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GLOBAL IMPACT OF FRICTION ON ENERGY USE IN TRANSPORTATION AND INDUSTRY*

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Abstract

About 100 million terajoule is used annually worldwide to overcome friction and that is one fifth of all energy produced. The largest quantities of energy are used by industry (29%) and in transportation (27%). Based on our recent studies on energy use in passenger cars, trucks and buses, we concluded that it is possible to save as much as 17.5% of the energy use in road transports in the short term (5-9 years) by effective implementation of new tribological solutions. This equals to annual energy savings of 11.6 exajoules, fuel savings of 330 billion liters and reduction in CO_2 emission by 860 million tonnes. In a paper mill, 15-25% of the energy used is spent to overcome friction. The electrical energy used by a paper machine is distributed as 32% to overcome friction, 36% for the paper production and mass transportation, and 32% is other losses. In paper machines, 11% of the total energy used to overcome friction can be saved by the implementation of new tribological technologies. This would result in electrical energy savings worldwide of 130,000 terajoule, economic cost savings of 2 billion euros and CO_2 emission reduction of 11 million tonnes annually. An overview of the total energy saving potential by improved tribology in transportation and industry is presented.

Keywords: Friction; Energy; Lubrication; Transportation.

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1 INTRODUCTION

Energy is a key resource for our society today and will be crucial for our sustainability in the future. Much of our energy needs comes from non-renewable fossil fuels; however, there are limitations in the availability of these fuels in the long run. Burning of oil and other non-renewable products produces large volumes of greenhouse gases that give rise to climate change. Energy is also a major cost issue for many industries.

A considerable amount of energy is consumed to overcome friction, especially in the transportation, industrial, and power-generation sectors, and major economic losses are also due to wear of products and components and their replacement. Jost [1] 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 more 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. A major source of CO_2 emissions is cars and trucks. Transportation consumes about 20% of the global primary energy and accounts for about 18% of the total anthropogenic greenhouse gas emissions. Road transport has the largest share and 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 [2,3].

In this paper we summarize our studies for calculating the global energy consumption due to friction and potential savings from friction reduction in transportation and in industry [4-6]. We first focused our attention on passenger cars for two reasons: passenger cars form a major consumer of energy and also generate a considerable part of the greenhouse emissions. The other reason was that the energy use in passenger cars has been largely studied on the system-to-component level. The present study is based on the current set of technical solutions for passenger cars, trucks, buses and advanced industrial productions machinery here represented by paper machines, while the effects of expected changes, future trends, and predictions in this set are not included.

2 METHODS

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

a) Global energy distribution analysis
b) Energy consumption break down
c) Operational cycle effect analysis
d) Friction loss distribution
e) Tribocontact friction levels today and future
f) Global energy consumption today and potential savings

This methodology was first developed in our study on friction energy loss in passenger cars [4]. The same methodology was later used in our studies on paper machines [5] and trucks and buses [6].

