GfT Gesellschaft für Tribologie e.V.

# Tribology in Germany

Interdisciplinary technology for the reduction of $CO_2$-emissions and the conservation of resources

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## Interdisciplinary technology for the reduction of $CO_2$-emissions and the conservation of resources

An Expert Study of the German Society for Tribology
(Gesellschaft für Tribologie e.V. – GfT)
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# CONTENT

## About this study

Following a survey determining tribology activities at German universities the German Society for Tribology conducted in 2014, this study focuses on a more comprehensive approach. Leading experts from automotive and lubrication industry as well research institutes give account of the status quo of tribology activities in Germany from their perspective and provide insight in the future of tribology. Due to the great importance of the motor vehicle industry and the technological breakthroughs currently unfolding, emphasis of this current study was put on this industry and the correlation of friction and $CO_2$ emissions and environmental issues, such as fine dust and e-mobility.

This study aims to demonstrate to what extent research and development in tribology can contribute to the turnaround in energy policy, conservation of resources and reduction of pollutant emissions.

The application of tribology in other important areas, such as power engineering, food industry or medical technology (e.g. artificial joints) will be subject of a continuation of this study projected for 2021. It will reflect the developments in digitalization, improved analytics and new methods of simulating tribosystems. Another study focusing on „Wear protection and sustainability" is planned for 2020. GfT encourages all experts in the field to contribute with their expertise and know-how.

Parallel to this expert study, an online survey on the current status of tribology in Germany has been conducted. The survey was not exclusively aimed at persons dealing with tribology professionally and thus provided information on the general awareness of tribology. The results are published on the GfT website and in Volume 6/2019 of the journal „Tribologie und Schmierungstechnik".

## The term „Tribology"

In 1966, Sir Peter Jost, first established the term „tribology"

> *„Tribology is the science and technology of interacting surfaces in relative motion and of related subjects and practices"*

Friction, wear and lubrication, the key elements of tribology, aim to control the use of friction, to reduce wear over a long service life and to remove motion resistance and wear by means of lubrication. Solutions for the challenges posed by tribology require a holistic system analysis with an interdisciplinary conception.

# Brief summary of the GfT Tribology Study 2019

***TRIBOLOGY**, the science of friction, lubrication and wear is an inter-disciplinary technology of economic significance. As basic technology, it promotes energy efficiency and resource conservation through the reduction of friction and wear as well as the use of $CO_2$-neutral fuels (e-fuels, hydrogen, etc.).*

## Less $CO_2$ emissions through friction reduction

Friction reduction, particularly in mobility, is, apart from recuperation, the core element for improved energy efficiency. It reduces $CO_2$ emissions and decreases the dependency on energy imports. The proportion of friction losses of the primary energy consumption is 23% – the realistic long-term and total reduction potential of primary energy consumption generated by friction losses amounts to 8.6%. Results provided by the research cluster Low Friction Powertrain yielded that engine friction losses offer a reduction potential of 30%. This would translate into a fuel consumption reduction of 0.94 l/100 km or 12.1% along with additional reduction potentials for transmission, wheel bearing, auxiliary units etc. of the powertrain. If the calculated 12.1% fuel consumption reduction was applied to the fuel quantity sold with the fully exploited friction reduction potentials, the fuel quantity consumed in Germany could be reduced by 2.2 million tons of gasoline (or 2.98 billion liter) amounting to 6.92 million tons less $CO_2$ emissions. The diesel consumption could be reduced by 4.68 million tons (or 5.5 billion liters), translating into approx. 14.95 million tons of decreased $CO_2$ emissions. Altogether almost 22 million tons of $CO_2$ or 6.4% of the $CO_2$-reduction projected by the German government for 2030 could be saved by friction reduction alone without affecting the utility value.

Other friction reduction potentials of lubrication technology, particularly through low-viscosity oils and/or lubricants with high viscosity index interacting with the surface topography, offer numerous additional opportunities for the reduction of $CO_2$ emissions based on high functional safety. Reducing frictional resistance in the powertrain is a core task of future mobility and should be pursued independently of the respective drive technology as such.

Reducing the fuel consumption through lowering the engine oil viscosity by only 1% would yield calculated savings of 1.7 million tons of $CO_2$-emissions based on the total 170 million tons of $CO_2$ emissions generated by German road traffic annually.

Transferring the generally expected proportion of total friction losses of primary energy consumption, the reduction potential calculated for Germany alone would amount to 208 million tons of $CO_2$ thus corresponding to 60% of the greenhouse emission reduction targeted by the German government for 2030.

Beyond friction reduction, tribology is embedded in systems of recuperating energy from exhaust heat which offer additional fuel saving potentials between 5% and 10%.

## E-mobility

Electric powertrains may not require engine oils, but they use specific lubricants and functional fluids, such as lubricant greases for rolling bearings, coolants (for battery, e-motor and power electronics) and transmission fluids (e.g. for high-speed planetary gear sets). This will require new developments because such transmission oils, coolants and greases come in contact with electrical modules, sensors and circuits, and also with insulating materials or special polymers. In addition, energy saving generated by friction reduction will increase the range at constant battery capacity.

## Air pollution control

Approx. 90% of all particulate matter emissions in road traffic are not generated by the exhaust of combustion engines but by the abrasion from tires, brakes and road surfaces (non-exhaust emissions). Generally, this is not any different for battery- or fuel-cell-powered vehicles; recuperation performance will only slightly reduce the load on the brakes. Trams and trains also contribute to particulate matter emissions with pantographs (current collectors), wheel tires (even if made of steel!) and brakes. Here, tribology can make a significant contribution to the reduction of wear particles by means of more wear-resistant materials while maintaining all other functional properties.

## $CO_2$ neutral energy

Mastering tribology for components coming into contact with alternative fuels is a key issue for a successful market launch. Common approaches for tribology solutions encompass coating technologies and new alloys. $CO_2$-neutral e-fuels, in particular e-gases, such as hydrogen and methane will have direct impact on the formulation of engine oils. Implemented research results of tribology studies provide the hydrogen industry with the every-day-use of wear-free and long-life components suitable for end users. New material developments must feature low abrasive wear to ensure minimum hydrogen contamination with wear particles. The application in combustion engine requires new, water-soluble engine oils. Resistance against hydrogen embrittlement and „affordable" alloys are other demanding requirements.

## Environmental protection

In proportion to the fuel quantity consumed in Germany, the lubricant quantity corresponds to approx. 1%. Raw materials for long-life lubricants can be synthesized from biomass, whereby various synthesis routes allow for the use of esters, polyglycols and hydrocarbons. Compared to mineral oil products, bio-lubricants feature lower friction and burden the ecosystem significantly less.

## Substitutes for Prohibited Substances

Due to the environmental and chemicals policies of the European Union, a pressure arises for the substitution of proven and established coatings or materials as well as for many common functional lubricant additives. In view of these concerns, tribology provides a valuable contribution to the development of alternative solutions in metallurgy and lubricant technology that also meet the functional and toxicological requirements.

## Research

Contrary to the past, tribology no longer received special and autonomous funding within the research bodies German Research Foundation (DFG) and Federal Ministry of Education and Research (BMBF), although, as an omnipresent interdisciplinary technology, it made significant contributions to meet technological and ecological demands.

After several years of low public funding commitment, the Federal Ministry of Economics and Energy (BMWi) has established „Research Field Tribology" in 2017, which cross-sectorally joins all important players from science and industry under the umbrella of a research network focusing particularly on the objective to prevent $CO_2$ emissions by the reduction of friction.

Tribology has been part of the curriculum at many colleges and universities but it has not been taught in sufficient magnitude and depth. Therefore, it is absolutely necessary to promote disseminating the basics of friction, wear and lubrication in the degree programs of technical studies.

Basic research is the essential driver for new developments in tribology. Today, most significant tribology test instruments with international penetration have their origin in Germany.

# A. Economic importance

Past studies, such as by Jost 1966 [1, 2], ASME 1977 [3] and BMFT 1976 [4, 5] limited the importance of tribology for the reduction of friction- and wear-induced material losses to economic considerations, e.g. cost cuts and/or quality improvements (see Table 1).

Significantly high material losses occur in the mining, the metallurgical, and the construction machinery industry where machines and equipment are predominantly exposed to abrasive and erosive wear. Mechanical production facilities of the manufacturing industry also use large amounts of cutting lubricants.

The title „Strategy of Energy Conservation through Tribology" of the ASME study of 1977 [3] emphasizes the focus on energy efficiency but neglects wear-induced losses. In 1976, the estimated saving of 10.9% primary energy translated into a monetary value of 16.2 billion U.S. Dollars or 40.8 billion German marks. The GNP of the U.S.A. in 1976 was 1.877 billion US Dollar so that the estimated savings of primary energy amounted to 0.86% of the GNP. The strategy of this ASME study was certainly impacted by the first „oil shock" in 1973. „Industrial Innovation", the initiative set forth on 31 October 1979 by President Jimmy Carter included generic technologies of economic significance including tribology (friction, lubrication and wear).

In Canada in 1984, losses due to friction amounted to 1.22 billion Canadian Dollars and losses due to wear to 3.7 billion Canadian Dollars [6, 7] of which 25% can be classified as avoidable. Related to the GNP in 1982 of 388.7 billion Canadian Dollars, the economic loss resulting from friction and wear amounted to 1.3% of the GNP.

The study by Forschungskuratoriums Maschinenbau e.V. (Mechanical Engineering Research Forum) for Bundesministerium für Forschung und Technologie (German Ministry of Research and Technology) (BMFT FB T 76-38) accounted the economic loss through friction and wear for 1975 to 1% of the Gross National Product (GNP). Direct losses for machinery and equipment, accounted through friction and wear in Germany in 1985, amounted to 38.7 billion DM [4] or 2.0% of the GNP in 1985 (GNP in Germany in 1985 = 984 billion €).

Nowadays, environmental damage is added to the economic losses caused by friction and wear. Due to drastically increased crude oil prices, the economic share of the primary energy consumption and its resulting energy savings potential is many times higher than in the 1970s.

In summary, it can be concluded that the various studies of the past either relate to energy (Jost, A.S.M.E.) or monetary (BMFT, NRC) savings potentials. The environmentally important aspect of $CO_2$ emissions has not been considered.

