On the Competition between Fluid and Electric Automotive Drives

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Abstract

The present general lecture gives a view over the relevance and potential of fluid power systems for automotive applications in the present and future, compared to electric drives as their major challengers. In order to address their respective relevance, the classification of automotive vehicles according to ISO/DIN 70010 is shown in the introduction. There are different reasons which stimulate innovations in drive engineering, where the need for saving energy during production and operation of automobiles can be considered as the first order demand for the future.

For assigning the appropriate drive technology, a distinction between traction ("main") drives and additional drives ("auxiliaries") is determined. In order to utilise their specific advantages, more and more different energy sources and/or energy converters (drives) have been combined in one vehicle, known as hybrid traction drives having certain topologies. To understand the relationships, the influence of different drive characteristics and efficiencies on the driving and braking performance of the vehicle is discussed. Selected types of drives are compared, where particularly the aspect of energy storage has to be taken into account.

From the engineering point of view, an automobile's auxiliary drives are of same level of interest as its traction drive(s). In this area a tendency to electric actuation can clearly be identified, which allow a "power on demand" strategy in an appropriate manner. At present, the low voltage board net may considered as the major handicap, however, once having high voltage aboard, a remarkable breakthrough of electric auxiliary drives can be expected. Anyway, due to their specific advantages, fluid power solutions may retain their importance in automotive engineering, e.g. pneumatic springs and servo brakes and hydrodynamic torque converters. In conclusion, the necessity of significant reduction of energy during the whole automotive life cycle should remain in the focus, particularly during the phases of production and utilisation.

KEYWORDS: automotive drives, driving performance, energy, efficiency

1. Introduction

At present, remarkable changes of automotive drive technologies are in progress. The oncoming changes in the field of transport and traffic pose an enormous challenge to all participating disciplines. The most significant challenges are:

- Further worldwide increasing transport and passenger capacity,
- Emerging markets aim at individual mobility,
- Climate change due to greenhouse gases and emissions,
- Finiteness of fossil fuels,
- Commercial production of energy carriers, their distribution and storage,
- Reduction of traffic accidents and their consequences.

In affluent societies, approximately one third of the total energy consumption is spent for mobility and transport /1/, see **Figure 1.** Thereby it should be mentioned that another third of energy consumed by traffic is expended for the production of the respective vehicles, which is included in the part "industry" in the upper chart. Furthermore, the distribution of energy consumption between different means of transport is shown in the lower chart of Figure 1. One can recognise the dominant share of road vehicles in the overall situation, which characterise the achievement of "individual mobility" and road transport.

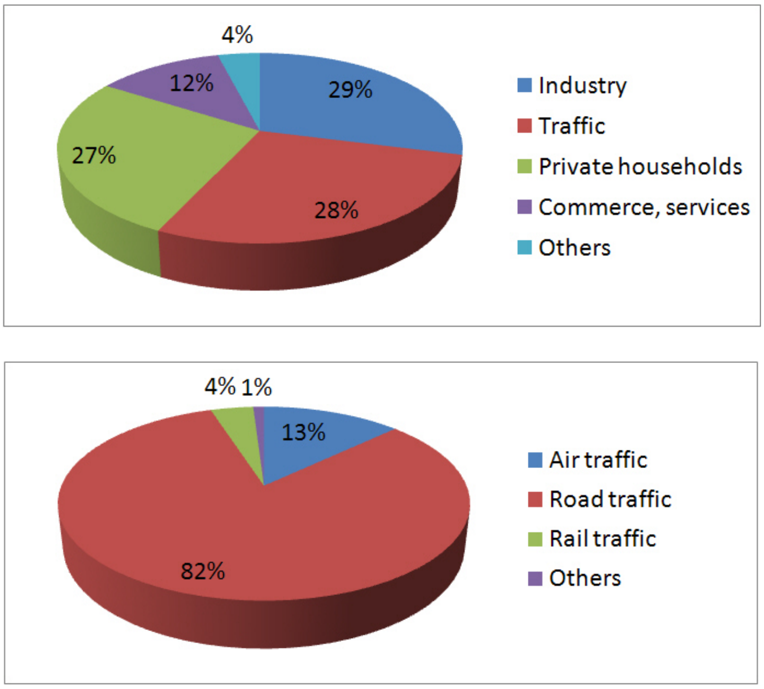


Figure 1: Total and related energy consumption in Germany 2009, /1/, /2/

Obviously, the need for saving energy during production and operation of automobiles can be considered as the first order demand for the future. This fact may be seen as the main driver for innovations in the area of automotive drive technology /1/. Based on the classification of automotive vehicles according to DIN 70010 /3/, different drive technologies can be identified. Motor vehicles ("automobiles") include passenger cars and commercial vehicles (single trucks or combined with trailers or semi-trailers). Motor vehicles represent typical mass products.

