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Impact of lightweight design on energy consumption and cost effectiveness of alternative powertrain concepts

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Abstract

This study analyses the impact of weight reduction on the energy consumption and related costs for different advanced electric powertrain concepts. Several hybrid architectures (parallel/serial hybrid, with/without external charging) and a full battery electric vehicle are assessed and compared to a conventional car with internal combustion engine. To evaluate the effects of lightweight on fuel economy a large set of parameter variations was performed applying a vehicle simulation tool. The simulation results were integrated in a total cost of ownership model to analyze the implications on the cost efficiency from a user perspective. The assessment shows that the potential to reduce the energy consumption through lightweight decreases with increasing degree of electrification. As a consequence the savings of operating costs in EUR/km per kilogram saved are smaller for EVs than for ICEs. However, the conclusion changes if indirect effects of lightweight (e.g. potential resizing of the battery capacity) are taken into account.

The outcome of this assessment will help decision makers in the automotive industry to gain a better understanding to which extent investments in weight reductions are effective for future powertrains and which additional effect should be considered.

Keywords: Hybrid electric vehicle, battery electric vehicle, energy consumption, life cycle cost, lightweight

1 Introduction

The reduction of energy consumption and greenhouse gas emissions is one of the greatest challenges for the transport sector over the next decades. This is especially true for the automotive industry, which currently faces ambitious CO_2 targets set by politics as well as a growing awareness of fuel economy from the customer side. In this context lightweight design is an important lever to increase the energy efficiency of a car. This topic gains additional relevance for hybrid and electric vehicles which have to carry a heavy-weight traction battery on board.

A rule of thumb says, a gasoline car saves about 0.3 liter fuel per 100 km by reducing its mass by 100 kg. However, the situation is becoming more complex, if electrified powertrains are taken into account, as they enable the recuperation of kinetic energy, which decreases the weight influence. A systematic answer to the question *“how much should a (rational) user be willing to pay for 1 kg of weight reduction”* depends on a variety of factors, such as vehicle size, driving characteristics, expected holding duration and especially the selected powertrain technology. The objective of this paper is accordingly a holistic assessment of the impact of lightweight design on energy consumption and total cost of ownership for different powertrain concepts.

2 Methodology

The paper follows a four-step approach:

- In the first step a wide set of vehicle simulations are performed to examine the energy consumption and its sensitivity to a change in vehicle mass for several drivetrain architectures. For this purpose the DLR proprietary *Modelica* library *Alternative Vehicles* is applied, which is introduced in paragraph 2.1.
- Based on the outcome of the vehicle simulations the impact of lightweight design on the cost effectiveness is analyzed from user perspective. The underlying total cost of ownership model and basic assumption for the calculation are described in paragraph 2.2.
- The results of this analysis are presented in chapter 3. Furthermore, side effects of a weight reduction are discussed (e.g. improved vehicle dynamics, increase in electric driving range)
- The paper concludes with an outline of key implications from the analysis and an outlook on further research needs in chapter 4.

The assessment covers a wide range of powertrain technologies including conventional cars with internal combustion engines (ICE), hybrid electric vehicles as well as full battery electric vehicles (BEV). In the hybrid propulsion category three different topologies are considered: A parallel hybrid electric vehicle (HEV) without external charging, a plug-in version (PHEV) with larger e-motor and battery size, and an extended range electric vehicle (EREV) which is designed as series hybrid with a combustion engine for on-board electricity generation.

The setup of the ICE reference vehicle is based on a market analysis to reflect the configuration, weight, retail price and fuel consumption of an average midsize passenger car sold in Germany (according to KBA and ADAC data [1]). The basic parameters of the different powertrain concepts are summarized in Table 1.