*Table 1: Energy consumption saving potential through friction reduction with tribological measures*

| Study | Year of publication | Energy saving potential | | Economic saving potential of reduced friction and wear | |
|---|---|---|---|---|---|
| | | % of energy consumption | EJ related to the consumption of primary energy in 2017 | in % of GNP | in billion € related to GNP of 2017 |
| Jost (G.B.) | 1966 | 5% | 0,4 EJ | 2% in G.B. | 2%= 46,5 billion € |
| A.S.M.E. (USA), Pinkus&Wilcock | 1977 | 10,9% | 10 EJ (93 EJ) | – | – |
| BMFT (DE) | 1976 | – | – | 1% in Germany* | 1%= 32,7 billion €* |

1 EJ= $10^{18}$ Joules; A.S.M.E.= The American Society of Mechanical Engineers; BMFT= Bundesministerium für Forschung und Technologie (German Ministry for Research and Technology: now named „German Ministry for Education and Research (BMBF)"): *Absolute economic losses

## B. Significance of tribology in relation to energy (Exajoule Issue)

The various forms of friction creating resistance to the relative movement of machine elements inevitably cause energy losses in tribosystems. They ultimately result in the loss of drive energy which is irreversibly converted into heat. According to a more recent publication by Holmberg et al. [8] on the energy consumed by friction in automobiles, practically all useable work generated by the fuel's combustion heat for propulsion is lost as friction in the various tribosystems and thus converted into heat.

When taking into consideration that the import of energy resources significantly burdens an economy's trade balance, it is no surprise that the topic of energy efficiency has made inroads into US-American politics. Resolutions #916 of 28 Sep 2016 and #306 of 02 May 2017 by the „House of Representatives" state „the importance of tribology for economic growth and competitiveness of the United States". See also the excerpts of the citations below:

> *„Whereas approximately a third of the world's primary energy consumption is attributed to friction, and about 70 percent of equipment failures is blamed on lubrication breakdown and wear loss;*

.....

> *Whereas reduction of friction is at the very core of improving fuel economy and reducing greenhouse gas emissions; ...".*

Therefore, friction reduction can make an important contribution to the reduction of $CO_2$ emissions, since 81.5% of the global primary energy is extracted from fossil fuels [9].

Whereas crude oils prices determined energy-saving measures during the past 45 years, climate policy with the objectives of conserving the environment and nature have increasingly come to the fore.

Relating the methodology used by Holmberg et al. in [8] to the estimation of frictional losses in engines on a global economic level, friction points or tribocontacts use 23% of the global primary energy according to Holmberg et al. [10]. This 23% subdivides into approx. 20 percent for overcoming friction and 3 absolute percent for the repair and maintenance of worn components.

However, it must be taken into consideration that friction is an unresolved phenomenon that cannot be completely eliminated. There is „desired" friction, such as with tires and brakes, providing operational safety. On the other hand, the friction in rolling and plain bearings, but also in piston aggregates of combustion engines would ideally be reduced to „zero". Holmberg et al. in [8] assume a moderate potential reduction of frictional losses of -40% which would correspond to an absolute reduction of the global primary energy consumption of -8.6%.

Depending on the source [11, 12], global $CO_2$ emissions in 2017 amounted to approx. 32,500 million tons (Mt) of which 905 Mt $CO_2$ [13] were produced in Germany. Since frictional losses, according to Holmberg et al. [8], account for 23% of the global energy consumption, friction contributes to global $CO_2$ emissions with 7,475 Mt. At 40% reduction (as discussed above) this would be approx. minus 3,000 Mt of $CO_2$ per year.

In Germany, the potential long-term $CO_2$ emission savings created by friction reduction amounts to approximately 208 Mt annually. According to 2017 German government figures, it is the objective to lower greenhouse gas emissions to less than 563 Mt $CO_2$ by 2030. Based on the results by Holmberg et al. [8], frictional reduction alone offers a potential for lowering greenhouse gas emissions by 60%. Therefore, the core mission for future transportation must be the reduction of the friction resistance throughout the entire powertrain – regardless of the powertrain technology.

# C. Optimization of friction in transportation

The properties of tribosystems generally require a number of measures to mitigate friction, among them accurate adjustment of surface topography, material and coating technology and improved lubricants. The successful use of recuperations systems largely depends on their efficiency and wear resistance.

***Tribology**: A basic technology for enabling energy efficiency and resource conservation by means of friction reduction and utilization of biofuels and e-fuels on the basis of renewable resources as well as hydrogen (from $CO_2$-neutral production) or (bio-)methane as energy carriersenergy carriers.*

## C1. Energy flows and friction reduction potentials in motor vehicles with combustion engine

The thermal value (caloric heat) of the fuel converted by a combustion engine is usually subdivided as follows:

a. Thermodynamic losses
   - 30%-37% are emitted as exhaust gas,
   - 25%-33% are dissipated in the coolant

b. Mechanical work
   - 33%-40% are available as mechanical work, of which 3-12% must be excluded to overcome drag for speeds up to 100 km/h.

Friction can only be reduced while mechanical work is being generated, whereas recuperation can partially recover heat quantities from exhaust gas and coolant (thermodynamic losses), see also chapter C.4. In order to achieve this, piston expanders forming multiple friction points requiring tribological optimization are considered as possible solutions.

Within the framework of the Cooperative Industrial Research Programme (IGF), the comprehensive Research Cluster „Low Friction Power Train“ [14] formed cross-sectoral research group funded by of the Federal Ministry of Economics and Technology (BMWi) and the $CO_2$ Collaborative Research Programme of the Research Associations for Power Transmission Engineering (FVA) and Combustion Engines (FVV). This research cluster analyzed energy flows on a mid-class passenger car (Mercedes C-Class) with mechanically supercharged 1.8 liter gasoline engine (M271 KE) and manual transmission. The research work, conducted between 1 October 2008 and 30 September 2012, was based on the fuel consumption within the New European Driving Cycle (NEDC). The research activities yielded numerous detailed simulation models (piston, ring package, transmission, main bearing etc.). The resulting data was merged into an overall energy model. For this overall model, individual measures for the reduction of friction were examined in interaction with combinations of measures and ultimately evaluated.

The reference series configuration yielded a fuel consumption of 7.81 l/100 km and $CO_2$ emissions of 183 g/km within the test cycle. The energy 27313.8 kJ contained in the fuel is attributed to wall heat dissipation 34.3%, indicated work 28.4% and exhaust gas enthalpy 37.2%. Related to the primary energy consumption 27313.8 kJ, the indicated work is broken down into effective work 4427.8 kJ (16.2%) and friction work 3333.5 kJ (12.2%) (see Fig. 1). The effective work adjusted for coupling losses 37.8 kJ (0.1%) and transmission losses 255.3 kJ (0.9%) yield a useful work of 4134.7 kJ (15,1%) required to overcome rolling resistance 2202.7 kJ (8.1%) and to overcome drag 1352.3 kJ (5.0%).

[1] Figures were derived from a simulation model for the overall vehicle into which maps of individual modules were integrated. Individual maps for friction on the piston ring, in the connection rod bearing, in the main bearing or in the valve train were compiled and validated by measurements. Similarly, other project partners contributed figures for rolling resistance, drag and transmission loss.

*Table 2: Abbreviations in energy flow diagrams (Figure 1 to Figure 3)*

| Abbr. | Explanation | Abbr. | Explanation |
|---|---|---|---|
| Ko | Friction on piston (skirt + ring + pin) | Ne | Friction in additional aggregates (power steering pump, air conditioning compressor, vacuum pump, fuel pump) |
| WP | Friction in water pump | ML | Friction in compressor (Eaton engine charger) |
| VT | Friction in valve train (including drive) | LLK | Charge-air cooler |
| Pl | Friction in connecting rod bearings (auxiliary bearings) | ÖWWT | Oil-water heat exchanger |
| KW | Friction in crankshaft main bearing | HK | Main water-cooled radiator |
| MA | Friction in mass balance | RS | Heat loss through dissipation in water lines |
| OP | Friction in oil pump | Hzg | Heat flow in car interior heater |
| Ge | Friction in generator (without drive) | dU | Modification of internal energy |
| ÖW | Heat dissipating from oil to ambient environment (mainly through oil pan) | | |

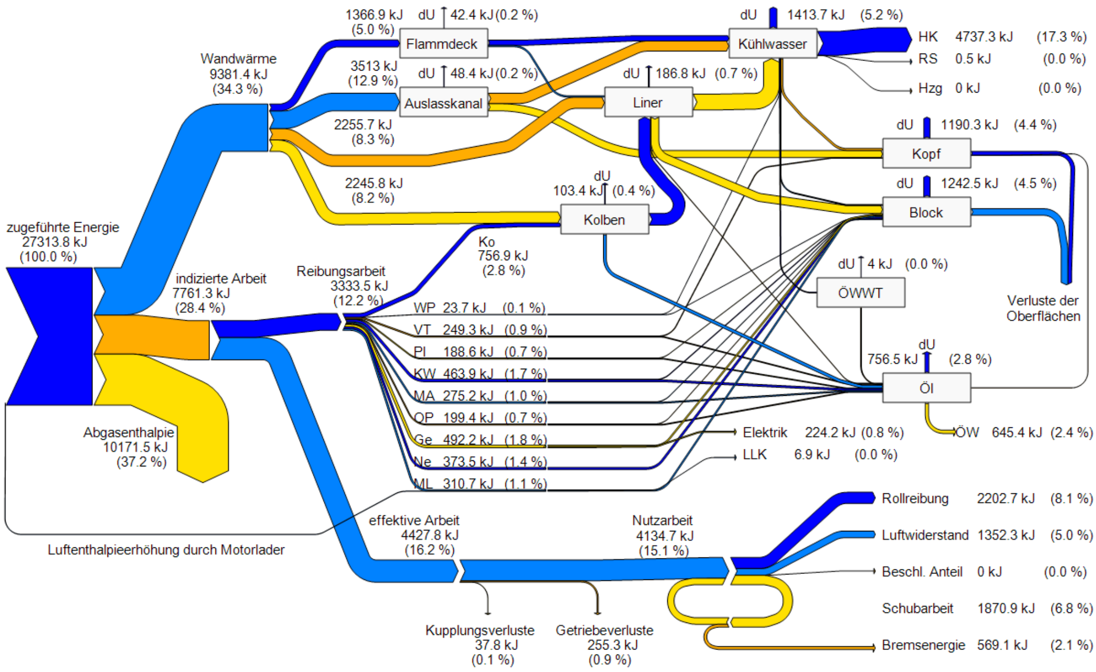


*Figure 1: Accumulated energy flows at the end of a NEDC for the basic vehicle (I) [14]*

The largest portion of frictional losses in an engine is generated by the piston module (20.9%), followed by the generator (13.6%), the crankshaft main bearings (12.8%), and the auxiliary drive (10.3%).