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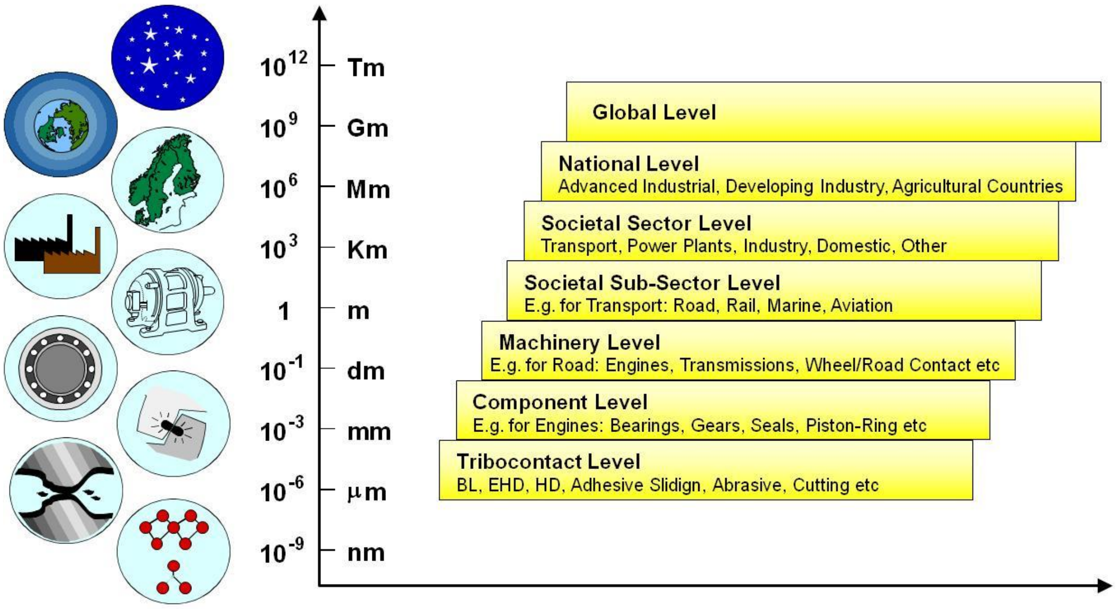

Figure 1: Scale levels for calculating friction losses in passenger cars from global energy demand for overcoming friction to friction losses in microlevel tribocontacts.

3 GLOBAL ENERGY CONSUMPTION AND ENVIRONMENTAL ASPECTS

The energy production worldwide (Total Primary Energy Supply TPES) was 13113 million tonnes oil equivalent (Mtoe) in 2011 which equals to 549 EJ [7]. Of this, about one third was consumed within the energy sector by power plants, furnaces, energy transfer losses and energy industry's own use leaving 373 EJ for the global final energy consumption (Total Final Consumption TFC). This part was used by industry (29%), transportation (27%) and other energy consumers like households and services (35%) and for non-energy use (9%) such as for raw materials. Oil is the largest part of the global energy supply (41%) by a value of 152 EJ, as shown in Figure 2. Oil is also the main source of energy for the transportation sector covering 96% of its energy need.

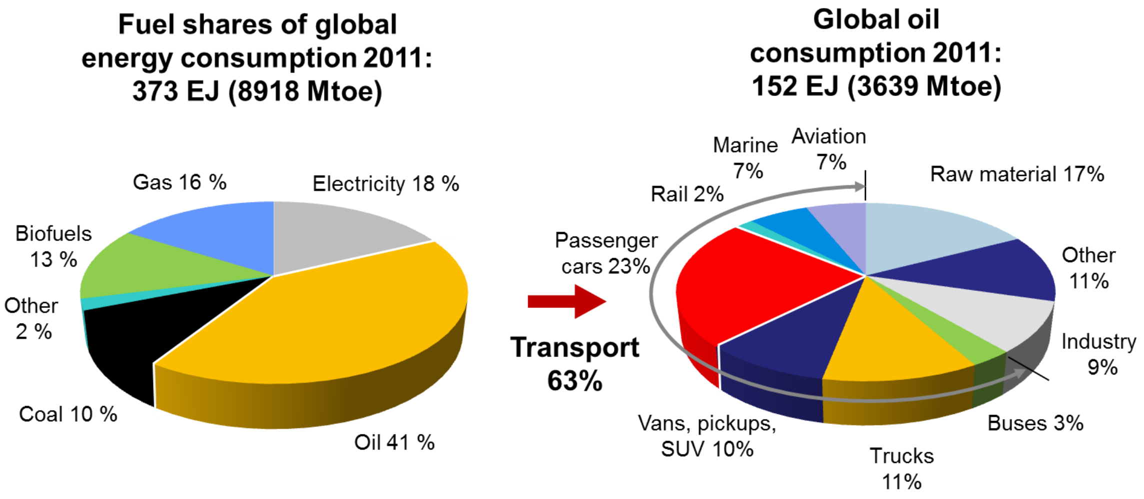

Figure 2. Global energy and oil consumption 2011 [7].

