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Perspectives for the Future of Automotive Powertrains

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Abstract: Based on recent publications and conferences an overview is compiled for the kind of applied automotive drives in the foreseeable future, especially with regard to the use of renewable, regenerative energies. The contribution begins with a summary of liquid and gaseous fossil and synthetic fuels, including e-fuels and bio-fuels. Then the CO_2 legislations for 2030 are considered and their consequences for combustion engines. Some properties of battery-electric drives, different hybrid drives and fuel-cell drives are discussed. This allows to compare their energy consumption, emissions, driving ranges, charging or tanking facilities. Then a forecast is derived for the used powertrains in 2030. The contribution serves as introduction to the invited session on "Future automotive drives and the role of automatic control".

Keywords: Automotive powertrains, synthetic fuels, electric vehicles, hybrid vehicles, fuel-cell vehicles, CO_2 emissions, comparison.

1. INTRODUCTION

The slow decrease of worldwide CO_2 and other greenhouse emissions require that also the traffic emissions have to be reduced drastically. The CO_2 legislation determines for the fleet of passenger cars from one manufacturer for 2020/21 95 g/km (EU), 105 g/km (JP), ~ 140 g/km (US). For 2025 81 g/km for EU are required and for 2030 a further step of -37,5 % to 59 g/km has to be fulfilled, which corresponds to a fuel consumption of about 2.5 l/100km for vehicle fleets with combustion engines (ICE). As this is probably not reachable with gasoline or diesel engines alone, alternative powertrains and fuels are necessary.

2. PRESENT AND FUTURE FUELS FOR COMBUSTION-ENGINES

2.1 Conventional Fuels

Liquid fuels have the advantage of a large energy density of about 11 – 12 kWh/kg (gasoline: 11.1 – 11.6 kWh/kg; diesel: 11.9 kWh/kg). Except fossil crude oil refined gasoline and diesel fuel, bio-ethanol from biomass and rapeseed based diesel-fuel are already used totally or as 7 % – 10 % mixture with fossil fuels. Liquefied Petroleum (LPG) in the form of propane and butane with a tank pressure of 20 bar – 30 bar as a by-product from refineries is also used to a smaller extent.

Gaseous fuels have the disadvantage of a lower energy density of about 2.5 kWh/kg and are in use as compressed natural gas (CNG) or methane with a tank pressure of 20 bar – 30 bar.

2.2 Synthetic Fuels

Synthetic fuels derived from renewable electricity (solar,

wind) are called e-fuels. Fuels from biomass are called bio bio-fuels. A first step for e-fuels is a power-to-gas (PtG) process where hydrogen (H_2) and oxygen (O_2) from an extrolysis of water (H_2O) is produced. The hydrogen can be used directly for fuel cells or it can be mixed with natural gas in pipelines (up to 5 – 10 %). A big advantage is these gases can be stored in pipelines or in underground caverns. Together with CO_2 (e.g. from biogas plants) methane (CH_4) can be produced, which can be directly used for combustion engines.

A *power-to liquid (PtL) process* requires the generation of synthesis gas (syngas) based on H_2, CO, and CO_2 as an intermediate to generate (liquid) methanol (CH_3OH). This is then the feedstock to produce classical fuels via the *methanol to-gasoline process* or to produce oxymethylene ether (OME) and dimethyl ether (DME).

An alternative is to use a syngas from H_2 and CO_2 for a Fischer-Tropsch synthesis to generate a hydro carbon mix into high quality fuels.

Methanol can also be used to generate oxymethylene ether (OME) by oxidation to formaldehyde. OME allows a combustion in diesel-engines with very low NOx and particle emissions. The required CO2 may be obtained from biogas, industrial processes (power stations, cement factories) or by direct air capture (filters).

However, the efficiency for the generation of synthetic liquid fuels is with 6 % – 12 % very low, Ausfelder, Wagemann (2020).