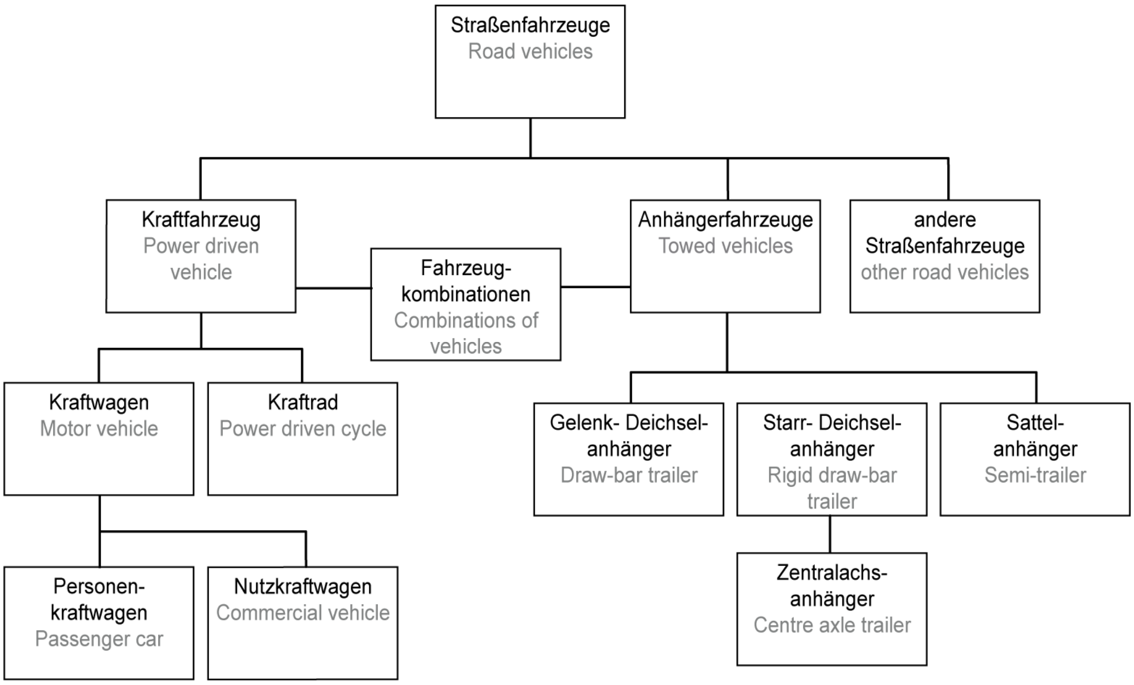


Figure 2: Classification of automotive vehicles acc. to DIN 70010, /3/

The main class "road vehicles" includes motor cycles, passenger cars, commercial and combined vehicles, which are purchased and operated in quite different economic surroundings having immediate influence on the applied technologies, **Table 1.** Different technical solutions and future concepts respectively are in direct competition, which should be considered in the following.

Vehicle type	Character	Purchase and operation	Pricing pressure
Motor cycles	Mainly fun products. Hardly any transport function	Purchasing emotionally guided. Commercial operation in the background	low
Passenger cars	Consumer goods *) Mainly transport function	Purchasing partly rational, partly emotional. Operation not necessarily economically oriented	medium
Commercial vehicles	Investment goods **) Pure transport function	Purchasing strictly rational. Operation purely commercial and profitable	high

*) Exceptions: Taxis, rental cars, company vehicles

**) Exceptions: Motor homes, race trucks, veteran trucks

Table 1: Comparison of the characteristics of road vehicles

2. Automotive drives

For assigning the appropriate drive technology, a distinction between traction ("main") drives and additional drives ("auxiliaries") is determined. Unlike machines working in steady-state modes, due to their non-steady-state operation modes the property efficiency of automotive drives depends on a certain driving cycle, e.g. NEDC (mixed urban cycle ECE 15 and extra urban cycle EUDC), FTP-75 or Artemis, /4/. For the related cycle, an average efficiency $\overline{\eta}$ can be determined, either by testing or simulation. Regarding to the energy flow shown in **Figure 2,** it is obvious to shorten the sequence of respective energy converters, since each conversion causes a more or less distinct loss of energy. E.g. for a fluid power drive (FPD), its efficiency is determined by

$$\overline{\eta}_{FPD} = \overline{\eta}_p \ \overline{\eta}_t \ \overline{\eta}_c \ \overline{\eta}_d \qquad (1)$$

whereby $\overline{\eta}_p, \overline{\eta}_t, \overline{\eta}_c, \overline{\eta}_d$ denote the partial cycle efficiencies of the hydraulic pump, the storage and fluid line, the control device and the power drive itself.