The global emission of CO_2, the major greenhouse gas, is steadily increasing since the beginning of industrial revolution and reached a level of 31 600 Mt in

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year 2011 [8]. The world transportation generated 23% of this (7 2000 Mt) and the largest part came from road transport. In year 2009, 71.7% of all transportation CO_2 emissions in Europe came from road transport, 14.6% came from marine, 12.3% from aviation and 0.8% from rail transport [9].

4 ENERGY CONSUMPTION IN TRASPORTATION

Transportation accounts for 63% of the total global oil consumption. The rest is used by industry, for raw materials and other uses. Within the transportation sector, road traffic is the largest user of energy (73%) followed by marine (10%), aviation (10%) and rail (3%) traffic, as shown in Figure 3 [10]. However, the ships are the largest carrier of world freight (75%) followed by rail (13%), road vehicles (12%) and aviation (0.3%) [11,12].

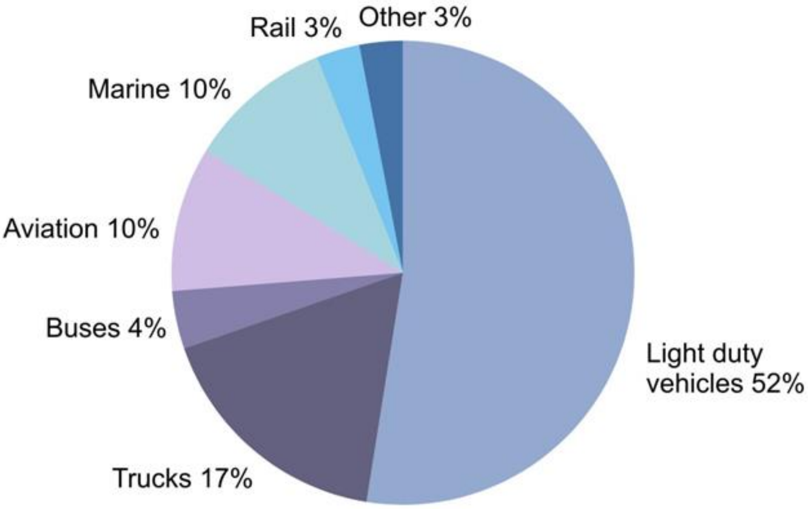

Figure 3. Global breakdown of energy consumption by transportation vehicles [10].

In terms of number of vehicles, passenger cars has been dominating with more than 1000 million road vehicles rolling on the streets and highways, see Table 1. Aviation, rail and marine are of lower orders of magnitude with 360 000 air crafts worldwide, 120 000 trains and 100 000 ships. The number of aircrafts and trains are well documented in available statistics [13,14] while the number of ships is more difficult to find because the definition is not so clear. There were 80 000 merchant vessels over 100 gross tonnage (GT) registered 2011 [15] but in addition there are almost 30 million pleasure boats and yachts of various types and sizes worldwide [16,17]. In our energy use comparison we have chosen to use 100 000 ships as representative for the marine transport.

In average, 21 GJ is annually used by road vehicles to overcome friction [4,6]. We have estimated based on statistics on general level that an average air craft would use about 2,800 GJ annually to overcome friction, a train 8,300 GJ and a marine vessel 30,000 GJ, see Table 1.

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Table 1. Global energy distribution in transportation

Calculated annually	Road transport	Rail transport	Marine transport	Aviation	Total
				Airline jets	
Number of units worldwide	1 040 million	120 000	100 000	360 000	1 041 million
Energy use worldwide, EJ	67	3	9	10	93
Part of global energy consumption, %	18	1	2.4	2.7	25
Energy use for friction, EJ	22	1	3	1	30
Energy use for friction / unit, GJ	21	8 300	30 000	2 800	

5 ENERGY CONSUMPTION IN ROAD TRAFFIC

The road traffic is dominated by 700 million passenger cars and 300 million other light vehicles like vans, pick-ups and sport utility vehicles (SUV) in terms of number of vehicles, see Table 2. In addition there are 36.5 million single-unit trucks, with a total weight over 3.5 tonnes, and truck and trailer combinations, and 3.6 million city buses and coaches. The annual mileage for the light vehicles is 13,000 km annually and 20,000 km for the trucks while it is 80,000 km for city buses and 100,000 km for coaches and truck and trailer combinations. The data for passenger cars and trucks and buses have been reported by Holmberg et al. [4,6] while the data for other light vehicles is estimated based on the passenger car data.