2.1 Vehicle simulation

To determine the energy consumption of the selected powertrain concepts the DLR *Modelica* library *AlternativeVehicles* is applied [2]. The software contains parameterized drivetrain components (e.g. electric drives, transmissions, batteries) to build up and model different powertrain architectures. The simulation facilitates the analysis of the dynamic system behavior while driving. The New European Driving Cycle (NEDC) has been used as standardized driving cycle to compare the energy efficiency of the powertrain concepts under varying conditions. As the impact of vehicle mass differs for urban and highway driving the simulations results have been evaluated separately for the urban and extra-urban section of the NEDC.

The simulation models are composed of the following major modules (see Figure 1):

- The internal combustion engine module uses an engine characteristics map to

Table 1: Definition of vehicle parameters

Parameter	**Unit**	**ICE**	**HEV**	**PHEV**	**EREV**	**BEV**
Vehicle architecture		Gasoline engine, direct ignition 2-wheel drive (identical for all), 6-speed automatic transmission	Parallel hybrid with 2 clutches, 6-speed automatic transmission with torque-adding electric machine	Parallel hybrid with 2 clutches, 6-speed automatic transmission with torque-adding electric machine external charge unit	Series hybrid with gasoline engine as range extender, single speed gear, external charge unit	Central electrical traction motor, single-speed gear, external charge unit
Power combustion engine	*kW*	100	75	50	50	-
Power e-motor	*kW*	-	25	50	100	100
Battery pack storage	*kWh*	-	2	5	15	30
Electric driving range	*km*	-	-	35	58	112
Share of electric driving	*%*	-	-	50%	67%	100%
Curb weight	*kg*	1,400	1,460	1,510	1,580	1,595
Average consumption auxiliaries	W	700	700	900	1100	1200

determine fuel consumption and torque as a function of the accelerator pedal position and the engine speed. The underlying map is based on a real-world engine, but can be adapted according to performance requirements in the simulation.

- The same applies to the electric drive module which uses the efficiency map and the speed-torque characteristic of a real electric motor.
- The battery module is an impedance-based model, which has been parameterized by battery tests under laboratory conditions.
- All vehicle models are controlled by a driver module, which adapts the accelerator pedal position by comparing the requested velocity from the drive cycle with the actual velocity of the car body at any time.
- In hybrid electric vehicles (HEV, PHEV and EREV) a hybrid control unit calculates the lever position of the electric drive respectively the combustion engine based on requested velocity by the driver and the battery state of charge. Thereby different operating strategies can be realized.

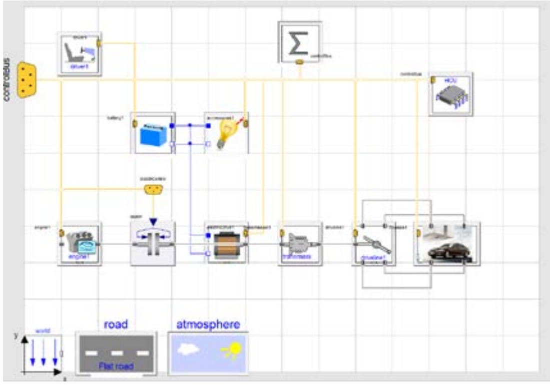


Figure 1: Dymola model of a parallel-hybrid electric vehicle

All examined vehicle models are configured to achieve similar driving performance (e.g. acceleration time 0-100 km/h ~ 9 s, top speed > 200 km/h). To reach these requirements a set of initial simulations has been carried out. The resulting vehicle configuration is summarized in Table 1.

The size of the traction battery is dimensioned to reach an all-electric range of more than 100 km for the BEV and more than 50 km for the EREV. The PHEV is able to drive 35 km all-electric in the urban part of the NEDC with a maximum velocity of 50 km/h. The HEV battery is large enough to store the entire recuperation energy during the cycle. In addition the usable capacity of the batteries was taken into account. Only 60% of the nominal capacity (between 30% and 90% SOC) is assumed to be available during the drive cycle.

