Global energy consumption due to friction in passenger cars*

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October 2011

To be submitted to *Tribology International*

*Work supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Program, under Contract DE-AC02-06CH-11357

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Abstract

This study presents calculations on the global fuel energy consumption used to overcome friction in passenger cars in terms of friction in the engine, transmission, tires, and brakes. Friction in tribocontacts was estimated according to prevailing contact mechanisms such as elastohydrodynamic, hydrodynamic, mixed and boundary lubrication. Coefficients of friction in the tribocontacts were estimated based on available information in the literature on the average passenger car in use today, a car with today's advanced commercial tribological technology, a car with today's best advanced technology based upon recent research and development, and a car with the best technology forecasted in the next 10 years. The following conclusions were reached:

- In passenger cars, one-third of the fuel energy is used to overcome friction in the engine, transmission, tires, and brakes. The direct frictional losses, with braking friction excluded, are 28% of the fuel energy. In total, 21.5% of the fuel energy is used to move the car.
- Worldwide, 208 000 million liters of fuel (gasoline and diesel) was used in 2009 to overcome friction in passenger cars. This equals 360 million tonne oil equivalent per year (Mtoe/a) or 7.3 million TJ/a. Reductions in frictional losses will lead to a threefold improvement in fuel economy as it will reduce both the exhaust and cooling losses also at the same ratio.
- Globally, one passenger car uses on average 340 liters of fuel per year to overcome friction, which would cost 510 euros according to the average European gas price in 2011 and corresponds to an average driving distance of 12 130 km/a.
- By taking advantage of new technology for friction reduction in passenger cars, friction losses could be reduced by 18% in the short term (5–10 years) and by 61% in the long term (15–25 years). This would equal worldwide economic savings of 174 000 million euros and 576 000 million euros, respectively; fuel savings of 117 000 million and 385 000 million liters, respectively; and CO_2 emission reduction of 210 million and 700 million tonnes, respectively.

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- The friction-related energy losses in an electric car are estimated to be only about half those of an internal combustion passenger car.

Potential actions to reduce friction in passenger cars include the use of advanced coatings and surface texturing technology on engine and transmission components, new low-viscosity and low-shear lubricants and additives, and tire designs that reduce rolling friction.

Keywords: friction, lubrication, passenger cars, energy

1 Introduction

Friction, the resistance to motion, has been a challenge for mankind throughout history. Important inventions in man's earliest struggle to overcome friction were to use water and later natural oils to lubricate moving contacts, such as the sledges that moved the heavy stones in construction of the pyramids in Egypt, 2400 BCE. A breakthrough friction-reducing invention was the wheel, invented around the same time (3000 BCE) in Mesopotamia, North Caucasus, and Central Europe. The basic mechanisms of friction were studied by Leonardo da Vinci (1452–1519) in Italy and formulated as laws by Guillaume Amontons (1663–1705) in France [1]. The scientific basis for the modern understanding of friction, lubrication, and wear was established by scientist like Heinrich Hertz [2], Osborne Reynolds [3], and Philip Bowden and David Tabor [4].

Friction, lubrication, and wear were recognized to have a major influence on the efficiency and lifetime of machinery in industry and thus on the economy of the United Kingdom in the mid-1970s. A governmental committee chaired by H. Peter Jost was asked to investigate the situation. The so-called "Jost Report" estimated that 515 million pounds sterling could be saved annually in the United Kingdom by implementing advanced tribological solutions [5]. The report coined the word "tribology" for the science and technology of interacting surfaces in relative motion and included several recommendations for corrective actions.

The Jost report was followed by similar studies in other industrialized countries. A strategy for energy conservation through tribology in the United States was worked out by Pinkus and Wilcock [6]. Their report estimated that 11% of the energy consumption in the areas of road transportation, power generation, and industrial machinery and processes could easily be saved. These areas account for about 80% of the total energy consumption in the United States.

In Japan in 1980–1983, the Ministry for Trade and Industry investigated ways to improve the functionality and durability of machinery through systematic tribological improvements [7,8]. In a Canadian report, the National Research Council (NRC) concluded that 22% savings could be achieved by reducing the wear losses in pulp and paper, forestry, mining, agriculture, and the transportation and electric sectors [9].

More recent updates and overviews confirm the general trend. Nonetheless, a considerable amount of energy is still being consumed to overcome friction, especially in the transportation, industrial, and power-generation sectors, and major economic losses are due to wear of products and components and their replacement [8,10–13]. Jost [14] concluded that studies carried out in several industrial countries indicate that 1.0% to 1.4% of the gross national product can be saved by introducing better tribological practices, requiring investment in research and development at a rate of one in 50 of the savings obtainable.

Today, considerable effort is being devoted to producing increasingly energy efficient vehicles and machines, not only for economic reasons, but also to help to meet the requirements for reduced CO_2 emissions arising from the Kyoto Protocol on climate change. In some countries this effort is linked to avoiding large government-imposed financial penalties.

A major source of CO_2 emissions is cars and trucks. In the European Union (EU) a new average CO_2 emission limit for passenger cars was introduced in 2009, imposing an average CO_2 emission reduction, to 120 g/km, until 2012 [15–18].

Another environmental problem is the use of mineral oil as lubricant because of the limited global oil resources and the need for disposal of oil waste in nature. About 1% of the total crude oil is used to formulate lubricants. Between 13% (in EU countries) and 32% (in the U.S.) of all used lubricants return into the environment more or less changed in properties and appearance. Even though the base oils are biodegradable in the long run, the presence of additives in the finished lubricants makes them poorly compatible with the ecosystem [19,20].

Transportation accounts for about 20% of the global primary energy consumption and about 18% of the total anthropogenic greenhouse gas emissions. Road transport accounts for 72% of the total energy use within the world's transportation sector and for more than 80% of the total CO_2 emissions. In the period 1990–2005, the energy requirements for transportation increased 37%, making transportation the fastest growing energy sector [18,21].

Passenger cars account for 45% of the total energy use and emissions in transportation. Several studies have been conducted on the energy consumption, energy efficiency, and role of friction in passenger cars. As part of a workshop arranged by the U.S. Department of Energy in 1999, Fessler and Fenske [15] concluded that 120 billion U.S. dollars could be saved annually by reducing friction and wear in engine and drive train components.

The rising transportation demand is the biggest hurdle to significant greenhouse gas reduction [22]. In Europe there is a growing desire to move toward a car capable of fuel consumption as low as 3 liters per 100 km. Several groups have published detailed studies of the energy use and friction losses in automotive vehicles as well as offered suggestions for what could be done to reduce friction losses [16,23–26].

This paper presents a method for calculating the global energy consumption due to friction and potential savings from friction reduction in passenger cars. We have chosen to focus in this first study on passenger cars for two reasons. One is that passenger cars form a major consumer of energy and also generate a considerable part of the greenhouse emissions. The other is that the energy use in passenger cars has been much studied from the system to component level. Other types of road transport such as trucks, buses, mid- and light-duty vehicles, motorcycles, and scooters are excluded from this study. The study is based on the current set of technical solutions for passenger cars. Expected changes, future trends, and predictions in this set are not included.

2 Methodology

The present analysis is based on the physical phenomena resulting in energy consumption in cars. Previous analyses have been a mixture of functional and component-level studies. Our energy loss analysis includes five parts:

1. Car energy consumption
2. Driving cycle effects
3. Friction loss distribution
4. Tribocontact friction levels today and future
5. Global fuel consumption today and potential savings

The friction loss energy calculations proceed in the following way and are presented in greater detail in Appendices A and B. We first chose the global fleet of passenger cars for analysis. The total energy consumption of the global fleet of passenger cars was calculated by using fuel consumption statistics, car fleet data, and traffic information. What can be considered as an “average” passenger car in average operation globally was defined based on car statistics. We subdivided the total energy loss of the average passenger car into operational and frictional energy losses, using the best available estimates in published friction loss studies for car engines, transmissions, and entire cars. The friction losses were further subdivided to the component and tribocontact level, defined as the “friction loss source” (see Fig. 1).

The friction loss sources of the average passenger car were identified and classified according to the tribological contact and lubrication mechanism. The engine sub-systems, transmission parts, and other energy consumers in cars were analysed with regard to lubrication and friction. The coefficient of friction was calculated or estimated for each friction loss source. The corresponding friction energy loss was calculated, and finally the total friction loss was determined.