The passenger cars use 11.2 EJ annually and the vans, pickups and SUVs use 4.6 EJ annually to overcome friction. The corresponding numbers for trucks and truck and trailer combinations is 4.9 EJ and for buses and coaches 1.3 EJ. The annual energy use per vehicle unit is highest for city buses, truck and trailer combinations and coaches, as seen from Table 2.

Table 2. Global average road vehicle key figures for friction and energy use according to situation 2011.

Calculated annually	Single-unit trucks	Trucks and trailers	City buses	Coaches	Passenger cars (1)	Other light vehicles (2)	Road transport total
Number of units worldwide, millions	29.2	7.3	2.3	1.3	700	300	1040
Average mileage (km)	20,000	100,000	80,000	100,000	13,000	13,000	
Energy use worldwide, EJ	5.2	10.5	2.5	1.2	34	14	67
Part of global energy consumption, %	1.4	2.8	0.7	0.3	9.1	3.7	18
Energy use for friction, EJ	1.6	3.3	1.0	0.3	11.2	4.6	22
Energy use for friction / unit, GJ	54	446	454	253	12	20	21

(1) Data from Holmberg et al. (2012) corrected and updated to the situation 2011.
(2) Vans, pick-ups and sport utility vehicles.

Breakdown of the energy use in an average passenger car on global level is shown in Figure 4. More than half of the fuel energy in an internal combustion engine goes to exhaust (33%) and cooling (29%) while the rest is transformed to mechanical power (38%). Of this part are the total frictional losses the main part (33%) while the air drag (5%) is a minor part. The largest groups of parasitic friction losses are those in the engine (11.5%), in the transmission system (5%) and that for overcoming rolling friction of the tires (11.5%). In addition, mechanical power is consumed by friction losses when braking and this deceleration energy can in average be considered as equal to the energy used for accelerating the vehicle. Thus actually only 21.5% of the fuel energy is used for moving the car, consisting of the tire rolling resistance, the air drag and the brake/acceleration energy, while the rest are energy losses.

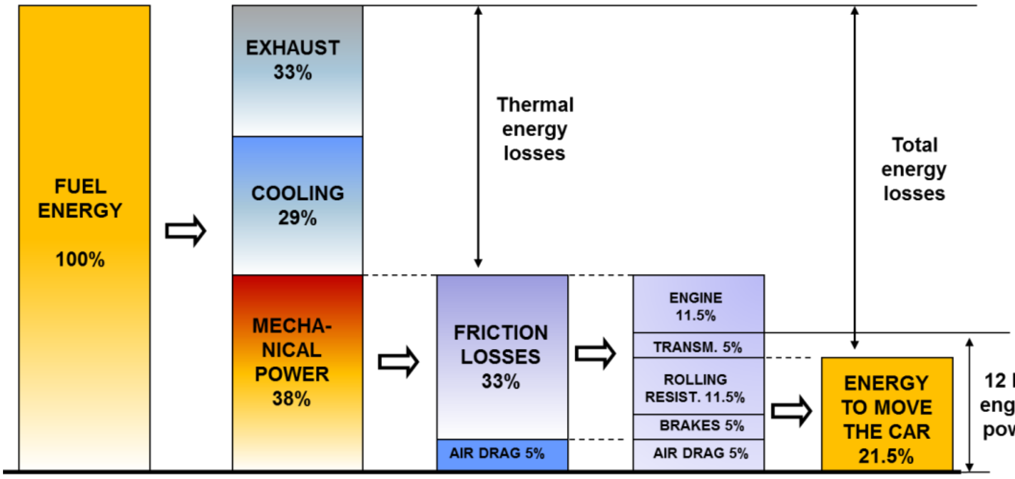

Figure 4. Breakdown of passenger car fuel energy consumption.