The simulation models have been validated by using real-world data. For the ICE model the ADAC auto database has been applied to calibrate the fuel consumption and performance according to a midsize passenger car sold on the German auto market. For the advanced electric vehicles the simulation results have been compared to the characteristics of EV models which are already available in series production (e.g. Nissan Leaf, Opel Ampera). To get realistic fuel economy data for the subsequent cost analysis, the power consumption of auxiliaries has been included in the simulation. (As the waste heat of the combustion engine is not available for heating in an EV the average auxiliary power demand is assumed to be higher, see Table 1.) The simulated energy consumption of the examined drive trains is shown in Figure 2.

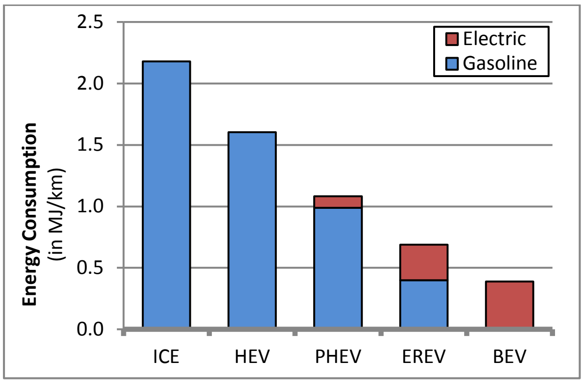


Figure 2: Energy consumption of a mid-size vehicle with different powertrains in the NEDC

To analyse the impact of changes in curb mass on the energy consumption of different powertrain architectures, an extensive set of simulations was conducted. Therefore a new simulation tool called SimVeC was developed and applied in this study. The tool enables to execute large parameter variations in Dymola and processes the resulting simulation data automatically.

2.2 TCO Analysis

Unlike previous studies [3] [4] [5], this paper does not only analyze the effects of vehicle mass on energy consumption, but also addresses the cost implication for a vehicle owner in a life cycle perspective. Therefore, the simulation results are integrated into a holistic total cost of ownership model. (For a detailed presentation of the model see [6]). The TCO assessment covers all types of expenses arising for a vehicle owner from purchase to resale of the car for different alternative powertrain options. The bottom-up model includes acquisition cost, operating cost, vehicle tax as well as maintenance and repair and the expected resale value [7].

Since EREV and BEV models are rarely available to the end-customer today, but will be introduced from many OEMs in the following time, year 2015 has been defined as base year of the cost analysis. For the core components of the electric drivetrain (traction battery, electric machine and power electronics) specialized models, which have been developed at the DLR Institute of Vehicle Concepts, are applied to projects the future cost development. For example the battery cost model allows estimating cell, module, and pack prices for the most important Li-ion chemistries. In this analysis NMC has been selected for high-energy storages with a learning rate of 86%. This implies that a decrease of battery prices to EUR 450 per kWh is likely if a moderate growth in EV sales is assumed by 2015.

For exogenous factors such as energy prices a modest business-as-usual scenario has been defined (see Table 2). For instance the oil price development is based on the *current policy scenario* published in the IEA World Energy Outlook 2011, which predicts a slow increase to 106 USD/barrel by 2015.

To consider different user types the mobility behaviour of more than 50,000 households collected in the German national travel survey (MiD 2008 [8]) has been analysed to derive typical driving patterns. Results show that the average driving speed for people living in rural areas is about 20% higher than for city residents. The TCO model reflects this by adjusting the share of urban and highway driving accordingly.

For the basic analyses in this paper a representative user has been selected, who holds his car over a period of four years, drives an annual mileage of 15,000 km and lives in a midsize town. All running costs are discounted with an interest rate of 5% to reflect the net present value (in EUR 2010). The resulting TCO for the selected powertrain options are summarized in Figure 3 on a EUR per km basis.

