Influence of different electrified vehicle concepts and driving cycles on the energetic efficiency of passenger cars

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***Abstract*-The design of electrified power trains for use in vehicle propulsion systems is a very difficult topic and thus often discussed in research worldwide. Very much effort has been undertaken to obtain simulation and design tools for entire vehicle development. The designed vehicle has to meet multi-objective criterion where to find an optimum for a specific usage. Facing decreasing resources of fossil energy and increasing demand of individual transportation worldwide passenger car designers have to offer new solutions resulting in higher efficiency power trains and perhaps new power train topologies to serve future demands of their customers. One first step towards future design tools is the detailed analyses of the influences of vehicle specific parameters on the efficiency and thus on the energy consumption of the resulting vehicle concept. This work deals with the analyses of different driving cycles representing the usage of the car and different power train topologies which are in the discussion of substituting state of the art power trains with internal combustion engine. The objective of the presented work is also to examine the influence of specific vehicle design parameters and the vehicle usage on the overall efficiency and moreover the distribution of the propulsion energy. The results show that there is no straightforward answer to the best power train. The right choice depends very strong on the prospected usage of the vehicle. Nevertheless the obtained analyses results can serve as a very important input on the design of power trains because they give a good overview on the energy demand of vehicles.**

I. Introduction

In the last few years the discussion about climate change and global warming has gained wide public interest. It is common sense that greenhouse gases and as one representative CO2 are most responsible for the climate change. Therefore a lot of effort has been undertaken to force CO2-neutral technologies in all sectors of society.

The second issue is, especially for Germany, the limited resources of energy resulting in the dependency of energy imports from foreign countries [1]. One goal is therefore the reduction of energy consumption as a whole.

Figure 1 shows the entire energy consumption of Germany since 1990. One can see that the total energy consumption remains on a fairly constant level with a light decrease in the last years. But the more interesting thing is that the amount of energy consumed in the transportation sector has increased from 25% to about 30% [1]. Besides this fact it has to be mentioned that the transportation sector is responsible for about 20% of the total CO2 emissions in Germany and is thus on the second order behind the energy industry.

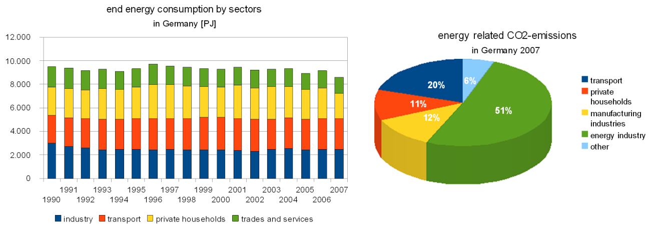

Figure 1. Energy consumption and CO2 emissions in Germany [2]

These figures show the importance of a significant reduction in both energy consumption and CO2 emissions in the transportation sector and thus a way towards sustainable mobility. An often discussed solution is the electrification and hybridisation of vehicles to solve the issues of an increasing demand of individual mobility.

The presented work analyses selected electrified vehicle concepts with respect to their potential in fuel economy. Furthermore an analyses of the distribution of the propulsion energy is included to show influences of vehicle parameters and usage. To get a comparable result the utilisation factor for the energy provision has been considered as well.

II. Vehicle Concepts

As mentioned above this work deals with the comparison of electrified vehicle propulsion concepts. Figure 2 gives an overview of the discussed concepts. The basis of the comparison is represented by a conventional passenger car with internal combustion engine.

Based upon this the second concept is a state of the art parallel hybrid electric vehicle (PHEV). As two new and more innovative concepts a range-extended electric vehicle (REV) and a battery electric vehicle (BEV) are also in the scope of this work.

