Global energy consumption due to friction in passenger cars, transportation and industry

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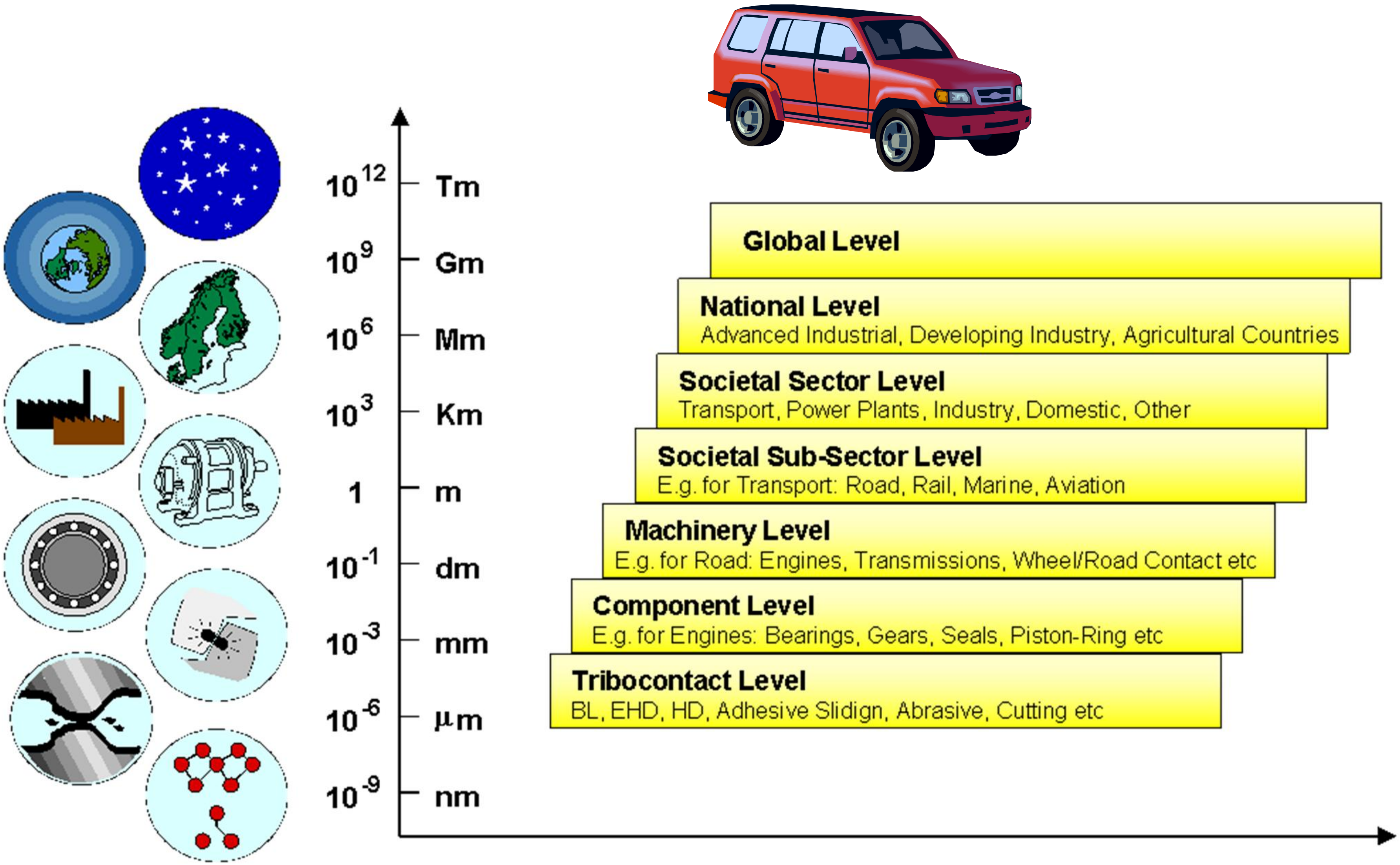
OUTLINE

1. Introduction
2. Friction related energy losses in passenger cars
3. Energy losses in all transportation
4. Friction energy losses in paper machines
5. Overall global energy losses due to friction
6. Potential solutions and future perspectives

Root causes of friction losses across all scales in passenger cars



Methodology for calculation of friction losses in passenger cars on global level

1. Total energy consumption worldwide 2009: ***11 164 Mtoe/a***

↓

2. Global consumption of crude oil for cars 2009: ***1083 Mtoe/a***

↓

3. Global oil fuel energy used in passenger cars: ***22 085 000 TJ/a***

↓

4. Divide by number of cars worldwide: ***612 million cars***

↓

5. Energy used in one global average car: ***36 000 MJ/a***

Definition of the global average passenger car 2010

- **Manufactured in 2000**
- **75 kW four-cylinder, in-line, four-stroke engine**
- **1.7 dm3 engine capacity**
- **1500 kg weight**
- **Gasoline fuelled by 70%, diesel fuelled by 30%**
- Engine oil viscosity class SAE 5W40 (age < 1 year)
- Tyre coefficient of rolling friction approx. 0.02. (Summer tires, size
- 185/65R15, age 4 years, average tyre pressure, on average road)
- Frontal area approximately 2.3 m^2
- Drag constant 0.345 (average for passenger cars of 2000 model)
- Hydro mechanical power steering
- Air condition with compressor in 25% of the cars
- Manual 5-speed gearbox. Oil SAE 75W-90 of 10 years age
- Front wheel drive
- Driving brakes based on friction linings and drums or discs

The global average driving conditions in 2010

- **13 000 km annual driving distance**
- **60 km/h average speed**
- **Average fuel consumption 8 litres/100 km**
- **12 kW engine power output on an average**
- **300 g/kWh fuel efficiency (@ 12 kW)**
- **2.5 kg CO_2 emissions per fuel litre burned, or 200 g/k**
- Average braking power: 2.4 kW
- Engine oil temperature estimate: 80°C
- Gearbox oil temperature estimate: 60°C
- As an average for 612 million cars

Fuel efficiency curves (g/kWh)

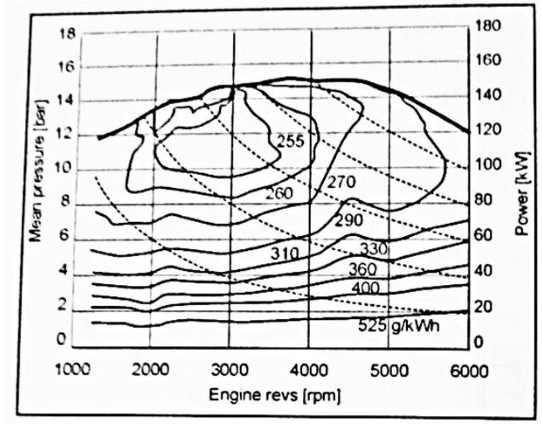


Fig. 3-9 Power and consumption curves for a car SI engine.[7]

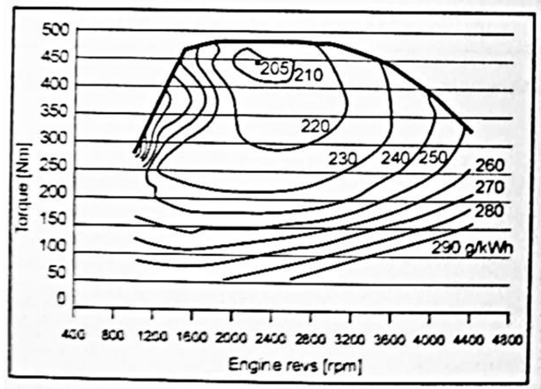
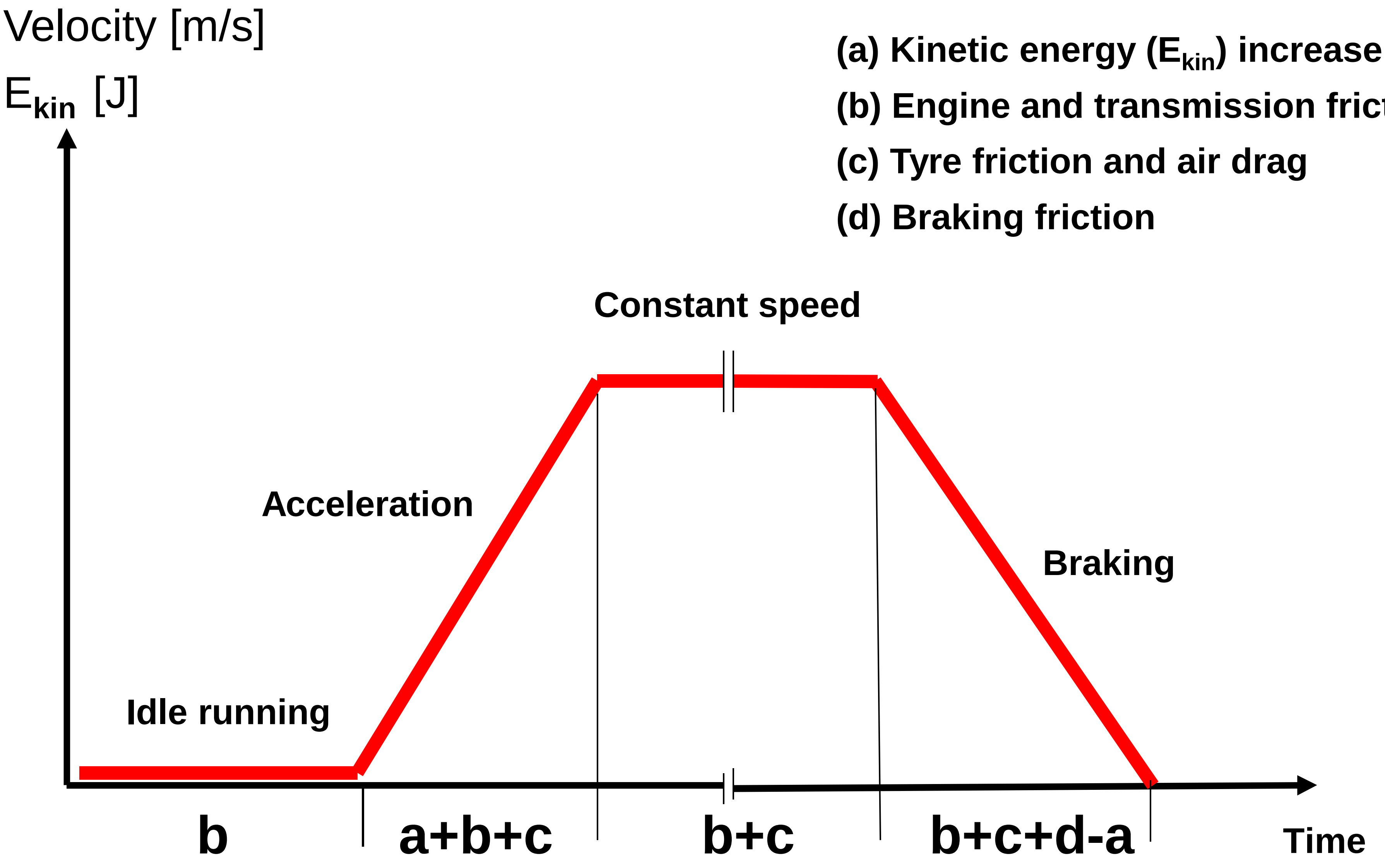
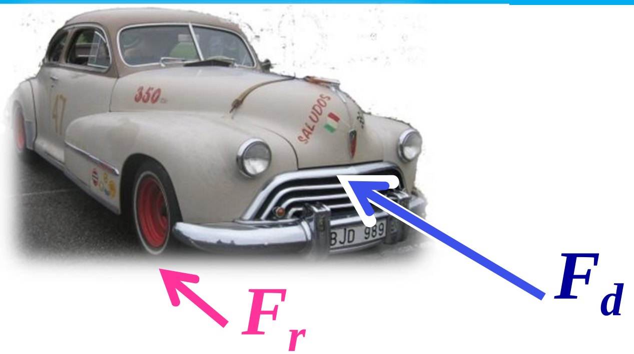