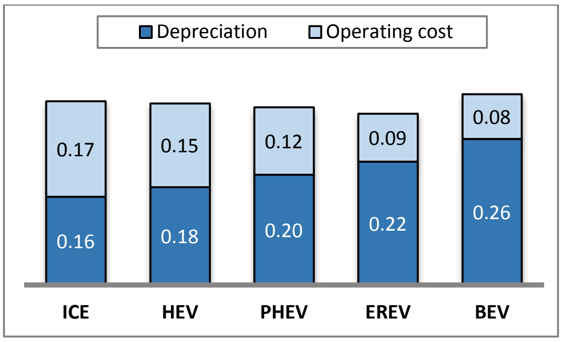


Figure 3: Total cost of ownership in EUR per km (annual mileage 15,000 km, holding period 4 years, depreciation = purchase price – expected resale value)

According to the TCO analysis, conventional powered vehicles with internal combustion engine will still be the most cost efficient powertrain option for an average driver in 2015. This is mainly due to the high production cost of the electric powertrains components. So a car buyer has to spend 11% (HEV) to 68% (BEV) more upfront when purchasing an alternative powertrain. However, the operating costs of EVs during the

Table 2: Relevant scenario parameters

Scenario parameter	Unit	Value 2015	Source
Oil price	USD/barrel	106	IEA World Energy Outlook 2011 [9] (Current Policy scenario)
Gasoline retail price	EUR/l	1.60	DLR analysis based on IEA scenario
Electricity cost	EUR/kWh	0.24	BMU study 2010
Battery pack cost (high energy)	EUR/kWh	450	DLR battery cost model (NMC, 30 kWh)
Battery pack cost (high power)	EUR/kWh	840	DLR battery cost model (NCA, 2 kWh)
Electrical storage energy density	Wh/kg	100	[10] (system level)

following years are significantly lower (e.g. 47% for a BEV). For an EREV the savings in energy cost and maintenance will overcompensate the price premium over an ICE after a holding period of six years. Generally, it can be stated: The more kilometres a user drives per year the more attractive is the purchase of car with an electrified powertrain from a cost perspective [6].

3 Impact assessment of lightweight design

To evaluate the effect of a weight reduction for various powertrain architectures a wide set of systematic parameter variations has been carried out. Starting from the reference configuration described in Table 1 the total mass of the tested vehicle has been changed in discrete steps in each simulation run, while all other parameters were kept constant. The resulting changes in energy consumption for a BEV are plotted in Figure 5. The simulation results show a nearly linear relationship. To describe the effect mathematically a mass influence factor on fuel economy is introduced and defined as:

$$\varepsilon_m = \frac{\partial E}{\partial m} \tag{1}$$

The quantity ε_m expresses the sensitivity of a car's energy consumption to a change in its total weight. (Graphically it corresponds to the slope of the linear regression line indicated as triangular in Figure 5). The higher the value of ε_m the greater is the impact of lightweight design on the resulting energy consumption of a car.

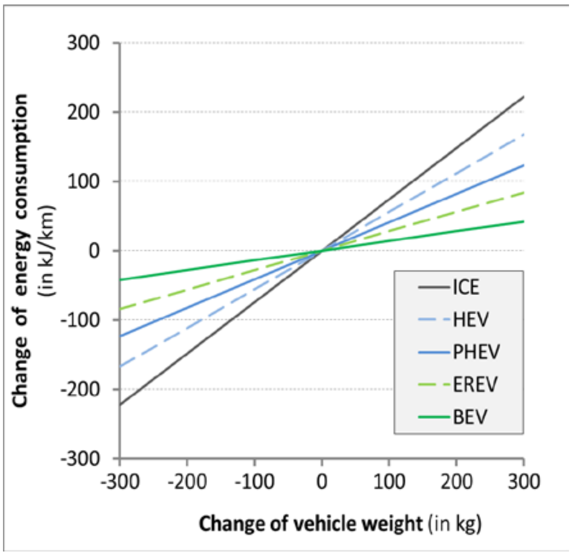


Figure 4: Change of energy consumption in NEDC for different powertrain as a function of vehicle weight

