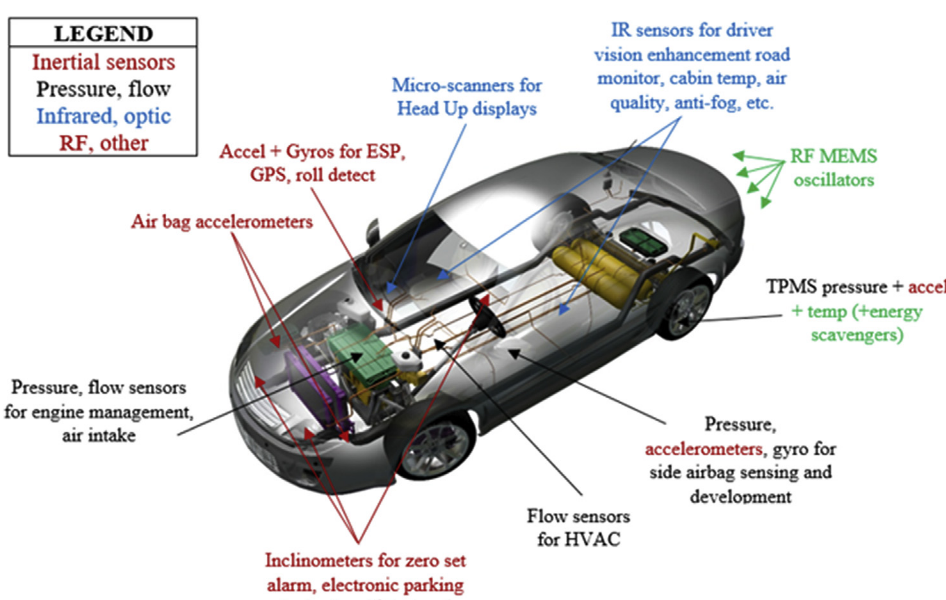

Fig. 7. Examples of MEMS-based sensors used for hybrid and electric vehicles.

produced by the shock absorbers becomes apparent even in modern EVs, so it represents a concern for drivers and passengers [173,174]. Squeak noise is perceived by drivers and passengers as a quality deficiency, or even, an EV malfunction. Although there are different hydraulic or pneumatic shock absorbers, namely, twin-tube, mono-tube, spool valve and magnetic, the most popular for passenger cars are those hydraulic twin-tube and mono-tube. They operate using spring-loaded check valves and orifices to control the flow of an oil/hydraulic fluid inside the tubes through an internal piston moving in reciprocating motion. A dynamic seal is used to retain the oil/hydraulic fluid inside the shock absorber tube avoiding leakages.

Within the long-term use and high speeds, the shock absorbers exhibit problems caused by the lateral friction between the piston rod and the dynamic seal conductive to reduction of performance, generation of noises due to wear of piston rod and seal, and shock absorber's oil leakage [175]. It can be optimized by reducing friction at the piston rod and seal interface using advanced oil/fluids [176], advanced seal design and materials (see Section 2.2.3), and novel shock absorber hardware configurations [175].

2.10. Micro-electro-mechanical systems

An EV generally consists of different subsystems forming a coordination among themselves to allow the EV work efficiently. There are multiple technologies which can be applied in EVs to make all the subsystems work together. MEMSs are one of the most popular technology applied in modern vehicles. Examples of the most used MEMS in hybrid vehicles and EVs are illustrated in Fig. 7. They can be defined as miniaturized mechanical and electro-mechanical elements that are made using techniques of microfabrication. The physical dimensions of MEMS can vary from less than one micron to several millimetres [177].

The most common MEMSs applications are MEMS-based sensors for airbags and vehicle stability control systems. MEMS-based sensors convert a mechanical signal to an electrical signal producing friction and wear due to its operation. Accelerometers, gyroscopes, inclinometers, flow and pressure sensors, energy harvesters, oscillators, IR sensors, etc., are examples of modern automotive MEMS-based sensors [178–181]. Although, MEMSs are currently having good acceptation in different applications, high level of stiction, dynamic friction and wear are restrictive factors for the widespread reliability of MEMSs for EVs [182,183]. Due to the small scales (micro- and nano-scales) of MEMSs components, the capillary force, Vander Waal, chemical bonding and electrostatic contributes to adhesion, which in turn significantly influences friction. To overcome such negative factors, self-assembled molecular coatings, hermetic packaging, the use of reactive materials in the package and surface modification have been demonstrated as effective solutions [183–186]. Therefore, the enhancement of tribological performance of MEMS devices has been reached by increasing the lubricity and hydrophobicity of MEMS surfaces through reducing the intrinsic friction and adhesion forces using thin films, namely, self-assembled monolayers, ionic liquids and DLC coatings [186,187]. In more recent investigations, the use of different lubricating films, such as: perfluoropolyether (PFPE) [188], multiply-alkylated cyclopentanes [189], triazine dithiol monosodium [190], eco-biodegradable lubricant based on hydroxypropyl methylcellulose [191] and dual or multilayer coatings [192,193], have demonstrated superior tribological properties, in particular, to reduce friction in MEMSs. The dual film coating, involving the lubrication synergy of solid and liquid combination, has become the most popular design concept for increasing service life and load carrying capacity for MEMS devices [186].