To assess the friction reduction potential of today’s best commercial solutions, the coefficient of friction at each friction loss source was replaced by a lower value representing the best commercial tribological solution found in the literature. The

corresponding friction energy loss was calculated for each friction loss source, and finally the total friction loss was determined.

The potential impact of the best tribological research results available today was also assessed. The coefficient of friction at each friction loss source was replaced by a value representing the best tribological research results available today, and the corresponding friction energy loss was calculated. The same procedure was carried out once more, this time replacing the values for the coefficient of friction with estimates of what the values could be after 10 years of intensive and focused tribology research.

The energy consumption of one average passenger car in average operation, after the above reduction in the coefficients of friction, was calculated from the useful energy consumption, the operation of the machinery, and the reduced friction loss energy.

The savings on the global level were calculated from the savings for one average passenger car multiplied by the total number of cars globally. The economical savings were calculated for various regions and countries based on the oil use of those areas.

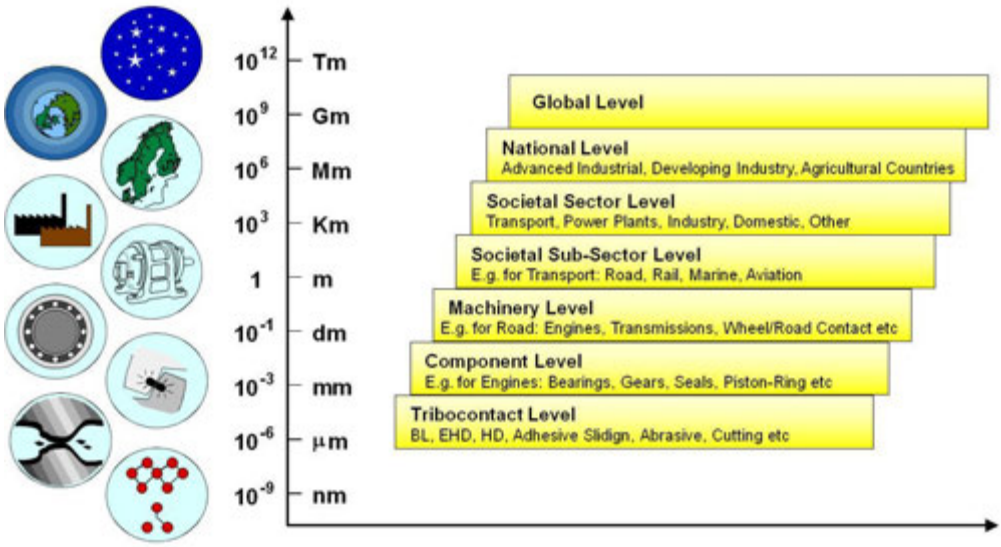

Fig. 1. Scale levels for calculating friction losses in passenger cars from global energy to overcome friction to friction losses in microlevel tribocontacts.

3 Analyses

3.1 Car energy consumption

In the present analysis we identified what we considered to be an average passenger car globally:

- manufactured in 2000,
- 75 kW four-cylinder engine,
- 1.7 dm^3 engine capacity,
- 1400 kg weight,

- gasoline fueled, and
- 8.5 liter/100 km average fuel consumption.

The technical details for the average passenger car are given in Appendix A, Table A-1. The information was collected mainly from EU statistics and converted to fit the average car in use globally [27,28]. Data for cars manufactured in the year 2000 and subjected to normal maintenance were used. The present analysis assumes that the average car is operated in average traffic conditions, equivalent to those leading to the average fuel consumption figures given by car manufacturers, as shown in Appendix A, Table A-2. The main average operating features are:

- 12 000 km annual mileage,
- 60 km/h average speed,
- paved-road driving,
- 350 g/kWh fuel efficiency at 14 kW, and
- 2.5 kg/liter CO_2 emissions.

The fuel burned in the combustion chamber releases potential energy as the chemical structure of the fuel is broken down from liquid hydrocarbons into exhaust gases, mainly CO_2, H_2O, and NO_x. The chemical energy release is transferred into heat, and the mechanical energy is used as power to move the car, overcoming both air drag and frictional losses.

The fuel energy is dissipated through the following mechanisms (Fig. 2) based on collected information from Pinkus and Wilcock [6], Lang [29], Andersson [30] Bartz [23], Taylor [25], Basshuysen and Schäfer [31], Tung and McMillan [26], Hikita et al. [32], and NRC [33,107]:

- **33%** (range, 30–37%) goes to **exhaust gases**, mainly as thermal energy, and disappears by convection (also includes gases of lower energy content that exit through the exhaust pipe).
- **29%** (25–33%) goes to **cooling,** which is heat dissipated by conduction through the engine structure, the cooling radiator (and oil cooler), and occasionally the car's heating system, and further dissipated to the environment.
- **38%** (33-40%) is converted into **mechanical power** to overcome air drag and friction losses. This part can be sub-divided into:
    - **5%** (3-12%) to overcome **air drag**, including both external and internal air flow resistance, as well as losses in the electrical and indoor cooling system, and
    - **33%** to overcome **friction** in the car (Fig. 2).

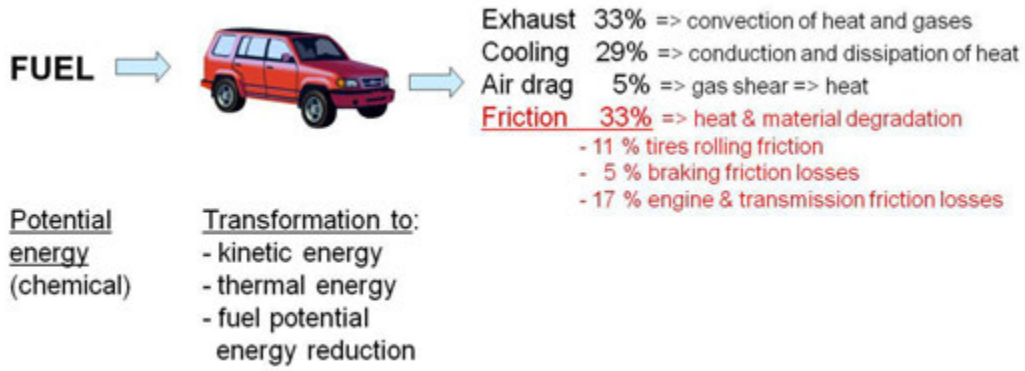

Fig. 2. Fuel energy dissipation in passenger cars, as approximated for a speed of 60 km/h.

The external **air drag** is the air resistance of the car when it moves on the road. It is proportional to the square of the driving speed and directly related to the size and shape of the vehicle, usually expressed as a multiplication of the drag coefficient by the projected front area [34,35]. In this study, 60 km/h is assumed as an average driving speed for all cars globally in urban, highway, and any other kind of driving. The influence of wind direction is excluded from this study because globally, on average, it can be assumed to be close to zero, even if local head and tail winds will influence energy consumption.

The internal air drag is the resistance of air to circulation of air inside the car for ventilation, heating, or cooling, and air drag in the engine compartment. Its contribution is considered to be minor, only 20% of the total air resistance. It is assumed that laminar or turbulent shear is taking place in the gas, and this effect is causing dissipation of mechanical energy and warming of the gas, that is, a transformation of mechanical energy into thermal energy.

3.2 Driving cycle effects

As a car is moved from one location to another, the potential (fuel) energy reduction is temporarily stored as kinetic energy in the moving mass of the car while the rest of the released energy is transformed into thermal energy due to friction losses. The energy balance of the mechanical losses (excluding exhaust gases and cooling) during this process can be divided into four phases (Fig. 3):

- **Idle running**, when the car does not move and only the engine and part of the transmission components run. Here, the fuel energy is consumed only by the friction losses in the engine and the transmission.
- **Acceleration**, when fuel is consumed by increasing the kinetic energy of the car while overcoming friction in the engine, transmission, and tires, and the air drag.
- **Constant speed driving**, when fuel in consumed for overcoming friction in the engine, transmission, and tires, and the air drag.

- **Braking,** when fuel in consumed for overcoming friction in the engine, transmission, tires, and brakes, and the air drag, while energy is released from the reduction of the kinetic energy of the car when its speed is being reduced.

