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Comparative life cycle analysis of conventional and hybrid heavy-duty trucks

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Abstract

Heavy-duty trucks are one of the main contributors to greenhouse gas emissions in German traffic. Drivetrain electrification is an option to reduce tailpipe emissions by increasing energy conversion efficiency. To evaluate the vehicle's environmental impacts, it is necessary to consider the entire life cycle. In addition to the daily use, it is also necessary to include the impact of production and disposal. This study presents the comparative life cycle analysis of a parallel hybrid and a conventional heavy-duty truck in long-haul operation. Assuming a uniform vehicle glider, only the differing parts of both drivetrains are taken into account to calculate the environmental burdens of the production. The use phase is modeled by a backward simulation in MATLAB/Simulink considering a characteristic driving cycle. A break-even analysis is conducted to show at what mileage the larger CO_{2eq} emissions due to the production of the electric drivetrain are compensated. The effect of parameter variation on the break-even mileage is investigated by a sensitivity analysis. The results of this analysis show the difference in CO_{2eq}/tkm is negative, indicating that the hybrid vehicle releases fewer emissions over a lifetime. The break-even analysis also emphasizes the advantages of the electrified drivetrain, compensating the larger emissions generated during production after already a couple of months. The intersection coordinates, distance, and CO_{2eq}, strongly depend on fuel, emissions for battery production and the driving profile, which lead to nearly all parameter variations showing an increase in break-even distance.

Keywords: LCA (Life Cycle Assessment), heavy-duty, HEV (hybrid electric vehicle), sustainability, environment

1 Introduction

According to The German Government's Climate Action Programme of 2014, Greenhouse gas (GHG) emissions have to be reduced by at least 40% below 1990 levels by 2020 [1]. To achieve the GHG target, the German Government has defined two sub-targets among others: renewable generated electricity to increase to 35 % of gross electricity production by 2020 [2] and to have 1 million electric vehicles on the road by 2020 [3]. GHG emissions from the transportation sector accounted for about 18% of total German GHG emissions in 2013, approximately 95% of these were released from road transport [4]. Out of 52.4 million

registered vehicles in Germany 2013, passenger cars accounted for 83% and semi-trailer trucks for 0.3% [5]. The annual average mileage was 14,259 km for passenger cars and 102,832 km for semi-trailers [6]. Comparing additionally the average fuel consumption of 4.9 liters of diesel per 100 km (passenger cars) [7] and 34.5 liters of diesel per 100 km (semi-trailer truck, long-haul) [8], it can be concluded that the emission and energy reduction potential per vehicle of semi-trailer trucks is larger than the potential of passenger cars. Despite this enormous potential, drivetrain electrification is still not common for heavy-duty vehicles (HDV). In 2016 there are 12 hybrid and only 2 pure electric HDV registered in Germany [9] and there are currently no electric or hybrid HDV for sale.

In the context of HDV and life cycle assessment (LCA), research has been conducted comparing different conventional vehicles powered by internal combustion engines (ICEV) [10]. In [11] life cycle impacts have been analyzed by changes in truck materials, truck design, engine design, and operation by using liquefied natural gas (LNG) and Fischer-Tropsch (F-T) diesel instead of conventional diesel fuel. [12] published a comparative LCA of diesel and compressed natural gas (CNG) but for a special application of HDV (refuse collection). Further studies have analyzed environmental impacts of freight transportation alternatives in Europe [13] and in the U.S. but neglecting drivetrain electrification as having energy reduction potential. There is currently no study available evaluating the energy and CO_{2eq} reduction potential by substituting conventional with hybrid HDV in long-haul transportation in Europe.

2 Methodology

LCA is an established and widely used method to analyse environmental impacts of products and services [14]. According to the international standard [15] an LCA is divided into 4 phases: goal and scope definition, inventory analysis, impact assessment and interpretation.

2.1 Goal and Scope

This study presents a comparative assertion of the life cycle environmental impacts associated with a heavy-duty truck in long-haul application having a conventional or a parallel hybrid drivetrain and a total mass of 40 tons. It is investigated whether in 2017 in Germany hybrid electric vehicles (HEV) are competitive to ICEVs with respect to energy consumption (abiotic depletion) and CO_{2eq} emissions (global warming potential). Referring to this issue, the following two questions are answered:

- How large is the difference in environmental impact for the hybrid truck during its life cycle, using the conventional vehicle as a baseline?
- At what mileage are the larger environmental burdens due to the production of the hybrid drivetrain compensated compared to the conventional one and which parameters affect the break-even point?