The frictional losses are 33% of the total fuel energy and of this is 35% consumed in the tire-road rolling contacts, 17% in elasto-hydrodynamic contacts, 16% in hydrodynamic contacts, 8% in mixed and 2% in boundary lubricated contacts. Viscous losses are 7% and braking takes 15% [4].

6 POTENTIAL ENERGY SAVINGS IN ROAD TRANSPORTATION

Friction is a major energy consumer in transportation representing some 25 to 30% of the total energy use. However, new tribological knowledge and developments have resulted in breakthrough solutions where the friction has been reduced by even 50 to 90% from the level normally found in vehicles in use today [4,6]. Figure 5 shows this trend as estimated for the different tribological contact and friction mechanisms in heavy duty vehicles. The technology behind has been presented by Holmberg et al. [4,6].

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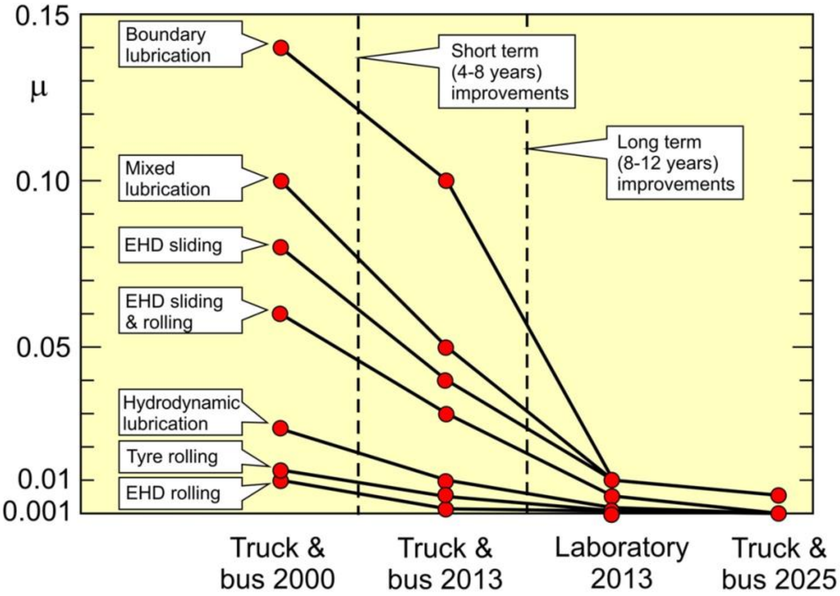

Figure 5. Trends in coefficient of friction reduction in four truck and bus categories for different lubrication mechanisms and for rolling friction.

Holmberg et al. [6] calculated for heavy duty vehicles that by implementing the most advanced tribological solutions in use in modern commercial heavy vehicles of today in all vehicles world-wide, the energy consumption due to friction could be reduced by 37% (Truck & bus 2013) in Fig. 5). If the best tribological solutions demonstrated in research laboratories were in use, this factor would be reduced by 60% (Laboratory 2013), and if the new solutions forecasted for 2025 were in use, it would be 68% (Truck & bus 2025). It is interesting to note that the savings in fuel energy can be 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 trucks and buses would require an enormous effort and would result in large implementation 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 four to eight years, by large scale concentrated research, development and implementation efforts on new tribological solutions resulting in 14% reduction in fuel consumption, as shown in Figure 5. The realistic long term reduction in fuel consumption was calculated to be 37%.

Due to the smaller number of heavy duty vehicles in the global fleet, the smaller number of vehicle owners, and their better organization, compared to owners of passenger cars, it has been assumed that changes to lower friction losses are easier to implement and will thus have a more rapid effect. It was estimated that a short-term penetration time for the global fleet of heavy duty vehicles is 4-8 years, compared with the 5–10 years for passenger cars.