To show the influence of the propulsion system on the energy consumption it is necessary to demand comparable conditions to the entire vehicle. This is ensured by the constant vehicle parameters shown in table 1. These parameters essentially describe the losses that are related to

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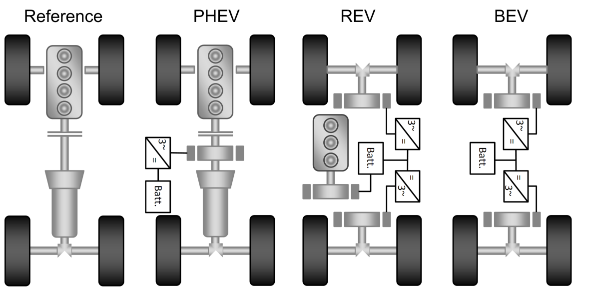


Figure 2. Overview of the investigated vehicle concepts

the chassis and the contact between the wheels and the road. A more detailed inspection of the relations is given in the next section where the driving resistances are discussed.

TABLE I
VEHICLE CHASSIS PARAMETERS

parameter	value	unit
A	2.17	m^2
c_w	0.32	-
μ_r	0.01	-
m_{ref}	1240	kg

The values of the regarded parameters are derived from a typical compact class car which represents the most utilized class of vehicles in Germany [3]. For the comparison it is assumed that these values remain constant. Only the vehicle mass is adapted according to the additional mass of the propulsion system components. This approach eliminates the influence of the chassis so only the powertrain can be examined.

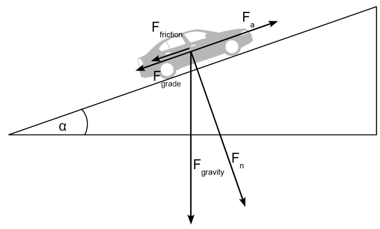
TABLE 2
PROPULSION SYSTEM SPECIFIC PARAMETERS

	reference	PHEV	REV	BEV
m_{total} [kg]	1240	1340	1420	1420
P_{prop} [kW]	66	66+17	2x35/30	2x35

The vehicle concept specific values and constraints are shown in table 2. The additional mass of the PHEV is related to the mass of the additional components, i.e. the electric machine with power electronics and the energy storage. The REV has the range extender module and the electric power train that results in a rather high additional mass. The maximum power that can be delivered by the range extender is 30kW resulting in a maximum continuous speed of 130km/h that can be driven without taking power of the electric storage. For the EV the benefit of the absence of the range extender module is compensated by a greater energy storage system.

III. DRIVING RESISTANCES

For a detailed analyses of the vehicle propulsion the knowledge about the forces that are acting on the vehicle are of major importance. Most of all the power train has to work against several resistances which are explained in the following chapter. Figure 3 illustrates these forces the vehicle is opposed.



The first force that has to be mentioned is the friction force $F_{friction}$ that consists of two separate components. On the one hand there is the friction caused by the contact between the road and the tires. It can be expressed by

$$F_{roll} = \mu_r \cdot F_N \quad (1)$$

where μ_r is the friction coefficient and F_N is the component of the gravity force which is normal to the road and can be calculated by

$$F_N = m \cdot g \cdot \cos(\alpha) \quad (2)$$

On the other hand there is the friction that is caused by the movement of the vehicle through the medium that surrounds it which is air in most cases. This component of the friction is given by

$$F_{air} = \frac{1}{2} \cdot c_w \cdot A \cdot \rho_{air} \cdot v^2 \quad (3)$$

When the vehicle doesn't move on a plane road an additional force

$$F_{grade} = m \cdot g \cdot \sin(\alpha) \quad (4)$$

is acting on the vehicle. And last but not least a force for accelerating the vehicle has to be applied by the power train. It is depending on the vehicle mass and the driver's desired acceleration and can be calculated by

$$F_a = m \cdot a (1 + \lambda) \quad (5)$$

where λ is the rotational inertia coefficient. All these forces are present during vehicle operation. The resulting force is the sum of all the single components described above.

$$F_{res} = F_a + F_{grade} + F_{air} + F_{roll} \quad (6)$$

It has to be mentioned that in the case of acceleration all components of the resulting force have the same direction and have to be applied by the propulsion system. In the other case of deceleration the resistances are opposed to the acceleration force of the power train and thus limiting the amount of possible energy recovery during breaking.

