The Impact of Tribology on Energy Use and CO_2 Emission globally and in Combustion Engine and Electric Cars

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Growing concerns over energy and environmental sustainability have lately sparked worldwide interest in more efficient and cleaner transportation systems and industrial activities. Friction roughly consumes one-fifth of all energy used worldwide. One-third of all energy used in transportation goes to overcome friction. At the same time, the fruits of decades of dedicated research on all-electric vehicles powered by advanced batteries are paving the way toward a much cleaner and sustainable transportation future. In this article, we provide a short overview of what are the energy efficiency and environmental impacts of current transportation, industrial, and residential systems and how much of that efficiency is adversely affected by friction and wear losses in moving mechanical parts and components. We also touch upon recent advances in new materials, lubricants, and design changes that could reduce energy losses by 18-40%, mainly resulting from friction and wear. The savings would be up to 8.7% of the total global energy use and 1.4% of the gross national products (GNP). Finally, we calculate the energy consumption and friction losses in battery-powered electric passenger cars and show the benefit of electric cars where the total energy use is in average 3.4 times lower compared to combustion engine powered cars. The CO_2 emissions are 4.5 times higher for a combustion engine car compared to an electric car when the electricity comes from renewable energy sources. Moving from fossil to renewable energy sources may cut down the energy losses due to friction in energy production by more than 60 %.

1. Background/introduction

Since the beginning of the industrial revolution, global energy consumption has increased tremendously, and it now stands at about 400 exajoules (EJ) annually. As in those early years, much of the energy produced today is still based on fossil fuels; admittedly, this has had a significant adverse impact on our environment. Nearly 30% of all energy produced today is consumed by transportation vehicles alone, and of that, about one-third is still lost to friction and wear in many moving parts of cars, buses, and trucks on which our mobility largely depends (Holmberg & Erdemir 2017). Despite obvious direct linkage between friction and energy loss, it has been rather surprising to see that not much attention has been paid in the past to the enormous adverse effects of friction and wear on global energy use and environmental issues. One such credible study was conducted back in the 1960s by a committee chaired by late Professor Peter Jost for the British government (Jost 1966). They documented that annually more than 500 million pounds (£500M) could be saved through the adoption of more advanced lubrication and tribological practices. In the following years, a few other studies emerged with similar goals of assessing the benefits of good tribological practices on energy savings (Jost & Schoefield 1981, JSPMI 1970, Federal Ministry for Research and Technology 1976, Tribology Institution of the Chinese Mechanical Engineering Society 1986, Pinkus & Wilcock 1977).

For the past several years, Holmberg et al. have been developing a more systematic approach toward assessing the global impact of friction and wear on energy and the environment in transportation and other industrial sectors where friction and wear are encountered (Holmberg et al. 2012, 2013, 2014, 2017, Holmberg & Erdemir 2017, Erdemir & Holmberg 2015). These impact studies confirmed that despite the significant advances made in controlling friction and wear, a considerable amount of energy is still lost to overcome friction, especially in the transportation sector. Back in the 1960s, the Jost committee concluded that by adopting advanced tribological materials, lubricants, and practices, economic gains in industrialized countries could reach 1.0% to 1.5% of their GDP by reinvesting about 2% of these gains. Today, we estimate that much less investment is needed to make even greater positive impact on energy savings resulting from the adaptation of advanced tribological solutions that have emerged in recent years.

The internal combustion engine (ICE) is currently used as the key power source in most transportation vehicles. In a typical passenger car, only 21% of the fuel is used to move the car, and the remaining 79% accounts for the energy losses, as shown in Figure 1. To curtail the inefficiencies and environmental impacts of current transportation vehicles, concerted worldwide efforts have been devoted to the design and manufacture of more energy efficient vehicles and machines, not only for economic reasons, but also environmental, i.e., to help meet the requirements for reduced CO_2 emissions arising from the Kyoto and Paris Protocols on climate change (EU Good practice in energy efficiency 2017, Kobayashi et al. 2009). In some countries, this effort is linked to avoiding large government-imposed financial penalties. Increased electrification of transportation vehicles in recent years is considered as a huge step toward curtailing adverse environmental impacts of internal combustion engines, provided that the energy stored in batteries is derived from renewable energy sources. Furthermore, in recent years, auto manufacturers and internet companies have joined their resources toward the realization of self-driving autonomous vehicles capable of navigating through busy traffic without human intervention or involvement. It appears that these developments are leading toward a new paradigm with higher degree of cleanliness, efficiency, and safety. However, despite all the advances made so far with effective lubricants and durable materials, energy and material losses due to friction and wear still remain as major concerns.