Fig. 3-10 Consumption curve, car diesel engine V8-TDI.[8]

Energy balance during four stages in typical car operation



(a) Kinetic energy (E_{kin}) increase
(b) Engine and transmission friction
(c) Tyre friction and air drag
(d) Braking friction



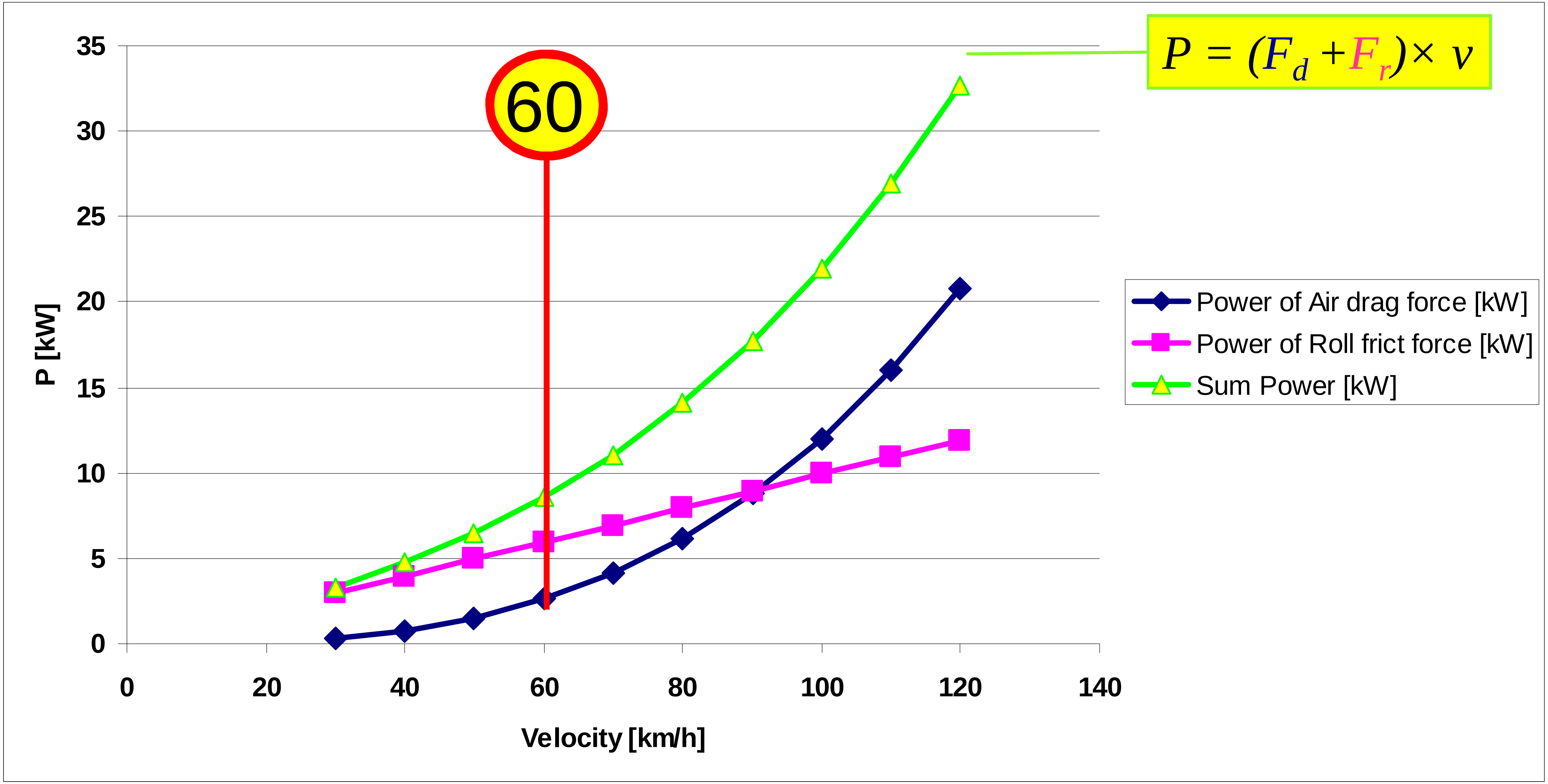
Running resistance

- Uphill driving, here compensated by subsequent downhill
- Effect of wind direction, here self-compensated
- Acceleration forces compensated by subsequent retardation
- Tyre rolling resistance $F_r = m \times g \times \mu_r$
- Drag force, $F_d = \rho \times v^2 \times A \times C_d / 2$

Tribology
m = mass of vehicle
g = 9.81 m/s²
μ_r = coefficient of tyre rolling friction

Aerodynamics (not tribology)
ρ = density of air
v = velocity of the vehicle
A = drag area
Cd = drag constant

Power losses from air drag and tyre rolling friction as function of speed



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

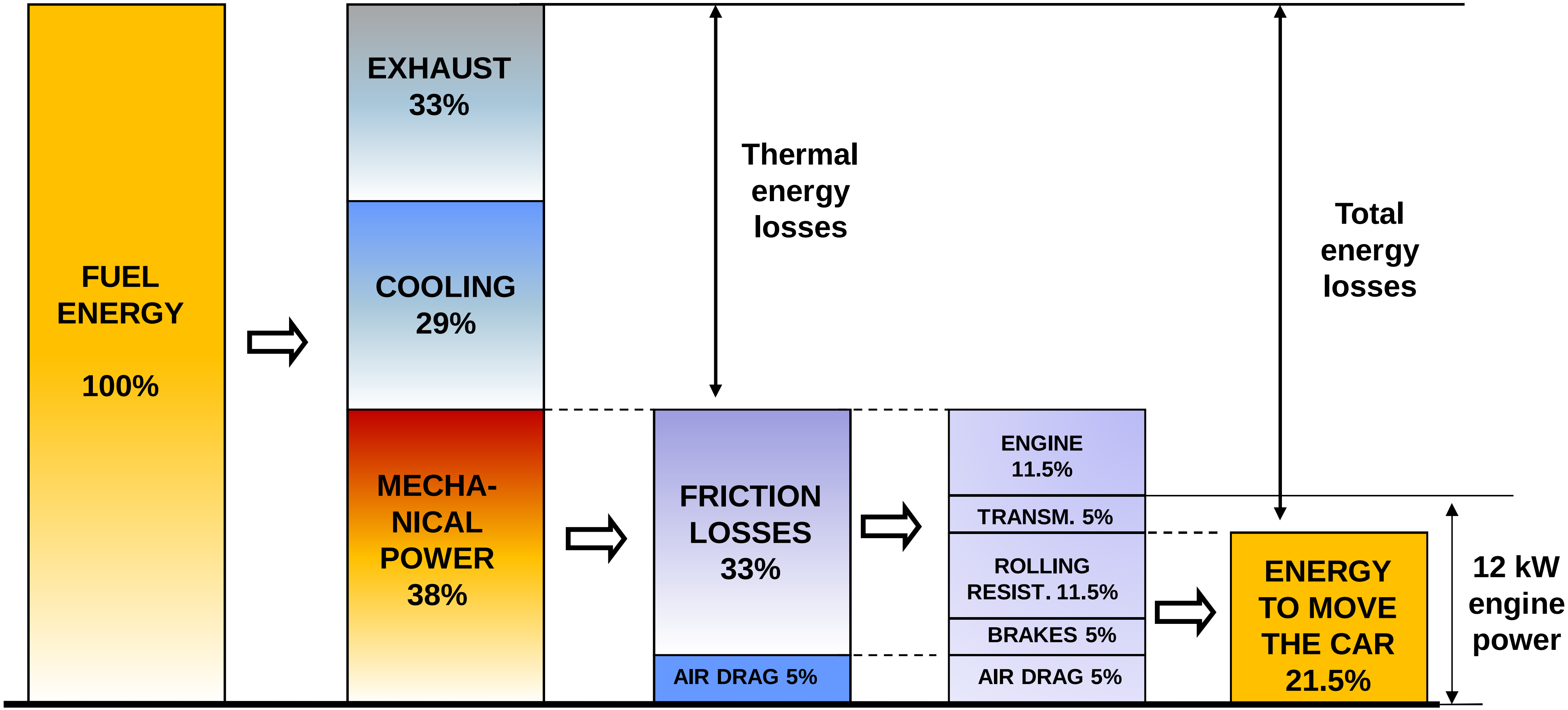
Exhaust	33%	=> convection of heat and gases
Cooling	29%	=> conduction and dissipation of heat
Air drag	5%	=> gas shear => heat
Friction	33%	=> heat & material degradation