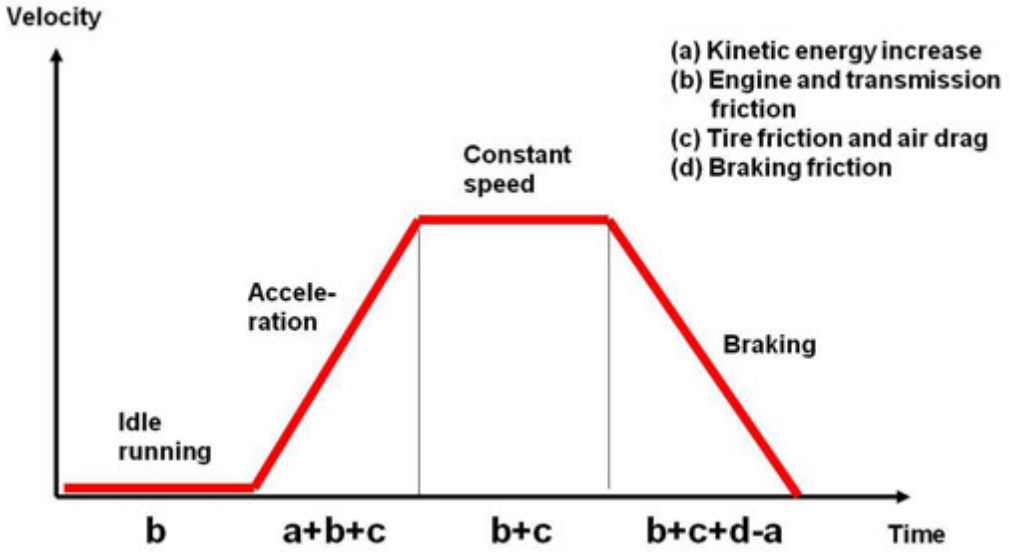

Fig. 3. Energy balance during four stages of car operation.

For simplicity and clarity, these four stages of the driving cycle are not separately analysed; instead, average values for friction losses during passenger car operation are used with the assumption of a global average passenger car, as defined in Section 3.1. The average driving speed of 60 km/h was estimated to be the global average speed covering all cars worldwide driving on highways, in cities, and on poor country roads, considering both rush hour and low-traffic conditions.

In a parametric study of the energy demands of car transportation between two UK cities, using two routes with different road profiles, Burges and Choi [36] identified five energy-loss components. They are rolling resistance, aerodynamic drag, inertial acceleration, gravitational losses, and cornering losses. We include in the present calculations only the first three items. The inertial acceleration equals the energy used for braking. Gravitational losses are zero on average on a global level for the total car fleet. The cornering effects are not directly included in the calculations, but they are considered as part of the car energy consumption.

This study does not separately take into account the energy needed to overcome the macro- or micro-**topographical changes in the road**. Macro-topographical changes originate from, for example, driving uphill, as it changes the potential (gravitational) energy of the car. When the car returns to the same altitude it started from, no change in potential energy has occurred. Micro-topographical changes like road surface bumps and undulation increase the fuel (energy) consumption. The energy dissipation results from increased hysteresis that heats up the tires (discussed in Section 4.4), heating of the oil in the shock absorbers, heating of suspension joints and springs due

to unbalanced tires, and reduced efficiency of the engine at operation under dynamic loads. In this study, average micro-topographical energy losses are applied.

3.3 Friction loss distribution

The part of the fuel energy devoted to mechanical power to overcome friction can be subdivided into groups (Fig. 4) based on data from Pinkus and Willock [6], Bartz [23], Taylor [25], Tung and McMillan [26], Pearce and Hanlon [37], Hoehn et al. [38] and NRC [107]:

- **35%** (12–45%) to overcome the rolling friction in the **tire-road contact**,
- **35%** (30–35%) to overcome friction in the **engine system**,
- **15%** (7–18%) to overcome friction in the **transmission system**, and
- **15%** (10–18%) to overcome friction in the **brake contact**.

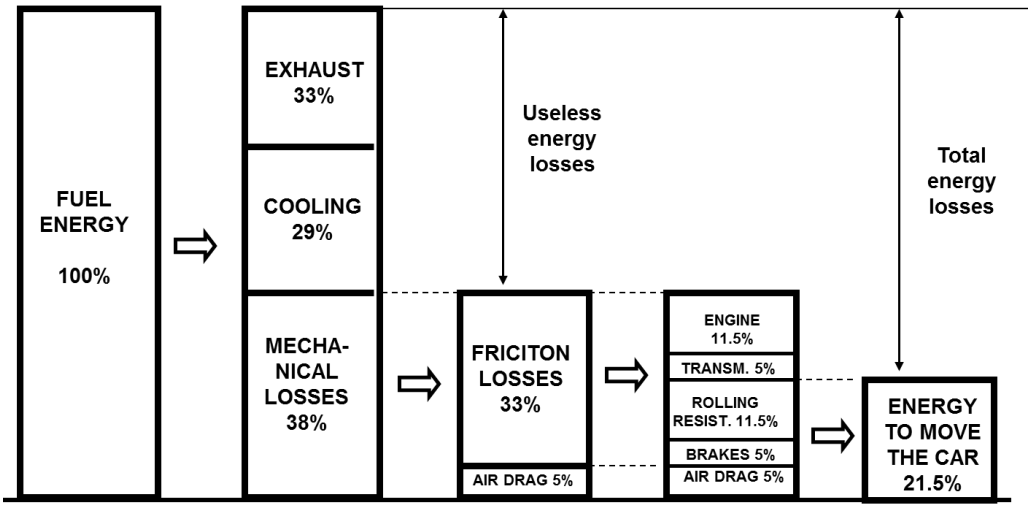

Fig. 4. Breakdown of passenger car energy consumption.

The above breakdown only considers the major contributors to friction. The minor contributors like various accessories are not analysed separately.

The driving resistance from the **tire-road contact** (TR) is due to the hysteresis in the elastomeric tire during driving and dissipates mechanical energy with corresponding thermal energy losses. For a given load and geometry, increasing the rigidity of the rolling components reduces the resistance to motion still further [33,39]. The hysteresis energy loss is lower for stiffer wheels and higher for softer wheels. The loss of hysteresis energy could be reduced by increasing the wheel air pressure, but that would also decrease driving comfort and might reduce the grip to the road and thus driving safety. Narrower tires would result in friction reduction due to smaller adhesive contact to the road. The viscoelastic effects in rolling friction are discussed in Section 4.4.

The **internal combustion engine** is the most important part of a passenger car, but it is equally used as a converter to mechanical energy in many other means of transportation such as buses, trucks, motorcycles, scooters, mopeds, vans, agricultural vehicles, construction vehicles, mining vehicles, trains, boats, and ships.

Engine systems in passenger cars have many designs but can be divided into three basic subgroups, namely, the piston assembly, the valve train, and the bearings and seals. The energy needed to overcome friction in these subgroups has been analyzed by Pinkus and Wikcock [6] and Taylor and Coy [16]. On the basis of data from Rosenberg [40], Lang [29], Hoshi [41], Goto and Kai [42], Bartz [23], Enomoto [24], Taylor [25,43], Merlo [44], and Tung and McMillan [26], we subdivided engine friction losses as follows:

- **45%** (38–68%) is consumed in the **piston assembly**,
- **30%** (20–44%) is consumed in **bearings**, seals, etc. (hydrodynamic lubrication),
- **15%** (3–34%) is consumed in the **valve train** (mixed lubrication), and
- **10%** is consumed by **pumping** and **hydraulic** viscous losses.

For engine bearings and seals, hydrodynamic lubrication (HD) dominates, while in the valve train, mixed lubrication (ML) dominates. Mixed lubrication includes effects from hydrodynamic or elastohydrodynamic (EHD) lubrication and boundary lubrication (BL). Boundary lubrication is normally regarded as a mechanism of nominal fluid film lubrication with occasional solid-to-solid asperity contact incidents. In our analysis the EHD contacts are divided in three groups: EHD in sliding contacts (EHDS), such as in piston-cylinder contacts and cam-follower contacts, with interfacial “Stribeck-type” friction; EHD in rolling contacts (EHDR), such as in ball-and-roller bearings, where friction originates from lubricant flow and elastic hysteresis; and EHD in sliding-rolling contacts (EHDSR), such as in gears, with a combination of sliding and rolling [45].

The tribocontacts in the **piston assembly** are more complex than the other engine components and have been divided as follows, based on data in Rosenberg [40] and Taylor and Coy [16]:

- **40%** HD lubrication, including the squeeze film lubrication effect at the top and bottom dead centres,
- **40%** EHDS lubrication,
- **10%** ML, and
- **10%** BL.