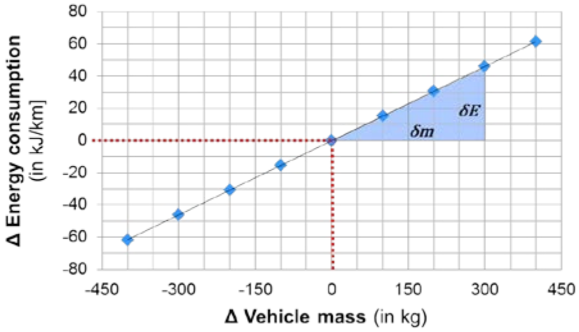


Figure 5: Parameter variation of vehicle mass for a BEV and resulting impact on the energy consumption in NEDC (relative to reference BEV)

The parameter variations have been repeated for all selected drivetrain technologies. The simulation results and the derived mass influence factors in urban and extra urban driving are summarized in Figure 4 and 6. The analysis indicates that the energy saving potential through weight reduction is significantly higher for a conventional ICE vehicle than for advanced electric vehicles. This applies particularly to the urban drive cycles due the high share of acceleration and braking.

There are two main reasons for this observation: First electric vehicles permit the recuperation of kinetic energy. During deceleration phases the electric machine operates as a generator and the gained electric energy can be used to recharge the battery. In contrast, conventional vehicles convert the kinetic energy during breaking into heat which is emitted by the breaking disks and therefore lost to the environment. The second reason for the observed low ε_m values for EVs is the higher

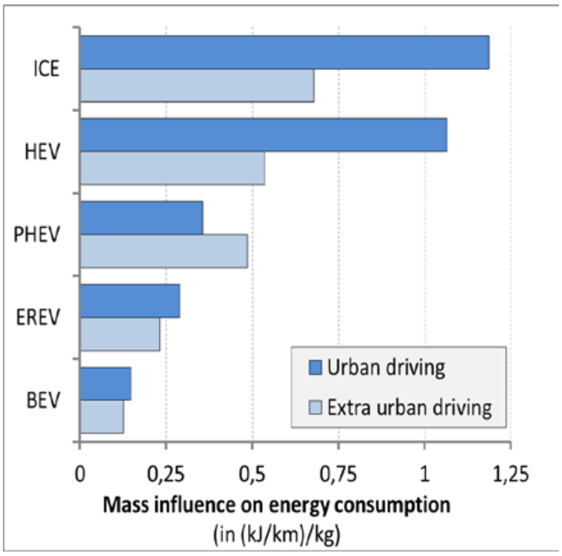


Figure 6: Mass influence factors for different powertrains in the urban and extra urban section of the NEDC

energy efficiency of electric drivetrains compared to ICEs. As illustrated in Figure 2 the simulated energy consumption in MJ/km of the BEV is only 18% of the reference ICE. Therefore the change in energy consumption in absolute numbers is also smaller for the BEV, while the relative change (ΔE/E) is similar for BEV and ICE (e.g., -3.6% versus -3.4% for a weight reduction by 100 kg).

In the next step the resulting weight influence factors are integrated in the cost model to determine the cumulated savings for different powertrain technologies. In contrast to previous TCO analyses [9] [7], the applied model is adaptable in annual mileage, holding period, and use characteristics (i.e., share of urban vs. highway driving). This allows analyzing the cost efficiency of lightweight measures in different use cases.