FUEL

Potential energy (chemical)

Transformation to:
- kinetic energy
- thermal energy
- phase transition

Passenger Car Energy Consumption



Friction losses in the main car components as part of the total friction losses of the car

Tyres 35% RF

Engine 35%

- valve train 15% ML
- bearings, seals 30% HD
- piston assembly 45%
  - HDsqueeze 40%
  - EHD 40%
  - ML 10%
  - BL 10%
- pumping, hydraul. 10% VL

Transmission 15%

- gears 55% EHD
- bearings 20% EHD
- viscous 20% VL
- seals, forks 5% ML

Brakes 15% SF

Literature data scatter

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**.

Break down of frictional energy losses in the global average passenger car with respect to the tribocontact mechanisms

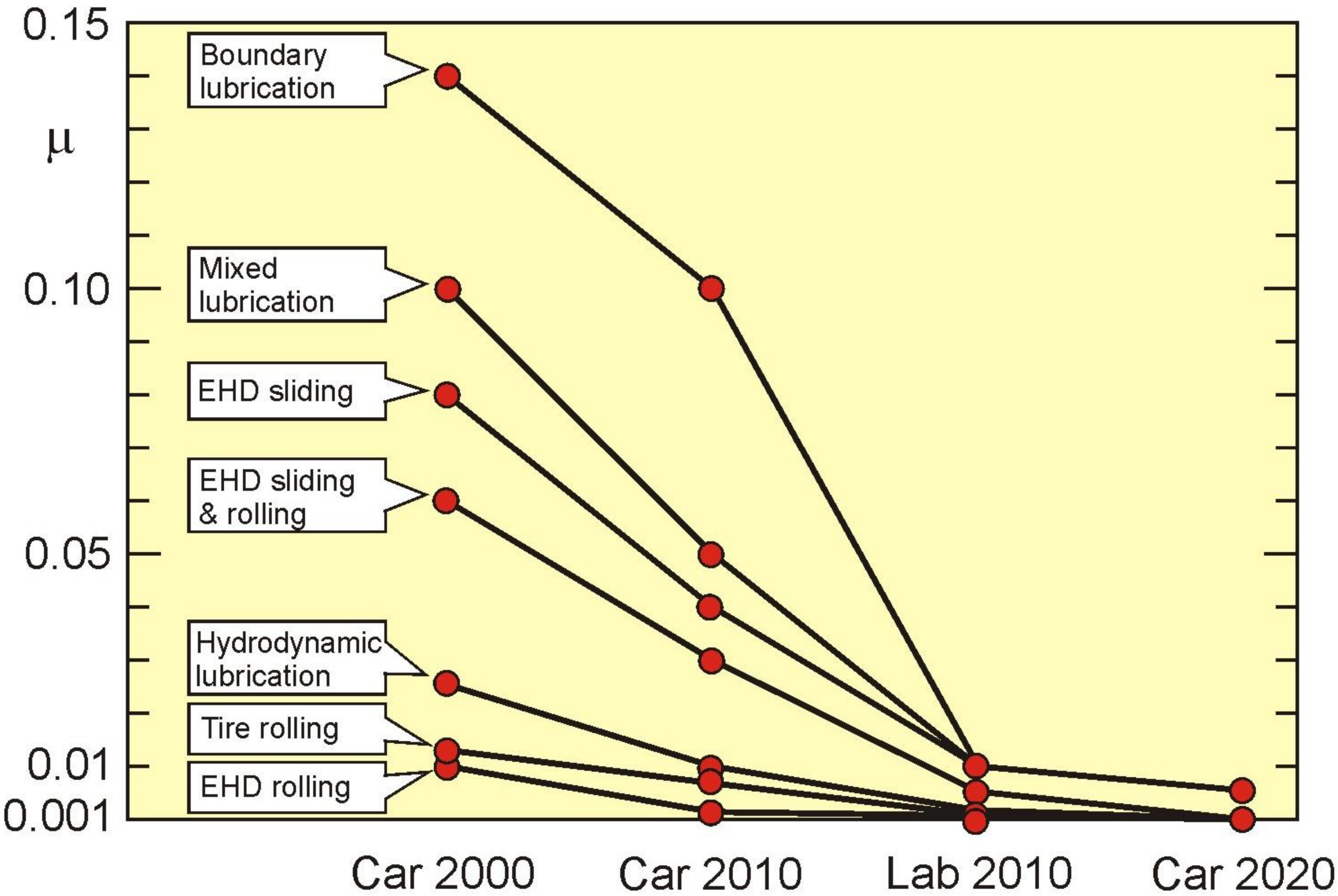
The 11 863 MJ to overcome friction is distributed as:

- **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

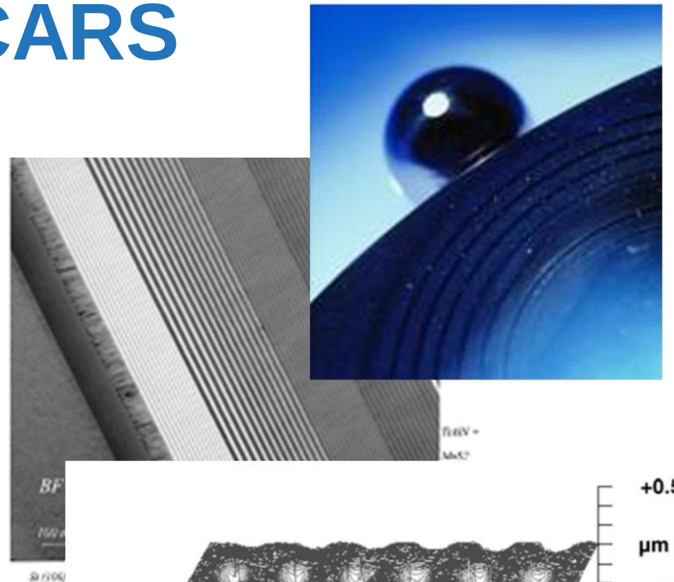
Friction losses in passenger cars categorised according to type of tribocontact

Friction loss source type	Energy consumed (MJ/car/a)	Fuel used (liters/car/a)	Percentage (%)
Tire-road contact	4 152	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

Trends in friction reduction for different lubrication mechanisms and rolling friction with reference to passenger car applications



EMERGING TECHNOLOGIES FOR FRICTION REDUCTION IN PASSENGER CARS

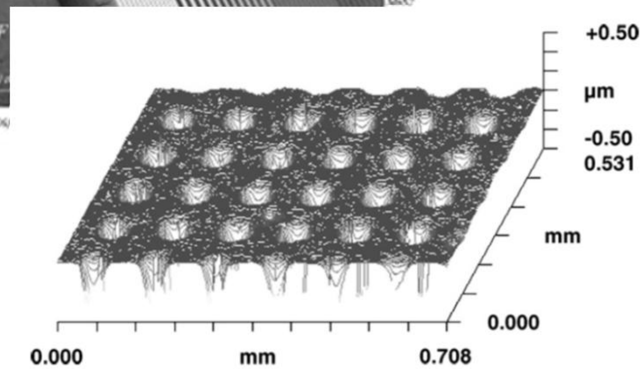


➢ Advanced coating structures

DLC, TS, nano-composites etc:
- dry in vacuum superlubricity μ= 0.001
- lubricated 10-50% friction reduction

➢ New surface texturing methods

Laser surface texturing:
- 25-50% friction reduction
- 4% engine fuel reduction

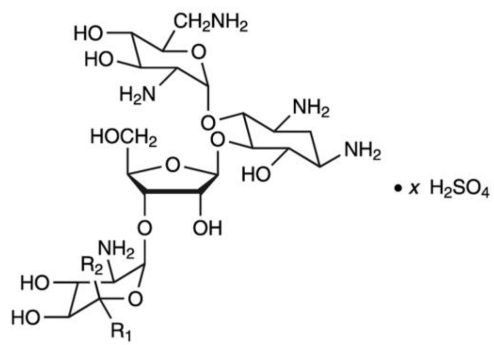


➢ New boundary lubrication additives and fluids

Glycerol mono-oleate in PAO vs DLC:

- μ = 0.005 in pure glycerol

Nanomaterials as additives like WS2, MoS2 H3BO3



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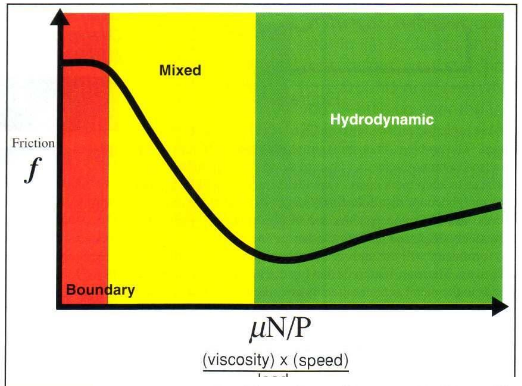
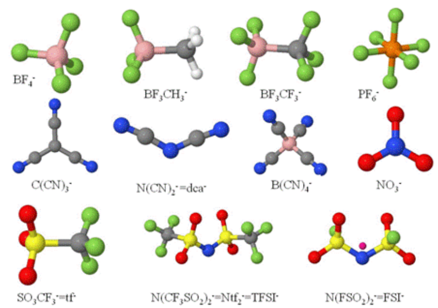