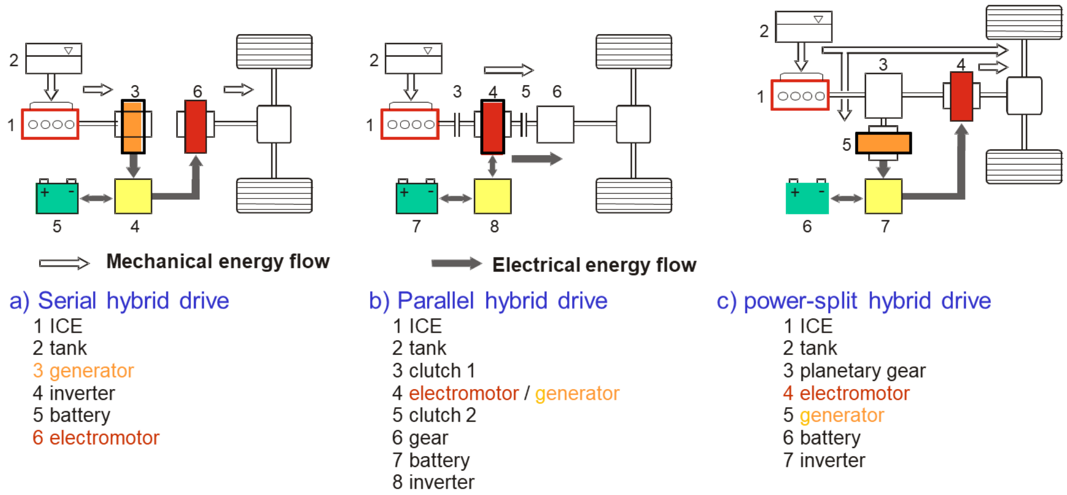

Fig. 3.1. Basic structures of hybrid electric drives according to the energy flow.

Another category of synthetic fuels are bio-fuels. A first generation is bio-ethanol (gasoline) or rapeseed (diesel) which are in competition to food products, however. The second generation is biomass-to-liquid (BtL) and uses biological waste, straw, and sewage to generate bio-ethanol via cellulose. Also biomaterial from wood or stalks can be processed via pyrolysis (550° C) and *hydrogenation* with H_2 to bio-diesel.

3. POWERTRAINS

3.1 Internal Combustion Engines (ICE)

Compared to 2010 combustion engines have improved fuel consumption of about -30 % for gasoline engines through higher pressure fuel injection, turbocharging, variable valve timing, downsizing, etc. and of about -35 % for diesel engines by high pressure multiple fuel injection, variable geometry turbo-charging, downsizing, etc. Also the engine control is much more sophisticated with nonlinear model-based methods and fine-tuned calibrated, Guzella, Onder (2010), Isermann (2014). Further improvements with regard to CO_2 reduction can be expected but with slower improvement steps.

3.2 Battery-Electric Vehicles (BEV)

The presently on the market available battery-electric vehicles have powers between about 40 kW and 500 kW, batteries with a capacity of 30 kWh to 100 kWh, and allow driving ranges of 250 km to 600 km under ideal conditions. New designs have a chassis-frame with battery-modules, safety-protection and liquid cooling. The preferred electrical motors are either asynchronous (AM) or permanently excited synchronous motors (PMSM). The lithium-ion batteries have voltages from 420 V to 800 V, ZVEI (2013). The energy density is presently about 140 Wh/kg and may be increased until 240 Wh/kg.

An advantage is that BEV are locally emission free. However, the manufacturing of Li-Ion batteries generates about 60 kg – 200 kg CO_2/kWh. The driving range is relatively small, especially in the winter period, and the charging times are long. However, high-power charging stations reduce the charging times. The well-to-wheel efficiency of BEV from renewable electrical energy is about $\eta_{wtw} \approx 57$ % - 63 %, (VDI/VDE (2019).

3.3 Hybrid Drive Vehicles (HEV)

The combination of combustion engines with electrical drives has many advantages. It is possible to drive 20 km to 30 km without emissions (e.g. in cities) and they do not need charging stations. For plug-in HEV charging at home saves CO_2. The driving range (DR) is similar to ICE and internal heating is provided by the waste-heat of the ICE.