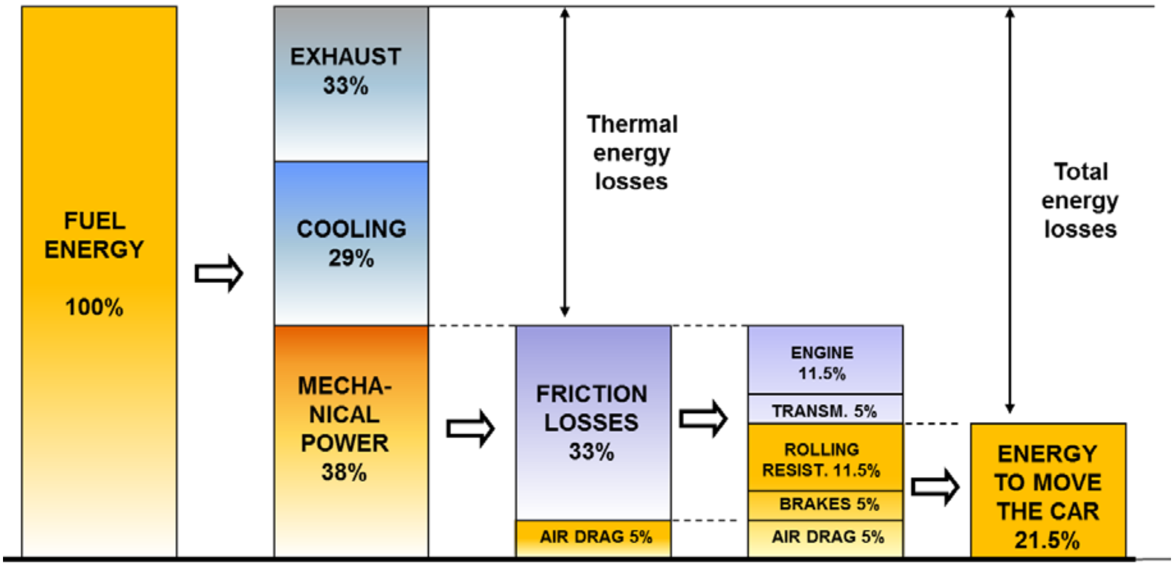

Figure 1. Breakdown of energy use for ICE driven passenger cars, tank-to-wheel calculations (Holmberg et al. 2012).

Referring to our earlier studies, we first summarise the current impact of friction and wear on global energy use, CO_2 emission and economy. We then estimate the potential savings that can be achieved by adopting advanced materials, new lubrication technologies and innovative design solutions. We finally present the advantages of switching to electric vehicles and the reduction in energy losses due to friction when moving from fossil fuels to renewable energy sources.

2. Methodology and calculations

In our work, we have used the methodology developed by Holmberg et al. (2012), where the impact of implementation of new low friction solutions in passenger cars can be calculated as quantifiable effects on energy use, CO_2 emissions, and costs on a global level. The calculations are based on statistical data concerning global and regional energy use that have been collected and reported by international organisations like the International Energy Agency (IEA), national agencies, and commercial organisations. These data were combined with data from research and development activities worldwide that, over the last fifty years, has opened completely new insights on friction and wear mechanisms and their interactions from the nanoscale to the machine component scale (Holmberg & Erdemir 2017).

The total annual energy use by passenger cars worldwide as found in global statistics was divided by the total number of passenger cars worldwide. In such a way, a specific global average passenger car was defined that used 48,000 MJ fuel energy, equalling 1,370 litres of gasoline, annually for driving. This global average passenger car was specified from available car manufacturer data with technical specifications such that it would be 10 years old, have a 75 kW four-cylinder engine, have a weight of 1500 kg, an average fuel consumption of 8 litre per 100 km, and an annual mileage of 13,000 km. The driving conditions have a considerable effect on fuel consumption and thus were the global average driving condition identified from global statistics to be 60 km/h driving speed, average road surface conditions, average wind conditions etc. In this article, we use this global average ICE passenger car and the global average driving conditions as reference when we analyse the impact of tribology in electric cars.

The global average passenger car with its specified technical data and driving condition was broken down to the component and tribocontact level to calculate the energy consumed in each micro contact in the car, including the engine and transmission systems. Calculations were carried out with different levels of coefficients of friction that represent different technical solutions, both from the past and in the future, and their impact on the energy consumption of the global average passenger car was calculated.

The most promising technologies to reduce friction in cars in use now and in the future were reviewed from the literature (Holmberg et al. 2012), and the energy savings resulting from their implementation was calculated. Potential energy, emission, and cost savings from large scale introduction of new tribological technologies in passenger cars were first calculated on the level of one global average passenger car and then upscaled to worldwide and regional calculations.

3. Global impact of friction and wear

Worldwide, our calculations showed that 200,000 million litres of fuel (gasoline and diesel) is used annually to overcome friction in passenger cars. This can potentially be reduced considerably by using new tribological solutions. Reduction in frictional losses will lead to a threefold improvement in fuel economy as it will reduce both the exhaust and cooling losses at the same time. We have estimated that friction losses in passenger cars could be reduced by 18% in the short term (5-10 years) and by 61% in the long term (15-25 years). In the short term, this would equal a worldwide savings of 174,000 million euros, 117,000 million litres of fuel, and 290 million tonnes of CO_2 emissions. In the long term, it would equal to savings of 576,000 million euros, 385,000 million litres of fuel, and 960 million tonnes of CO_2 emissions (Holmberg et al 2012).

It may seem contradictory that the savings in litres of fuel from reduced friction can be even bigger than the total amount of fuel used to overcome friction. Still this is correct and can be understood from Figure 1. If the friction losses are reduced by e.g. half the needed mechanical power will be reduced accordingly and in addition will also both the energy going to cooling and energy going to exhaust be reduced by close to half. Thus, a reduction in friction will result in an almost triple amount of energy savings.

We further have used the same methodology to calculate the impact of friction and wear on the efficiency and CO_2 emission of trucks, buses, paper machines and mining industry (Holmberg et al 2013, 2014, 2017). This gave us reference data to enable an expansion of the calculations to cover the main societal sectors: transportation, industry, power generation or energy industry, and residential.

Overall, our global level calculations show that 23% (119 EJ) of the total annual energy consumption worldwide originates from tribological contacts, based on data from year 2014 (Holmberg and Erdemir 2017). Of that 87% (103 EJ) is used to overcome friction, and 13% (16 EJ) is used to remanufacture worn parts and spare equipment due to wear and wear-related failures. The role of wear is bigger when the related economic losses are taken into consideration because wear failures also result in other problems than just energy costs, such as costs for maintenance work and production losses. Worldwide, the total economic losses originating from tribological contacts in all societal sectors are estimated to be 2,536,000 million euros annually, of which 73% is due to friction and 27% is due to wear.