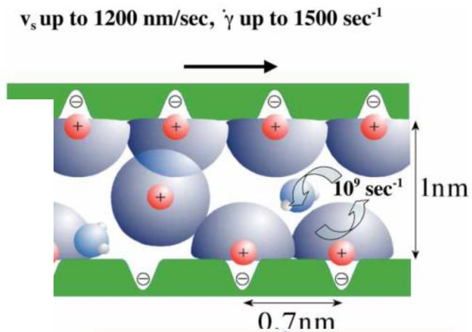
- **Low viscosity fluids**

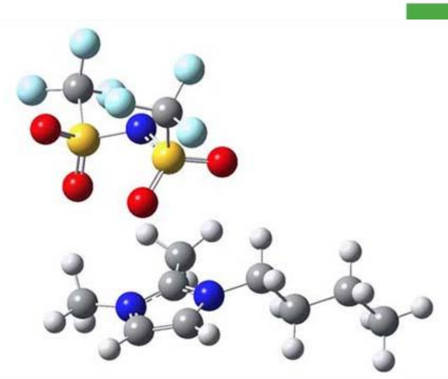
Polyalkyl glycols

- **Ionic liquids**

25-50% friction reduction with IL







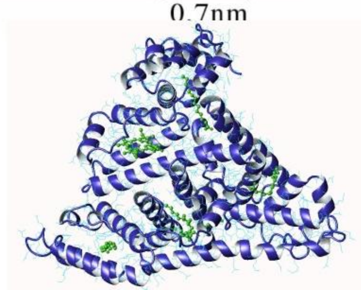
- **Biomimetics**

Biomolecular protein additives

Brushes of charged polyelectrolytes

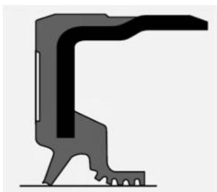
Porcine gastric mucin, glycoprotein mucin

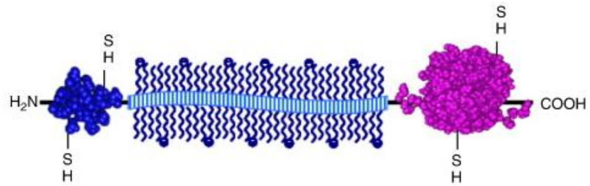
- μ=0.001-0.04



- **Low friction tyre design**

High pressure, small width etc





Methodology for calculation of friction losses in passenger cars on global level

1. Global consumption of crude oil for cars 2009: *1083 Mtoe/a*

↓

2. Global oil fuel energy used in passenger cars: *22 085 000 TJ/a*

↓

3. Divide by number of cars worldwide: *612 million cars*

↓

4. Energy used in one global average car: *36 000 MJ/a*

↓

5. Energy used to overcome friction in one average car: *11 860 MJ/a* = *340 l/a*

↓

6. Friction losses in car sub-systems: tyres, engine, trans-mission and brakes

↓

7. Friction losses in car components: gears, bearings, seals, piston, pumping etc

→

8. Friction losses in various tribocontacts: HD, EHD, BL, ML, VL etc

↑

9. Estimation of friction efficiency (= coefficient of friction) for each friction loss source for car 2000, car 2010, lab 2010 and car 2020

↑

10. Friction loss reduction potential for each friction loss source

↑

11. Energy saving potential for one average car by using today's advanced commercial (37%), best lab (61%) and best future solutions (70%)

↑

12. Potential savings globally by using today's advanced commercial (*350 000 M€*), best lab (*575 000 M€*) and best future solution (660 000 M€)

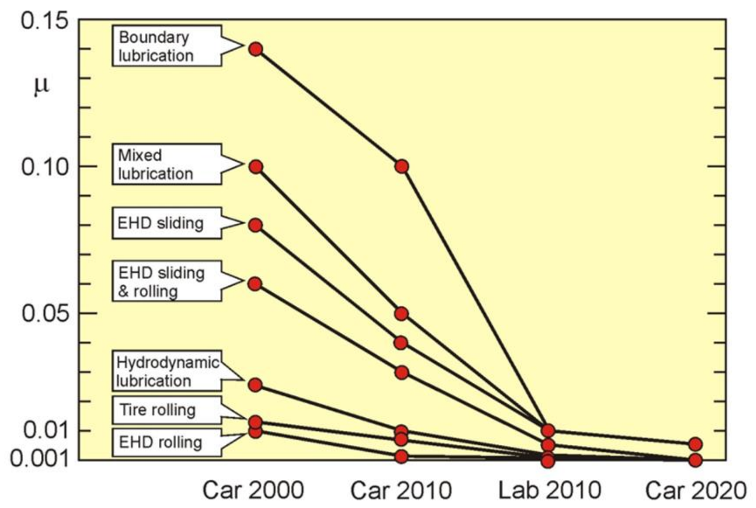
↓

13. Potential savings in regions e.g. for Europe by using today's advanced commercial (*60 200 M€*), best lab (*99 600 M€*) and best future solution (*114 000 M€*)

FUEL CONSUMPTION AND POTENTIAL FRICTION SAVING IN PASSENGER CARS GLOBALLY

Gas and diesel oil used to overcome friction	**208 000 million liters/a**
Energy used to overcome friction	**7.3 million TJ/a**

Potential savings by today's best commercial	**348 000 M€/a**
Potential savings by today's best solution	**576 000 M€/a**
Potential savings by future (10 a) best solution	**659 000 M€/a**



Realistic oil fuel savings (18% reduction)	**117 000 million liters/a**
Realistic CO_2 savings	**290 million tonnes/a**
Realistic savings after 10 years focused actions	**174 000 million €/a**

Worldwide and regional/national potential savings by implementation of advanced friction control technologies

	Energy Saving (TJ/a)	Cost Saving (10^6 euro/a)	Oil 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

MEANS TO REDUCE ENERGY CONSUMPTION IN CARS

Friction reduction:

- 10% tire rolling friction reduction => 3% energy savings
- 10% engine friction reduction => 3% energy savings
- 10% transmission friction reduction => 1.5% energy savings

Weight reduction and design:

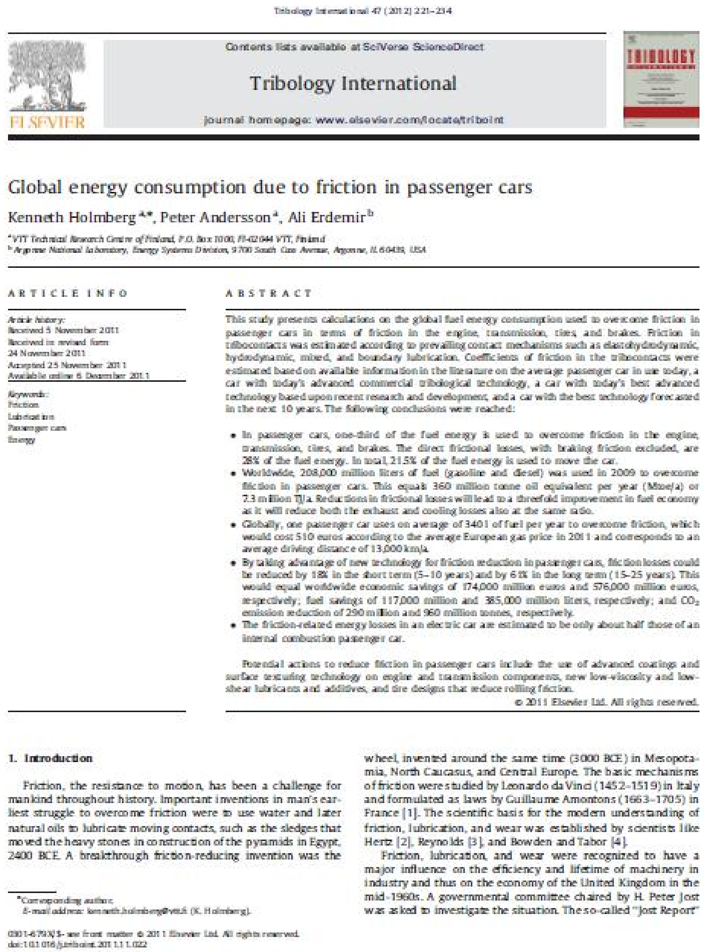
- 10% weight reduction => 8.3% energy savings
- 10% frontal area reduction => 2.2% energy savings

Driver actions:

- 10% speed reduction (110>100 km/t) => 16% energy savings
- 2 atm > 2.5 atm tire pressure => 3% energy savings

Background

Article “Global energy consumption due to friction in passenger cars”



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Global energy consumption due to friction in passenger cars

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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 of 340 l 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 13,000 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 290 million and 960 million tonnes, respectively.
- 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.

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 scientists like Hertz [2], Reynolds [3], and Bowden and 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-1960s. A governmental committee chaired by H. Peter Jost was asked to investigate the situation. The so-called "Jost Report"

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Steven Chu* & Arun Majumdar, "Opportunities and challenges for a sustainable energy future", *NATURE*, Vol. 488, 16 Aug 2012, 294-303.