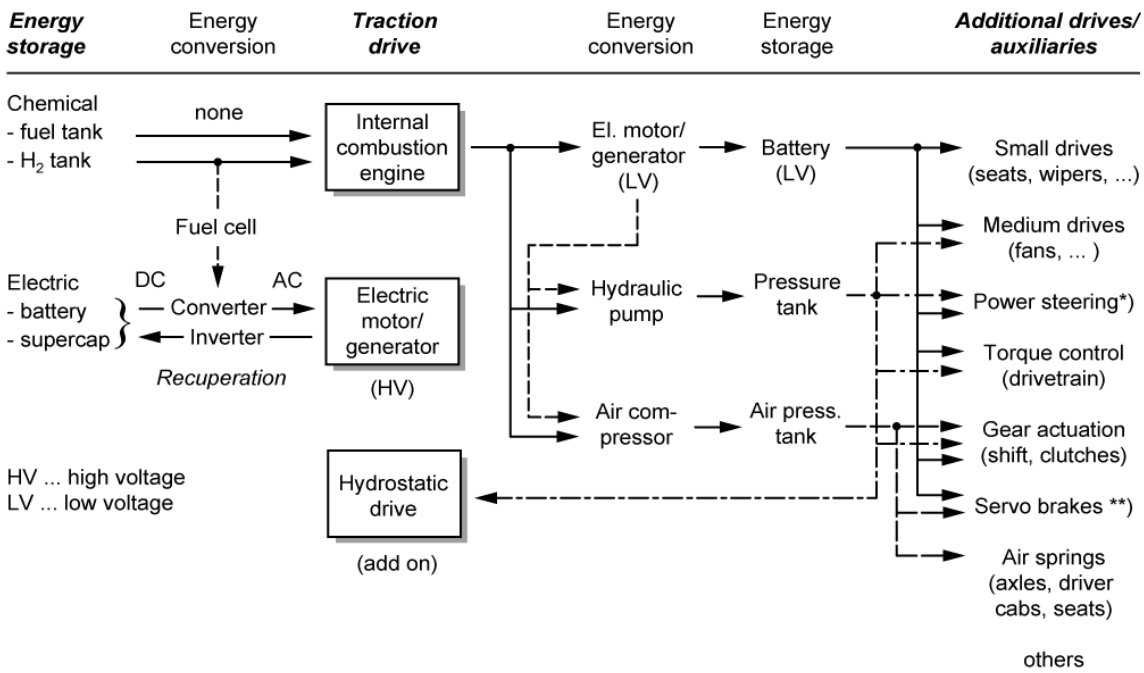


Figure 3: Energy flow in automotive drives

2.1. Traction drives

The internal combustion engines (ICE) represent the conventional main propulsion concept of automobiles, having quite a limited efficiency $\eta_{ICE} \leq 0{,}3$ in the best case. They are usually powered by fossil fuels (petrol, diesel, CNG) or partly by regenerative fuels like methyl ester of rapeseed (RME) or ethanol (E). However, these fuels allow huge densities of energy storage. At the present, the ICE acts as the standard drive not only for vehicle propulsion, but also to supply most of the subsequent auxiliary drives and devices respectively. This leads to quite long actuation sequences having limited levels of efficiencies in total, which will be considered below.

Compared to that, the upcoming electric motor/generators (EMG) offer excellent efficiencies in a wide operational range of $\eta_{EMG} \leq 0{,}95$ and $\eta_{Con} \leq 0{,}95$ of the frequency converters respectively. At present the comparatively limited storage capacity of the battery and supercap constitute the current weak point of the technology, see **Figure 3.** However, once having electrical energy stored aboard, electric drives deal quite economically with energy. Further qualities make them interesting for automotive application:

- The possibility to return energy back to the storage during generator mode, called “recuperation”,
- their principally simple assembly and easy maintenance and
- their low noise levels.

Automotive EMG drives are carried out either as permanent magnet synchronous motors (PSM) or asynchronous induction machines (AIM). Concerning the power density, PSM are slightly favoured, however, they require valuable raw materials for its permanent magnets. In an overall comparison, EMG have got acceptable power densities, which are somewhere between the leading hydrostatic power drives (HPD) and the ICE. This makes it possible to arrange EMG (like HPD) as wheel hub drives.