Furthermore, the amount of CO_2 emissions originating from friction and wear is 8,120 $MtCO_2$/year when the emissions are assumed to be directly related to the used energy. The share of friction of the total energy use is greatest in the transportation sector, where friction losses are in the orders of 30 % of the total energy use, compared with 20 % in the manufacturing and power-generating industry and only 10 % in the residential and commercial services sector.

Considerable savings in energy losses, costs, and emissions could be gained by implementing new tribological technologies in future mechanical systems. We carried out four case studies of potential savings on passenger cars, trucks and buses, paper machines, and the mining industry (Holmberg et al. 2012, 2013, 2014, 2017). The results showed large differences in the time scale of implementation, as shown in Figure 2. The savings and timescale of implementation shown in the figure are based on the assumption that the present structure in transportation and industry is the same as today and no future trends or changes like e.g. introduction of electric vehicles are here considered.

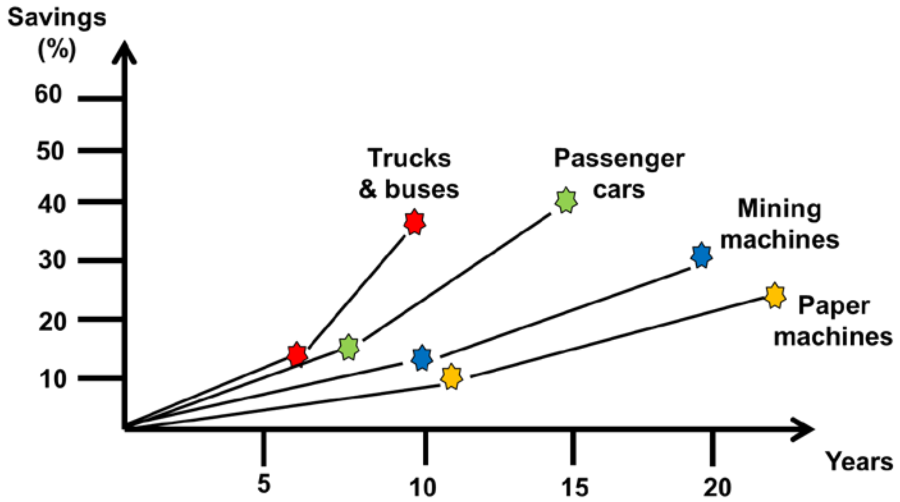

Figure 2. Calculated potential savings over current state of the art by the introduction of advanced tribology solutions in four case studies and their time scale of implementation (Holmberg & Erdemir 2017).

Trucks and buses represent big fleets with a limited number of owners, and their manufacturers are more progressive and quicker in implementing new technologies to their products, so the implementation time can be quite short. This situation contrasts with, for example, the mining industry, which has many owners with more scepticism or negative attitudes toward implementation of new technologies. On the other hand, the paper industry due to the long lifetime of the paper machines is more conservative and hence the implementation of new technologies may take long time because of the very rigid return on investment policies. The largest potential savings would come from the transportation sector and the power generation or energy industry, as shown in Figure 3.

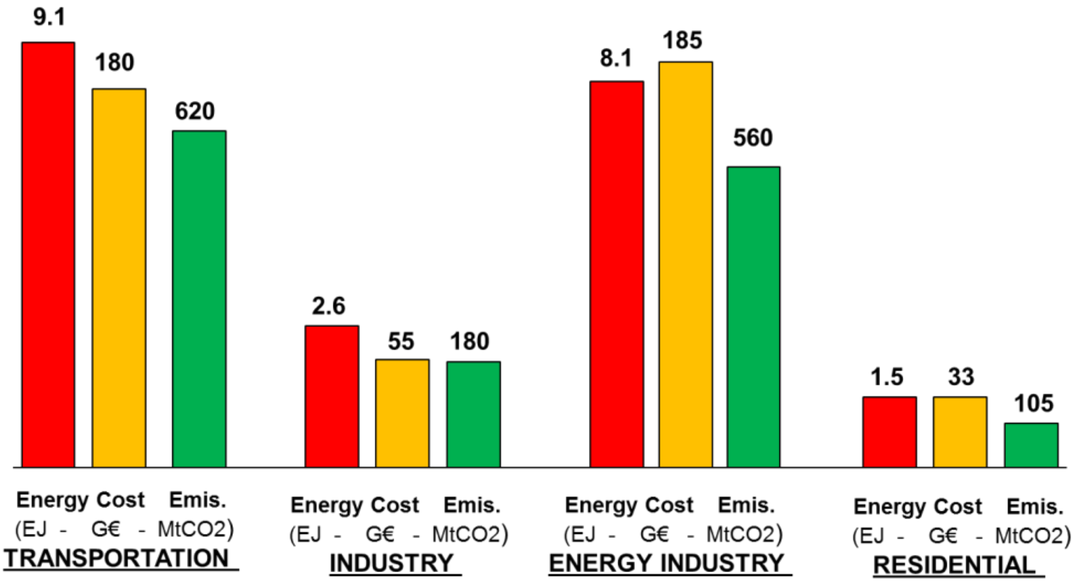

Figure 3. Potential annual energy, cost, and CO_2 emission savings globally after 8 years of intensive advanced tribology implementation (Holmberg & Erdemir 2017).

The implementation of new technology worldwide would save annually in the short term (over 8 years) 21.5 EJ energy, 455,000 million euros, and 1,460 $MtCO_2$ emissions. In the long run (over 15 years), the savings could easily be as much as 46 EJ energy, 973,000 million euros, and 3,140 $MtCO_2$ emissions. These savings would amount to 8.7% of the total global energy use and 1.39% of the GNP.