Finally, most of the tribological components identified for EVs are comprised in the infrastructure of modern and high performance ICEVs. Those components are being transferred and implemented in EVs to take advantage of the advances and improvements achieved to date. However, although all those tribological components have been effectively boosted for use in ICEVs, they still represent a challenge for optimization considering the particular operating conditions of EVs, which has been barely investigated.

The current state and gaps in tribological optimizations for the critical components identified for EVs were addressed and discussed generally in this pioneer review considering the most remarkable published literature. However, further specific identification and quantification of research quality and gaps for each tribological element for EVs comprises a more extended specific review work, which would be very valuable and complementary for specific research topics. It could be appropriately carried out through paper grading exercises like that proposed in the scientific article reported by Ishizaka et al. [194].

3. Conclusions

The current status of achievements in terms of tribological solutions applied to the components and the identification of research gaps for further works and developments have been reviewed and compiled. The main conclusions derived from this work are listed below:

- The most critical tribological components for electric vehicles were classified into electric motor, transmission, steering system, tires, wheel bearings, constant-velocity joints, kinematic energy recovery system/flywheel, comfort and safety devices, suspension and micro-electro-mechanical systems.
- The most efficient electric motor being investigated for application in modern electric vehicles is the synchronous permanent-magnet motor. The tribological elements to be optimized in the future for electric motors are rolling bearings and, in some electric motor types, brushes/sliding rings. It may be achieved by means of development of more efficient greases meeting with eco-friendly demands, materials and coatings. In addition, better understanding of tribology of complex sliding interfaces comprising lubrication with grease and electric contacts is needed for potential optimizations.
- In-wheel motor systems and multi-speed transmissions are the most attractive options for drivelines for modern electric vehicles with aims to become autonomous in future. In-wheel motor systems can be improved as like electric motors meanwhile multi-speed transmissions comprise critical tribological elements to be optimized further such as gears and dynamic seals. The trend of improvement for gears is by using more efficient oils meeting with eco-friendly demands, surface texturing and advanced coatings while the trend for dynamic seals is by using advanced seal materials, texturing in seal and shaft surfaces, and increased compatibility with oils and greases.
- In-wheel motor and electric power assisted steering systems are considered as the best options for the steering system in modern electric vehicles. However, electric power assisted steering system has more critical tribological elements, namely, rolling bearings, universal joints, pinion and rack gear, the rack guide yoke, the rack bushings, dynamic seals, belt and pulleys (in the case of belt driven rack systems) and tie rods, which can be enhanced via tribological solutions. Steer-by-wire systems are the most recent approach to reduce the number of tribological elements in an electric power assisted steering system, but it is still in research progress.
- The tyre-road contact produces the largest friction losses in electric vehicles. Friction in tyres can be reduced by optimizing the tyre design, operating parameters and materials. Lately, nanotechnology has demonstrated significant reduction in tyre friction loss, but high cost, unreliable production techniques and uncertainty over environment, health and safety risks limit its usage in the production of commercial tyres.
- The wheel bearings can be significantly optimized in terms of lower friction and higher durability by using advanced greases, improved rolling bearings and dynamic seals.
- The reduction of friction and increase of service-life of constant-

velocity joints can be achieved by optimization of the rolling elements, lubricity and service-life of grease, but majorly by improving the durability of the boot.
- The best options for energy storage of regenerative brakes in electric vehicles is the flywheel. To improve efficiency in regenerative breaking/flywheel, rising torque transmission in clutch and reducing friction in the rotation of flywheel is required. Friction generated in the flywheel could be reduced by enhancing the tribological performance of rolling bearings or by implementing superconducting magnetic bearings to reach zero friction values.
- Air conditioning systems and windshield wipers system are unavoidable critical components in electrical vehicles. The most common and modern air conditioning systems for vehicles are based on reciprocating compressors which can be enhanced by developing new and advanced refrigerants with nano-technology and coatings and reinforced polymers for sliding elements. Windshield wipers system could be optimized by improving wiper blades, rolling bearings or ball joints, the electric motor, pump and the washer fluid's lubricity.
- Ball joints and shock absorbers are the main tribological elements generating friction in electric vehicles. Ball joints can be boosted by modifying the ball stud and bearing according to its elasticity, surface roughness, resistance to temperature, and by increasing the durability of the boot while shock absorbers could be optimized by reducing friction at the piston rod and seal interface using advanced oil/fluids, seal design and materials, and novel hardware configurations.
- Micro-electro-mechanical systems-based sensors for airbags and vehicle stability control systems are being currently implemented in modern electric vehicles. However, high level of stiction, dynamic friction and wear are restrictive factors for the widespread reliability of micro-electro-mechanical systems. Different solid lubricating films have demonstrated noteworthy improvements in recent investigations, so they can be used for developing advanced micro-electro-mechanical system devices.

Overall, further friction and wear reductions in tribological components of electric vehicles could be reached by developing more advancements for each tribological element, but it may have a larger impact if the current advancements reported for each element or component are implemented and improved jointly.

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