**Nobel Prize in Physics 1997, Secretary of Energy in the Obama Cabinet .*

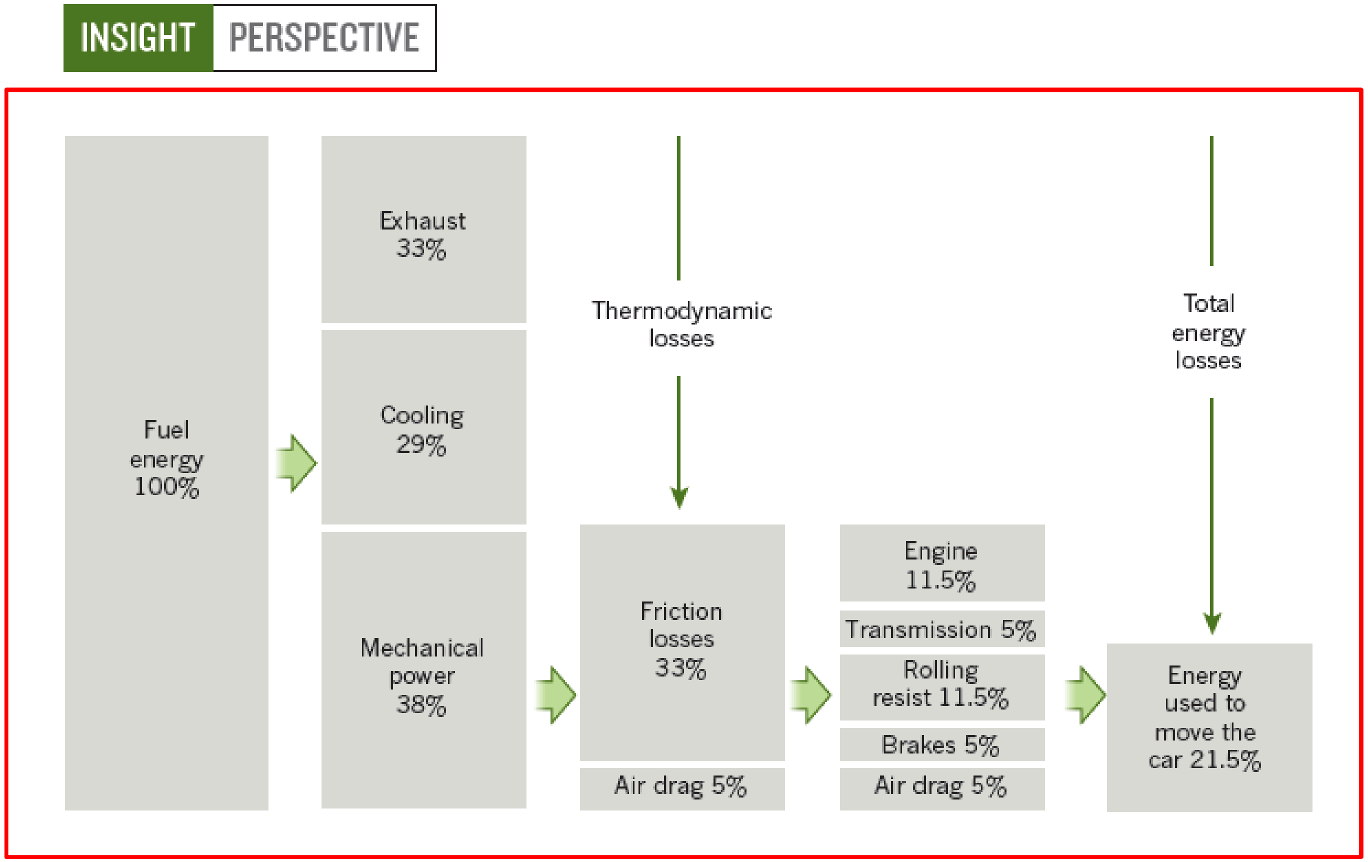
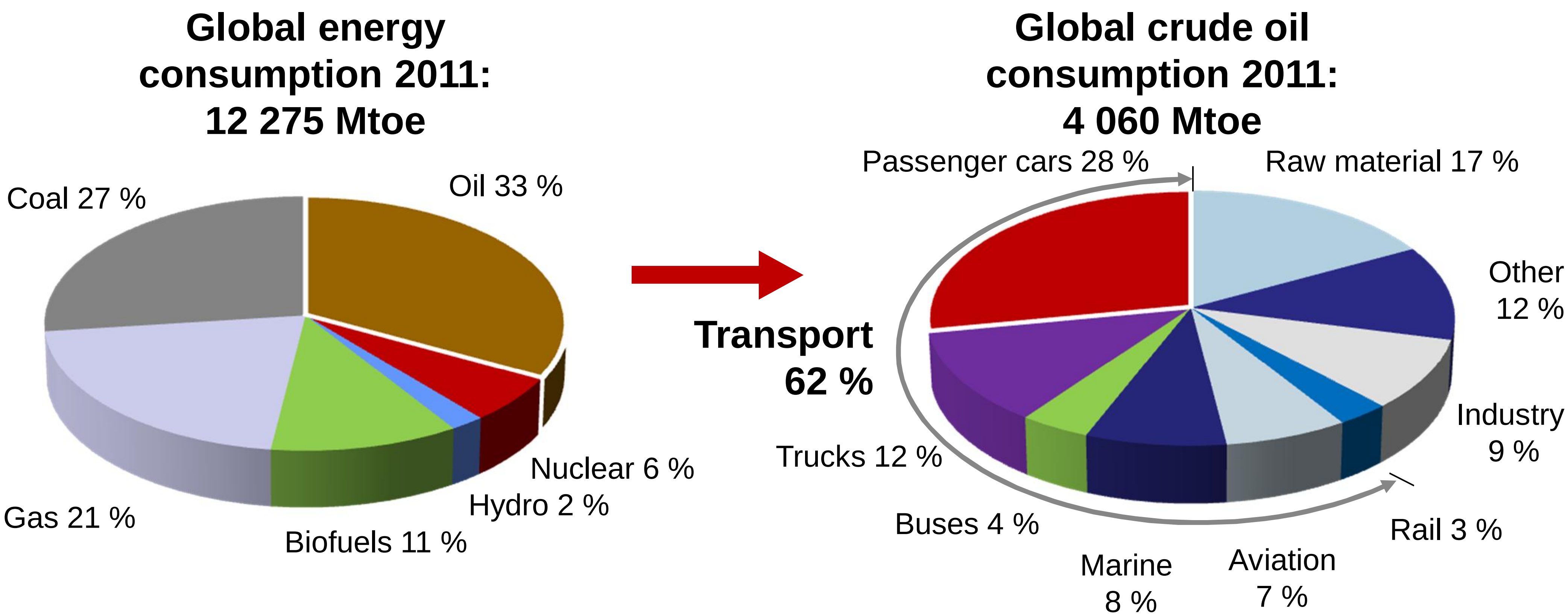


Figure 2 | Vehicle energy losses. Of the energy that fuel provides to vehicles a substantial proportion is lost. A breakdown of the average losses of internal-combustion-engine cars (fleet make up 70% petrol and 30% diesel) is shown. Heat lost constitutes 30–37% of the energy as a result of exhaust gases with lower energy content and convection. The other losses come from heat dissipation (25–33%), mechanical losses (33–40%), air drag (3–12%), rolling friction (12–45%) and brake losses (about 5%). These losses mean only about 21.5% of the energy is used to move the car. Adapted with permission from ref. 12.

*"**Reducing energy losses as a result of friction is also possible [12] (Fig. 2).** Advances in cost-effective technologies such as tribology, tyres, braking and waste-heat energy recovery, and aerodynamics could potentially lead to efficiency improvements of 20% in the short term and more than 60% over a longer term (15–25 years)."*

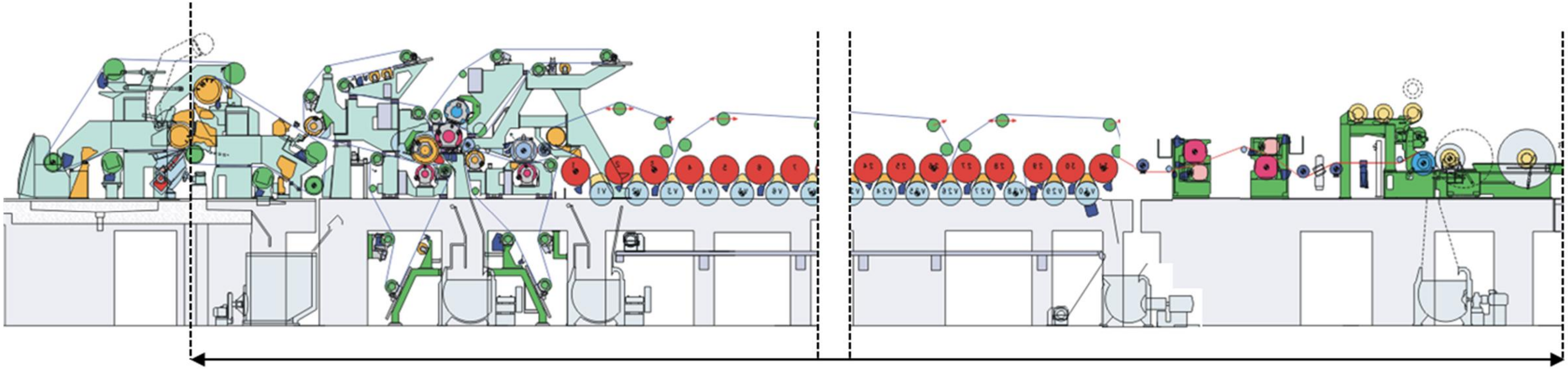
Global energy production and consumption 2011