The examination of a combination of measures under consideration of their various interactions demonstrates that the benefits of friction loss reductions are less significant than the superposition of the individual measures suggested. The recommended combination of measures encompasses modifications in the piston-liner area, the use of rolling bearings, changes in the cooling and lubrication system and a start-/stop-functionality.

Fig. 3 breaks down the measures for friction reduction in the tribosystem „piston/liner” into action mechanisms which can be attributed to

a. the additive in the lubricating oil,
b. the reduced circumferential pre-stress of the piston ring in combination with modified honing,
c. a piston clearance increase to 1,2 ‰, and
d. a reduced lubricant supply.

Friction occurring in engine bearings (nowadays plain bearings!) can be optimized by the use of rolling bearings. Due to their design, the integration of rolling bearings poses considerable challenges. Other reductions of engine friction can be achieved by

a. a map-controlled thermostat,
b. an electrically driven water pump,
c. split-cooling,
d. replacing the oil pressure pump with a volume-flow controlled oil pump of reduced gallery pressure and switchable piston spray nozzles,
e. a start-stop-strategy, and
f. transmission heating.

Having taken these individual correlations into consideration, the maximum predicted friction reduction in Fig. 3 amounts to 30.8% of the total friction and results in a reduction of the fuel consumption by 12.1% or 0.945 l/100km . Recalculations of various other test cycles yield friction reductions by 30% along with the corresponding reductions in fuel consumption.

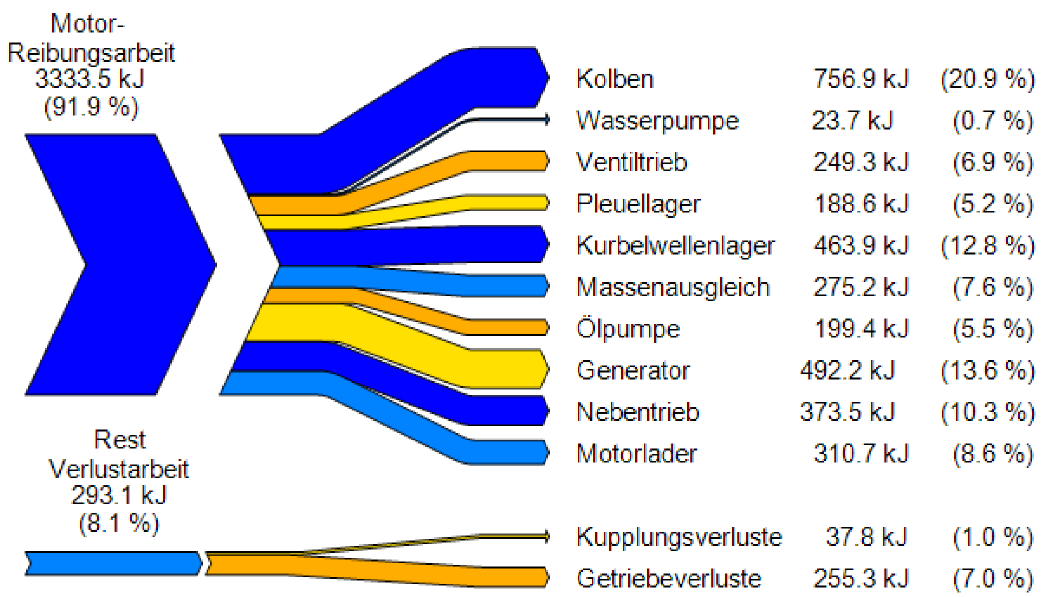


*Figure 2: Friction broken-down to the various powertrain aggregates [14]*

[2] The projected savings of 0.945 l gasoline/100 km are the equivalent of 2.249 kg $CO_2$/100 km. In 2017, about 18.3 (previous year 18.2) Mt of gasoline were marketed [Source: Annual Report for 2018 of the German Petroleum Industry Association (Mineralölwirtschaftsverbandes e.V.)]. The Research Cluster “Low Friction Power Train“ [14] determined maximum possible fuel consumption savings of 12.1% through friction reduction in a gasoline engine. These 12.1% alone could lower the consumed gasoline quantity by about 2.2 Mt gasoline (or 2.98 billion l at a density of 0.737 kg/l) respectively by a calculated equivalent of 6.92 Mt $CO_2$. Similar observations can be made for Diesel fuel, whereby the amount of Diesel sold in Germany in 2017 amounted to 38.7 Mt. The aforementioned friction reduction potential of 12.1%, applied to the consumed Diesel quantity, would reduce the consumption by about 4.68 Mt Diesel (or 5.50 billion l at a density of 0.850 kg/l), respectively by a calculated equivalent of 14.95 Mt $CO_2$.

Based on the EU-wide $CO_2$ emission thresholds for vehicle fleets as of 2020, the following relationship for fuel consumption and $CO_2$ emissions can be stated: 1 l of gasoline = 2.317 kg $CO_2$; 1 l of Diesel = 2.714 kg $CO_2$.

In 2017, the share of biogenic fuels in Germany amounted to 6.3% for gasoline and to 5.7% for Diesel.

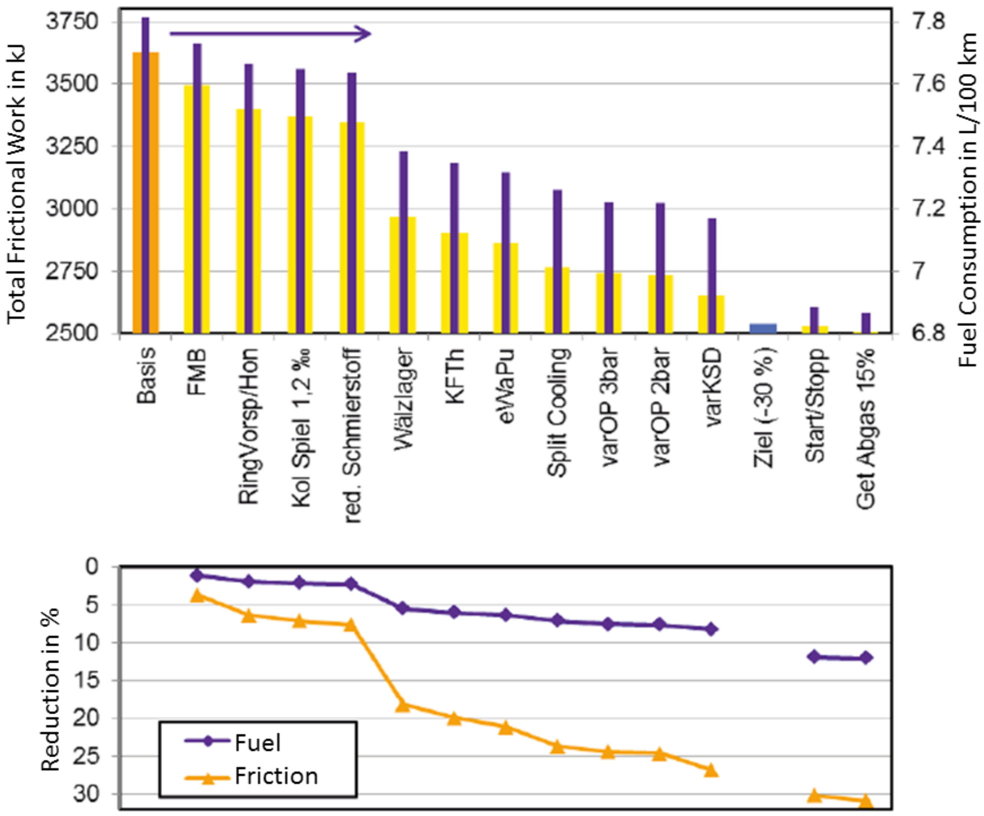


*Figure 3: Measures for friction reduction and impact on fuel consumption [14]*

*Friction reduction, particularly in mobility, is, apart from recuperation, the core element for improved energy efficiency. It reduces $CO_2$ emissions and decreases the dependency on energy imports. A long-term reduction potential generated by friction losses of 40% decreases the global primary energy consumption by 8.6%. Reducing the friction losses in engines offers a reduction potential of up to 30%, or, translated in fuel savings, of 0.94 l/100 km.*

## C2. Reduction of friction in the piston module

The piston module roughly generates 50% of power loss caused by friction in a combustion engine. The composite funded project PROMETHEUS of the Federal Ministry of Economics and Technology (01/19-12/21) provides promising new indications for a sustainable reduction of friction losses. The major approach of the project focuses on considerably improved operating conditions for lubrication molecules effecting the reduction of friction and wear. In order to achieve this, BMW AG, M.A.N. SE and Rolls-Royce Power Systems AG (MtU Engines) have further developed the tribological functionalities of their cylinder liners in close collaboration with lubrication manufacturer FUCHS Petrolub AG and piston module supplier FederalMogul Burscheid GmbH (TENNECO Inc.). Their studies have been conducted alongside the tribological test chain, i.e. from tribometer all the way to engine trial, and atomistic modelling.

Results found during the first project year already demonstrated that unconventional surface materials and textures in combination with adapted additives deliver significant friction reductions.

## C3. Friction reduction through thin coatings

The developments of friction-reducing coatings suitable for mass production have taken many years. In 2001, a standard hardened tappet with polished surface, as shown in Fig. 4, was used as reference and allotted a friction level of 100% at 2000 rpm at an oil temperature of 80°C. In a first step, the friction was reduced to 80% through an optimization of the surface topography. The parallel application of low-viscosity lubricants requiring thin coatings counteracted adhesive wear mechanisms.

The SCHAEFFLER Group developed Triondur® CN, a hard material coating based on chromium nitride (CrN) conserving the polished surface and consistently reducing friction to 75%. The SCHAEFFLER Group delivered about 20 million parts using this technology acclaimed by their customers with innovation and quality awards. The newly developed nano-structured, amorphous and hydrogenous carbon coating system (Triondur® C+) enabled meeting the increasing demands posed by market and customers concerning energy efficiency and legislative requirements for $CO_2$ savings. In combination with low-viscosity engine oils, valve train friction could be reduced by an additional 20%.