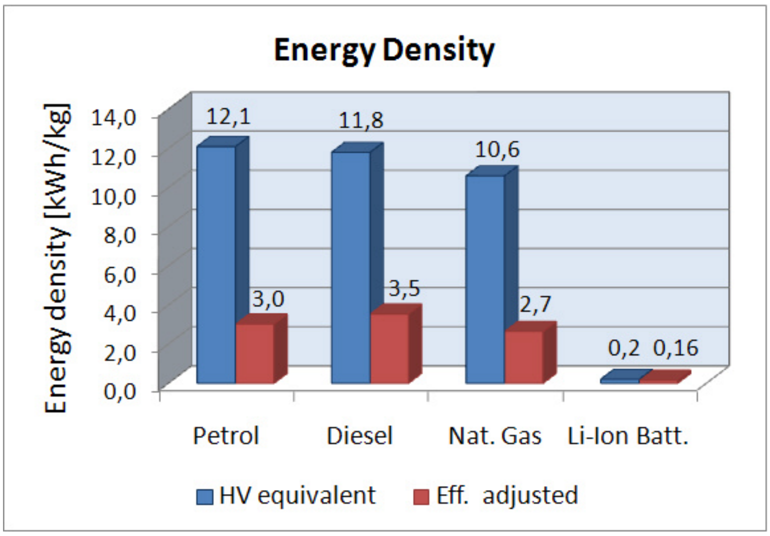


Figure 4: Mass densities of different energy carriers

The HPD benefits from its high power density, see above. Thus, it is well qualified for for in-wheel traction drives which may be considered as a parallel hybrid drive. There is, however, a long chain of energy converters acting, such that the overall efficiency of this drive type is restricted, particularly when it is driven by an ICE. This may be the reason why its application as traction is limited to special vehicles like agricultural tractors, harvesters and military vehicles. For commercial vehicles, used as heavy construction vehicles, special solutions of hybrid add-on hybrid HPD drives are known. E.g. MAN HydroDrive /6/ is an add-on hydrostatic drive at the front axle that can be switched on temporarily, see **Figure 4.**

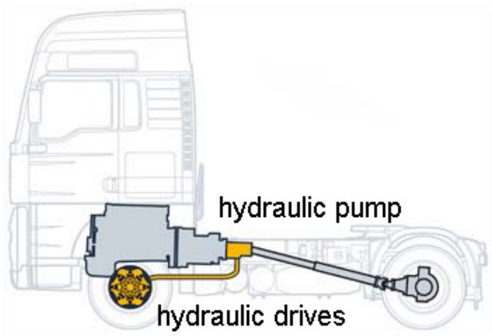


Figure 4: MAN HydroDrive, an add-on all-wheel drive on demand, /6/

2.2. Hybrid traction drives

In order to utilise their specific advantages, more and more different energy sources and/or energy converters (drives) have been combined in one vehicle, known as hybrid traction drives having certain topologies. The power train of a hybrid vehicle is considerably more complex than that of conventional vehicles. Whilst the topology of a conventional vehicle is generally fixed, the arrangement of the power train components for hybrid propulsion systems is a flexible one. The aim is to find those configurations which are optimal for the intended use /5/.

According to requirements, different topologies of hybrid drives have been established:

- Parallel hybrids are characterised by direct mechanical coupling of all the acting drives and the driven wheels. They are mainly applied for passenger cars as well as for commercial vehicles. In the case of power addition via the road, the system is called “Through-the-Road” or “Add-on” hybrid, see Figure 4.
- Series hybrid drives are characterised by a series connection of all energy converters acting in a vehicle. In particular, the ICE is decoupled from the driven wheels by electric or fluid power drives. Typically they are applied to urban busses.
- The power-split hybrid topology, applied to passenger cars, can be considered as a combination of the above mentioned series and parallel hybrid topologies. The mechanical coupling is performed by specific “summation gears”, allowing a continuously variable gear ratio /5/.

Comparing the above mentioned mechanical energy converters (motors), notable distinctions of their performance characteristics can be seen, **Figure 5.** The differences concern the the applicable speed ranges of the respective drives, where the normalised speed $n_N = n / n_{max}$ is plotted. The ICE can reach its best efficiency of $\eta_{ICE} \leq 0,3$ under full load, but this is not required under regular driving conditions. Its usable speed range is quite narrow, such that a variable torque converter (“gear transmission”) is needed to cover the whole velocity span of the automobile.

Both the EMG and the HPD offer nice efficiencies of $\eta_{EMG} \approx \eta_{HPD} \leq 0,95$, however, in opposition to the HPD, the EMG can manage a relatively wide area of operation. This makes it possible to apply the EMG with only one fixed gear ratio for the entire speed rang of the vehicle, **Figure 6.** The HPD requires a variable gear ratio to the driven wheels for an efficient operation. In opposition to railway locomotives, this concept is not yet applied for automotive drives. When applied to automobiles e.g. according to

Figure 4, the HPD supports only the low speed range of the vehicle. Beyond that it is usually not activated.