Mtoe = million tonnes of oil equivalent

4. Friction energy losses in paper machines

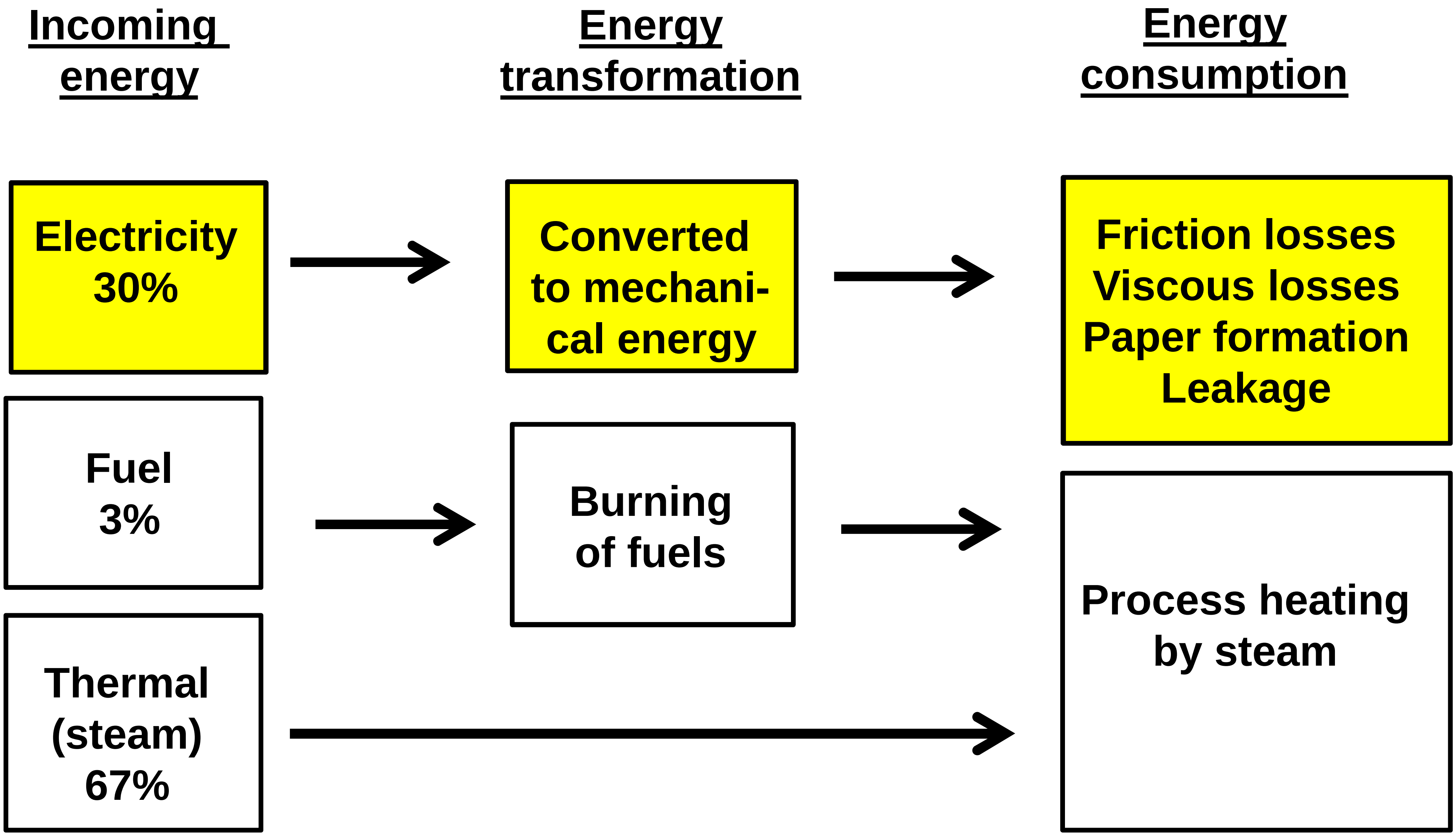
A typical paper machine vs passenger car



120 m

130 km/h

Paper machine energy flow

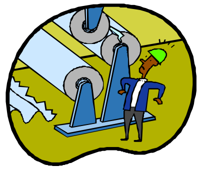


GLOBAL ANALYSIS METHODOLOGY

Global statistics, year 2012:

- 8525 paper and paperboard machines average
- 140 TJ/a electrical energy per machine

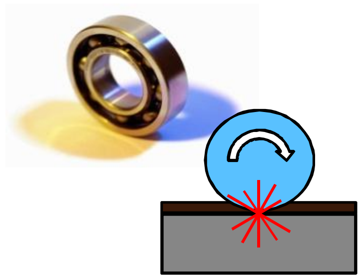
An average global paper machine and its operating conditions, operating cycles



Component level: mixer, pump, blower, vacuum pump, sectional drive, …

Tribocontact level & friction factor:

- dry contact / boundary / mixed / hydrodynamic lubrication
- water / oil
- sliding / rolling



New tribological techniques & lower friction factors

POTENTIAL SAVINGS WITH NEW TECHNOLOGY TO REDUCE FRICTION: Energy, CO_2 emissions

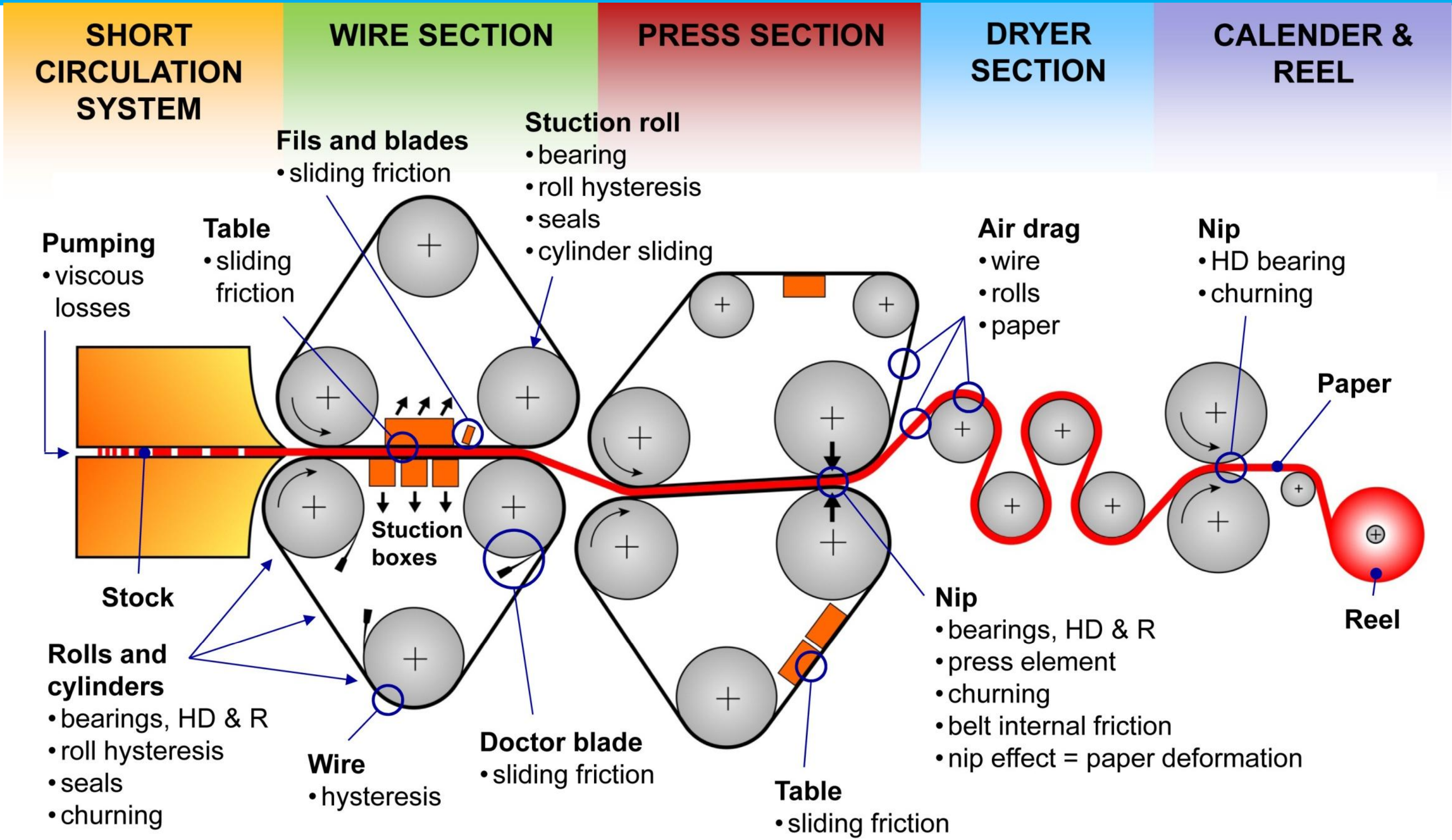
AN AVERAGE GLOBAL PAPER MACHINE

- **Built 1960 and rebuilt 1980,**
- **Design speed is 1200 m/min,**
- **Width is 6.5 m (trim width 6.0 m)**

- **Typical product is newsprint**
- **Basis weight 50 g/m2**
- **Annual production is 130–140 000 tonnes/a**
- **Electrical energy consumed 140 TJ/a**
- **Specific electric energy consumption is 440 kWh/tonnes**
- **In operation 300 days/year**
- **Stock composition is 70–80% mechanical pulp**