The classification of different HEV is as follows:

(1) Degree of hybrid is hybridisation
- Micro Hybrid (start-stop, belt-starter-generator)
- Mild-Hybrid (8 kW – 20 kW, 48V)
- Full-Hybrid (20 kW – 120 kW, 200V – 400 V, DR: ~10 km)
- Plug- in Hybrid (20 kW– 120 kW, large battery, DR: ~ 30 km – 100 km

(2) Energy-flow, see Fig. 3.1
- Serial energy-flow
- Parallel energy-flow
- Power-split energy-flow

(3) Topology
- Arrangement of the electrical motor (P0 to P4 for parallel HEV)

The degree of electrification increases from micro to plug-in hybrid. These hybrid electrical vehicles need a control-system of the ICE, the battery, the EM, transmission, acceleration, and braking with a higher management system. An overall electronic management has to optimise the operation of the engine and electromotor torque, battery charging and discharging, regenerative braking with the generator or friction brakes, see Fig 3.2. Herewith the state-of-charge of the battery is part of the control and may be optimized for pre-defined or actual driving cycles, Kunkel (2015).

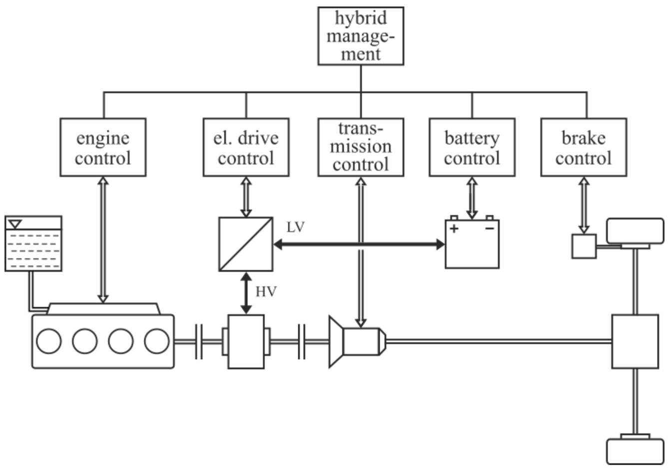

Fig. 3.2. Overall control architecture of a parallel hybrid drive P2

3.4 Fuel-Cell Electric vehicles (FCEV)

The fuel-cell consists e.g. of an anode, a polymer electrolyte membrane, and a cathode. At the cathode a catalyst causes hydrogen (H_2) to undergo an oxidation generating hydrogen ions and electrons. The ions penetrate the electrolyte to the cathode and the electrons flow through an external circuit to the cathode and generate electrical energy. At the cathode another catalyst causes ions, electrons, and oxygen (O_2) from the supplied air to form water (H_2O). The generated voltage of one cell is about 1V.

The hydrogen is for vehicles stored in a tank with about 700 bar. A stack of many fuel-cell elements is provided with pressure-reduced H_2 and pressurized air. A liquid cooling circuit keeps the charged air and the stack in certain temperature limits.

The big advantage of FCEV is that they generate no emissions if the hydrogen is produced by electrolysis from renewable electrical energy. Tanking from H_2-stations (900 bar) is possible within some minutes. However, up to now only a few H_2-filling stations do exist. Driving ranges are with 400 km – 800 km acceptable. The waste-heat from the fuel-cell allows internal heating. The well-to-wheel efficiency for FCEV is $\eta_{wtw} \approx 24$ % - 29 % and thus only about half of BEV.

With the assumption of using only renewable electrical energy the efficiency of BEV is with about 60 % better compared to FCEV with about 27 %.

4. COMPARISON OF DIFFERENT POWERTRAINS

For a comparison of the CO_2 emissions of the considered powertrains different evaluations are possible, such as

(1) Tank-toWheel (TtW): only driving
(2) Well-to-Wheel (WtW): fuel generation + TtW
(3) Cradle-to-Wheel (CtW): car production + CtW
(4) Cradle-to-Grave (CtG): CtW + disposal

Fig. 4.1 shows a comparison of the CO_2 emissions for different powertrains with different fuel and electrical networks for the case of cradle-to-grave (CtG). The total mileage of compact cars is assumed to 200,000 km.