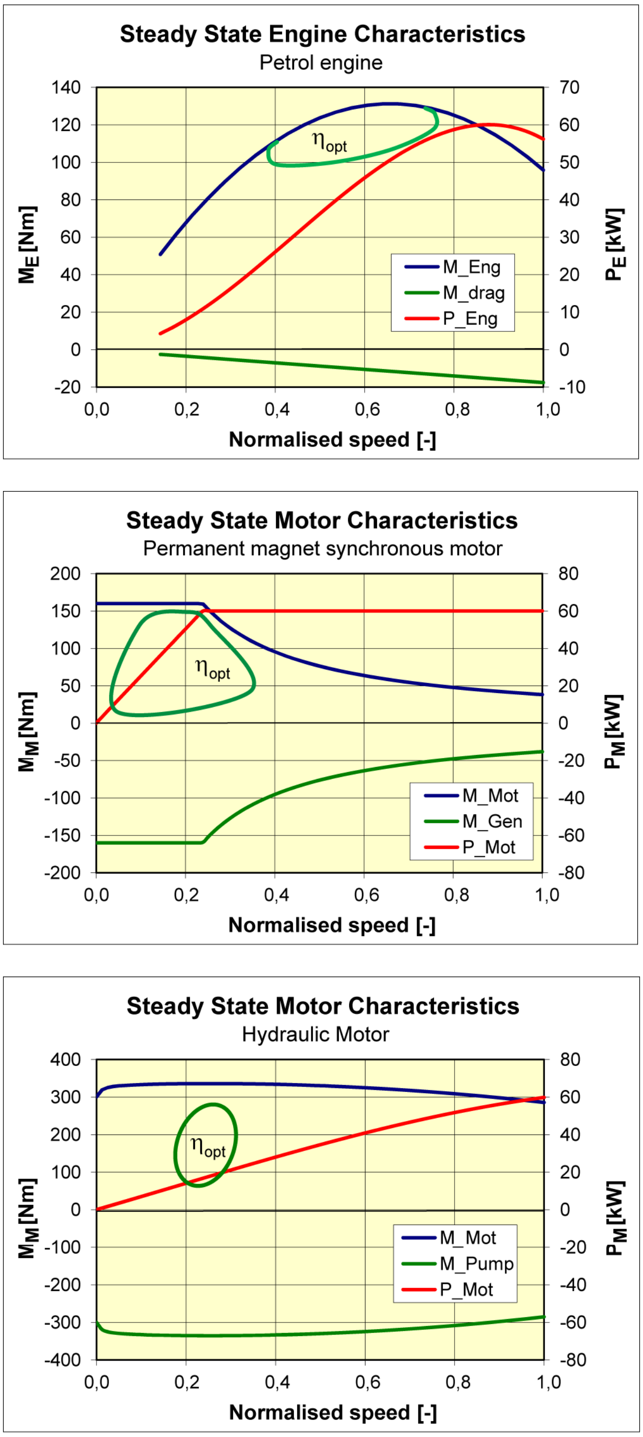


Figure 5: Steady state characteristics of different energy converters

The EMG as well as the HPD are qualified to act as generator and pump respectively, which allow to recuperate energy during braking. While the hydraulic pressure storage is quite limited for automotive energy recuperation, the state of charge (SOC) of the battery or supercap will define the reachable amount of recuperable energy.

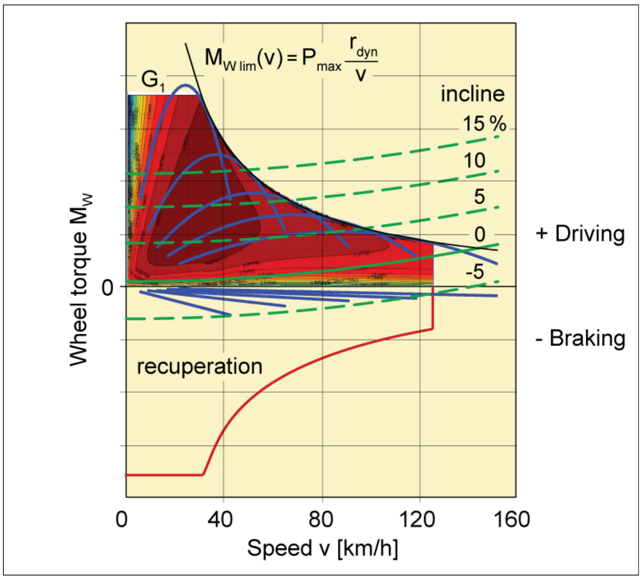


Figure 6: Steady state performance characteristics of ICE – EMG having same maximum power P_{max}

In conclusion, an alternative traction drive concept can be expected to become successful, if

- it allows to run the ICE in a more favourable area of fuel consumption (in the case of a hybrid drive),
- it follows the shortest possible sequence of energy converters (in the case of a pure alternative drive without ICE), particularly if only one conversion of mechanical energy is necessary. This advantage can obviously be fulfilled by electrical traction drives, Figure 3.