The average global paper machine details

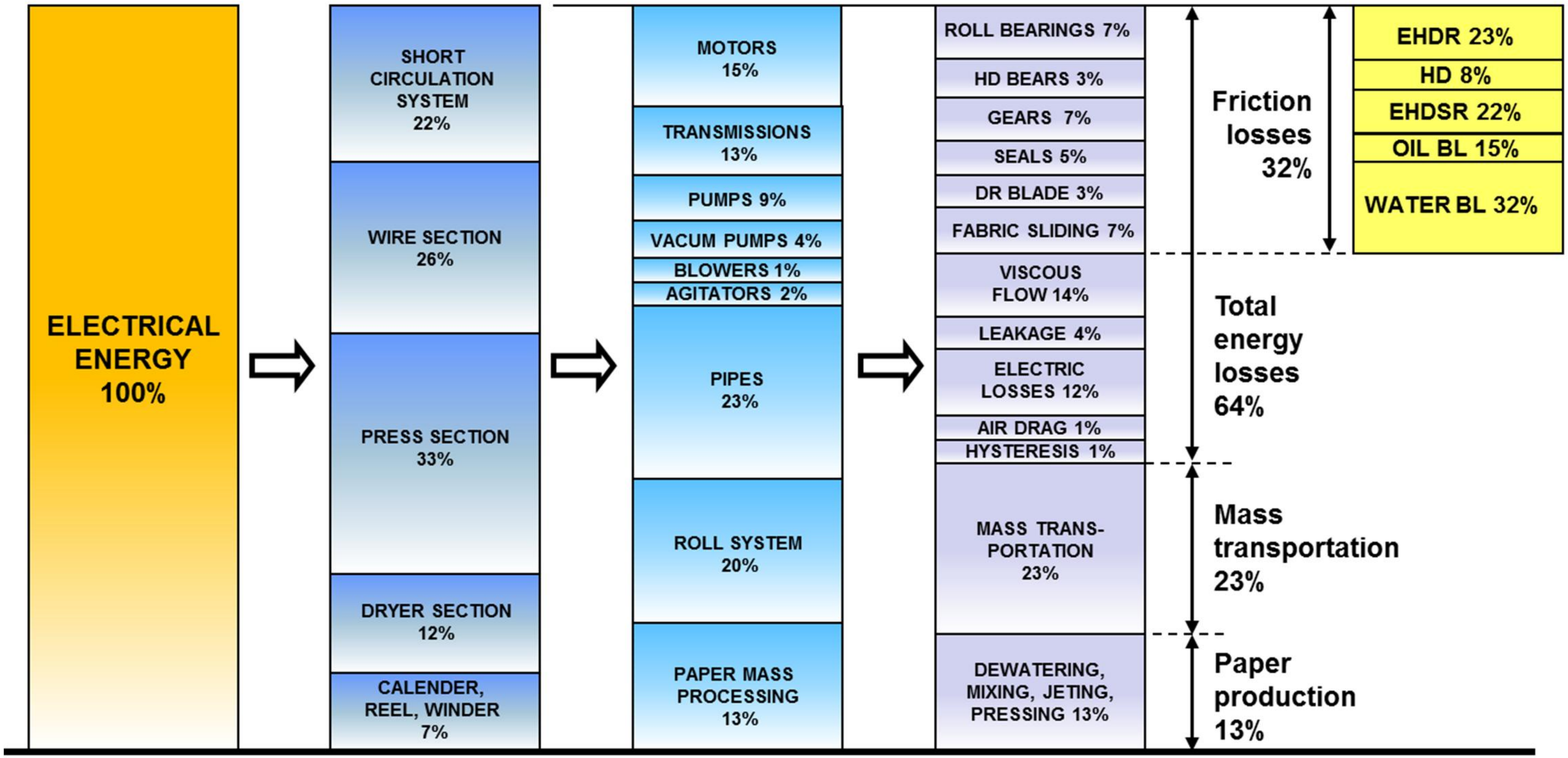
- **Electrical motors:** 72 pieces, average rating 173.7 kW, power efficiency 85%.
- **Transmissions:** 72 pieces, average power efficiency 82%.
- **Pumps:** 28 pieces, average rating 50 litres/s water at 3 bar pressure, power efficiency 65%.
- **Vacuum pumps:** 11 pieces, average rating 2 m^3/s air at -43 kPa pressure, power efficiency 67%.
- **Blowers:** 6 pieces, average rating 30 m^3/s air at 50 Pa pressure, power efficiency 63%.
- **Agitators:** 7 pieces, average power efficiency 82%.
- **Pipes** (incl. valves etc.); length: 16 km. The main part of the energy consumption occurs in the short circulation system, wire section and press section.
- **Roll system:** 22 drive rolls and 113 passive rolls.
- **Rolling bearings:** the energy losses are distributed as 50% from seal friction, 33% from rolling friction and 17% from churning of the lubricant.


SHORT CIRCULATION SYSTEM
WIRE SECTION
PRESS SECTION
DRYER SECTION
CALENDER & REEL
Fils and blades
• sliding friction
Stuction roll
• bearing
• roll hysteresis
• seals
• cylinder sliding
Pumping
• viscous losses
Table
• sliding friction
Air drag
• wire
• rolls
• paper
Nip
• HD bearing
• churning
Paper
Stuction boxes
Stock
Rolls and cylinders
• bearings, HD & R
• roll hysteresis
• seals
• churning
Wire
• hysteresis
Doctor blade
• sliding friction
Nip
• bearings, HD & R
• press element
• churning
• belt internal friction
• nip effect = paper deformation
Reel
Table
• sliding friction

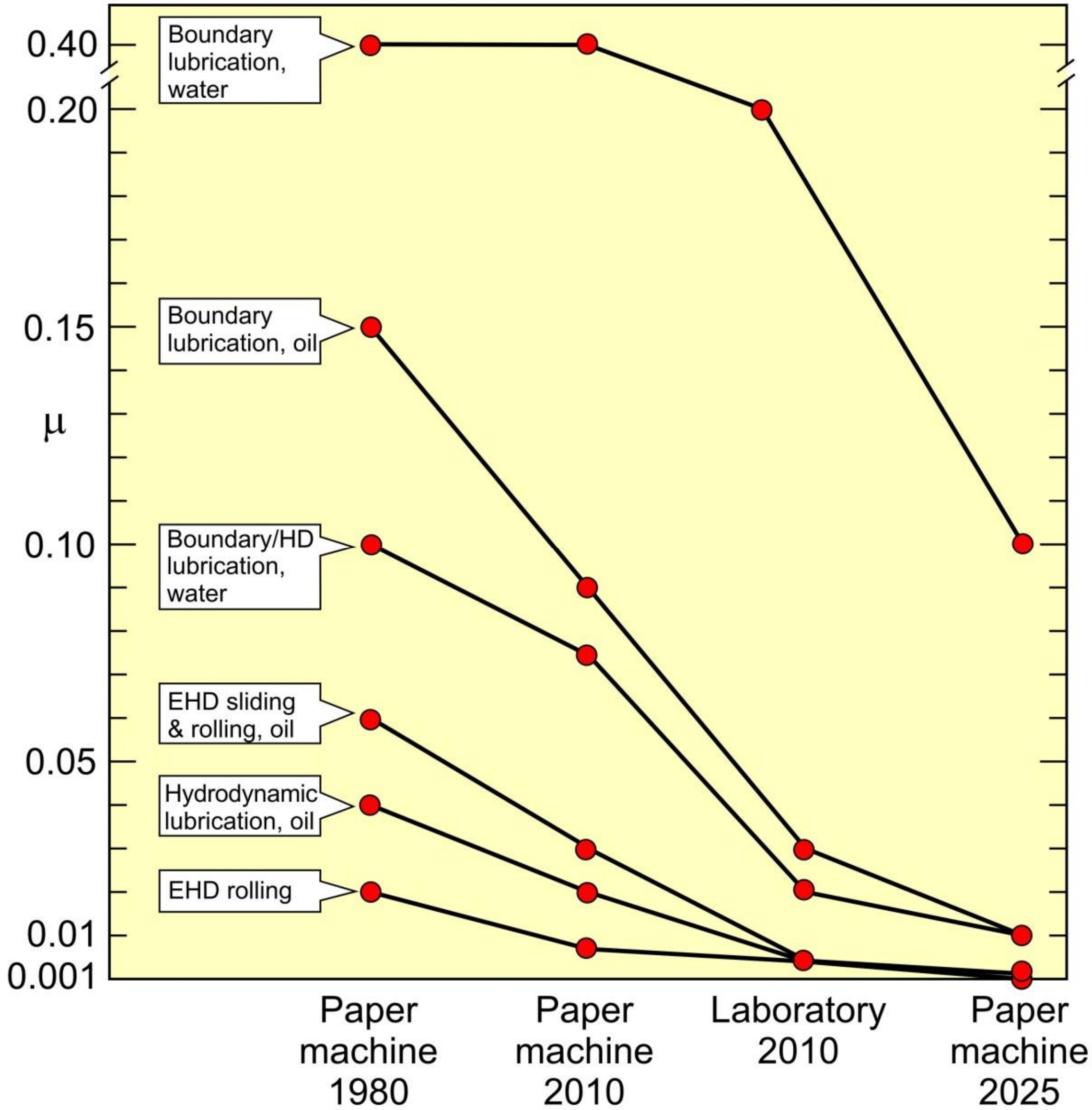
Energy break down in the global average paper machine

Global average paper machine 140 TJ/a	Motors	Trans-missions	Pumps	Vacuum pumps	Blowers	Agitators	Pipes	Roll system	Total energy	Total %
Total energy flow, TJ/a	140,0	119,0	37,5	17,6	4,3	7,7	38,6	34,0	140,0	100,0
Percentage, %	100,0	85,0	26,8	12,6	3,1	5,5	27,6	24,3		
Roll bearing (EHDR)	1,7	3,6	2,0	1,2	0,3	0,1	0,0	1,4	10,2	7,3
HD bearing (HD)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3,7	3,7	2,7
Gears (EHDSR)	0,0	9,8	0,0	0,0	0,0	0,0	0,0	0,0	9,8	7,0
Seals (BL)	0,6	0,9	1,3	0,9	0,2	0,0	0,0	2,8	6,8	4,9
Doctor blade (BL)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	4,6	4,6	3,3
Fabric sliding (BL&HD)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	9,6	9,6	6,8
Total friction losses	2,3	14,3	3,3	2,2	0,5	0,1	0,0	22,1	44,8	32,0
Viscous losses	0,0	3,6	6,6	2,2	0,0	1,3	0,0	5,8	19,4	13,9
Leakage	0,0	0,0	3,3	1,8	0,4	0,0	0,0	0,0	5,5	3,9
Electric losses	17,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	17,6	12,6
Air drag	1,0	0,0	0,0	0,0	0,6	0,0	0,0	0,2	1,8	1,3
Hysteresis losses	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,4	0,4	0,3
Mass transportation	0,0	0,0	0,0	0,0	0,0	0,0	31,8	0,0	31,8	22,7
Total losses	21,0	17,8	13,1	6,2	1,5	1,4	31,8	28,6	121,4	86,7
Slice jet	0,0	0,0	0,0	0,0	0,0	0,0	4,7	0,0	4,7	3,3
Dewatering/pressing	0,0	0,0	0,0	0,0	0,0	0,0	1,1	5,4	6,5	4,7
Mixing	0,0	0,0	0,0	0,0	0,0	6,3	1,1	0,0	7,4	5,3
Delivered energy	119,0	101,1	24,4	11,4	2,8	0,0	0,0	0,0		