Many designs **of transmission systems** are being used in cars. The present analysis assumes a gearbox with rolling bearings at all main shafts. In general, the energy consumed to overcome friction in the transmission system can be subdivided as follows [26,46]:

- **20%** to overcome viscous losses (VL) in the oil tank, gear contacts, synchronizers, and bearings,
- **55%** to overcome friction in gears (EHDSR),
- **20%** to overcome friction in bearings (EHDR), and
- **5%** to overcome friction in seals, forks, etc. (ML).

3.4 Tribocontact friction for different car classifications

Based on extensive research on tribological contacts and lubrication mechanisms, especially during the last 40 years, we now have a good understanding of how various contacts can be classified, and what level of frictional resistance they typically represent [47–50]. In this study, we calculated the amount of mechanical energy dissipated due to friction in various tribocontacts on the basis of the published data for friction coefficients typical of each contact type.

Friction levels for different tribocontacts in four types of vehicle were separately estimated: the typical 10-year-old car in use today ("Car 2000"), a car that represents a combination of today's most advanced commercial tribological solutions ("Car 2010"), a car that represents the best tribological solutions demonstrated in research laboratories today ("Lab 2010"), and a car that reflects estimations by the best experts in the field of what is possible to achieve in the future after about 10 years extensive R&D work ("Car 2020"). The coefficients of friction based on the above classifications are given in Fig. 5 and Table 1. The references in the table relate mainly to the friction values for Car 2010 and Lab 2010, while the friction values for Car 2000 and Car 2020 are estimates by the authors based on available present information and their own experience. Possible future technical solutions for friction reduction are discussed in Section 4.

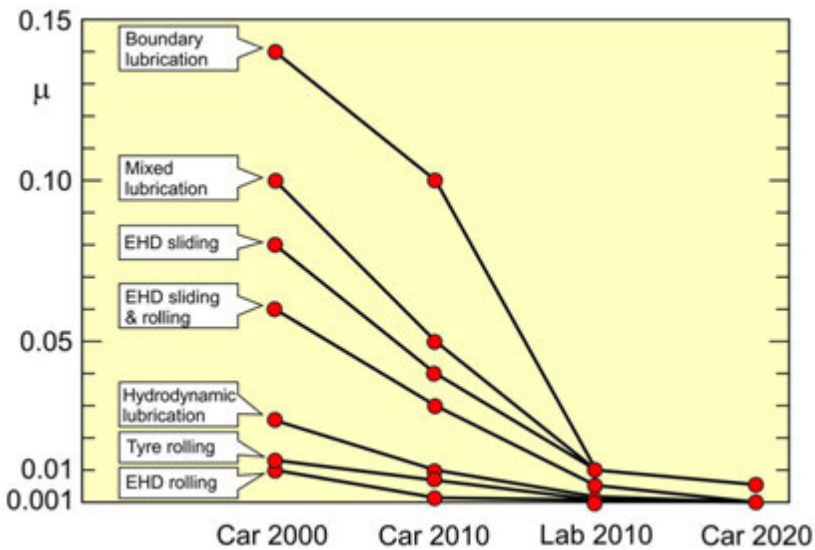

Fig. 5. Trends in the reductions in coefficients of friction in the four passenger car categories for different lubrication mechanisms and for rolling friction.

Table 1
Tribological contact performance for four classifications of passenger car [33,39,45,48, 49,51–67].

Contact types acting as friction loss sources	Coefficients of Friction			
	Car 2000	Car 2010	Lab 2010	Car 2020
Boundary lubrication (e.g., piston ring contact)	0.14	0.1	0.01	0.005
Mixed lubrication (e.g., piston ring contact)	0.10	0.05	0.01	0.005
HD lubrication (e.g. engine bearing)	0.025	0.01	0.002	0.001
EHD sliding (e.g., piston ring contact)	0.08	0.04	0.01	0.005
EHD sliding & rolling (e.g., transmission gears)	0.06	0.03	0.005	0.0008
EHD rolling (e.g., transmission roller bearing)	0.01	0.002	0.001	0.0005
Tire rolling[a]	0.013	0.007	0.003	0.001
Resistance to viscous shear (cSt at 80˚C)	18	12	8	1

[a] Tire rolling friction coefficients on paved roads.

Table 1 presents friction coefficients for common tribological contacts. The friction in such contacts can be controlled and reduced by improved scientific knowledge and advanced technological solutions. The friction estimates in Table 1 are based on commercial oil lubrication for Car 2000 and 2010 and on new often non-oil lubrication (e.g., water based, like polyalkylene glycol) for Lab 2010 and Car 2020.

Viscous losses in transmission systems are shear and churning of oil in the transmission case. In engine systems, pumping and hydraulic losses are related to viscous losses. The viscous losses are included in this study because, even if they are not directly friction losses, these losses can be reduced by tribological solutions resulting in lubricants with lower viscosity and thus also lower viscous losses. The reduction in viscous losses associated with the different classifications of car is shown by the bottom row of Table 1.

3.5 Global fuel consumption today and potential savings

The starting point for the analysis of friction losses in passenger cars is the total energy consumption worldwide.

The worldwide energy consumption in 2009 was 11 164 million tonnes oil equivalents (Mtoe) [68]. This amount was distributed according to regions of industrial development:

- 60% in industrialized countries,
- 35% in industrially developing countries, and
- 5% in agricultural countries.

The total crude oil consumption was 3 882 Mtoe (million tonne oil equivalent), and of that amount, 62% was used for transportation. The oil consumption was distributed according to form of transportation [15,21,69] as follows:

- 72% road,
    - 45% passenger cars
    - 20% trucks
    - 7% buses and light vehicles
- 13% marine,
- 11% aviation, and
- 4% rail.

For passenger cars, the global fuel consumption in 2009 was 631 $\cdot 10^9$ liters, including both gasoline and diesel fuel. By dividing this value by the total number of passenger cars worldwide (estimated to be 612 million) and converting the fuel consumption to energy, we get 36 000 MJ per year for one global average passenger car [21,27, 46].

Tables 2–5 present calculations based on the above classifications, definitions, assumptions, and approximations (see also Appendices B and C). Table 2 shows that the main friction loss sources are the tire-road contact, the hydrodynamically and elastohydrodynamically lubricated contacts, and the brakes. Annually, 340 liters of fuel is used for overcoming friction in an average passenger car.

Table 3 shows that by applying the most advanced tribological solutions available today in all existing passenger cars (Car 2010) and in all their tribocontacts, the following reduction could be attained: 42% in frictional energy losses and 37% in the total global fuel consumption, or, expressed in absolute fuel volumes, a reduction from 631 $\cdot 10^9$ to 400 $\cdot 10^9$ liter/a. The corresponding savings in fuel energy would be 8 170 000 TJ/a, which corresponds to 350 $\cdot 10^9$ euro/a (with European 05/2011 fuel price).

Table 2
Friction losses in one global average passenger car (Car 2000) according to type of tribocontact.

Friction loss source type	Energy consumed (MJ/car/a)	Fuel used (liters/car/a)	Percentage (%)
Tire-road contact	1 452	119	35
Hydrodynamic lubrication	1 993	57	16.8
Mixed lubrication	899	26	7.6
EHD lubrication, sliding	747	21	6.3
EHD, sliding and rolling	979	28	8.2
EHD lubrication, rolling	356	10	3.0
Boundary lubrication	187	5	1.6
Viscous losses	771	22	6.5
Braking contact	1 779	51	15
Total	11 863	340	100

Table 3
Global energy consumption to overcome friction and total potential savings due to improved friction control.

	Total fuel consump-tion (10^6 liter/a)	Total fuel consump-tion to overcome car friction (10^6 liter/a)	Total energy used to overcome car friction (TJ/a)	Reduction in fuel consump-tion from today's level (%)[a]	Savings in fuel energy annually (TJ/a)[a]	Savings in, European fuel price, 10/2010 (10^6 euro/a)[a]
Car 2000	631 000	210 000	7 350 000	NA	NA	NA
Car 2010	397 000	132 000	4 620 000	37	8 171 000	348 000
Lab 2010	246 000	82 000	2 870 000	61	13 472 000	576 000
Car 2020	189 000	63 000	2 205 000	70	15 460 000	659 000

a. Reduced fuel needed is limited to power for friction resistance (87%) while air drag is constant (13%).