To present the whole picture of energy consumption in road transportation worldwide, Table 3 summarizes the key data [6]. It reveals that more than 1000 million road vehicles in our planet use annually about 22 EJ fuel energy to overcome friction. In the short term (4 to 8 years), on average, 14% of the energy used could be reduced by efficiently implementing new technological solutions. On an annual global basis, this energy savings would result in economical savings of 475,000 million euros and reduced CO_2 emissions of 856 million tonnes.

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Table 3. Potential energy and economic savings and CO_2 emission reduction as a result of implementing new tribological solutions in road transport.

Calculated annually	Single-unit trucks	Trucks and trailers	City buses	Coaches	Passenger cars (1)	Other light vehicles (2)	Road transport total
Short-term saving period, years	4 - 8	4 – 8	4 – 8	4 - 8	5 – 10	5 - 10	5 - 9
Short-term savings/reduction, %	12	15	11.5	15	18.5	18.5	17.5
Energy savings from reduced friction in short term, EJ	0.62	1.6	0.29	0.18	6.3	2.6	11.6
Cost savings from reduced friction in short term, 1000 x million €	24.4	61.7	11.3	7.1	260	110	475
Fuel savings from reduced friction in short term, 1000 x million litres	17.5	44.1	8.1	5	178	73	326
CO_2 savings from reduced friction in short term, million tonnes	45.9	116.0	21.2	13.3	468	192	856
Short-term savings/reduction, %	12	15	11.5	15	18.5	18.5	17.5

(1) Data from Holmberg et al. (2012) corrected and updated to the situation 2011.
(2) Vans, pick-ups and sport utility vehicles.

7 ENERGY CONSUMPTION IN PAPER MACHINES

In another study we calculated the energy going to overcome friction in an advanced industrial production machine as represented by a paper machine [5]. There were 8525 paper machines in operation worldwide and they used 101 400 GWh of electrical power in 2012 to overcome friction. In this study we used the same methodology as above for cars and defined the global average paper machine and its global average operating conditions. This machine was analysed in detail. The main subsystems and the machine elements with friction loss contacts are shown in Figure 6.