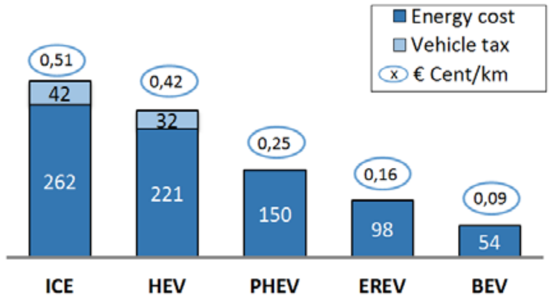
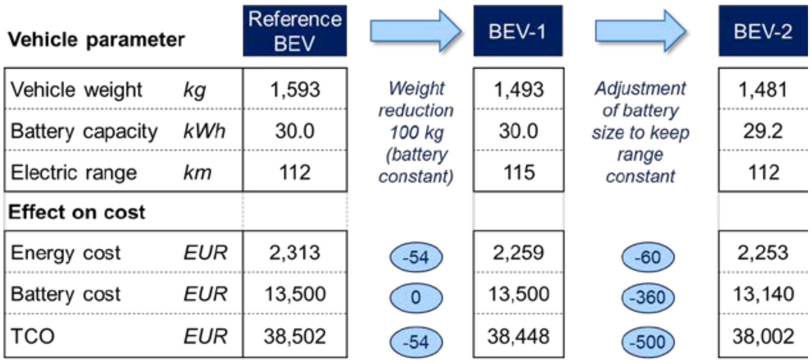


Figure 8: TCO savings in EUR for 100 kg weight reduction (assuming 15,000 km annual mileage over 4 years of operation)

For an average ICE owner driving 15,000 km per year a weight reduction of 100 kg (ca. 7% of the curb mass) will result in cost savings of EUR 302 over a holding period of four years (or equivalently 0.51 € Cent/km). The major part of these savings results from lower expenses for fuel (EUR -262). Additionally the holder will benefit from a vehicle tax reduction of EUR 42 as cars with CO_2 emission greater than 110 g/km are charged with an additional annual tax per gram CO_2 in Germany. (Potential CO_2 penalties for the automotive manufacturer from the EU are not considered here.) For users of a hybrid or full electric vehicle the savings due to lightweight design are significantly lower (see Figure 8). With a 100 kg decrease of curb weight the end-user will save energy cost of 0.4 € Cent/km with a HEV and 0.09 € Cent/km with a BEV. These savings are rather low compared to 0.51 Cent/km for the ICE. The larger savings for the ICE result from the higher energy consumption in MJ/km and higher energy price for gasoline compared to electricity in EUR/MJ.

However, it should be highlighted that the analysis in Figure 8 uses a simplification. It assumes that the weight of the car body is reduced by lightweight measures, but all other components of the car stay constant. In the real world, automotive engineers will resize several components (e.g. breaking system, suspension) and adapt the dimensioning of the powertrain according to the reduced vehicle weight. This will lead to additional savings in production cost. Of special interest is the effect of lightweight design on the size of the energy storage, since battery costs are the major cost driver of electric drivetrains. If the energy consumption decreases as direct impact of the lighter vehicle structure, the battery size can simultaneously be reduced while keeping the electric driving range constant.
Figure 7 illustrated this indirect effect of lightweight constructions on an electric vehicle in a simple example: According to the simulation results the reference BEV with 30 kWh battery capacity and 1,593 kg curb weight is able to drive 112 km without recharging and induces energy cost of EUR 2,313 (over four years with 15,000 km annual mileage). In the first step the weight of the car body is reduced by 100 kg while all



Vehicle parameter		Reference BEV		BEV-1		BEV-2
Vehicle weight	*kg*	1,593	*Weight reduction 100 kg (battery constant)*	1,493	*Adjustment of battery size to keep range constant*	1,481
Battery capacity	*kWh*	30.0		30.0		29.2
Electric range	*km*	112		115		112
Effect on cost						
Energy cost	*EUR*	2,313	-54	2,259	-60	2,253
Battery cost	*EUR*	13,500	0	13,500	-360	13,140
TCO	*EUR*	38,502	-54	38,448	-500	38,002