Table 4
Potential global annual savings per year in short and long term.

	Short term (5-10 years)	Long term (15-25 years)
Savings/reduction (%)	18.5	61
Reduction in fuel consumption (million liters)	117 000	385 000
Energy demand reduction (TJ)	4 086 000	13 472 000
CO_2 emission reduction (million tonnes CO_2)	210	693
Economic savings (million euros)	174 000	576 000

Table 5
Estimated realistic energy, cost and fuel savings, and CO_2 reduction by region. Values represent 50% of total potential energy savings by using today's best commercial tribological solutions after five to ten years of concentrated actions to reduce friction in passenger cars worldwide. The regional values are estimated as the regions share of the total global savings, equal to its share of the total fuel oil consumption [68].

	Energy Saving (TJ/a)	Cost Saving (10^6 euro/a)	Fuel Savings (10^6 litre/a)	CO_2 Emission Reduction (10^6 kg/a)
World	4 086 000	174 000	117 000	210 000
Industrialized countries	2 452 000	104 000	70 200	126 000
Industrially developing countries	1 430 000	61 000	41 000	73 500
Agricultural countries	204 000	8 700	5 900	10 500
EU	707 000	30 100	20 200	36 300
USA	887 000	37 800	25 400	45 600
China	424 000	18 100	12 200	21 100
Japan	204 000	8 700	5 900	10 500
UK	81 000	3 500	2 300	4 200
South Africa	25 600	1 100	740	1 300
Finland	10 200	430	300	500

If the best solutions today demonstrated on the R&D laboratory level are taken into account in all tribocontacts in the global fleet of cars (Lab 2010), fuel consumption would be reduced by 61% from today's level, to a value of only 250 $\cdot 10^9$ liter/a. The corresponding savings in fuel energy would be 13 500 GJ/a, which corresponds to 580 $\cdot 10^9$ euro/a.

Finally, if the future solutions estimated to be available after a 10-year period of extensive global R&D activities are taken into account for all tribocontacts in the global fleet of cars (Car 2020), fuel consumption would be reduced by 70% from today's level, to a value of 190 $\cdot 10^9$ liter/a. The corresponding savings in fuel energy would be 15 500 GJ/a or 660 $\cdot 10^9$ euro/a.

Note that the savings in fuel energy are much larger than the total energy used to overcome friction because reduced friction results in reduced energy demand, and thus the energy going to exhaust and cooling is also reduced, as shown in Figure 4.

Obviously, implementing today's advanced commercial solutions in all passenger cars would require an enormous effort and would result in large application costs, which cannot be commercially justified. Nonetheless, it would be realistic to estimate that perhaps half of this level could be reached in the short term, within five to ten years. As shown in Table 4, that improvement would result in an 18.5% reduction in fuel consumption, which on the global level corresponds to 4 090 000 TJ/a energy savings, equal to 174 000 million euros saved annually worldwide. Table 5 shows the energy and cost savings broken down by region.

4 Tribological means of reducing friction

Tribological inventions have a long history, starting with sparsely appearing new inventions in ancient times but drastically boosted by the industrial revolution in the 18th to 19th century [70]. After the global breakthrough of "tribology" as a scientific discipline almost 50 years ago, interest has rapidly grown in the subject both scientifically and industrially, and this has resulted in a range of new inventions and improvements, e.g., in the development of mass-produced passenger cars in the 20th century [71].

In Figure 5 we illustrated the technical possibilities for reducing friction in various friction loss sources within passenger cars in the short and long term. Discussed next are some of the known possible new solutions which could be implemented to achieve such reductions in friction losses. These solutions would mainly correlate to what above has been called Lab 2010 and Car 2020.

4.1 Low friction coatings on mechanical components

Tremendous advances have been made in the area of surface coating technology during the last 20–30 years. New techniques, such as physical vapor deposition (PVD), chemical vapor deposition (CVD), and thermal spraying (TS), make it possible to industrially deposit coatings on car components. The coating thickness may range from half micrometer to several millimeters. The very thin coatings are of special interest since they can be deposited on existing components and do not change the dimension or geometry and thus do not require redesign or remanufacturing. Still, applying new surface coatings on a component in a car or other machines is not an

easy or straight-forward task. It needs re-examination of the design, optimization of the coating and contact system, and friction, wear, and lifetime testing.

The friction of components with new advanced surface coatings has been decreased by more than 90% for dry contacts and by 10-50% for boundary-lubricated contacts [50,72,73]. The high values of friction reduction by coatings are related to dry or boundary-lubricated contacts, since HD and EHD contacts have few asperity contacts, and the shear takes place within the lubricant. The role of a coating is then to be a safety layer. The lifetime improvements achieved by using surface coatings have been impressive. A ten-fold increase of fatigue lifetime in rolling contacts, a seven-fold reduction in bearing wear, and a three-fold increase in gear lifetime have been reported [50,74]. Most fuel injector plungers used in fuel delivery systems of modern diesel engines are now coated with a slick and durable coating.

Passenger cars have many sources of frictional losses where friction can be reduced by applying an advanced coating technology. To some extent, this is already being done today. The most important tribocontacts producing friction losses are typically the piston ring and cylinder liners, gears, bearings, valve and cam, and shim contacts. Additional contacts with minor friction effects are, for example, the fuel injector, commutator, ball pivots, connecting rods, gear selection shaft, synchronizer rings, clutch parts, shifter forks, joints, shock absorber parts, steering system parts, and brake components [24,75]. Even if the friction loss in some of these parts may not be great, friction may increase wear and reduce lifetime and sometimes even result in breakdown of the whole car.

The development of PVD coatings of low friction, hard, and thin diamondlike carbon (DLC) has offered new possibilities for friction reduction in cars [76,77]. Podgornik and Vizintin [58,78] reported more than 30% decrease in friction in lubricated contacts by applying DLC compared to a steel/steel contact, while Gåhlin et al. [79] reported a 70-fold lifetime increase by applying tungsten carbide/carbon (WC/C) coatings in FZG gear contacts. Other new and potential coatings for improved friction performance in automotive components have been investigated: Cr-N; TiN; Ni-SiC; $AlMgB_{14}$; MoS_2; WC/Co; TiAlN; W-C:H; $AlMgB_{14}$-TiB_2; composite coatings with TiN, TiC, or TiB_2 particles embedded in Si_3N_4 or SiC ceramic matrix; and various nanostructured coatings [24,26,44,80–84].

4.2 Surface topography and texturing

The topography of a surface in sliding contact has a remarkable influence on friction in both dry and lubricated sliding. This friction has long been considered only as a surface roughness property of the component. Recent research has shown that the influence of the micro- and nanoscale topography is more complex but, at the same time, offers interesting possibilities for friction reduction. Changing the surface topography of gears to be smoother by superfinishing has been shown to reduce friction by typically 30% [85]. Fine-particle peening treatment of the contacting

surface has produced a surface with microdimples that can reduce friction in lubricated conditions by up to 50% [86].

The most promising results originate from investigations with modifying the contacting surface in a very controlled way by partial laser surface texturing (LST). Small dimples with a crater diameter of about 100 μm, a depth of about 10 μm, and a surface coverage of 60% have been produced according to a controlled pattern on the surface [87]. These microdimples can, when correctly designed, produce a wedge flow effect, and hydrodynamic pressure in the contact may reduce friction by about 25% [88]. This technique has been of special interest for the piston-ring and cylinder liners in car engines, where the friction losses are large. Advanced theoretical calculations of the most beneficial dimple dimensions resulted in an optimal piston ring texture design. Engine bench tests showed that the textured piston rings can reduce the engine fuel consumption up to 4% [89–91].

4.3 Lubricants

The lubricant in a car has several functions. First, it provides a fluid film between load-carrying and fast-moving components, as in bearings, gears, and piston ring/cylinder contacts, assuring that shear takes place within the lubricant with low friction, and that solid contacts are avoided. Second, it helps to form a chemical film on surfaces to avoid wear and breakdown. Third, it prevents corrosion, provides cooling by heat transport, and transports contamination away from the system. However, oil churning results in energy losses due to the viscosity of the lubricant [16,26].

As mentioned earlier, viscous losses and shear in hydrodynamic contacts are considerable sources of friction loss in passenger cars. If the lubricant viscosity could be reduced without detriment to the other functions of the lubricant, large energy savings could be achieved. To that end, several approaches have been suggested.