In 1966, the so called Jost report concluded that 515 million UK pounds can be saved annually in UK after ten years of large scale implementation of new tribological technology and that would be 1.36 % of the UK GNP (Jost 1966). Our calculations show that 50 years later when much of the advanced technology have already been implemented, the potential savings are still of the same order of magnitude, i.e., 1.39 % of the global GNP. The reason for this is that the role of friction in the potential savings was much smaller fifty years ago, only 5 %, compared to potential savings from improved wear protection and reduced costs from wear parts, maintenance work, breakdown and increased lifetime, see Figure 4. The role of energy is much more important today and thus would 74 % of the savings come from reduced friction while the role of wear protection is much smaller as the machinery used already is to a large part very advanced, well performing and reliable.

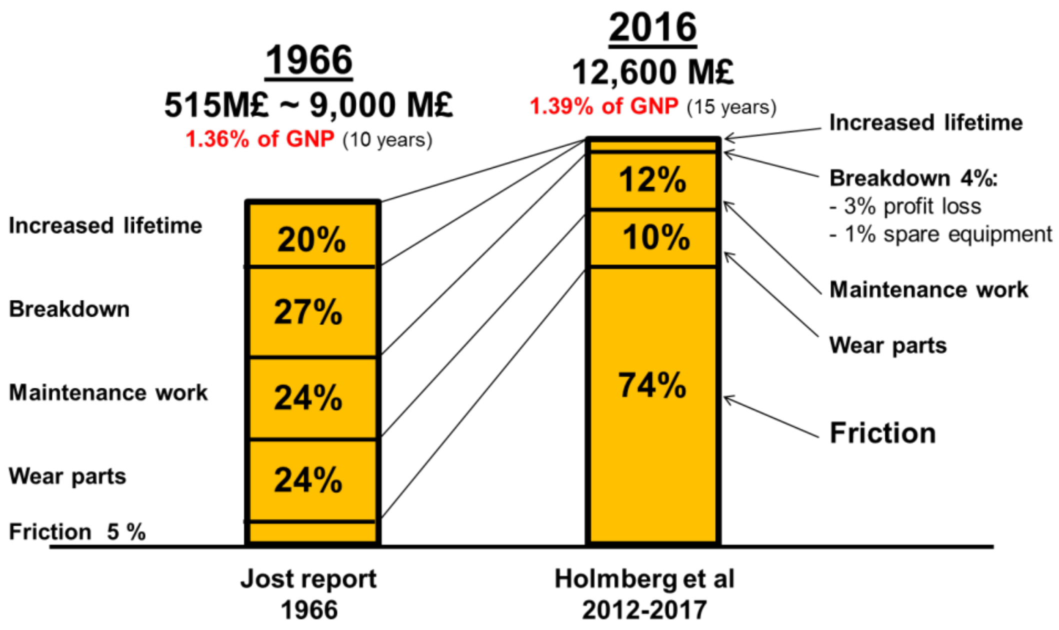

Figure 4. Potential savings in UK 1966 and 2016 by implementing new tribology in machines and equipment, 515 million UK pounds converts to 9,000 million UK pounds of 2017 value (Holmberg & Erdemir 2017).

4. New technologies to reduce friction and wear

Over the last few decades, tremendous advances have been made in the science and engineering of sliding surfaces, bulk tribological materials, and thin protective coatings that can provide ultra-low friction and wear. In textbooks published 25 years ago, the lowest coefficient of friction between two sliding solid surfaces was reported to be that of PTFE (polytetrafluoroethylene) contacts, 0.08. The lowest values reported today are far lower, 0.0005 levels.

The new low friction solutions demonstrated to reduce friction by orders of magnitude are not based on only one or two scientific findings or inventions. On the contrary, there have been many breakthrough research results to achieve this reduction over the last decades. They are related to material development, new lubricants and lubrication solutions, and more advanced component designs. New technologies that have benefitted friction research include nanotechnology, biomimetics, and integrated computational material engineering (Holmberg & Erdemir 2017).

The change from traditional engineering materials like steel or cast iron to some polymeric, ceramic, or composite materials has been one solution to achieve low friction performance. New material treatment and surface modification methods as well as thick composite coatings have also positively influenced the development of low friction surfaces. For example, the technology of depositing a component with a thin surface layer by vacuum techniques (physical vapour deposition or chemical vapour deposition) has been a major breakthrough to radically reduce and tailor friction. Adding a thin layer that is typically only a few micrometres thick does not change the component geometry but improves both friction and wear (Holmberg & Matthews 2009).

Thin diamond-like carbon (DLC) and ceramic coatings are good examples of successful friction control technologies that can help to reduce friction coefficients to 0.001 level. For example, Erdemir and his co-workers developed a highly hydrogenated DLC that provided friction coefficients of 0.001 in inert environments (Erdemir et al. 2000). In other studies involving lubricated sliding with highly polar organic additives like glycerol, hydrogen-free DLC provided friction coefficients down to 0.005 (Bouchet et al. 2017).

Use of mineral-based oils is the traditional way of lubricating sliding components, while synthetic-based oils are on the rise due to their attractive thermal and oxidative stability and longer life. Tribological research has revealed several ways to further improve the performance of traditional lubrication such as low viscosity oils, vapour phase lubrication, ionic liquid lubrication, and nanotechnology based anti-friction and anti-wear additives (Martin & Omae 2008, Kalin et al. 2013, Erdemir et al. 2016, Scherge et al. 2016, Tormos et al. 2017, Choo et al. 2007, Zhou & Qu 2017, Zhang 2015, Arigbay et al. 2010, Kim et al. 2016).