IV. ENERGETIC EFFICIENCY/UTILISATION FACTOR

Efficiency plays an important role regarding technical systems, especially when comparing several technologies. In this case the efficiency can serve as a major characteristic feature. Great attention has be taken into account when defining the efficiency of a system.

An often used definition for the efficiency is the ratio of the effective power and the supplied power.

$$\eta(t) = \frac{P_{eff}(t)}{P_{supply}(t)} \tag{7}$$

The drawback with this type of definition is that it only represents an instantaneous value. An energetic comparison however is only reasonable if an integrated value is regarded. Therefore the utilisation factor is defined as the ratio of the effective energy and the supplied energy.

$$\xi = \frac{E_{eff}}{E_{supply}} \tag{8}$$

In other words this is a measure for the amount of energy that is of use at the output of the system. A major consequence of this type of integral definition is that the utilisation factor can only be specified when evaluated over an entire driving cycle. The dependency between the two definitions can be given by the integral expression.

$$\xi = \frac{\int_0^T \eta(t) \cdot P_{supply}(t)\, dt}{\int_0^T P_{supply}(t)\, dt} \tag{9}$$

One can see that for a constant η(t) the efficiency has the same value than the utilisation factor. But unfortunately the efficiency varies with the varying operation points increasing the importance of realistic driving cycles for evaluation. Within this work three often used driving cycles are evaluated. First of all is the New European Driving Cycle (NEDC) which is mandatory for the determination of fuel consumption and emissions of passenger cars in the European Union [4]. The counterpart for the United States exists in the form of the Federal Test Procedure (FTP).

These two statutory driving cycles often lack in a realistic representation of real driving situations. That's especially true for the NEDC which is a very artificial driving cycle. Therefore many more realistic cycles have been proposed by several institutions. One of those is the driving cycle that has been developed by the European research project called ARTEMIS [5].

V. Results

In the chapters above the prerequisites for an energetic evaluation have been described. Based on this a more exhausting investigation can be made. The first step of the analysis deals with the energy flow in the vehicle itself. Figure 4 shows a more detailed representation of the vehicle based on the system approach discussed earlier. The figure also considers the amount of energy that can be recovered by regenerative breaking.

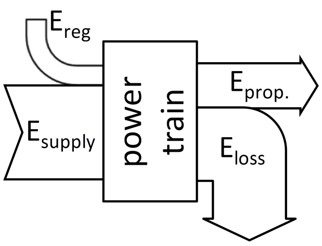


Figure 4. power train energy flow

By evaluating the driving resistances over a given driving cycle a sense for the theoretical potential of breaking energy recovery can be achieved. In the same way we can calculate the amount of energy that is needed for vehicle propulsion. As a characteristic value for the vehicle concept the ratio of these two values can be considered.

Figure 5 shows the results for the three different flavours of electrified vehicle concepts. The REV and BEV are not distinguished because they are based on the same electric power train and additionally have the same vehicle parameters as mentioned in the overview in chapter 2.

The relatively small amount of regenerative breaking in the PHEV is due to the small electric machine in relation to the internal combustion engine. Furthermore the maximum deceleration in the PHEV configuration is assumed to be limited to 0.5 m/s² due to vehicle dynamic reasons.

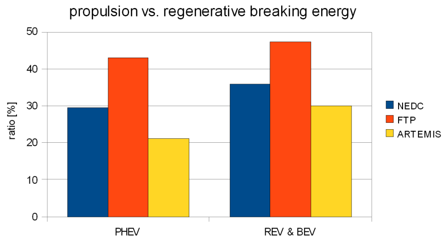


Figure 5. ratio of regenerative braking and propulsion energy

It can be stated that for a theoretical potential of 30 to over 40% compared to the propulsion energy the regenerative breaking has a major influence on the entire energy consumption of the vehicle. This is especially important for the REV and BEV configuration.