Doping elements improved the functional interactions of amorphous carbon coatings with the lubricant additive. As a result of these ongoing coating developments, valve train friction could be halved, depending on engine oil and selection of thin coating (hydrogenous and doped carbon coating system Triodur® CX+ or ultra-hard, tetrahedral and hydrogen-free and amorphous carbon coatings Triondur® CH). Ultimately, these coatings offer valuable 1 to 2% fuel consumption savings for the consumer and the tremendous annual $CO_2$ emission savings of 307,500 tons for the society.

Where the application of new materials, coatings and lubrication technology is concerned, the automotive industry is the „forerunner". Implementing this experience horizon in general mechanical engineering and processing technology offers huge potentials for the reduction of friction losses and $CO_2$ emissions.

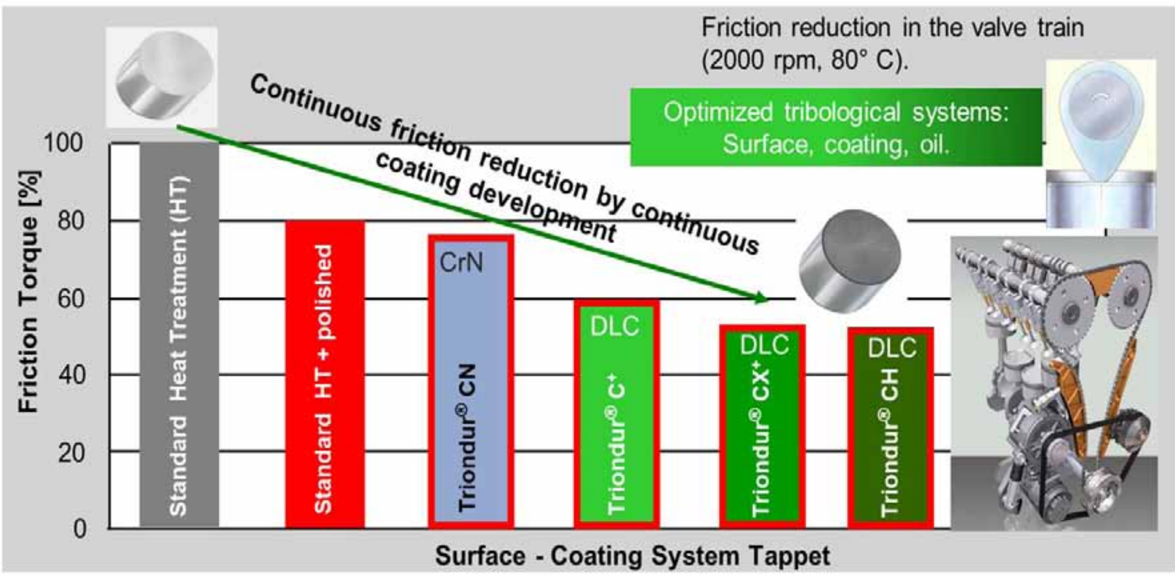


*Figure 4: Measures reducing valve train friction (photo: SCHAEFFLER AG)*

## C4. Friction reduction through improved engine oils

Lubricants reducing friction through their viscosity can be differentiated between:

1. Low-viscosity oils and/or
2. Oils with high viscosity index[3].

### C4.1. Low-viscosity oils

Depending on the load status [15, 16], the total engine friction losses amount to 25%-35% of a fuel energy of 100%. To which degree the fuel consumption can be reduced by the lubricant grade largely depends on the lubricant's viscosity, the driving cycle and the engine design (including the material selection). Where the impact of engine oil viscosity in standard driving cycles for both passenger car and commercial vehicles is concerned, the various systematic studies all agree that a lower viscosity decreases fuel consumption, although the total fuel savings also depend on the engine design and the selection of suitable materials.

SAE J300 defines the globally applicable viscometric classification of engine oils. In 2015, the currently lowest SAE 20 ($HTHS^{150C}$ = 2.6 -2.9 mPas)[4] of SAE J300 was supplemented by the following low-viscosity:

SAE 16, $HTHS^{150C}$ = 2,3-2,6 mPas
SAE 12, $HTHS^{150C}$ = 2,0-2,3 mPas
SAE 8, $HTHS^{150C}$ = 1,7-2,0 mPas

Given the task of engine lubrication, one must imagine that a SAE 8 at 150°C with a dynamic viscosity ($HTHS^{150C}$) of 1.7-2.0 mPas is only 1.7 times as viscose at water at 20°C! Experts currently even discuss SAE 4 ($HTHS^{150C}$ = 1.4-1.7 mPas). The undoubtedly positive contribution of low-viscosity engine oils to fuel consumption gives rise to reservations concerning a larger mixed friction share and a higher risk of wear in the engine. Both can be counteracted by optimized design and materials.

Table 3 states possible fuel savings through decreasing the high-temperature-high-shear-viscosity (HTHS at 150°C) by 1 mPas. Similar correlations exist between the kinematic viscosity at 80°C [17, 18] or 100°C [19] and the fuel economy. The transition from NEDC (New European Driving Cycle) to WLTP (Worldwide harmonized Light vehicles Test Procedure) may change this relationship.

Based on the 170 million tons of $CO_2$ emissions produced by German road traffic in 2017 [13], improving fuel economy through lowering the viscosity by only 1% would save 1.7 Mt of $CO_2$ emissions. A combination of the previously mentioned tribological measures may even yield higher savings (see Chapter B).

*Table 3: Correlations between viscosity (HTHS) and fuel consumption saving (FE= Fuel economy)*

| Study | Test cycle | Fuel savings in % for decrease of dynamic viscosity at 150°C [% FE per $HTHS^{150C}$ in mPas] |
|---|---|---|
| R.I. Taylor et al., 2004 | Passenger car (M111) | ~1.6 |
| SAE 2009-01-2856 | Commercial vehicle (13 mode ESC-cycle) | ~0.8 |
| M. Carvalho et al., 2014 | Passenger car (NEDC) | ~1.5 |

[3] The viscosity index (VI) is a measure for the viscosity stability as the oil temperature rises. The viscosity of each lubricant decreases by orders of magnitude as the oil temperature rises. A high VI indicates that the decrease in viscosity is lower as the oil temperature increases.

[4] HTHS= high temperature high shear viscosity. This dynamic viscosity is measured at 150°C and a shear rate of $10^6$ $s^{-1}$.

[5] For market launches as of October 2019, the JASO (The Japanese Automotive Standards Organization) issued JASO M 364:2019 ("GLV-1") for low-viscosity engine oils.

Likely obstacles for technical implementation are function limits concerning the physical evaporation of low-viscosity oils (increasing oil consumption and higher emissions!) which are distinctly lower for esters and polyglycols of identical viscosity.

## C4.2. Oils with high viscosity index

A high viscosity index can either be achieved through polymer viscosity index improvers (VI) or by intrinsic base oil properties (polarity of esters and polyglycols). Since the viscosity does not so much depend on the oil temperature and since the design depends more on the viscosity or lubrication film height at normal operating temperatures, a lubricant with high VI at low oil temperatures will yield low viscosities and thus reduced friction losses. Ultimately, this is beneficial in transient operation modes of the oil temperature (short range traffic, cold-warm-cold driving profiles) [20, 21]. In return, the arithmetically constant lubrication film height increases operational reliability and reduces wear. Three features describe the performance of VI-improvers:

1. Viscosity index (VI)[3],
2. Low temperature behavior, and
3. Shear stability.

Shear-stable, high-performance VI-improvers help solving the predicament of the lubrication film being too thin for high temperatures leading to wear and higher friction, mixed friction or to thick and sticky lubrication films at moderate temperatures, ultimately causing more friction (hydrodynamic losses) and increased fuel requirements. It is possible to formulate oils according to SAE 0W-20 with these high-performance VI-improvers. Such a formulation reduces the fuel consumption by 1% compared to SAE 0W-16. Depending on engine design and viscosity class, the fuel requirements can be further reduced by 0.5-1.5% through the use of a structurally optimized VI-improver (see Fig. 5).

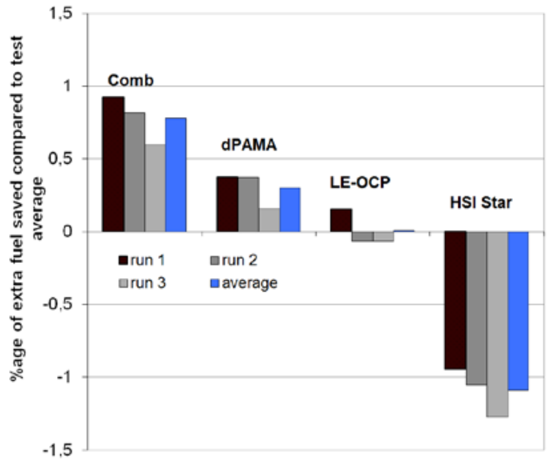


*Figure 5: Impact of the molecular structure of a VI-improver on the fuel consumption with engine oils featuring a HTHS von 3.5 mPas (Daimler 350 CGI, NEDC) [22]*

Fig. 6 illustrates additional fuel consumption savings for formulations with very high viscosity index based on a 2 Liter turbocharged gasoline engine. Depending on the test cycle, the reduced fuel consumptions range between 0.80-1.60%.

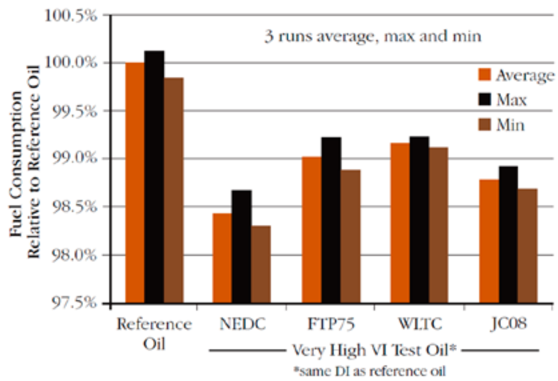


*Figure 6: Impact of test cycle on fuel consumption reductions for an engine oil formulation with high viscosity index [23] (Reference oil: VI= 164 (DEXOS 1, ILSAC GF-5), Test oil: VI= 242)*

[6] FTP75= U.S. EPA Federal Test Procedure (urban driving cycle); JC08= Japanese chassis dynamometer test cycle for light vehicles.