The structure, property, and performance characteristics of the lubricant film are especially important in the very thin highly loaded contacts appearing in engines and transmissions. The thickness of the oil film separating the two sliding surfaces may be only a few micrometres and still carry a load with a nominal contact pressure of 3-4 GPa. The oil film is expected to provide low shear and good protection against wear and surface failure. Coefficients of friction below 0.01 have been measured for lubricating DLC-coated surfaces in the presence of friction modifier additives like glycerol mono-oleate (GMO) or pure glycerol (Kano 2015).

The roughness and surface topography have a remarkable influence on friction and wear. Properly designed dimples, grooves, and protrusions prepared at the micro- and nano-scales can have a beneficial effect, especially in lightly lubricated contacts such as e.g. journal bearings and dynamic seals. Laser texturing of piston rings has been shown to reduce the fuel consumption of engines by 4%, and micro-dimples processed by fine particle shot peening have reduced friction by up to 50% (Kovalchenko et al. 2004, Klingerman et al. 2005, Ryk & Etsion 2006, Etsion 2012, Etsion & Sher 2009, Ishida et al. 2009, Vlădescu et al 2017).

Superlubricity is a sliding state with nearly zero friction, by definition with coefficients of friction below 0.01. Extremely low friction coefficients (even down to 0.0005) has been measured on nano and microscale with sliding surfaces involving highly hydrogenated and polymerlike DLC films, graphite, graphene and other 2D materials (Erdemir & Martin 2007, Nosaka, et al 2015, Hod et al 2018) The research on superlubricity on macroscale in similar contact conditions as appears in real engineering components like in bearings and gears has intensified in recent years, and with the development of hybrid sliding systems involving graphene, nanodiamond, and DLC, and friction coefficients close to 0.004 have been measured (Berman et al 2015). In other studies, superlubricity has also been achieved with MoS_2 as a 2D lubricant additive, which, when combined with nanodiamond particles, aided in the formation of nano-onions at the sliding interface (Berman et al. 2018). In addition to these studies involving solid-state superlubricity, researchers have also achieved extremely low friction coefficients i.e., 0.01 to 0.002 with a variety of liquids especially when used on ceramic surfaces thus opening up the possibility for applications in real mechanical systems (Ge, et al 2019).

5. Impact of increased number of electric cars

In our calculations on the transportation sector, we have analysed the impact of friction and wear according to the present situation, where internal combustion engine (ICE) vehicles dominate and represent more than 99% of all driving systems in use (Statista 2017). One important trend evident today is the introduction of electric vehicles, which are foreseen to replace ICE powered vehicles to a large extent in the future, especially in light-duty and urban vehicles (IEA Global EV outlook 2018). The reasons are related to the low energy efficiency, use of fossil fuels, high carbon emissions, and noise levels of ICE vehicles. In the following we will compare the impact of all-electric with ICE vehicles.

Battery electric vehicles (BEV) differ from ICE vehicles in that the combustion engine is replaced by an electric motor; the mechanical transmission system is simplified; electricity storing, charging, and control systems are added; and brake energy recovery systems are used (Emadi et al. 2008, Ehsani et al. 2010, Zhang et al. 2011, Larminie & Lowry 2012, Faria et al. 2013, Tie & Tan 2013, Apostolaki et al. 2017, Lohse-Busch 2013, Rhodes 2017, Sorniotti et al. 2018). The electric powertrain is more efficient because of low thermal losses and low friction, the latter due to the lack of reciprocating parts and high pressures.

Figure 5 shows the energy breakdown for an electric passenger car that is charged with energy from the grid. Here we define as global average electric car a 2017 model middle size plug-in electric passenger car with lithium ion batteries, a 75 kW electric motor, a one-step mechanical transmission, with a weight of 1500 kg, an average electricity consumption of 18 kWh per 100 km and an annual mileage of 13,000 km (Baptista et al 2013; Ke et al 2017; Lohse-Busch 2013). The driving conditions are defined as the same as we used in the ICE driven passenger car calculations presented above with 60 km/h average speed and global average-road driving conditions including highways, urban and dirt roads (Holmberg et al 2012).

The electric energy from the grid (100 %) and the recovered energy from the brake system (6 %) is used for charging the car battery here defined to be a lithium battery with 10 % energy losses in charging and discharging (Sun 2010; Ehsani et al 2010; Elgowainy et al 2010; Dunn et al 2012; Larminie & Lowry 2012; Tie & Tan 2013; Leou 2016; Apostolaki et al 2017). About 5 % of the energy is used for cabin ventilation, heating, cooling, brake and steering assistance, cooling pump and lights. In an electric car, there is no heat or high motor temperature and thus no thermal energy that can be used for cabin heating like in ICE powered cars (Fueleconomy 2018; Rhodes 2018). The power electronics in the electric car results in 4 % energy losses and the electric motor has 7 % energy losses from stator and rotor resistance, core and strayload losses, windage and friction (Campanari 2009; Ymazaki et al 2004; Emadi et al 2008; Zhang et al 2011; Larminie & Lowry 2012; FMA 2013; Motor Challenges 2014; Rhodes 2017; GreenRiverside 2018).

Thus there will be left 80 % of the energy taken from the grid and recovered energy to be used as mechanical power (Ehsani et al 2010; Larminie & Lowry 2012; Tie & Tan 2013). The energy used to overcome friction is in total 57 % of the energy from the grid which includes 41 % to overcome rolling resistance, 19 % goes to inertia at acceleration and braking. However, 7 % is recovered through the use of the electric motor as a brake generator, hence the true loss for acceleration and braking is only 12 %. The recovered energy will be reduced to 6% due to battery charging and discharging losses. The transmission losses are 3 % and the friction losses in the electric motor are 1 % (EnergyMatters 2013; FMA 2013; GreenRiverside 2018; Sorniotti et al 2018).