Figure 7: Effect of 100 kg weight reduction on battery size and cost of a BEV (assuming 15,000 km annual mileage, 4 years holding period)

drivetrain components are not modified. As a result the energy consumption of BEV-1 declines by 3.6%. On the one hand this leads to a decrease of the related electricity cost by EUR 54. On the other hand the driving range of BEV-1 rises to 115 km. In a second step (see BEV-2) the battery capacity is adjusted to 29.2 kWh to maintain the original range of 112 km. This reduces the battery production cost by EUR 360 and the TCO for the user by EUR 500. (The total savings also include additional effects, e.g. lower maintenance costs and a further decrease of energy cost due to the smaller and lighter battery). This small case study shows that for electric vehicles the secondary effect of a lightweight construction (decrease of battery cost) exceed the primary effect (decrease of energy cost). Therefore the indirect impact of weight reduction efforts should also be included in any cost-benefit analysis.

To decide whether a lightweight measure is economically efficient or not, the additional production costs have to be compared with the realizable savings. In moderate lightweight design conventional steel is often replaced by high-strength steel, aluminum, magnesium and hybrid structures. Weight reductions for a midsize car of 18-30% can be achieved at additional cost of EUR 3-4 per kg saved. For extreme lightweight design applying e.g. carbon fiber in structural parts to reach a maximum weight reduction additional costs of EUR 8-10 per kg saved incur according to [10]. The lightweight measures are accompanied by reduced operating costs, which (partly) offset the additional production costs over time. For a break-even analysis the cumulated TCO savings of a 1 kg mass reduction are plotted over the operating time for a conventional vehicle (Figure 9) respectively a full electric vehicle (Figure 10). On the y-axis the additional production cost for moderate and extreme lightweight design are indicated as a range.

Initially only the impact on the energy consumption is assessed keeping all other vehicle components constant. As described before the cost savings are significantly higher for the ICE than for the BEV. For an ICE owner driving 15,000 km per year the extra cost of moderate lightweight will amortize after 4-6 years of operation. For a frequent driver with 30,000 km annual mileage the payback period diminishes to 2-3 years (see red line in Figure 9). However, extreme lightweight costs only pay off for frequent users after more than 10 years.

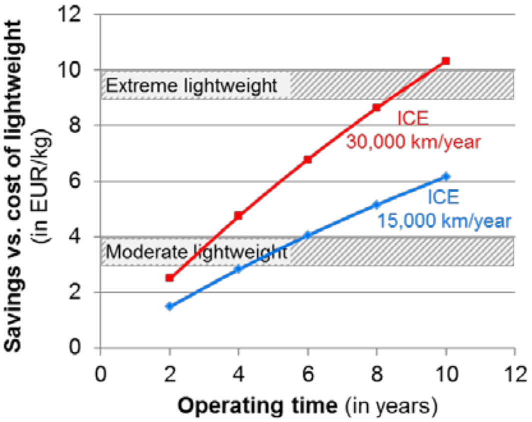


Figure 9: Benefit of 1 kg mass reduction for an ICE over operating time vs. additional lightweight costs (without indirect effects through resizing)

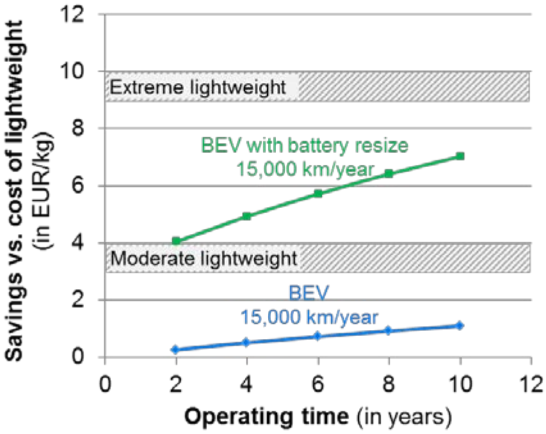


Figure 10: Benefit of 1 kg mass reduction for a BEV (with/without resizing of the battery) over operating time vs. additional lightweight costs