For hydraulic applications, such as excavators, forest machinery, injection molding machines und machine tools, hydraulic fluids with VI over 160 and high shear stability can tremendously decrease energy requirements and improve productivity. Fig. 7 illustrates the significant share of hydraulics for the energy requirements of a machine tool.

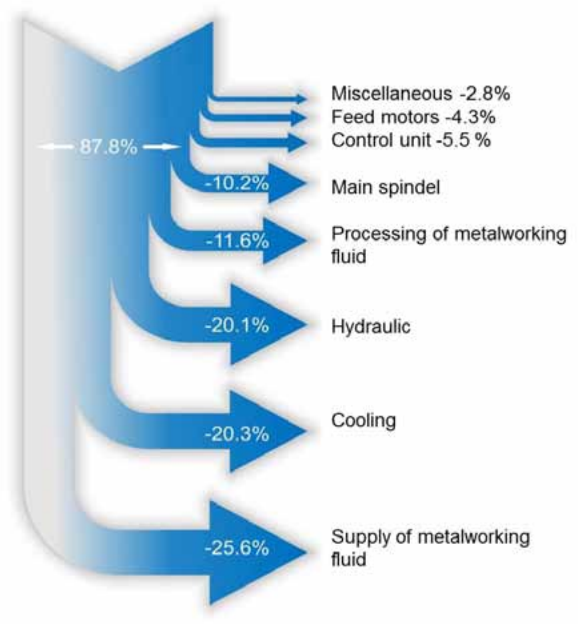


*Figure 7: Energy requirements for the individual components of a machine tool [24]*

The high VI provides optimum rheology thus offering energy savings over a wide range of working temperatures. Furthermore, the high VI increases the wear resistance at high temperatures while enhancing startability and good operation performance at lower temperatures. In relation to the work expended, fuel consumption savings of up to 20% can be accomplished for excavators [25], energy of up to 10% can be saved for injection molding machines [26] and between 2 and 20% for machine tools [27]. Since higher energy efficiency coincides with reduced losses and ultimately with a smaller increase in temperature, production facilities require significantly less cooling. During the regular production operation of a plastic kneader, for instance, the measurements of the cooling water read temperatures reduced by 10°C.

VI-improvers have been optimizing rheological profiles of transmission fluids for quite some time. Cold start at -40 °C and peak operating temperatures of up to 180°C require a high viscosity index. Within the same viscosity class, the efficiency can be significantly increased while the operating temperature can be reduced by more than 10°C [28]. This considerably extends the life of both transmission and lubricant

*The friction reduction potentials of lubrication technology interacting with surface topography reveal numerous percentages for lowering $CO_2$ emissions based on high functional safety.*

## C5. Recuperation

Since approx. 40% of the heating value of the energy source (fuel) deflagrates unused as exhaust heat (see Fig. 1), recuperation is the next logical step when making further use of combustion processes.

Recovery (waste heat recovery, exhaust energy recovery, energy harvesting) can be accomplished by using two different technologies:

a. Hot vapor technology with expander and electrical generator, and
b. Thermoelectrics[7] (SEEBECK effect).

[7] The primary effect of the thermoelectrical generator (TEG) is called Seebeck effect. It describes the direct generation of electric voltage along an electric conductor caused by a temperature gradient (hot-cold-gradient). TEGs can convert a share of the lost engine heat directly into usable electric energy.


*Figure 8: Recuperation unit and fuel consumption reduction achieved in driving tests (photo: EXOÉS)*

The thermoelectrical generator (TEG) is rather compact and does not require any friction points. For volume automotive application, however, certain raw materials, such as tellurium and bismuth, are only scarcely available for its production.

Piston expanders are favored for the expansion of hot vapor produced by vehicles. They form various friction points and need water-compatible lubricants but also require materials resistant to vapor-degradation. Rising temperatures increase the water acidity and tend to cause hydrolytic lubricant degradation. That is why piston modules and vapor-carrying areas of the expander cannot be lubricated. In order to tackle this issue, tribology research aims to develop friction- and wear-resistant materials capable of forming good tribological profiles even under hot-vapor conditions. Due to the requirements for both considerable space and heat quantity, recuperation will preferably be applied in commercial vehicles. The picture exemplifies fuel consumption saving potentials in commercial vehicles through 5-10% recuperation, regardless of friction reductions in the powertrain. For large engines, the proven fuel consumption savings potential through recuperation ranges between 5.5% - 12.7% [29].

The inevitable infiltration of working fluid into the lubricant requires water- and ethanol-miscible lubricants, such as polyalkylene glycols - one of major drivers for more tribological developments.

Pumped Thermal Energy Storage (PTES) or so-called Carnot-batteries [30] feature a new technology for the storage of heat quantities from regenerative sources in a GWh-range, if necessary, these heat quantities can later be recovered into electrical energy. Argon gas and melted Salt (eutectic $NaNO_3/KNO_3$) serve as heat storage medium requiring cryogenic hydrocarbon fluids for the heat transfer. In such a heat transfer, thermodynamic cycles form points of low friction for high efficiency.

## C6. Alternative drives

In order keep stride with the predicted growth of global mobility both in terms of economy and ecology, the use of various energy sources, drive technologies and new forms of mobility awaits implementation: Among them are:

1. E-mobility
2. Hydrogen (equally suitable for fuel cells and internal combustion engines) and methane as energy sources
3. Biomass utilization (cellulose, algae, sugar) for synthetic fuels (e-fuels).

Depending on the future market penetration, vehicles driven with batteries and fuel cells will impact and reduce lubricant consumption and product mix. In Germany, the automotive industry currently consumes 55 – 60% of the total lubricant quantity of approx. one million tons (2018: 1,017,267 tons). It is expected that e-vehicles will require approx. 1.5 – 2 kg of lubricating greases.

## C6.1. E-Mobility

By 2040, according to the estimate of the International Energy Agency [31], the number of e-vehicles will grow to 300 million worldwide, while at the same time, the number of vehicles with a combustion engine will rise from 1.3 billion to 2.1 billion vehicles. That is why the combustion engine will remain the most important motorization in the foreseeable future. However, combustion engines will need to be supplied with suitable, environmentally compatible energy sources tapping more $CO_2$ emission reduction potentials through frictional optimizations.

Apart from the electricity network capacity, supplying batteries with resources, such as cobalt and lithium is the limiting factor for a growing share of e-mobility unless other battery concepts (e.g. based on $LiTi_2NbO_7$)[8] reach series maturity. Therefore, it is fair to assume that the development of engine oils will continue.

Tribology and lubricant applications are directly affected by e-mobility. E-vehicles use fewer components that are subject to wear, repair and periodic maintenance. E-drive concepts will no longer require oil lubrication, belt drive, seals and many wearing parts of the combustion engine. However, brake systems and tires will remain. Electrical powertrains require more rolling bearings, grease and specialty lubricants, such as:

» lubricating greases[9] (ca. 1.5-2.0 kg grease/vehicle) for rolling bearings,
» coolants for battery, e-motor and power electronics, and
» transmission fluids (e.g. for high-speed planetary gear sets).

The currently most popular e-configuration encompasses minimum one reduction gear and one differential (see Fig. 9) all lubricated with one fluid (about 3-4 Liters). Quantities of 20 l of functionalized coolants are also being discussed. Where the many subsystems (steering, brakes, shock absorbers, joints, seats, actuators, climate control etc.) of modern automobiles are concerned, no significant changes in the application of lubricants can be predicted, although an increased use of greases and anti-friction coatings is expected in the future.

Friction reduction is important for e-drives in terms of range, but it is equally crucial for combustion engines because the reduction of $CO_2$ emissions has the highest priority as development objective.

New developments will be required because transmission fluids, coolants and greases come in contact with electrical modules, sensors and circuits exposed to electromagnetic fields, but also with insulating materials and special polymers.

Hybrid drive technology plays an important role in transportation because it links the large range of classic drive concepts to their energy-dense fuels and to the recuperation of motion energy in batteries ultimately saving valuable energy.

However, hybrid drive technology changes the traditional load situation in the combustion engine. Additional vibration loads affect the engine during standstill in electrical operation mode. During this phase, the combustion system cools down and is stressed by an increased number of cold starts. Particularly unfavorable is the infiltration of blowby gas into the engine oils during the warm-up phase. Auxiliary drives for climate compressor or generator of future hybrid vehicles will no longer be driven by the combustion engine but electrically instead or they will be coupled to the transmission. Therefore, friction partners, as we know them today, will no longer exist. When the battery is depleted or the velocity outside city limits is more than between 70 and 80 km/h, the combustion engine runs in the plug-in-hybrid mode instead of continuous operation. This driving mode poses demanding tribological

[8] $LiTi_2NbO_7$ or $LiNb_{18}W_{16}O_{93}$ is characterized by so-called ion channels or tunnels with a larger diameter in the crystal enabling lithium ions quicker insertion and extraction by the crystal. The ions also diffuse (mitigate) faster in the crystal thus distinctly reducing charging times.

[9] Greases are consistent (pasty) lubricants which do not circulate in a circuit.

[10] Anti-friction (AF-)coatings are solid lubricants whose solids are bonded in an organic binder. They are applied onto the components according to state-of-the-art painting technologies and additionally cured, if necessary. Consequently, the component runs dry, i.e. free of grease or oil.