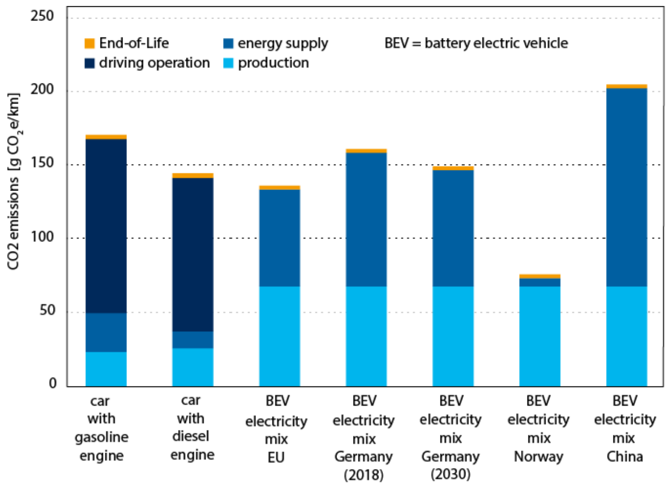

Fig. 4.1. CO_2 emissions according to cradle-to-grave evaluation of combustion engines and electrical powertrains of a compact car for different electricity generation networks, Clauss et al (2018).

Diesel engines have compared to gasoline engines an advantage of about 25 g CO_2/km. For BEV the CO_2 emissions of the battery production have a significant share. An advantage for the CO_2 emissions of BEV over gasoline driven vehicles is only obtained after about one to three years driving for the European electricity generation mix.

Hence, BEV are for the electrical energy generation in Europe after 200,000 km only marginal better than vehicles with diesel-engines. Best values are obtained for BEV with only renewable electrical energy (as e.g. in Norway). In this case FCEV are better if they have smaller capacity Li-Ion batteries. The CO_2 emissions for recycling is assumed to be similar for all vehicles, but may be higher for BEV.

An estimation of the -well-to-wheel efficiencies of different powertrains which take into account also synthetic fuels for ICE is given in Ausfelder, Wagemann (2020). Some results are summarized in Table 4.1 for the case that only renewable electrical energy is used as primary energy, which is set to 100 %. Hence, BEV have the best efficiency, followed by FCEV, where the water electrolysis is assumed with 70 %

and the fuel cell with 60 % efficiency. However, the use of synthetic e-fuels has with 4 % - 12 % a very low efficiency. Here following efficiencies have been assumed: water electrolysis 70 %, methanol synthesis 70 %, and ICE 30 %. Hence, the multi-step process chains are responsible for this low total efficiency. This means that very large powers of renewable electrical energy are required for the use of synthetic e-fuels with combustion engines.

Table 4.1 Comparison of efficiencies (Well-to-Wheel) for the use of renewable electrical energy with $\eta_{el,ren} = 100$ % according to Ausfelder, Wagemann (2020). PtL: Power to Liquid. Heat integration for process steps not considered.

BEV	FCEV	ICE (PtL, gasoline	ICE (PtL, OME, diesel)	ICE (syn. gas)
62-86 %	26-36 %	9-12 %	4-10%	8-11%

5. CONCLUSIONS

Especially with regard to the emission gas legislation it can be assumed that for passenger cars and light-duty vehicles electrical (BEV) and hybrid vehicles (HEV, PHEV) are ordered in short time. Fuel cell vehicles (FCEV) will be accepted only if more hydrogen filling stations are available. It can also be expected that combustion engines will be using mixtures of gasoline and diesel fuels with bio- and e-fuels. The industry presently assumes that in 2030 the distribution of BEV : HEV : ICE is 30 % : 40 % : 30 %. This means that 70 % of passenger cars have electro motors and 70 % combustion engines, Schaeffler (2018).

For heavy duty vehicles, busses, and trains it is expected that diesel combustion engines will stay as main powertrains and in long-term fuel-cell drives may increase. However, the development of e-mobility will strongly depend on the progress of renewable electrical energy generation.

Sophisticated automatic control methods are required for the management of hybrid or electrical driven vehicles. A great challenge is also the optimal control of fuel-cells with regard to an optimal management of the air path with humidification, the hydrogen path, and the cooling system.

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