2.3. Additional drives and auxiliaries

Apart of the situation in innovative traction drives a distinctive competition between electric and fluid power drives and actuators respectively can be stated. The major drivers for further innovations are:

- Energy saving and reduction of fuel consumption,
- adoption of new functions, particularly in the field of driver assistance systems,
- Improvement of comfort,
- Enhancement of active and integrated vehicle safety,
- Cost reduction of production and maintenance by reducing the number of installed operating media (electric, liquid, gaseous).

Automotive engineering offers a wide range of application for additional drives ("auxiliaries"), which can be classified with respect to their major functions SAF … safety, DAS … driver assistance, COM … comfort, AUX … auxiliary function.

The following table of applications **(Table 2)** is without the intention to be exhaustive.

Application	Function	Type	Actuation
Power steering	Amplification of steering torque, steering assistance, multiple steering, all-wheel steering (AWS)	COM DAS, SAF DAS, SAF	A *)
Servo brakes	Amplification of brake forces, automatic brake system (ABS), vehicle dynamics control (VDS), Variable load brake system	COM SAF, DAS SAF	A
Torque control	Control and distribute driving/drag torque among the driven wheels	DAS, SAF	A, SA
Gear actuators	Actuation of shifted gears, continuously variable transmissions (CVT) and clutches	COM	A
Advanced spring systems	Air spring systems, hydro-pneumatic spring systems	COM, DAS	SA
Small drives	Seat adjustment, air ventilation screen wipers	COM SAF	A
Medium drives	Radiator fans, truck working equipment (crane, dumper etc.)	AUX	A

*) A … active, SA … semi-active

Table 2: Applications of auxiliary drives

The technical implementation of auxiliaries is partially different for passenger cars and commercial vehicles. The distinct technologies are derived from different operational conditions of the vehicle types, rather than by historical reasons.

Some of the above listed applications should be considered a bit more in detail.

2.4. Selected solutions

The ongoing competition between the different drive systems should be considered by means of a few selected examples of application.

2.4.1. Medium sized drives

Nowadays, the electric fan is the standard solution for radiator fans in passenger cars and light commercial vehicles. Due to design space restrictions, heavy busses with rear engines prefer controlled hydro power drives due to their advantageous power densities, **Figure 7.** Heavy commercial trucks still utilise mechanically driven fans with temperature control by viscous clutches. Regarding to medium sized hydro power drives (related to the vehicle's main power source) one can recognise commercial vehicles as the major field of their application.

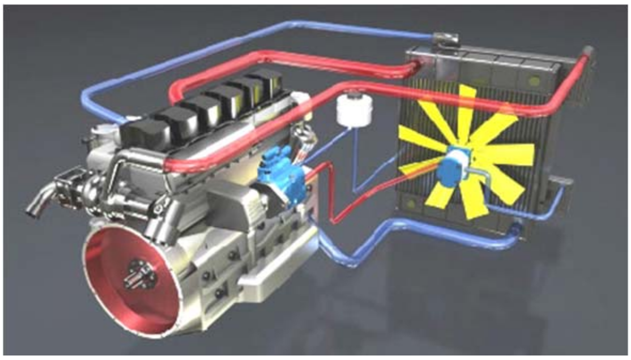


Figure 7: Hydrostatic fan drive, Bosch Rexroth /7/

2.4.2. Power steering

The conventional hydraulic power steering gets more and more displaced by electric power steering. The process of displacement occurs in two steps: Electro-hydraulic power steering allows flexible "on-demand" propulsion of the hydraulic pump. Pure electromechanical steering (cf. **Figure 8**) make is easy to implement and control additional functions like

- Parking assistant,
- Lane keeping assistant,
- Disturbance compensation.

Regarding to the ongoing electrification of automobiles, one can identify the disadvantage of low voltage (12 Volts in passenger cars, 24 Volts in trucks and busses) as the main handicap for electrical auxiliaries. Once having high voltage aboard as supply for hybrid or pure electrical traction drives, a tremendous breakthrough of electric auxiliary drives can be expected.