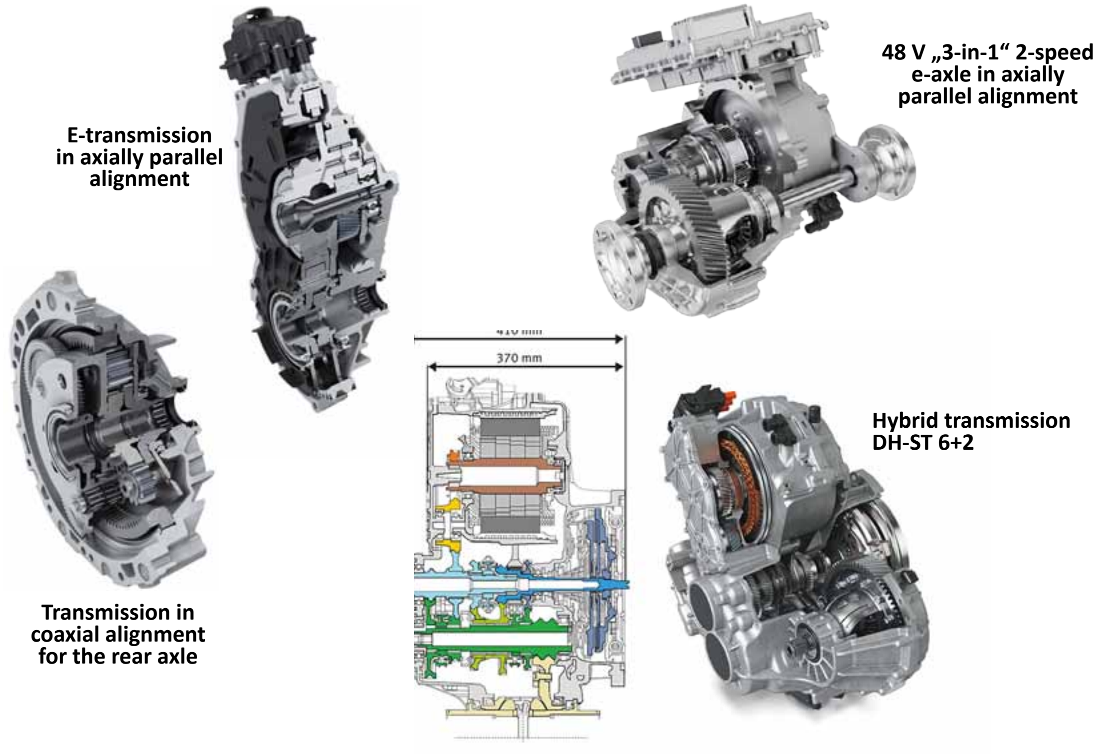


*Figure 9: Illustrations of e-mobility components by SCHAEFFLER*

challenges to the friction partners in the combustion engine because they must operate at high speeds without a separating lubrication film built between them. Therefore, material mixes and coatings will need to be developed that enable maximally dry run but minimally deficient lubrication at high contact temperatures. For engines running in such operation modes, the use of rolling bearings for the crankshaft is recommended. Tribosystems in e-drives are increasingly exposed to the electrical stress of stray currents or transient fields. Avoiding the resulting damage caused by the passage of electrical current (e.g. on bearing points) requires a systematic conduction of electrical current or electrical insulating components which can be implemented by insulating layers of electrically non-conductive material. Altogether, these changed operating conditions demand more robust tribosystems. Electrically insolating, and, at the same time, thermally conductive materials will considerably gain in importance and require lubricants with new electrical and thermal properties, more stability, and improved heat management.

Since electric motors also feature adaptive efficiencies, the use of automatically shifted transmissions in electrically driven vehicles is probable. Due to wide speed ranges, e-drives use fewer gears compared to classic drive concepts while the design of their rolling bearings must be robust enough to withstand operation at high speeds.

For e-drives, the reduction of friction remains a crucial development objective – not only in terms of reducing the energy consumption per se and saving resources but also because the available energy density of batteries is limited and the fuel consumption reduction directly impacts the vehicle range.

E-vehicles do not generate any combustion noise. Therefore, the focus moved towards the operating noise of the mechanical powertrain (driving comfort). It will be one of tribology’s foremost tasks to develop low-noise contact points.

## C6.2. Hydrogen and methane as energy carriers

Currently, the public discussion focuses on e-drives using a battery (usually cobalt-based) as power source. Effective ranges still lag distinctly behind vehicles driven by combustion engines but they are sufficient for urban traffic cycles. Vehicles driven by hydrogen or natural gas [32] are possible alternatives. Currently, there are 76 hydrogen filling stations available in Germany. Hydrogen can either

a. be directly combusted, or
b. electrified through fuel cells.

When using fuels cells, the hydrogen purity requirements compliant with SAE J2719 and ISO 14687-2 must be met. Recently, much emphasis has been put on compressed or liquefied natural gas (CNG, LNG) [33, 34] as bridging technology. Although natural gas is also a fossil energy resource, it consists to 99% of methane. Compared to gasoline or diesel fuels, the combustion processes of methane produce between 15 and 30% less $CO_2$ emissions. Although methane is a main constituent of biogas, it can also be produced synthetically. That way, natural gas can serve as the bridging technology for the utilization of regenerative fuels in the transportation sector.

Today, more than 22 million road vehicles worldwide are fueled with natural gas. Recent studies revealed that in China alone, about 200,000 trucks and busses run on cryogenic liquefied natural gas offering benefits particularly in long haul commercial use [33]. In this context, it must also be noted that stationary combustion engines fueled with natural gas contribute to power generation, e.g. in cogeneration plants. Engine oils must be developed to meet the requirements of such „gas engines" and specialty oils required for gas engines are already available [35, 36, 37].


e-fuel Methane Hydrogen Electricity

*Figure 10: The fuel dispenser question based on $CO_2$-neutral energy sources*

*The results of tribology research empower the hydrogen industry to deliver solutions for maintenance-free and long-life components and supply networks for consumer-friendly and every-day use. Materials to be developed must be low-wear ensuring minimal contamination of hydrogen with tiny wear particles. Engine combustion requires new water-miscible engine oils. The resistance to hydrogen embrittlement and affordable alloys will also pose sophisticated challenges.*

Promoting natural gas and hydrogen in the transport sector requires establishing an infrastructure for reliable and safe fuel supply. In the long term, the industry has opted for Power-to-Gas (P2G) which is considered the key technology for an energy turnaround. P2G uses wind or solar power for the electrolysis of water thus obtaining $CO_2$-neutral hydrogen. In an optional second step adding carbon dioxide, methane or natural gas can be synthesized. This process allows the utilization of temporarily excess electrical energy for the electrolysis of water. The obtained hydrogen can be converted back into electricity, recirculated into the existing gas supply directly after the methanation with $CO_2$ or sold as fuel at filling stations.

Both components for drives fueled by hydrogen- or natural gas and the corresponding infrastructure must meet the same high standards for safety, maintenance-free operation and reliability as conventionally driven vehicles supplied with fossil fuels. Frictionally stressed surfaces of compressors, pumps, control and shut-off valves are especially critical, because over long distances both gases are transported usually in the liquid state. The boiling temperature of natural gas is -161.5°C, for hydrogen it is -253°C, thus distinctly lower than the solidification points of lubrication oils and greases. However, also utilization as gas at room temperature requires specifically adjusted lubricants. In particular, fuel cell technology places high demands to hydrogen purity thus restricting the choice of suitable lubricants used in the periphery. The corresponding components require safe, low-cost and wear-resistant material solutions that are fail-safe even under long-term operation conditions and when in contact with these alternative fuels. Here, tribology makes a major contribution to the safe handling and market introduction of hydrogen and methane.

The relevant EN16942 contains pictograms for altogether 13 different fuel grades, although only five to six grades are currently available at filling stations. The question must be raised whether the fuel diversity (see Fig. 10) should be increased in order to promote the economic and ecologic growth of transportation for which $CO_2$-neutral energy sources are of paramount importance.

## C6.3. Synthetic liquid fuels

Sustainable greenhouse gas-neutral e-fuels and feedstocks are essential in order to attain the climate protection goals set out by EU for the transportation sector. Since liquid energy resources deliver about 98% of the drive energy in the transportation sector, synthetic fuels are of central importance. The expert discourse focuses on the supply of biogenic resources while ensuring appropriate eco-balance and target cost level. For the generation of biogenic base materials (fuels), various approaches have been pursued, such as

a. biomass (lignocellulose, vegetable oils, used frying oils, etc.),
b. sugar and
c. algae,

as well as excess power (preferably from regenerative energies, such as solar and wind power) for the conversion $CO_2$ into liquid hydrocarbons (power-to-liquid, P2L).

Prerequisite to maintain an acceptable cost level slightly above that of fossil energy resources is the commitment to large-scale industrial system technology. $CO_2$-neutral e-fuels offer the advantage of utilizing the existing gasoline/diesel/kerosene infrastructure (pipelines, filling stations, vehicles) and natural gas infrastructure. They also feature backward compatibility.

Automotive and aviation industry are the trailblazers for $CO_2$-neutral e-fuels and have tried and tested the following possible molecules:

a. triptane ($C_7H_{16}$, octane number: 112; from methanol & dimethylether),
b. paraffines from a Fischer-Tropsch process utilizing biomass,
c. tri- und tetraoxymethylenglycoldimethylether obtained from bio-methane,
d. biodimethylether (Bio-DME) obtained from bio-methanol,
e. bio-olefines obtained from algae (botryococcane) or
f. "farnesenes" ($C_{15}H_{32}$) obtained from sugar.

In a best-case scenario, these $CO_2$-neutral alternatives would be suitable to directly replace conventional fuels because liquid products with high energy density only require insignificant modifications of engine concepts and infrastructures.

In this context, it must be mentioned that related to the expended electrical energy, the total efficiency of a P2L-driven vehicle ranges only between 15 and 20%. 50% thereof are lost during fuel liquefaction. The efficiency of an internal combustion engine [38] in comparison is approx. 40%. Since the high energy density of liquid fuels is essential for aircraft fuels, P2L would rather be a suitable alternative to kerosene.

Other feasible technological solutions where hydrogen is not bonded to carbon but otherwise are in the pipeline for the production of synthetic energy sources. Such solutions would require a reversible chemical bond of hydrogen to specific carrier molecules, thus by-passing the problematic safety aspects when transporting and distributing hydrogen. Toluene/methylcyclohexane, N-ethylcarbazole, dibenzyltoluene, benzyltoluene, naphthaline, azaborine are considered suitable as additional liquid organic hydrogen carriers but the technology is still in the state of demonstration projects.

*Mastering the tribology of components operated by means of alternative fuels is the key challenge for the successful launch of $CO_2$-neutral fuels. Tribological solutions include coating technologies and new alloys. These new e-fuels also directly impact the formulation of engine oils.*

## D. Importance in light of sociopolitical discourse

The economic importance of tribology for the reduction of friction- and wear-induced energy and material losses increasingly includes human- and eco-toxological aspects, such as

a. environmental impact of lubricants on water, soil and air quality, and predominantly economical aspects, such as

b. friction reduction = energy efficiency and conservation of resources ($CO_2$ emissions) or

c. wear protection = material efficiency and conservation of resources (waste reduction, resource import cuts)

For a country with few natural supplies of raw materials, any import of resources weighs negatively on the total economic balance. Sustainable use of resources and efficient utilization of materials including high secondary cycles (recycling) improve the economic balance. Reduced import and increased export plus high added value from the imported resources will eventually unfold overall positive environmental effects because resources are used to their full capacity.