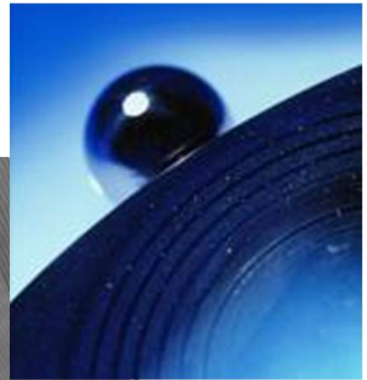
Energy break down in the global average paper machine

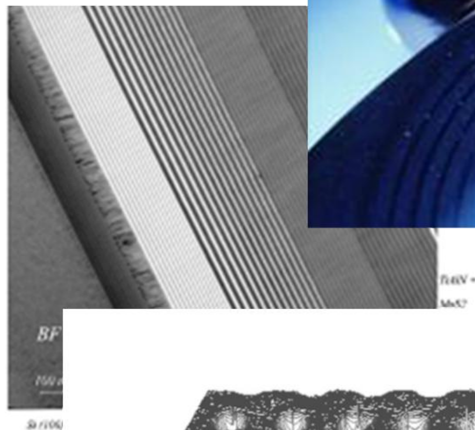


Friction in paper machine tribocontacts



EMERGING TECHNOLOGIES FOR FRICTION REDUCTION IN PASSENGER CARS





➢ Advanced coating structures

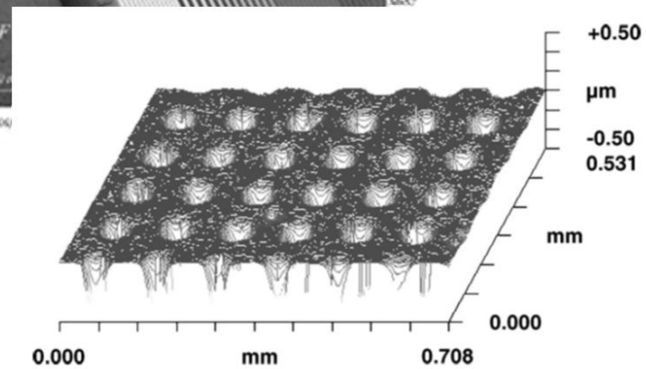
DLC, TS, nano-composites etc:

- dry in vacuum superlubricity μ= 0.001
- lubricated 10-50% friction reduction

➢ New surface texturing methods

Laser surface texturing:

- 25-50% friction reduction
- 4% engine fuel reduction

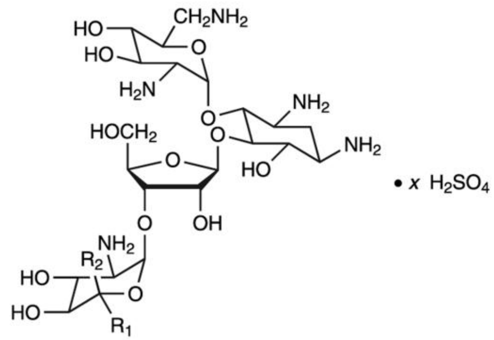


➢ New boundary lubrication additives and fluids

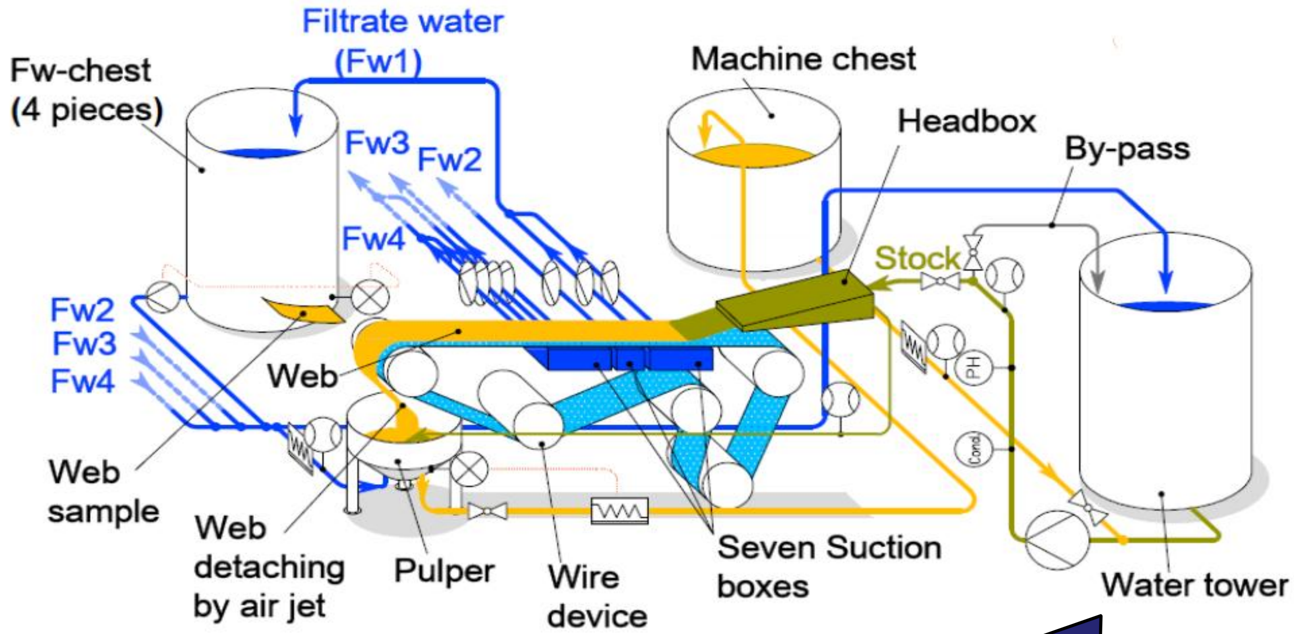
Glycerol mono-oleate in PAO vs DLC:

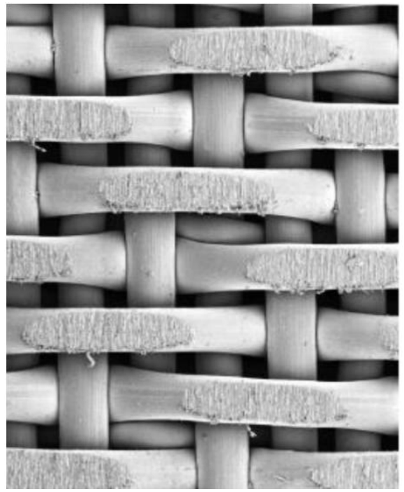
- μ = 0.005 in pure glycerol

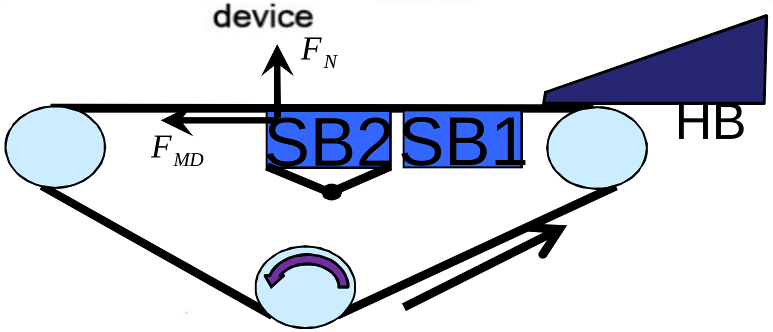
Nanomaterials as additives like WS2, MoS2 H3BO3



Wire and doctor blade friction in paper machine







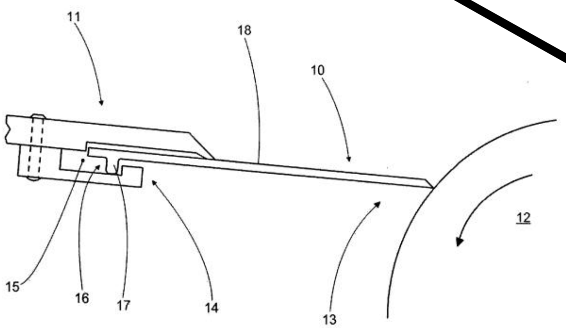


Fig. 1

Annual savings and energy reduction in paper machines

	Short term (10 years)	Long term (20-25 years)
Savings/reduction from the present state (%)	11.5	23.3
Reduction in electricial power consumption (GWh)	38 125	77 246
Energy demand reduction (TJ)	137 679	278 683
CO_2 emission reduction (million tonnes CO_2)	34.7	70.3
Economical savings (million euros)	20 200	40 920

Summary

Globally

- 15 – 25 % of the total energy consumption worldwide is used to overcome friction (100 milj. TJ/year)
- 7 000 milj. tonnes of CO_2 emission originates from work to overcome friction

Transport

- about 30% of the fuel energy is used to overcome friction
- 18% potential savings can be achieved in short term (5 years) by implementing new tribological solutions
- friction losses in electric cars are ½ of those in IC cars

Industry

- about 20% of the industrial energy is used to overcome friction
- 11% potential savings can be achieved in short term (5-10 years) by implementing new tribological solutions

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