As shown in Figure 5, 77% of the energy is actually used for moving the car and the remaining 23% for overcoming various energy losses. The energy needed for the fundamental action of moving the car is employed to overcome the rolling friction of the wheels and the air drag, as well as inertia energy for acceleration where electrochemical energy is transformed into kinetic energy. The inertial energy is equal to the braking energy. Due to regenerative braking, the kinetic energy is transformed back into electrochemical energy, and frictional thermal energy loss takes place. This is shown as an additional 6 % energy input in addition to the 100 % electric energy coming from the grid and resulting in 106 % energy to be consumed by the car, as shown in the second column from left in Figure 5.

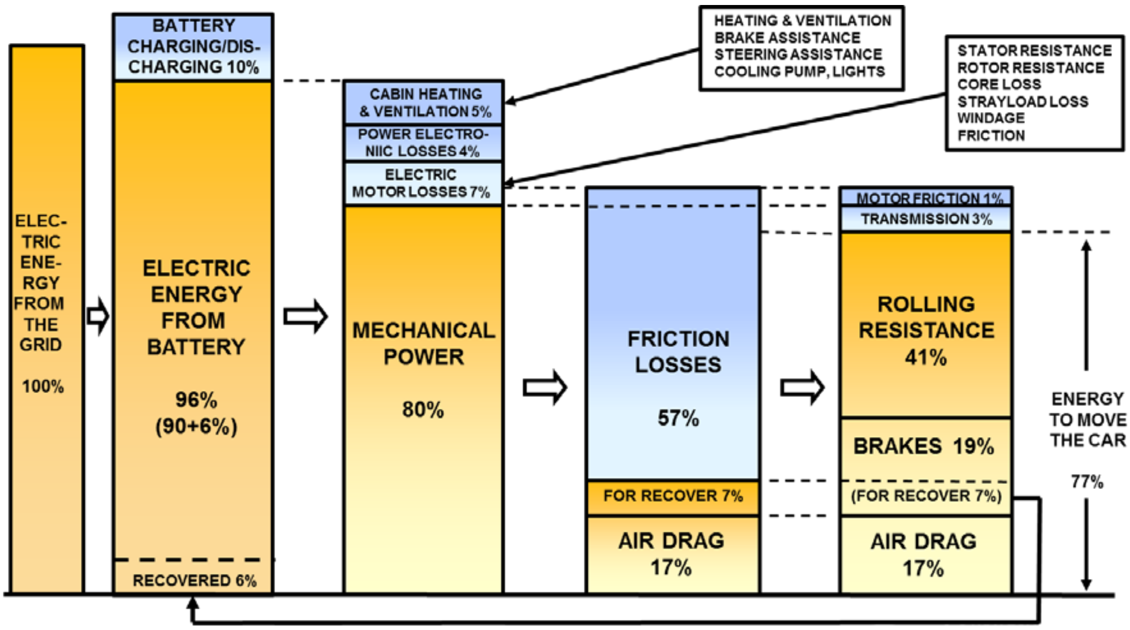

Figure 5. Breakdown of the energy use in a battery electric passenger car, grid-to-wheel calculations.

In the calculations presented in Figures 1 and 5, we have used similar cars and the same driving conditions when comparing the energy use in a combustion engine and an electrically powered passenger car. The ICE powered car represents a global average car for 2010, and the electric car is a 2017 model. The energy efficiency for the combustion engine car is only 21.5 % while it is 3.6 times higher, 77 % for the electric car. The friction losses within the car, with braking and wheel rolling friction excluded, are 16.5 % for the ICE car and only 6 % for the electric car.

We further compared the above defined global average electric car with the earlier analysed global average ICE car (Holmberg et al. 2012), defined in section 2. However, as we did not want to compare a new electric car with an old combustion engine car, we assumed that both are manufactured in 2017. Thus, we changed the fuel consumption for the combustion engine car to 7 litres per 100 km to better represent and correlate to the present situation. We also assumed that the electric car has an additional weight of 200 kg due to the heavy batteries. All other technical data were assumed to be unchanged.

The combustion engine car uses 7 litres of fuel, equalling 230 MJ, for driving 100 km, and of that 180 MJ is energy losses from the engine, drive train and control system and 50 MJ is from rolling resistance, braking, and air drag, as shown in Figure 6. For driving the same distance, the electric car uses 18 kWh electricity, which equals 65 MJ, and of that 15 MJ is attributed to energy losses. The rolling resistance is higher for the electric car due to its higher weight, but the braking losses are smaller due to the energy recovery system. The result is that both cars require about 50 MJ for moving the car over 100 km (Björnsson & Karlsson 2016, Jungmeier et al. 2015).