The use of lubricating oils of lower viscosity will reduce the energy losses from viscous work. A reduction of the engine oil viscosity by approximately 25% corresponds to a change in viscosity class from SAE 40 to SAE 30 or from SAE 30 to SAE 20 at a reference temperature of 100°C; this change is equivalent to fuel savings of 0.6 to 5.5%. The fuel savings for a similar lowering of the viscosity of a gear oil is on the order of 0.2 to 2.5% [16,23].

A friction coefficient of 0.04 is about the lowest that can be attained when using today's advanced conventional oils and additives in boundary-lubricated conditions. These lubricants include mineral or synthetic oils that typically consist of chemically based extreme pressure additives such as sulfur, chlorine, and phosphorus which may cause poisoning of catalyst and after-treatment devices of engines. New additive packages containing little or no-sulphated ash, phosphorus and sulphur anti-wear additives are now being developed for use in future engine oils [111]. New and

interesting research indicates that with different approaches much lower friction can be achieved. For example, the addition of the friction modifier glycerol mono-oleate to a poly-alpha-olefin oil yielded a friction coefficient of about 0.05 in sliding contact with two DLC surfaces (tetrahedral amorphous carbon), and the same experiment carried out with pure glycerol resulted in superlubricity conditions with a friction coefficient close to 0.005 [64,92–94]. This friction reduction is to about one-tenth compared to traditional solutions. In HD lubricated conditions new research has shown that considerable friction reduction can be achieved by the use of organic friction modifiers [95] or by liquid crystal mesogenic fluids [96].

Another approach is to use ionic liquids as lubricants. Ionic liquids are composed of cations and anions instead of neutral molecules, such as in conventional oils. There are many ionic liquids with typical properties that include inherent polarity, high thermal stability, non-flammability, high flexibility in molecular design, and environmental friendliness. The viscosity of a fluid correlates to its molecular structure, and ionic liquids can be produced in a wide range of viscosities, from 50 to 1500 cP at 23ºC. Tribological lubricated sliding experiments have shown coefficients of friction of about 0.1 for hydrocarbon oils and 0.06 for an ammonium ionic liquid. There was a 20-35% lower friction compared to conventional engine oil in all lubrication regimes and a decrease in wear of 45–55%. In piston ring-on-flat tests, the coefficient of friction was reduced by 55% [97–100].

Certain nanomaterials, such as WS_2, MoS_2, H_3BO_3, carbon nano-onions, fibers, and tubes as well as many other inorganic nanomaterials, have been considered in the past as potential lubrication additives, but their friction and wear reducing capabilities have not been realized until quite recently. With advances in nanomanufacturing techniques, some nanomaterials have become readily available in large quantities and relatively cheap. They are now being tested for their potential for further enhancing the anti-friction and -wear characteristics of base and formulated oils. At optimized concentrations and particle sizes, significant friction reductions have already been demonstrated with nanomaterials such as WS_2, MoS_2, and H_3BO_3 [101].

One more friction-reducing approach is to learn from lubrication in nature, as is done in biomimetic research. The low friction solutions produced by nature, such as the lubrication of a human joint, where the friction coefficient in boundary lubrication can be as low as 0.001 are among the lowest coefficients of friction observed so far. New biomimetic low friction concepts are mainly based on water lubrication and contain polymeric or protein additives such as brushes of charged polymers (polyelectrolytes), porcine gastric mucin, and glycoprotein mucin. Such lubricants have attained coefficients of friction as low as 0.0006 to 0.04 [102–104].

4.4 Rolling resistance of tires

During the last five decades, car tires have been subjected to advanced product development; however, very little information is available about them in the open

literature. Part of the development work has been focused on reduction of the rolling resistance. A 10% reduction in rolling resistance corresponds to a 2% reduction in energy demand, or a 2% reduction in fuel consumption [33,36].

The trend of reduced friction in passenger car tires can be seen from a large study carried out during the last three decades [33]. More than 250 new passenger car tires representing 36 brands and models, all of radial-ply construction and 195/75R15 size, were tested in 1982-1983 under SAE J1269 standard test conditions. The coefficient of rolling friction fell in the range 0.0098 to 0.0138, with a mean of 0.0113. With 18 bias-ply tires, the mean rolling friction was 20.2% higher than that for the radial-ply tires. In addition to improved driving comfort and safety, the change from the older bias-ply tire to the new radial-ply tire in the 1960s and 1970s led to lower rolling resistance. In 1995, the friction measurements with new radial-ply tires gave a mean value of 0.0107 for replacement tires and 0.0092 for new original equipment tires. Measurements in 2005 gave coefficients of rolling resistance with a mean value of 0.0099, mainly for replacement tires.

The rolling friction of viscoelastic bodies like pneumatic tires depends on the rotational speed because the relaxation of the material at the trailing edge of the contact is slower than the compression at the leading edge, and this effect is expressed by a hysteresis factor. The rolling resistance, furthermore, depends on the micro-slip at the rolling interface, which arises from different elastic constants of the wheel and the road. As a third factor, the rolling resistance depends on the roughness of the road [105].

The hysteresis loss in the viscoelastic rubber material of rolling tires is of particular importance. Under rolling contact, some energy is stored as compression and released as relaxation of the elastically deformed sections of the tire. The rest of the rolling resistance energy is converted into heat by the viscous nature of the rubber. The hysteresis losses are determined by the tire materials, geometry, and construction in combination with the load, velocity, wheel alignment, air pressure, and temperature. The main geometry features are the outer diameter, rim diameter, and tire width, all of which affect the rolling resistance. The rubber contains additives for several purposes, and these additives are known to influence the rolling resistance. The rubber of the tread is of particular importance, since more than one-half of the rolling resistance can originate from the deformation that takes place in the tread. As a consequence of this, tire wear reduces the rolling resistance [33].

In rolling, the frequency of the deformation in the rubber tire is of the order of v/L where v is the tangential velocity and L is the length of the tire-to-road contact area in the rolling direction. These frequencies are typically much smaller than the deformation frequencies during sliding, which are of the order of v_{slip}/d, where d is the diameter of a contact between a road asperity and a tread block in the tire-road contact.

Typically for road surfaces, d is between 1 mm and 1 cm, while L is of the order of 10 cm. The low values of d lead to much higher deformation frequencies during breaking than during rolling. This implies that in order to have a low rolling friction

but a high breaking friction, the ratio Im E / Re E should be as low as possible for rolling frequencies, however as large as possible at sliding frequencies. Im E is the imaginary part and Re E the real part of E, which is the viscoelastic modulus of the rubber. Consequently, the rubber compound should be designed to optimize this relationship [108-110].

Today, the typical air pressure in car tires is about 32 psi (220 kPa). A lower tire pressure gives a larger tire-to-road contact area and thus makes fast acceleration and braking possible. In addition, lower tire pressure gives better driving comfort on bumpy roads. Rolling resistance reduction is also possible by increasing the tire pressure, but it would require use of improved car damper technology and acceptance of slower speeds and slower acceleration for safety. An increase of tire pressure from 24 to 29 psi (165–200 kPa) reduces rolling resistance by 10%, and for tires inflated to pressures of 24 to 36 psi (165–250 kPa), each drop of 1 psi (7 kPa) leads to 1.4 % increase in rolling resistance [33].

It is common to drive with under-inflated tires due to infrequent tire pressure checks. About 25% of all cars drive with pressure in at least one tire 25% below the pressure recommended by the manufacturer. Tires lose typically about 1 psi (7 kPa) of air pressure per month and can lose considerably more during a sharp change in ambient temperature, about 1.7 psi (12 kPa) for each 10ºC drop [37]. Significant energy savings can be achieved by continuous tire pressure monitoring.

The real average coefficient of friction for the tire rolling resistance of the average global passenger car is about 0.02. This value was calculated based on the weight of the average global passenger car, the mileage, and the consumed fuel. This coefficient of friction is about double the coefficient of friction calculated for driving on paved roads with properly inflated tires because, in reality, roads often have a rougher surface and tires are often under-inflated. We also calculated from the total energy balance that the average global passenger car has about 25 full-stop braking events per day from the average speed of 60 km/h.

It is interesting to compare the rolling resistance of passenger cars with that of steel wheels on rail vehicles like trains and trams (Table 6).

Table 6
Coefficient of rolling friction for cars, trams and trains [33,39,52,67].