Figure 8: Electromechanical power steering, Volkswagen /8/

2.4.3. Pneumatic spring systems

Since air spring systems are able to meet high requirements with respect to operational flexibility, comfort and safety, one can expect their extended application in automobiles. This will not only include commercial vehicles but also increasingly concern to passenger cars in the upper price segment. Even in modern commercial vehicles, air springs have been covering a field of applications: axle-chassis springs, springs for driver cabs and seats. Obviously, in combination with the pneumatic brake system, compressed air acts as an unique operation medium for heavy trucks and busses respectively, however, compressed air actuation is "to slow" for high frequencies control. Hence, semi-active implementations are preferred, which offer the control of spring stiffness in order to restrict additional energy. Similar to other automotive applications great attention is spent for any concepts of "power on demand" supply, **Figure 9.**

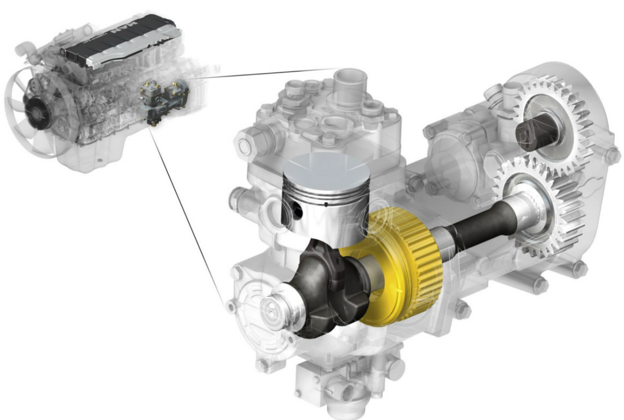


Figure 9: On-demand air compressor, MAN /6/

The particular advantages of pneumatic springs are

- stiffness adaption to variable load,
- niveau regulation,
- less friction,
- isolation of structure-born noise.

The first item “stiffness adaption” aims at a constant natural frequency of the vertical motion of the partial vehicle body, **Figure 10.** Obviously, this requirement leads to a progressive spring rate $c_S = dF/ds$ for arbitrarily loaded vehicle body part with mass m_B. Due to the polytropic change in the suspension bag of the air spring, an almost ideal progression of the spring stiffness can be obtained, **Figure 11.**