As a further result the utilisation factors of the regarded vehicle concepts can be examined in more detail. Therefore the amount of energy that is consumed by the vehicle was retrieved using an entire vehicle simulation described in [7] that was extended to handle REV and BEV. The results are presented in figure 6.

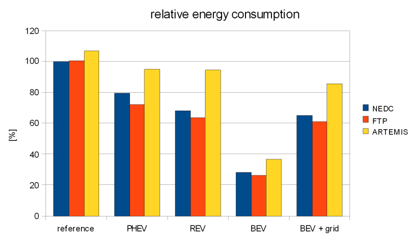


Figure 6. relative energy consumption of regarded vehicle concepts

To get a comparable result a common value has to be taken into account in this approach. This is especially important for the BEV because it doesn't have a fuel consumption that can be measured. Therefore the consumptions of the fuel powered vehicles are converted to the equivalent amount of energy by the fuel values given in table 3. The values are normalized to the consumption of the conventional vehicle driving the NEDC. This way the influence of the driving cycle becomes more obvious.

TABLE 3
ENERGETIC VALUES OF ENERGY PROVISION [3]

	gasoline	diesel	electricity
ξ energy provision	0.88	0.88	0.38
Fuel value [kWh/l]	8.6	9.9	-

To get a comparable result the provision of energy has to be considered as well. A detailed analyses is out of the scope of this article. Thus constant values for the utilisation factor are assumed based on [6].

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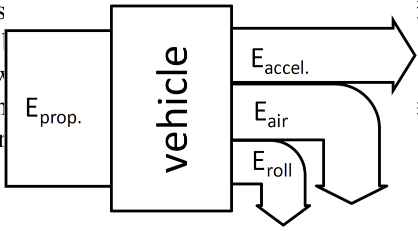

Figure 7. distribution of the propulsion energy

The result of this examination proves the result stated above where the proportion of regenerative braking energy and propulsion energy is encountered as a characteristic value of a given vehicle concept. This becomes obvious regarding figure 8. Only the amount of energy that has been distributed for acceleration can serve as a potential for regenerative breaking. The other two components are pure losses by the mean of energetic considerations.

VI. CONCLUSION

As the presented results show electrification is an effective instrument for decreasing the energy consumption of vehicle concepts. Since the hybridisation of vehicles offers more degrees of freedom to the whole system it cannot be stated that one flavour of electrified power train is better than another one. On the one hand it depends on the usage of the vehicle. For long distance exurban use it doesn't make much energetic sense to drive a hybrid electric car because of the additional mass that has to be carried.

On the other hand hybridisation offers the opportunity of merging the benefits of different technologies. That becomes especially obvious regarding the BEV. To achieve an acceptable range of operation large electric storage devices have to be used increasing the weight and in consequence the cost of the vehicle not mentioning the limited resources needed for the energy storage. In this case it might be reasonable to make use of a range extender like in the REV discussed above. Although there is a double energy conversion from tank to wheel it can be energetic competitive with state of the art PHEV offering the opportunity to decrease the stored electric energy. Despite of these facts BEVs are in the discussion of leveling grid loads due to regenerative power generation and times with low energy demand. Investigations in this field of research can be found

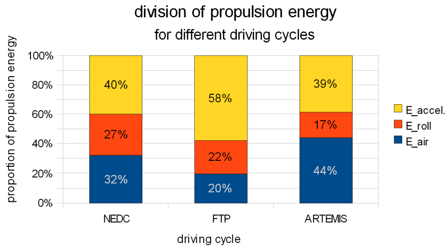

Figure 8. energy distribution of reference vehicle

in [8] and [9]. Unless this is forced by other reasons it is doubtful whether this makes overall sense [10].

It can be concluded that more effort has to be done to get an optimum result for a given requirement. However, the presented work can serve as a method for the energetic comparison of a given vehicle concept and moreover, with the gained energetic overview, as input values of new tools for the design of vehicle propulsion systems.

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