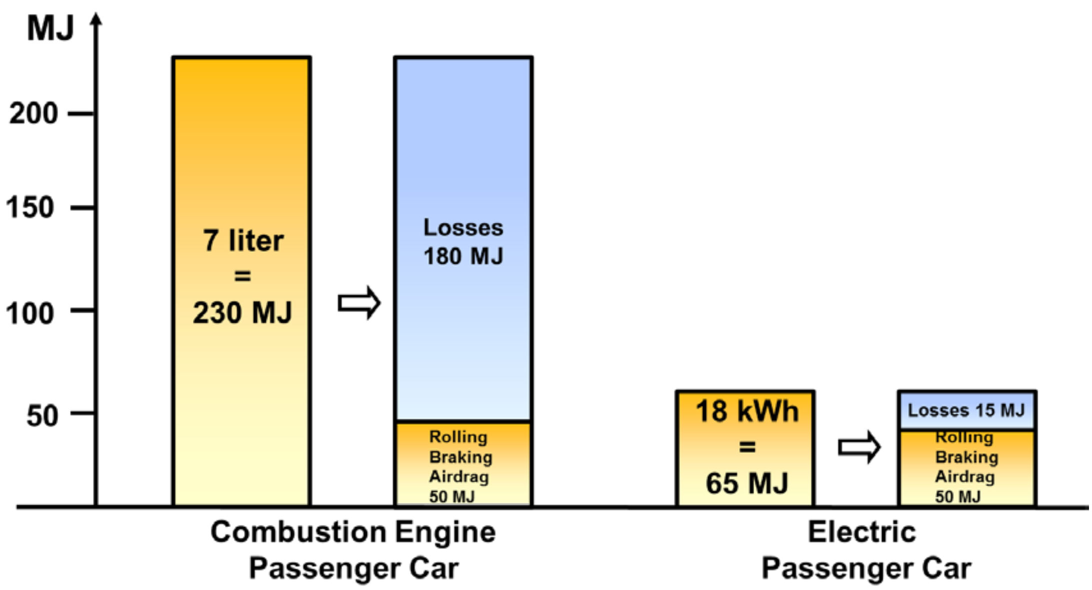

Figure 6. *Energy consumption of global average internal combustion engine and battery electric passenger cars for 100 km driving, tank/grid-to-wheel calculations.*

We carried out a lifecycle analysis based evaluation to get the whole picture of the energy efficiency and the generated CO_2 emissions of the compared cars. The calculations include not only the utilisation stage from tank-to-wheels related to driving the vehicle, but also the fuel and electricity production stage from well-to-tank and the manufacturing, maintenance, and recycling stage from cradle-to-grave of the vehicle itself. We used lifecycle data presented in literature and applied it by making adjustments so that it would fit our two cases of global average ICE passenger car and global average battery electric passenger car (Campanari et al. 2009, Elgowainy et al. 2010, Hawkins et al. 2012, Baptista et al. 2013, Nordelöf et al. 2014, McLaren et al. 2016, Jungmeier et al. 2017, Ke et al. 2017).

We conclude that the CO_2 emissions from the ICE car are equal to 224 g per kilometre (Baptista et al. 2013, Ke et al. 2017). Of this 31 g originates from the vehicle manufacturing, maintenance, and recycling stage, 30 g from the fuel production stage, and 163 g from the driving stage, as shown in Figure 7. The emissions originating from the vehicle manufacturing stage are higher, 48 g/km, for the electric car, but there are no emissions at all when the car is driven. However, the total CO_2 emissions from the electric car depends very much on the energy source for the electricity used (IPCC 2012). Emissions from the electricity generation are 180 g/km if coal is used, 151 g/km for oil, 84 g/km for natural gas, and only 8 g/km for solar photovoltaics and geothermal energy. The lowest emissions level from electricity generation, only 1-3 g/km, is when the electricity source is biomass, nuclear, wind, hydro or concentrated solar power (IPCC 2012, Nordelöf et al. 2014, Messagie et al. 2017). The emissions would be 124 gCO_2/km for the electric car when using electricity produced by a European energy mix.

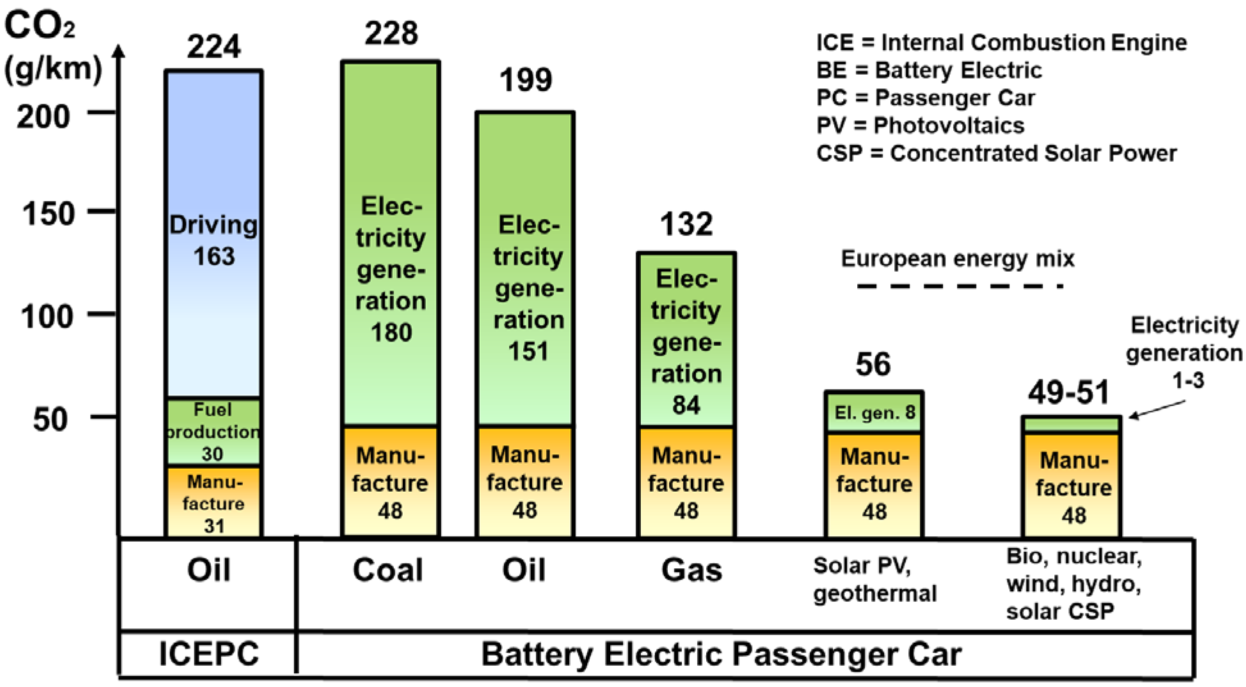

Figure 7. CO_2 emission footprint for internal combustion engine and battery electric passenger cars according to fuel and electricity energy source, cradle-to-grave calculations. The dotted line shows the CO_2 emission footprint 124 gCO_2/km for BEV when using European energy mix for electricity generation.