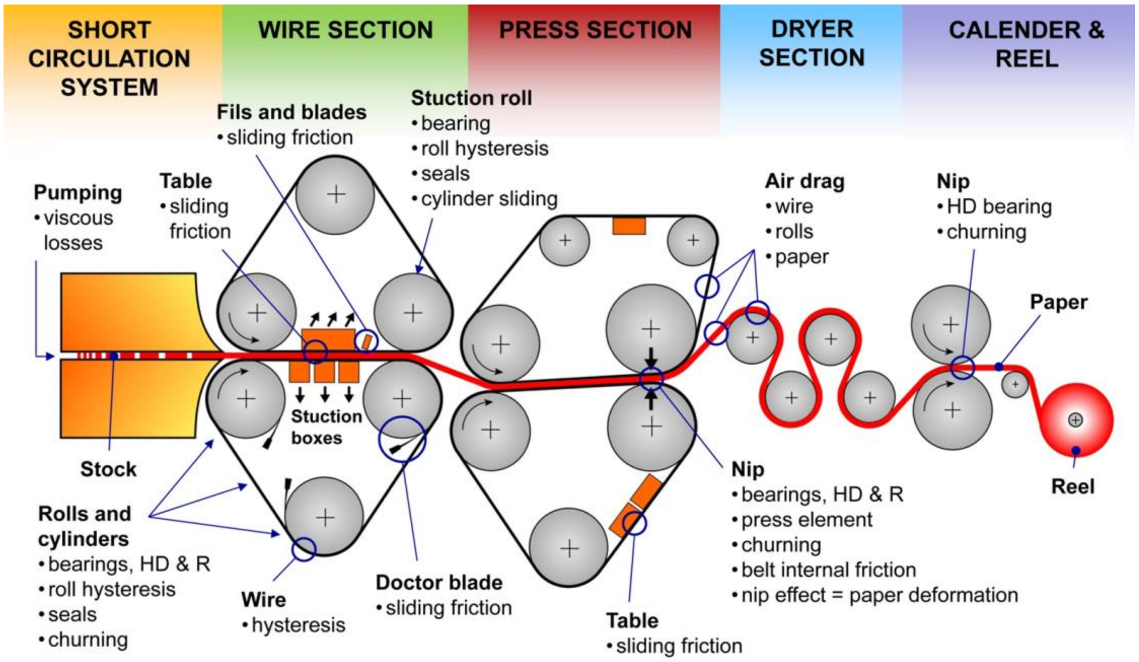

Figure 6. Friction sources causing in energy losses in a paper machine.

The electrical energy consumed when operating the paper machine forms not more than 30% of the total paper machine energy consumption. The remaining part is 67% steam energy for process heating and 3% factory fuels.

The direct friction losses are 9.2% of the total paper machine energy consumption and 32% of the electrical energy used. Of this 48% was consumed in EHD contacts, 9% in HD contacts, 18% in seal boundary lubricated seal contacts, 23% in water lubricated sliding contacts at fabrics and 2% in water lubricated sliding contacts at doctor blades. The breakdown of energy consumption in the global average paper machine is shown in Figure 7.

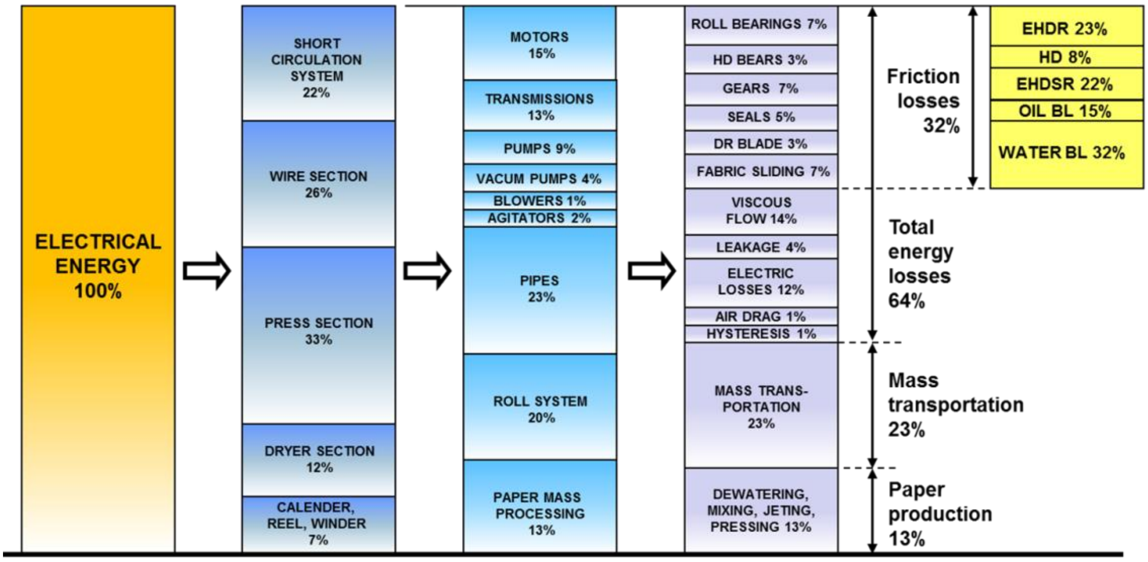

Figure 7. Breakdown of the global average paper machine energy consumption

Based on data published in the open literature, the coefficients of friction were estimated for the relevant lubrication and contact mechanisms in four categories of paper machines, see Figure 8. The Paper machine 1980 represents the global

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average paper machine and it was manufactured in the year 1980, the Paper machine 2010 represents a new global average paper machine manufactured in 2010, Lab 2010 represents the lowest friction values reported in tribology laboratories worldwide and Paper machine 2025 represents a paper machine with the best tribological solutions forecasted within the next 15 years.