Vehicle	Surface	Coefficient of friction	Note
Car (pneumatic tires)	Paved road	0.01	Reference value
Car (pneumatic tires)	Sand	0.3	30 times higher than car on paved road
Train or tram (steel wheels)	Steel rail	0.0005	20 times lower than car on paved road

As shown in Table 6, the rolling resistance for the contact between the steel wheel and steel rail is 20–50 times lower than that of the contact between a car tire and the paved road. In a comparison of the energy efficiency for road and rail transport, several other factors than only the rolling resistance need to be considered, such as rail track and road gradients, speed variations, frontal area, mass, etc., but such considerations are outside the scope of this study. Still, huge energy savings would result from changing transportation as much as possible from roads to rails.

5 Discussion

The effects of the different parameters influencing fuel consumption in passenger cars can be summarized as follows [36,84]:

- 10% mass reduction => 8.3% reduction in energy demand
- 10% rolling resistance reduction => 2% reduction in energy demand
- 10% frontal area reduction => 2.2% reduction in energy demand
- 5% speed reduction => 6% reduction in energy demand
- 10% mechanical loss reduction => 1.5% reduction in fuel consumption

In this comparison, the mechanical losses do not have the largest impact on energy saving. However, some parameters such as the frontal area and the car mass have been the subject for extensive optimization efforts, and further reductions are not easily made. Friction, on the other hand, offers considerable possibilities for reductions, as evident in Fig. 5, and is thus an important unused possibility for energy savings. The friction reduction may lead to further benefits, like mass reduction, which in turn can contribute to a reduction of the friction power losses.

The accuracy of the friction loss calculations and corresponding savings are directly related to the quality of the basic data used. We have used the best available data in the open literature. Many studies have been done on energy and friction in cars and engines; however, many are poorly documented, and the friction loss sources are not classified in a uniform way. Typical is that operational driving conditions are mixed with performance of mechanical components. We have avoided this classification problem by first defining standard global driving conditions for the average passenger car and then analysing the friction losses purely related to the mechanical performance.

The basic breakdown of energy losses in a car into exhaust gases (33%), cooling (29%), and mechanical power (38%) is much used today. However, it originates from a U.S. Department of Energy study that is more than 40 years old [6]. We also used this breakdown because we have not found any more reliable information. These data are probably still adequate as they are in wide use today in publications both from the car industry and academia. In those cases where we believed that the data were not reliable or well documented, we have cross checked from different sources and also

investigated the data directly via correspondence with experts in the field (see Acknowledgements).

The analysis presented in this paper can, in part, be applied to rechargeable all-electric and hybrid cars. At present, electric cars only constitute a small fraction of all vehicles, but with the inevitable proliferation of electric and hybrid cars, their energy consumption will soon become an issue. For such analyses, the present methodology can be adopted by selection of a power supply other than a direct-acting internal combustion engine and transmissions different from those that include a multi-speed gearbox and a reduction gear.

The conversion of fuel (nuclear, coal, solar, etc) into electric energy for rechargeable all-electric cars is done at power stations. This shift transfers some of the friction issues from car power generation to the power station. Because electric motors do not idle when the vehicle is temporarily stopped, this eliminates all idling losses, including friction. With an advanced electric drive motor, the torque for moving the car can be obtained at a wide range of speeds, and this quality makes the gearbox and part or all of the reduction gears unnecessary and, hence, reduces the number of sources for friction energy loss. In electric cars, the braking energy can be completely or partly converted into electrical energy and stored in batteries for subsequent use. In traditional and hybrid cars, cooling losses from the engine are used for heating of the ventilation air, while in rechargeable electric cars any heating will require electrical energy or fuel-powered heaters.

Converting the energy consumption breakdown for internal combustion cars (Fig. 4) to one for electric drive cars requires considerable changes: mainly radical reduction of the engine and transmission losses, elimination of the exhaust losses, and radical reduction of the cooling losses. The tire rolling resistance and the air drag would remain unchanged, but the braking friction losses would disappear because the braking energy is reused. Overall, the friction energy losses in an electric car would be only about half those in an internal combustion passenger car.

This study and the calculations reported are based on the current set of tribological technical solutions in passenger cars. In the future there could be changes in this set that influence the calculations for “Car 2020”. Possible changes are 1) increase in proportion of cars in developing countries, 2) increase in number of hybrid and electric cars, and 3) downsizing of cars and engines. These and similar expected changes, future trends, and predictions have not been analysed in this study.

For simplicity, we have assumed that all components in a car scale with the coefficient of friction. We are well aware that this is not the case. For example, power loss in a contact depends on load and speed as well, and thermodynamic efficiency depends on temperatures and compression rates. Nonetheless, our simplified method provides a rough and relevant estimation, on the global level, of the energy consumption and costs of friction in passenger cars.

6 Conclusions

We reached the following conclusions from our analysis of friction in passenger cars:

- One-third of the fuel energy is used to overcome friction in the engine, transmission, tires, and brakes. The direct frictional losses, with braking friction excluded, are 28% of the fuel energy. In total, 21.5% of the fuel energy is used to move the car.
- Worldwide, 208 000 million liters of fuel (gasoline and diesel) was used in 2009 to overcome friction in passenger cars. This equals 360 Mtoe/a or 7.3 million TJ/a. Reductions in frictional losses will have a threefold improvement in fuel economy, as it will reduce both the exhaust and cooling losses also at the same ratio.
- Globally, one passenger car uses on average 340 liters of fuel per year to overcome friction, which would cost 510 euros according to the average European gas price in 2011 and corresponds to an average driving distance of 12 130 km/a.
- By taking advantage of new technology for friction reduction in passenger cars, friction losses could be reduced by 18% in the short term (5–10 years) and by 61% in the long term (15–25 years). This would equal worldwide economic savings of 174 000 million euros and 576 000 million euros, respectively; fuel savings of 117 000 million and 385 000 million liters, respectively; and CO_2 emission reduction of 210 million and 700 million tonnes, respectively.
- The friction energy losses in an electric car are only about half those in an internal combustion passenger car. The total energy balance when comparing electric and internal combustion cars is further influenced by possible friction energy losses in electricity production and in fuel production.
    - Potential mechanisms to reduce friction in passenger cars include the use of advanced coatings and surface texturing on engine and transmission components, low-viscosity and low-shear lubricants and novel additives, and tires with reduced width and increased pressure for lower rolling friction.

Acknowledgments

Persons that have contributed with valuable comments and information to this study: Yoshitsugu Kimura, Japan; Bo Jacobson, Lund University, Sweden; Hugh Spikes, Imperial College, UK; John Williams, Cambridge University, UK; Peter Blau, Oak Ridge National Laboratory, USA; Wilfried Bartz, Technische Akademie Esslingen, Germany; Ameneh Schneider, AC2T Research, Austria; Arup Gangopadhyay, Ford, USA; Ian Hutchings, University of Cambridge, UK; Patrick Swan, South Africa; Bo Persson, Research Centre Juelich, Germany.

This study has been carried out as part of the Finnish joint industrial consortium strategic research action coordinated by FIMECC Ltd within the program on Breakthrough Materials called DEMAPP in the Friction and Energy Project. We

gratefully acknowledge the financial support of Tekes, the Finnish Technology Agency, the participating companies, and VTT Technical Research Centre of Finland. Additional support was provided by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Office of Transportation Technologies, under Contract No. DE-AC02-06CH11357.

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Appendix A: Characteristics of global passenger car

Table A-1
Assumed global average passenger car, year model 2000.

Feature	Value and unit	Reference
Weight	1400 kg	[28]
Engine capacity	1.7 dm^3	[28]
Maximum engine power	75 kW (extrapolated from development for 2002-2008)	[28]
Engine configuration	Four cylinders in line	
Type of fuel	70% gasoline, 30% diesel fuel	[28]
Fuel efficiency at max. power, when new	255 g/kWh (when new)	
Drag coefficient, C_w	0.345	[35]
Projected frontal area	2.5 m^2	[18]
Rolling resistance of tyres	0.013 (tire age approx. 4 years)	[33]
Engine oil grade	SAE 5W40 (age < 1 year)	
Gearbox oil grade	SAE 5W40 (age 10 years, usually never exchanged)	
Equipment	Hydro mechanical power steering, air condition with compressor in 25% of the car fleet, manual 5-speed gearbox, front wheel drive, driving brakes based on friction, standard summer tires 185/65R15 with an average age of 4 years	

Table A-2
Assumed global average operational conditions, year 2010.