The Mercedes-Benz Actros is selected as product system equipped with a conventional and a parallel hybrid drivetrain. Both vehicles have a common generic glider (all components are the same except the drivetrain [16]). Therefore, this study is an assessment of the different drivetrain components of ICEV and HEV. The setup of both drive trains is shown in Figure 1:

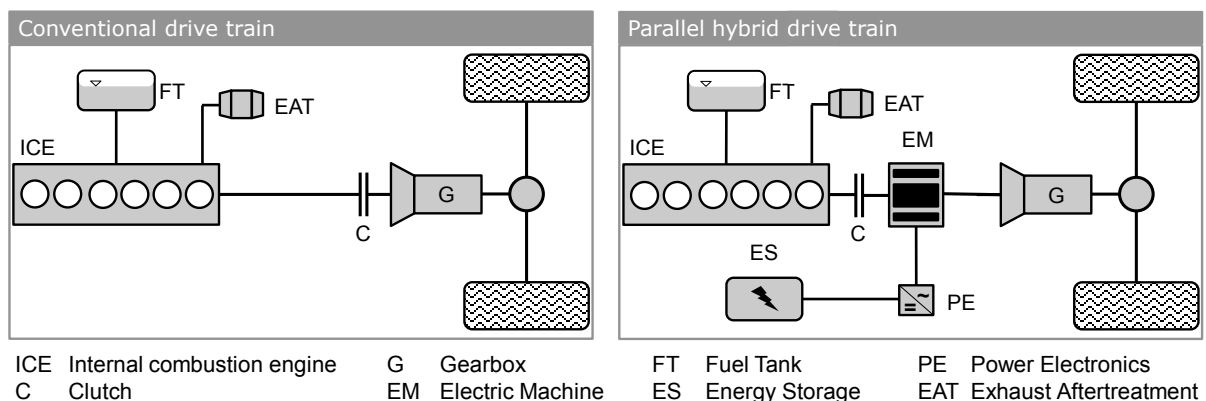


Figure 1: The product system studied

The primary function of the system analyzed is to carry a defined cargo throughout its lifetime, which is assumed to be 8 years and 1,040,000 km (according to [17]). The functional unit is chosen to be the transportation of 1-ton cargo over a distance of 1 km. A hilly motorway driving cycle with many acceleration and deceleration sections has been used in this study.

Due to the large annual mileage of on-road HDV in long haul operation, the share of energy demand and CO_{2eq} emission of vehicle use to the overall vehicle life cycle is larger than 90%. In this case, the share of end of vehicle life is relatively small. Therefore and due to a lack of data, it is omitted in this study. Moreover, the production of infrastructure is excluded because it is assumed to be the same for ICEV and HEV. In summary, the modelled life cycle stages in this study are vehicle production and vehicle use.

2.2 Life Cycle Inventory

The drivetrain production consists of the raw material extraction, production, and assembly of components. Major components in the HEV drivetrain identified as being additional are electric machine, inverter, converter, high voltage cable, lithium ion battery and power distribution unit. The inventory data base on literature studies, existing datasets, research reports and published information of the vehicle manufacturer. The software openLCA has been used to perform this study.

The use phase is separated into a well-to-tank (WTT) and a tank-to-wheel section (TTW). The production, transportation and distribution of fuels have been modelled based on results from [18]. Due to the fact that the TTW section has the largest share of CO_{2eq} emissions in HDV life cycles, the calculation of the energy consumption has been simulated in MATLAB/Simulink in order to generate a precise and applications specific result. The simulation model used for the energy consumption in this paper is a so-called backward simulation (see Figure 2).