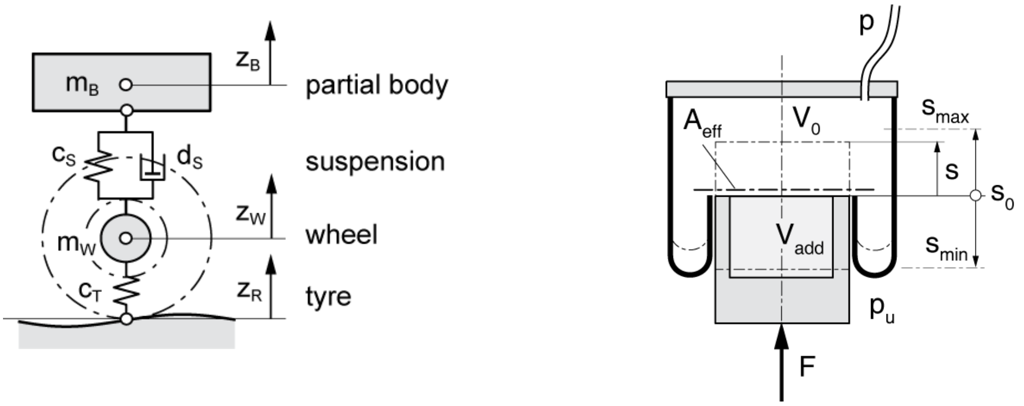


Figure 10: Adaption of the spring stiffness c_S of a suspension air spring, /9/

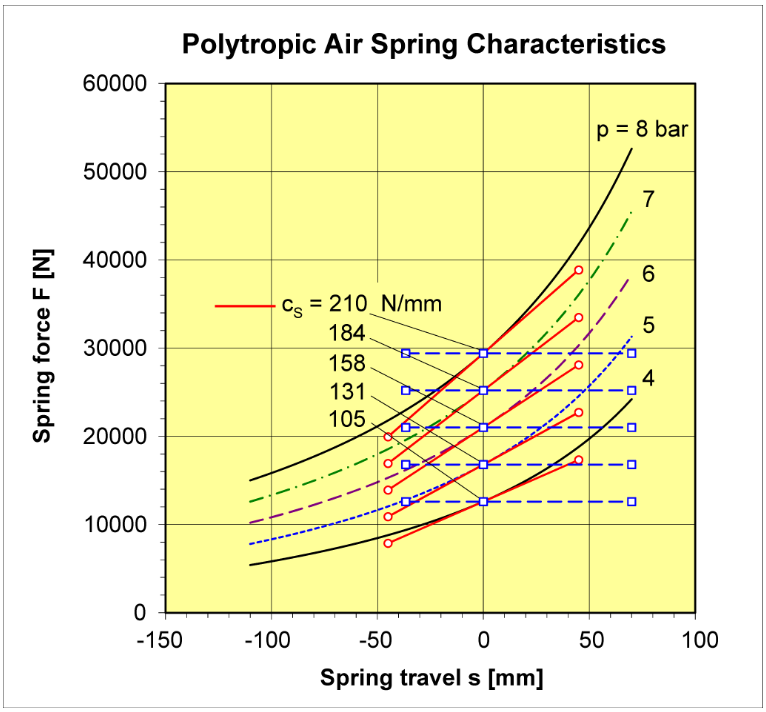
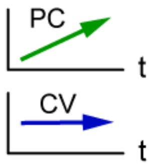
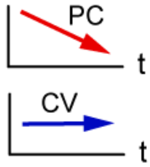


Figure 11: Progressive stiffness characteristics of an air spring, /9/

3. Future trends

Present developments show different future trends in the application of electric and fluid power solutions for passenger cars and commercial vehicles. Table 3 gives a principal view over recent changes in automotive drive technology (in the sense of additional drives). While the electrification of passenger cars is still in progress, alternatives for reliable commercials vehicle solutions hardly make sense, particularly in the field of pneumatic actuation of brakes and springs and also hydraulic working devices. Anyway, the progress of electrification will be stimulated due to the upcoming availability of high voltage aboard.

Application	Function	Electric actuation	Fluid power act.
Power steering	Amplification of steering torque, steering assistance, multiple steering, all-wheel steering (AWS)		
Servo brakes	Amplification of brake forces, automatic brake system (ABS), vehicle dynamics control (VDS), Variable load brake system		
Torque control	Control and distribute driving/drag torque among the driven wheels		
Gear actuators	Actuation of shifted gears, continuously variable transmissions (CVT) and clutches		
Advanced spring systems	Air spring systems, hydro-pneumatic spring systems		
Small drives	Seat adjustment, air ventilation, screen wipers		
Medium drives	Radiation (radiator fans), truck working equipment (crane, dumper etc.)		

PC … passenger cars, CV … commercial vehicles

Table 3: Short/medium term future trends for electric and fluid power applications in automotive engineering

Long term prognoses for automotive drive technologies should take not only technical items, but also expected changes in traffic and transport into account. In order to meet challenges to save resources of the world, particularly fossil energy carriers, a diversification of automobiles can be expected. Instead of today's "all-purpose vehicles" specialised cars will come up, e.g. for intra-urban operation. This will strongly influence the applied drive technologies in the direction to reasonable powered vehicles, where we are a long way from them. Some comfort attributes will then lose their relevance, e.g. light urban vehicles will not necessarily need any power steering device. In that score, passenger cars still have greater potential in terms of efficiency than more rational designed commercial vehicles.

4. Conclusion

Automotive electric and fluid power drives are presently in a distinct competition. Stimulated by the increasing electrification of traction drive trains, a technological change is still in progress, which also influences the additional drives ("auxiliaries"). This process is driven by the worldwide efforts to reduce energy consumption, particularly the consumption of fossil fuels during production and operation of automobiles.

The technical implementation of auxiliaries is partially different for passenger cars and commercial vehicles. The distinct technologies are derived from different operational conditions of the vehicle types, rather than by historical reasons. While the electrification of passenger cars is still in progress, electric alternatives for reliable commercials vehicle solutions hardly make sense, particularly in the field of pneumatic actuation of brakes and springs and also hydraulic working devices. Anyway, once having high voltage aboard, used as supply for hybrid or pure electrical traction drives, a tremendous breakthrough of electric auxiliary drives can be expected.

For automotive fluid power applications, the reconquest of lost terrain will be difficult. It may succeed in those cases of application, where convincing functional alternatives combined with adequate "tank-to-wheel" efficiencies could be offered.

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6. Nomenclature

c_S	spring rate	N/mm
F	air spring force	N
M, M_W	torque, wheel torque	Nm
n_N	normalised rotational speed	---
r_{dyn}	dynamic tyre radius	m
v	driving velocity	km/h
p	pressure	bar
s	spring travel	mm
$\eta, \overline{\eta}$	efficiency, average cycle efficiency	---