The change from fossil fuels to renewable energy sources will also have an impact on the global energy used to overcome friction since the structure of energy production technology and methods will change. The renewable energy sources, especially solar PV, geothermal, wind and solar CSP, do not include large machinery and transportation systems in their production stage and thus they have much less energy expenditure due to friction. Based on our previous studies (Holmberg & Erdemir 2017) we analysed the energy production technology structure of the various energy sources. We estimate that friction losses are highest 35 % in coal production including the mining of coal, while it is 20 % for oil production, 15 % for gas, 10 % for bio, hydro and nuclear, 5 % for wind and geothermal, and close to zero for solar energy.

A change from fossil to renewable energy sources would reduce the share of global friction losses in energy production from 20 % today to 13 % on shorter term (2035) and to 8 % on longer term (2050). At present 81% of the energy is produced from fossil energy sources (oil, coal, gas), 17.5 % by heavy renewables (bio, nuclear, hydro) and 1.5 % by light renewables (solar, wind, geothermal). The short term calculations assume that the balance would change to 40 % from fossil, 30 % from heavy renewables, and 30 % from light renewables, and the long term assume a balance of 10 %, 40 %, and 50 % respectively.

6. Discussion

In this paper we have presented the present situation worldwide on how friction and wear impacts the energy consumption, CO_2 emissions and costs. We have calculated potential savings due to large scale implementation of new tribological solutions and technology based on the present structure in industry, transportation and other parts of our society. In that sense, our calculations give a reference point or benchmark to compare against when evaluating future trends and structural changes.

Today we see that there are already several trends that will change these structures, such as collective actions related to climate change and how to achieve a sustainable future. In transportation field, the introduction of electric cars is one and the introduction of autonomous vehicles can be considered as another. The electric car is more energy efficient and involves less friction. The whole impact of such changes is very challenging to estimate due to their complexity including influence of smart grids, development of battery technology, smart charging stations and changes from fossil dominated fuels to renewable fuels.

Friction in the electric motors and powertrains in electric cars is much lower than in ICE car. Still in road traffic, the rolling friction of the rubber tires is a great energy consumer and if this could be drastically reduced by some future technical solution it could certainly have a great positive impact on fuel efficiency.

We have pointed out several tribological solutions to reduce friction in mechanical systems, some of which could reduce friction even by orders of magnitude. In fact, there now exist numerous materials, coatings, and lubricants that can afford superlow friction to sliding surfaces in laboratory scales but these and others needs to be further optimized and integrated into future mechanical devices in order to realize their full benefits. Among the major drawbacks of current superlubric materials and lubricants are that they are very restrictive on their operational ranges. Specifically, many of them cannot provide such low levels of friction and wear over broad ranges of loads, temperatures, environments, and other operating conditions.

Finally, the cost is always one parameter that will influence when decisions on implementing new technical solutions is considered. More sophisticated material and design solutions may increase the manufacturing costs. Other important considerations are the impact of the new solutions on climate and environment as well as how sustainable they will be in the long run? Overall, these and other potential future challenges will determine when and if a new tribological technology can be implemented to further reduce friction and wear.

7. Conclusions

We have analysed in detail the global average energy consumption due to friction in passenger cars, trucks, busses, paper machines and in mining industry. Based on four case studies we have calculated the total global energy consumption due to friction and wear in the main energy consumption sectors: transportation, industry, energy industry and residential. We have also calculated the potential energy and cost savings and CO_2 emission reduction from the use of new technology. Our main findings are:

- 20 % (103 EJ) of world total energy consumption goes to overcome friction,
- 18-40% of that can be saved by applying new technology and that would correspond to 8.7% of the global energy use and 1.4% of the global GNP,
- the biggest saving potential is in transportation (9.1 EJ/a) and energy industry (8.1 EJ/a),
- in an average internal combustion engine passenger car, the total average energy losses are 78.5%. About 30% of the fuel consumption goes to overcome friction,
- friction losses in electric cars are about half of what they are in ICE cars,
- total energy use is 3.4 times higher (230 MJ /100 km) in ICE passenger cars compared to similar battery electric passenger cars (65 MJ / 100 km),
- CO_2 emissions are 4.5 times higher (224 CO_2 g/km) for an ICE passenger car compared to a similar battery electric passenger car (50 CO_2 g/km) when the electricity comes from renewable energy sources like bio, nuclear, wind, hydro or concentrated solar power, and
- moving from fossil to renewable energy sources would cut down the energy losses due to friction in energy production by more than 60%.

There is no doubt that our dependence on modern transportation vehicles and industrial machinery will continue to increase in coming years. However, while embracing such an increasingly more mobile and mechanical world, we must ensure that these machines are very efficient, durable, and green. With the adaptation of e.g. electric and autonomous vehicles, the role of tribology in all these might somewhat diminish, but we must remember that any types of remaining inefficiencies and durability gaps will still be mostly due to tribological issues. Specifically, energy and material losses due to friction and wear in these vehicles will still create economic and environmental burdens. Accordingly, research toward more effective materials, coatings, and lubricants should intensify in coming years to further enhance efficiency and durability as well as lower emission targets in all forms of transportation vehicles for a sustainable future.

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