### D1. Lubrication market

Table 4 breaks down the German lubricant market (2018) according to product categories. Beyond the explicitly mentioned automotive consumables, there are considerable amounts of hydraulic fluids (shock absorber oils and brake fluids amount to approx. 30,000 tons alone) compressor oils (refrigeration machine oils) used as operating fluids in motor vehicles. Furthermore, engine cooling requires large amounts of radiator antifreeze. Altogether, distinctly more than 40% of the lubricants used in Germany are attributed to the automotive sector.

Due to elimination of classic engine oils, it can be expected that the total lubricant quantities will significantly drop for battery-driven electric vehicles (BEV). However, any estimates of operating fluid requirements per vehicle should be based on the currently most common e-configuration, i.e. a system with high-speed e-motor, minimum one reduction gear and a differential - all lubricated by about 3-4 l of fluid. Coolant requirements will rise considerably because apart from the e-motor, power electronics and batteries also require active cooling, i.e. 10 to 20 l of radiator antifreeze or comparable liquids.

*Table 4: Lubrication market in Germany according to product categories (Mineral oil statistic of Federal Office of Economics and Export Control)*

| Lubrication category/Application | Tonnage in 2018 |
|---|---|
| Engine oils | 275,314 |
| Automotive transmission oils | 103,425 |
| Industrial transmission oils | 21,940 |
| Automotive greases | 8,006 |
| Non-automotive greases | 25,070 |
| Hydraulic fluids | 73,083 |
| Metal working fluids* | 95,172 |
| Compressor oils | 8,475 |
| Turbine oils | 1,566 |
| Insulating oils | 11,117 |
| Machine oils | 27,316 |
| Other non-lubricant industrial oils, process oils etc. | 366,783 |
| **Total** | **1,017,267** |

*(Hardening oils, water-miscible and non-water-miscible cooling lubricants, anticorrosion oils)

## D2. Bio-lubricants

Liquid lubrication is the core technology of tribology for the reduction of friction and the protection from wear. The total consumption of lubricants in Germany consistently amounts to slightly over a million tons a year. About 60% of the lubricants sold are recovered through waste oil collection [39, 40, 41]. These figures have not significantly changed over the past 20 years. An additional portion will end up in the environment as a result of internal engine combustion products, loss lubrication, leakage and other system-related reasons. A residual quantity of approx. 20% is released to the German environment via unaccountable routes.

Bio-lubricants released through these routes of entry impact the environment and particu-larly the water quality. This fact has been known for many years and is absolutely undisputed. In 1994, the Association of German Machinery and Equipment Constructors (VDMA) published several guidelines on „Fluid power – Environmentally acceptable hydraulic fluids – Minimum technical requirements“ (VDMA Specifications 24568 and 24569) forming the basis for DIN ISO 15380 „Environmentally compatible hydraulic oils” in 2002. Parallel, the German eco-label „Blue Angel” was established for lubricants and initially divided according to fields of application:

a. RAL-UZ 48 „Readily biodegradable chain lubricants for power saws“ (since 1988),

b. RAL-UZ 64 „Readily biodegradable lubricants and mold release agents “ (since 1991), and

c. RAL-UZ 79 „Readily biodegradable hydraulic fluids“ (since 1994).

From 2012, the three eco-labels were harmonized to RAL-UZ 178 „Biodegradable lubricants and hydraulic fluids“.

In parallel step, the European eco-label „Euro-Margerite“ was introduced; from 2005 as Directive 2005/360/EC, from 2011 under 2011/381/EU and finally 2020 under 2018/1702/EU.

Individually and as a whole, all these approaches have internationally established the basic eco-toxological requirements for bio-degradable lubricants (bio-lubricants). In addition, the „European Eco-label“ mandates a minimum share of renewable resources. Surprisingly, this requirement was discontinued with the third amendment (2018/1702/EU).

Due to the various approaches and the different terminology for environmentally compatible lubricants, the European Commission has assigned CEN with the standardization mandate M491 for the term „bio-lubricant“. The resulting DIN EN 16807:2016 set forth the criteria and requirements for bio-lubricants and bio-based lubricants. The following core requirements were defined:

a. readily bio-degradable (complete mineralization, no primary degradation),

b. 2-3 aquatic toxicities according to OECD 201, 202 and 203, as well as

c. minimum proportion of renewable resources of 25%.

With regard to environmentally relevant criteria for lubricants, much has been accomplished during the past 20 years. Throughout Europe, the use of bio-lubricants is not generally statutory thus limiting their market share. Since eco-friendly variants are restricted to voluntary use, their market share has never exceeded 3-3.5% (about 120.000 tons p.a.) during the past ten years [42].

In order to eliminate this implementation deficit, the European Lead Markets Initiative (LMI; {COM(2007) 860 final} of 21 Dec 2007) addressed the EU Commission with the recommendation in 2011: „Consider the possibility of an obligation to use bio-degradable lubricants and hydraulic fluids in environmentally sensitive areas.” This could, for instance be implemented by legislative protection of soil and water. Until today, this recommendation has not been implemented.

The U.S.A., a „trailing country“ for bio-lubricants, went a different way. The „Vessel General Permit” (VGP) under the Clean Water Act for discharges incidental to the normal operation of vessels, enacted as of 19 December 2013 and prescribing the mandatory use of environmentally-acceptable lubricants for vessels within the territorial waters of the U.S.A. („Water to sea interfaces“) could act by way of example. Products with European eco-label for lubricants (2011/381/EU) are compliant with the second issuance of VGP.

Initially, bio-lubricants entering the environment seem equally hazardous to mineral-based lubricants, even if, due to the quick bio-degradability, their toxic effect is much lower and their dwell time is distinctly shorter. However, the problem with liquid lubricants lighter than water is the “floater criterion“ (density threshold), i.e. their tendency to float to the top thus bearing the inherent risk of directly contaminating marine life. This floater criterion has led to the German Administrative Regulation on the Classification of Substances Hazardous to Waters [43] to classify bio-lubricants in Water Hazard Class 1 (slightly water-pollutant).

Generally, readily bio-degradable lubricants are not formulated from mineral oils or synthetic hydrocarbons. Suitable base oils mostly consist of natural and synthetic, biogenic esters but also of polyalkylene glycols. They both can be synthesized from biomass or regenerative raw materials. However, biogenic polyalkylene glycols have been hardly available in the marketplace. Instead, so-called bio-olefines, obtained from regenerative raw materials and considered relatively well bio-degradable, may be marketable in the future.

Bio-lubricants are predominantly offered by independent lubricant manufacturers whose petrochemical production facilities are not operated with backward-integration. Due to their application experience and additive know-how, mechanical engineers, no longer have to consider the choice of materials when using base oils along the value added chain and at the final customer. Only polymers still require specific material selection.

Since it became apparent that many ester- and polyglycol-based lubricants feature particularly low coefficients of friction, the interdisciplinary approach of tribology has facilitated the market launch of bio-lubricants. Their relatively high viscosity index and low evaporation loss (convenient when decreasing the viscosity) are additional technological benefits. Ester- and polyglycol-based lubricants are ready to face the recent challenges of energy efficiency and $CO_2$ reduction. Despite the various product proposals, especially for more environmentally compatible engine oils, bio-lubricants have not yet made inroads in significant quantities in the large market sector of automotive lubricants (engine and transmission oils).

*The quantity of lubricants corresponds to about 1% of the fuel quantity in Germany. Raw materials for long-life lubricants can be synthesized from biomass. The various synthesis routes allow for esters, polyglycols and hydrocarbons. Furthermore, bio-lubricants positively impact friction reduction and water quality when released to the environment.*

## D3. Legislative eco-political measures

A large number of coatings proven for friction reduction and wear protection is widely available, some additionally protects against corrosion. Due to the EU-Directive EC/1907/2006 (REACH= Registration, Evaluation, Authorization and Restriction of Chemicals) many functional additives commonly used in lubricants are subject to substitution pressure. The same applies for established coatings containing chrome ($Cr^{VI+}$) and chromates but also for materials with cobalt and nickel contents which all feature a wide range of proven functionalities. Tribology not only contributes to delivering the classic functional profile but also develops alternative metallurgical solutions that meet the functional and toxicological requirements.

Alternative metallurgical solutions for the design of tribosystem encompass thin films made of diamond-like carbon (DLC, ta-C), but also $CrN_x$ or $MoN_x$, organically solid bonded films or niobium carbide bonded with nickel.

Contrary to the U.S.A., European legislation has not stipulated any mandatory rules and national legislation only few mandatory rules for the application of bio-lubricants (see chapter D.2).

## D3.1. Fine dust from abrasion

Road traffic emissions without those from combustion engines (non-exhaust), particularly considerable quantities of tire and brake abrasion, are not just a decorative nuisance but also contribute to 90% of wear particle emissions produced by road traffic vehicles [44]. Even vehicles driven by batteries or fuel-cells will continue to produce tire and brake abrasion in the future.

Depending on the driving profile, tire abrasion is between 0.04 and 0.5 g/km [45]. Table 5 summarizes the corresponding abrasion quantities generated by brake systems [46].

*Table 5: Total wear of brake disk and brake pads in NEDC driving cycle*

| Tribological parameter | ECE-1- NEDC Cycle: 1 - 20 | ECE-1- NEDC Cycle: 21 - 40 |
|---|---|---|
| Brake pad wear [g] | 3.45 | 1.75 |
| Brake disk wear [g] | 5.75 | 3.45 |
| Total wear [g] | 9.20 | 5.20 |
| Specific wear rate [mg/cycle-km] | 42.0 | 24.0 |

*Figure 11: Porsche Surface Coated Brake (PSCB) with friction surface made of tungsten carbide (PORSCHE SE)*

Tribology can make a contribution to the reduction of wear particles by developing more wear-resistant materials while maintaining all other functional properties. In fall 2002, the fully functional demonstrator „ELLYPSE“ by RENAULT SaS proved [47] that change intervals for tires and brake systems could be extended to 100,000 km. These results should be reconsidered as valuable approaches for future research activities.

At the end of 2017, PORSCHE introduced the Porsche Surface Coated Brake (PSCB) [48], a carbide-coated, grey-cast brake disk (see Fig. 11) for the reduction of wear particles from brake abrasion. This brake generates 90% less „brake dust“ and that is why the caliper is painted in white color.

Trams and trains also contribute to wear particle emissions [49] through:

a. pantographs (current collectors),
b. wheels (even if made of steel!), and
c. brakes.