According to the break-even analysis of the full electric vehicle lightweight seems to be unattractive at first glance if only the running costs are considered (see blue line in Figure 10). For a BEV owner the extra effort for lightweight will not be paid off by lower energy expenses over the lifetime of the vehicle. However, the situation changes significantly if secondary effects are included in the analysis. The decrease in energy consumption allows adjusting the battery capacity while the electric driving range stays constant. As a result the TCO savings increase to more than EUR 4 per kg weight reduction taking a resizing of the battery into account (see green line in Figure 10). So the additional cost of moderate lightweight are already covered within a very short amortization period.

4 Conclusions and outlook

The presented work analyzes the impact of lightweight on the energy consumption and associated cost for several advanced electric powertrain concepts in comparison to a conventional vehicle. For this purpose two computer models have been applied: A vehicle simulation tool to determine the energy consumption of different powertrain architectures and configurations, and a TCO model to assess the implication on the cost effectiveness from a user perspective.

Results show that the energy saving potential through lightweight decreases with increasing degree of electrification. This is mainly due to higher efficiency of electric drives as well as recuperative breaking. As a consequence the savings in running cost in EUR/km per kg saved are smaller for EVs than for ICEs. However, the picture changes if indirect effects of lightweight are considered. If the battery capacity of a BEV is resized (maintaining a constant electric range), the cost saving potential is significant.

Moreover, there are additional effects of lightweight design which exceed the scope of this assessment, but should be mentioned here:

First, a decrease of curb weight also leads to an improvement of the driving performance of a car if the engine is not modified. The acceleration of a vehicle depends strongly from the power-to-weight ratio (see Figure 11). As a consequence of a weight reduction by 100 kg the acceleration time (from 0 to 100 km/h) will decline on average from 9.5 s to 9.0 s in case of an ICE. On the one hand the improved driving dynamics have a positive impact on the willingness to pay of customers. On the other hand, if an enhanced acceleration behavior is not intended by the manufacturer, the motor size and power can be reduced accordingly, which results in an additional cutback of production cost (e.g. for combustion engine, electric drive, transmission).

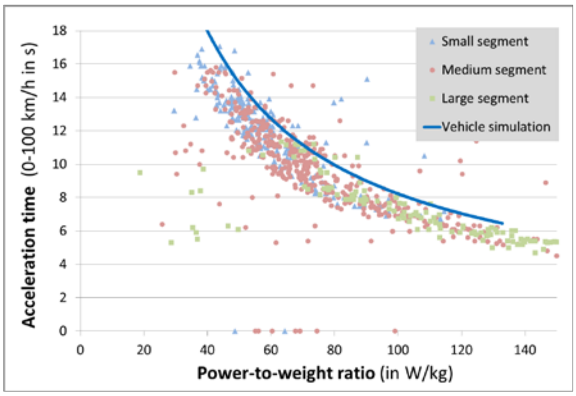


Figure 11: Acceleration performance over power-to-weight ratio of real-world vehicles [9] and simulation

Another effect which should be addressed by further investigations is the impact of material choice on the maintenance cost of a vehicle: This is especially important for the use of carbon composites (CFC). As the material characteristics make it complex to predict the failure behaviour and safety of CFC components there is a risk that major parts have to be exchanged over lifetime or after an accident. Therefore the application of lightweight materials like CFC could have a negative impact on the expected maintenance and repair cost for a car holder.

From OEM perspective there are even more aspects which should be taken into account when investigating the use of lightweight materials throughout a new car development: Availability of raw materials, production capabilities, research and development efforts to realize weight savings, brand image, safety and CO_2 regulations are only some of them.

Nevertheless, the present article intends to make a contribution to facilitate the discussion about cost and benefit of lightweight and its application in future powertrain concepts. The outcome of this assessment will help decision makers in the automotive industry to gain a better understanding as to which extent investments in weight reductions are effective and which additional effect should be considered.

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