Feature	Value and unit	Reference
Annual mileage	12 000 km	[27]
Velocity	60 km/h	§ 3.2
Road conditions	Paved road, no inclination	§ 3.2
Influence of wind	No contribution of wind	
Average CO_2 emissions	180 g/km	[28]
Average CO_2 emissions per fuel liter	2.5 kg /liter	[31]
Average fuel consumption	8.5 liter/100 km	
Average engine output power	14 kW	
Fuel efficiency at 14 kW power	350 g/kWh	[31]
Average braking power	2 kW	§ 3
Engine oil temperature	80°C	Estimate
Gearbox oil temperature	60°C	Estimate

Appendix B: Calculations of savings from friction reduction

Calculations related to passenger car energy loss and economical saving based on energy consumption information from 2008-2010:

1. **Total energy consumption worldwide** (2009) was 11 164 Mtoe/a (=11 164 $\cdot 10^9$ kg/a oil equivalent) including oil, gas, coal, nuclear energy, and hydroelectricity [68].

2. **Total fuel crude oil consumption** worldwide (2009) was 3 882 Mtoe/a [68].

3. Total **crude oil consumption** used for **transportation** worldwide (2009) was about 2 407 Mtoe/a; calculated from 62% of total oil use being for transportation [106].

4. Total **crude oil consumption** used for **passenger ca**rs worldwide (2009) was 1 083 Mtoe/a; calculated from 45% of transportation energy use being for passenger cars [21].

5. Total **fuel** (gasoline and diesel) **consumption** used for **passenger cars** worldwide (2009) was 631 $\cdot 10^9$ liter/a; calculated from one liter crude oil needed for producing 0.5 liter fuel (gasoline + diesel**),** *(= $1083 \cdot 10^9 / 0.8581 \cdot 2$)* .

6. Total **energy contents** in the fuel used for **passenger cars** worldwide (2009) was 22 085 000 TJ; calculated from a total energy content of about 35 MJ per liter which equals to 45 MJ/kg [31] *(= $631 \cdot 10^9 \cdot 35$*).

7. **Fuel energy** (2009) in **one average passenger car** produced in 2000 in average operation was about 36 000 MJ/a; calculated from there being about 850 million road vehicles in use worldwide and, of those, 612 million (=72%) being passenger cars [21,27] (*= $22\,085 \cdot 10^6 \cdot 10^6 / 612 \cdot 10^6$).*

8. The 35 948 MJ/a fuel energy in **one average passenger** car is distributed as:
   - 11 863 MJ (33%) for exhaust gases,
   - 10 425 MJ (29%) for cooling,
   - 1 797 MJ (5%) for air drag, and
   - **11 863 MJ (33%) to overcome friction**.

9. The 11 863 MJ to overcome friction is distributed as:

- 4 152 MJ (35%) in the tire-road contact
- 4 152 MJ (35%) in the engine system distributed as:
    - 1 868 MJ (45%) in the piston assembly distributed as:
        - 747 MJ (40%) in HD tribocontacts
        - 747 MJ (40%) in EHDS tribocontacts
        - 187 MJ (10%) in ML tribocontacts
        - 187 MJ (10%) in BL tribocontacts
    - 1 246 MJ (30%) in bearings, seals, etc., mainly in HD tribocontacts
    - 623 MJ (15%) in the valve train, mainly in ML tribocontacts
    - 415 MJ (10%) by pumping and hydraulic viscous losses
- 1 779 MJ (15%) in the transmission system distributed as:
    - 356 MJ (20%) to viscous losses
    - 979 MJ (55%) to gears in EHDSR tribocontacts
    - 356 MJ (20%) to bearings in EHDR tribocontacts
    - 89 MJ (5%) to seals, forks, etc., in ML tribocontacts
- 1 779 MJ (15%) in the brakes to produce the brake force

10. The **annual energy** and **fuel consumption** to overcome friction for **one average passenger car** is calculated below for each tribocontact (i.e., friction loss source) separately (*1 MJ = 1/35 liters of fuel*):

Friction loss source type	MJ/a	liter/a
- Tire-road contact	4 152	119
- Hydrodynamic lubrication	1 993	57
- Mixed lubrication	899	26
- EHD lubrication / sliding	747	21
- EHD / sliding & rolling	979	28
- EHD lubrication / rolling	356	10
- Boundary lubrication	187	5
- Viscous losses	771	22
- Braking contact	1 779	51
Total	11 863	340

11. The use of 340 liters of fuel to overcome friction corresponds to 1 030 liters of fuel used in one car average annually and would result in 12 129 km/a driving distance with a fuel consumption of 8.5 liter/100 km.

12. The **friction losses** per source type calculated for Car 2000. The corresponding values for Car 2010, Lab 2010, and Car 2020 are calculated by multiplying Car 2000's value with the corresponding reduction factor from Table 1. The corresponding costs and savings are calculated based on gas market price level in Europe in May 2011, which was about 1.5 euro/liter *(1 MJ = 0.043 euros).*

Table B-1
Friction losses and fuel costs for different tribological contact mechanisms by classification of car.

	Car 2000 (today in use, average)		**Car 2010** (today's advanced commercial)		**Lab 2010** (today's best known solution)		**Car 2020** (future best solution)	
	MJ/a	**%**	**MJ/a**	**%**	**MJ/a**	**%**	**MJ/a**	**%**
TR	4152	35	2236	33	958	27	319	14
HD	1993	17	797	12	159	4	80	3
ML	899	8	449	7	90	3	45	2
EHDS	747	6	374	5	93	3	47	2
EHDSR	979	8	489	7	82	2	13	1
EHDR	356	3	71	1	36	1	18	1
BL	187	2	133	2	13	0	7	0
VL	771	7	514	8	343	10	43	2
BF	1779	15	1779	26	1779	50	1779	76
Total	**11863**	**100**	**6843**	**100**	**3553**	**100**	**2351**	**100**
Friction loss costs /car (€)	**510**		**294**	**58%**	**153**	**30%**	**101**	**20%**
Total fuel cost/car (€)	1545		977		604		468	
Fuel cost savings/car (€)*			568	37%	941	61%	1077	70%
Friction costs global (10^9·€)	**312**		**180**	**58%**	**94**	**30%**	**62**	**20%**
Savings tot. global (10^9·€)			**348**	**37%**	**576**	**61%**	**659**	**70%**

* The reduced power need is limited to reduced friction resistance, and the air drag resistance is constant (reduced friction effect on power = 87% = 33·100/38).

13. Corresponding savings (Table B-2) are calculated for various regions based on their share of the global fuel oil consumption and European average gasoline price in May 2011 (= 1.5 euro/liter).

Table B-2
Cost savings for tribological improvements in various regions.

	Europe market price (10^9 euros)		
	Car 2010	Lab 2010	Car 2020
World	348	576	659
Industrialized countries (60%)	209	346	395
Industrially developing countries (35%)	122	202	231
Agricultural countries (5%)	17.4	28.8	33.0
EU (17.3%)	60.2	99.6	114
USA (21.7%)	75.5	125	143
China (10.4%)	36.2	59.9	68.5
Japan (5%)	17.4	28.8	33.0
UK (2%)	7.0	11.5	13.2
Finland (0.25%)	0.9	1.4	1.6

Appendix C: Conversion factors

1 million	= 10^6
1 billion	= 10^9
1 tonne	= 10^3 kg

Oil weight-to-volume conversions

1 kg	= 1.165 liters
0.8581 kg	= 1 liter oil
1 million tonne	= $1.165 \cdot 10^9$ liters
1 million tonne	= $7.33 \cdot 10^6$ barrels
1 barrel	= 159 liters
0.72 kg	= 1 liter gasoline

Oil refinement and environmental conversions

1 liter crude oil	=> converts to about 0.5 liter passenger car fuel
1 barrel crude oil	=> 19 gallons gasoline + 10 gallons diesel oil
1 liter crude oil	=> 0.45 liter gasoline + 0.24 liter diesel fuel => ave. 0.5 liter oil fuel
1 kg passenger car fuel	=> 45 MJ = 12.5 kWh
1 kg passenger car fuel	=> converts to about 2.5 kg CO_2 emission

Oil prices

1 liter gasoline	= 1.5 euro on an average in Europe, May 2011

Energy conversions

1 kWs	= 1 kJ
1 kWh	= 3.6 MJ
1 Mtoe	= million tonnes of oil equivalent