## D3.2. Tungsten carbide and wear protection

Tungsten carbide (WC, “hard metal“) has dominated wear protection for decades and is the standard material of choice for machining applications. 80% of the globally extracted tungsten is mined China and considered a critical resource [50]. Tungsten carbide combines approx. 70% of all previously used tungsten. With rising toxicological concerns about cobalt-bonded WC and the dependence on tungsten reservoirs in China, interest in niobium carbide (NbC) as an alternative bio-material alternative has distinctly increased [51]. Both niobium carbide and niobium oxide ($Nb_2O_5$) are registered in conformity with REACH. STELLITE™, an alloy with high cobalt and chrome content, is also widely used in various wear protection applications. Batteries trigger the demand for cobalt which is only available in by-pass production and limited quantities thus resulting in high raw material prices. In addition, the toxicological profile of cobalt compounds gives rise to concerns. For a production-oriented economy, the availability of machining materials also for wear protection purposes is essential. In view of the 90 years of experience with WC, tapping the potentials of substituting mostly cobalt-bonded tungsten carbides with nickel-bonded NbC[11] is challenging both in terms of metallurgy and tribology.

[11] With a production of approx. 85% of all globally extracted niobium (about 100,000 t in 2018), Brazil forms an oligopoly. However, niobium mined in Brazil can be considered an alternative and is not as critical as tungsten produced in China. Assuming that NbC replaces the total volume of WC, the capacity of the currently available and not yet exploited reservoirs could provide niobium for the next hundreds of years. Germany practically has no exploitable deposits of niobium but there are reservoirs in the EU, e.g. in Motzfeldt or Sarfartoq, both in Greenland (Denmark).

# E. Education and research

Many universities and colleges have included tribology contents in their curriculum. However, there are only very few lectures exclusively featuring tribology as autonomous technology. Instead, such lectures are only integrated in the curriculum for mechanical engineering. The following chapter shall describe the situation based on important chairs with predominantly tribological contents. The vast majority thereof are institutional members of the Association for Tribology (GfT).

## E1. GfT Study – „Tribology at universities and colleges"

In 2014, GfT conducted a study [52] to determine tribological activities at German universities. Universities and colleges were contacted using known addresses of the discontinued „Vademecum" (list of German research institutes), lecture schedules of German universities and colleges and generally through the internet. The study surveyed:

a. 82 institutes at 36 universities and technical colleges,

b. 76 faculties/institutes/subjects at universities of applied sciences, and

c. 20 research centers and research institutes.

Where lectures offered at universities and colleges were concerned, the study yielded that tribology was predominantly subject of higher-level courses (e.g. machine elements) mostly within the framework of teaching basics during the first semesters and therefore not available to a wider audience of engineering or science students. Distinct tribology lectures featuring an overview over all the fields of tribology only amounted to 20% of the courses. In addition, they were predominantly offered as electives. Lubrication technology was only marginally represented in the curriculum. It can be assumed that this situation has not changed much to this day.

As expected, ongoing R&D-projects mostly deal with machine elements and drive technology (rolling and plain bearings, seals, free wheels, chain drives and clutches). Next in line are developments and optimizations of material and surface technologies. A multitude of projects dealt with the specific issues related to internal combustion engines and transmissions. Research activities at universities related to lubricants and lubrication in medical technology applications are equally insignificant.

The 2014 study also recorded test rigs with the corresponding metrology and analysis equipment. The focus of standard test procedures was on meshing, rolling bearings, seals and plain bearings. Half of the test rigs were proprietary constructions customized to the specific applications typical in mechanical engineering. Most frequently used standard test rigs were FZG[12] testing machines, pin-on-disk tribometers, two-disk test rigs and SRV[13] translatory oscillation apparatuses (see table 6). Eventually, out of the 28 categorized test rigs included in the GfT tribometer and test rig database[14] only 17 were used.

Within the scope of its capabilities, the Society for Tribology has established a genuine education system offering exams and certificates with the objective to broaden the knowledge horizon of tribology. Nevertheless, these efforts can by no means satisfy the enormous demand for the dissemination of this knowledge, particularly in the area of academic education.

[12] FZG stands for „Forschungsstelle für Zahnräder und Getriebebau (Gear Research Centre) of the Technical University of Munich, Department of Mechanical Engineering.

[13] SRV® stands for Schwingung, Reibung, Verschleiss (German); oscillating, friction, wear.

[14] https://www.gft-ev.de/de/tribologische-pruefstaende/

*Tribology has been part of the curriculum at many colleges and universities but it has not been taught in sufficient magnitude and depth. Against the backdrop of the economic and ecologic importance of tribology and its omnipresence in machine elements and specialized disciplines, it is absolutely necessary to promote disseminating the basics of friction, wear and lubrication in the degree programs of technical studies.*

## E2. Research

### E2.1. Research funding

Between 1960 and 1969, the German Research Foundation (DFG) funded the Priority Programme „Basic research on wear, friction and lubrication" with 4.5[15] million DM [53]. Later in 1978, the German Ministry for Research and Technology (BMFT) funded „Tribology" in 181 individual projects with 49[16] million DM for over eight years. From 1986 until 1991 the BMFT continued funding „Tribology" with altogether 21.3[17] million DM. Subsequently, no more such programs were conducted until 2017.

### E2.2. Priority Programmes and Collaborative Research Centers of the German Research Foundation (DFG)

Many Priority Programmes and Collaborative Research Centers of the German Research Foundation (www.DFG.de) have focused on projects dealing with the aspects of tribology. The following Priority Programmes integrated tribology as core content:

- Processing-related surface textures and tribological characteristics of ceramic components, SPP 322 697
- System dynamics and long-term behavior of railway chassis, track and track bed, SPP 1015
- Resource-efficient design elements, SPP 1551
- Fluid-free lubrication systems with high mechanical load[18], SPP 2074

### E2.3. Funding by the German Federal Ministry of Economics and Energy (BMWi)

After more than 25 years of no significant programmes funding tribology, the German Federal Ministry of Economics and Energy (BMWi) created a field of research for tribology and established a network of players across the sectors from science to industry. An interface between politics, research and economy, this field of research pools activities strengthening tribology as a key technology – all with the objective of promoting efficient use of energy in the future.

Bringing together experts from universities, research institutes und companies is a challenging but feasible endeavor. Scientists who are part of such funded projects share their findings and thus contribute their experience to bring tribology to the fore. The philosophy of networking among the players shall create incentives for interdisciplinary research and raise the awareness that tribology has tremendous economic importance. The monetary economic expenditures of industrial countries caused by friction and wear are estimated to range between 1 and 2 percent of the gross national product (see Table 1), for which ecological considerations were disregarded.

[15] Corresponds to a purchasing power in 2018 of 19.7 million Euros.
[16] Corresponds to a purchasing power in 2018 of 111.1 million Euros.
[17] Corresponds to a purchasing power in 2018 of 36.3 million Euros.
[18] Apart from the numerous contributions of liquid lubricants, optimization potential can be foreseen by expanding the range of applications for so-called consistent lubricants. They are applied, for instance, to integrated components of surface coatings. Highly-stressed rolling bearings are the focus of Priority Programme 2074, initiated by the German Research Foundation in 2018.

## E3. Tribological testing technology (tribometry)

Following, an overview over the tribometry technology used in research and industry shall round off this study. A more detailed list of tribometers can be found under "Publications" on the website (www.gft-ev.de) of the Society for Tribology.

Tribometers or instruments for the measurement of friction and wear form the basis for most tribological examinations. The purpose of a tribometer is the simulation of friction and wear under controlled conditions with the aim of determining the functional profile of lubricated or unlubricated friction partners. Tribometry validated and extrapolated to the corresponding applications, speeds up product developments thus cutting costs, offering guidance and ensuring innovative power.

Table 6 lists tribometers of international penetration developed and manufactured in Germany. The many different test standards in international standards organizations cover those testing technologies and emphasize the diversity of standardized testing concepts. Among the older tribometers developed in Germany are the Almen-Wieland[19] wear testing machine and the indicator for the measurement of sliding friction according to TANNERT (DIN E 51387).

*Table 6: Important tribometers of international penetration*

| Tribometer | Testing category | Test Standards |
|---|---|---|
| SHELL-Four-Ball-Machine | Model/laboratory test | DIN 51350, Parts 1-6, ISO 20623, ASTM D2266, ASTM D2596, ASTM D2783, ASTM D4172, ASTM D5183, CEC L-45-A-99, IP 239, PSA D55 1136, Renault D55 1994 |
| SRV® Translatory Oscillation Apparatus | Model/laboratory test | DIN 51834, Parts 1-4, ISO 19291; ASTM D5706, ASTM D5707, ASTM D6425, ASTM D7217, ASTM D7420, ASTM D7421, ASTM D7594, ASTM D8227, GB/T 38074-2019, SAC SH/T 721, SAC SH/T 784, SAC SH/T 847, SAC SH/T 882, SAC SH/T 920, T/CSAE 109-2019 |
| Pin-on-disk tribometer | Model/laboratory test | DIN 50324, ISO 20808, ASTM G99, EN 1071-13 |
| BRUGGER lubricant tester | Model/laboratory test | DIN 51347 |
| FZG Gear Test Rig | Component/subsystem bench test | DIN 51354, ISO 14635, ASTM D4998, ASTM D5182, CEC L-07-95, CEC L-84-02, DGMK 377, DGMK 575, DGMK 623, FVA 2, FVA 54, FVA 345, FVA 371 |
| FE8 Rolling bearing lubricant tester | Component/subsystem bench test | DIN 51819, Parts 1-3 |
| FE9 Rolling bearing lubricant tester | Component/subsystem bench test | DIN 51821, Parts 1-2 |
| V104C Vane pump test | Component/subsystem bench test | DIN EN ISO 20763, DIN 51389, Parts 1-3, ASTM D7043 |
| Coefficient of Friction of Automatic Transmission Fluids (DKA Friction Machine) | Component/subsystem bench test | CEC L-11-A-98, FVA 626, SAE 2 |

FVA= Forschungsvereinigung Antriebstechnik (Research Association for Power Transmission Engineering); CEC= The Coordinating European Council; SAC= Standardization Administration of China; DGMK= Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. (German Society for Petroleum and Coal Science and Technology); ASTM= American Society for Testing and Materials

[19] FALEX pin and vee block has the same test geometry as Almen-Wieland.

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