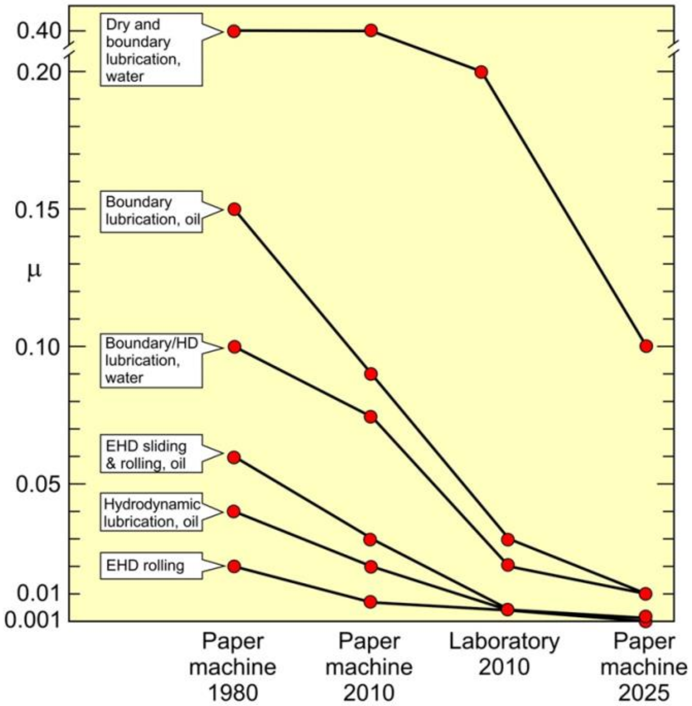

Figure 8. Past and forecasted reductions in the coefficient of friction for different lubrication and contact mechanisms in the four paper machine categories.

We estimated that by taking advantage of new technology for friction reduction in paper machines, friction losses could be reduced by 11% in the short term (about 10 years), and by 23.6% in the long term (20-25 years). This would equal to worldwide economic savings of 2 000 million euros, electricity savings of 36 000 GWh, and CO_2 emission reductions of 10.6 million tonnes in the short term and economic savings of 4 200 million euros, electricity savings of 78 000 GWh, and CO_2 emission reductions of 22.7 million tonnes in the long term.

Potential mechanisms to reduce friction in paper machines include the use of low-friction and highly durable coatings, surface engineering including texturing, low-viscosity and low-shear lubricants and fluids, novel additives, new materials in seals, doctorblades and fabrics, as well as new designs.

Based on the very detailed analysis of three cases - passenger cars, trucks and buses representing the transportation sector and paper machines representing the industrial sector – this study gives us some insights into how much energy is lost to overcome friction and how to control it to improve the efficiency of future mechanical systems.

Transport and industry are the two largest users of energy, and they are currently consuming almost one third each of the total energy production. About 30% of the energy in transport is used to overcome friction, while in industry the corresponding amount is about 15-20%. In residential and other areas, the energy used to overcome friction is less than 10%. The overall conclusion is that about 20% of the total energy production in the world is used to overcome friction.

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8 CONCLUSIONS

About 100 million terajoule is used annually worldwide to overcome friction and that is one fifth of all energy produced. This is contributing to the global emissions with 7 000 million tonnes of CO_2 annually. The largest quantities of energy are used by industry (29%) and in the transportation field (27%). Based on our calculations, we conclude that it is possible to save as much as 17.5% of the energy use in road transports in the short term (5-9 years) by effective implementation of new tribological solutions. This equals to annual energy savings of 11.6 exajoules, fuel savings of 330 billion liters and reduction in CO2 emission by 860 million tonnes. In a paper mill, 15-25% of the energy used is spent to overcome friction. In paper machines, 11% of the total energy used to overcome friction can be saved by the implementation of new tribological technologies. This would result in electrical energy savings worldwide of 130,000 terajoule, economic cost savings of 2 billion euros and CO2 emission reduction of 11 million tonnes annually.

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