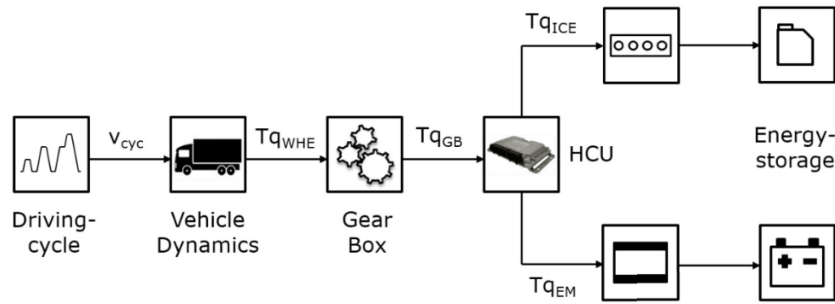
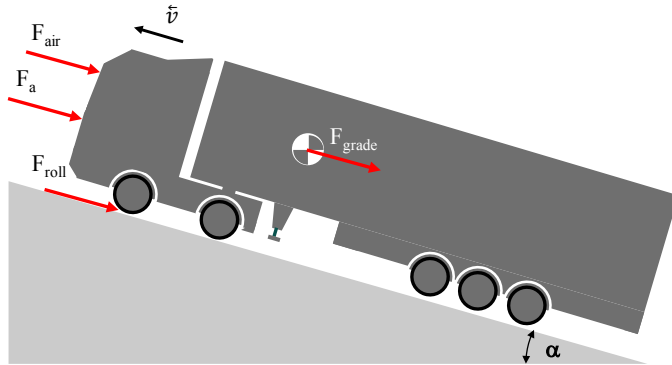


Figure 2: Backward simulation approach

This approach reverses the physical causality as it appears in a real vehicle. Based on a velocity profile $v_{CYC}(t)$ of the driving cycle and the vehicle geometry, the forces respectively resistances acting at the vehicle are calculated according the following equations and

Figure 3:



$$F_{air} = \frac{1}{2} \cdot A \cdot c_D \cdot \rho_{air} \cdot v_{cyc}^2 \quad (1)$$

$$F_{grade} = (m_v + m_t) \cdot g \cdot \sin(\alpha) \quad (2)$$

$$F_{roll} = (m_v + m_t) \cdot g \cdot \cos(\alpha) \cdot f_r \quad (3)$$

$$F_a = (m_v \cdot e_i + m_t) \cdot a \quad (4)$$

Figure 3: Driving resistances acting at the truck

Where A is the vehicle frontal area, c_D is the air drag coefficient, ρ_{air} is the air density, v_{cyc} is the speed, a is the acceleration, g the gravity, α is the road gradient, m_v is the vehicle mass, m_t is the trailer mass, f_r is the coefficient of rolling resistance and e_i is the mass inertia coefficient. Summing up these forces/resistances to F_{tot} at a certain time and speed (operation point) and multiplied by the average wheel radius the required torque $Tq_{WHE}(t)$ at the wheels can be determined. This torque is then fed backwards from the wheels via the energy converters to the energy storage systems. In order to determine the energy consumption of the vehicle, the efficiency of the gearbox, energy converters and the electric energy storage system is taken into account operating point depending.

This approach is well suited for the examination of measures to reduce the fuel consumption as well as the design of hybrid control strategies. One of the main advantages is the low computational effort compared to the forward simulation approach. As the dynamics of the powertrain and feedback control problems can be neglected, the backward approach was identified as optimal approach [19].

The specifications of the examined vehicle are summarized in Table 1. The 40 ton truck features a P2-hybrid architecture.

Table 1: Technical specifications powertrain [20], [21], [22]

ICE	$V_H = 12,8 \text{ L}$; $P_{max} = 330 \text{ kW @ } 1800 \text{ rpm}$
Gearbox	12-gear AMT 14,929-1,0
EM	$P_N = 70 \text{ kW @ } 1000 \text{ rpm}$; $P_{max} = 120 \text{ kW}$
Battery	Li-Ion; 2.5 kWh usable
Vehicle weight	$m = 18,000 \text{ kg}$ (max. load capacity 22,000 kg)

The hybrid functions of this heavy-duty hybrid truck differ from that implemented in hybrid vehicles with lower gross vehicle weight. [23] gives an overview of the implemented hybrid modes in the a real heavy duty hybrid vehicle and indicates the fuel reduction potential. The major difference lies is the application of the pure electric mode. This mode is used in passenger cars during low load driving situations where the ICE has a low efficiency. In the P2-heavy-duty hybrid truck the pure electric mode is only used for manoeuvring at distribution centres. Therefore, the electric mode is neglected in the simulation model. In addition to that the EcoRoll-Mode as well as the support of the refrigeration trailer by the hybrid system are neglected. The implemented hybrid control strategy in the simulation model used therefore only applies to a hybrid mode that includes recuperation and boosting. Next to this, the conventional drive (ICE-only) is implemented.

Neither the hybrid control strategy nor the shifting strategy is disclosed in any publication or other source in detail and therefore has to be developed on sensible assumption. The shifting strategy is designed in a way that the operating point of the ICE mostly lies at around 1200-1400 rpm.

The design of the hybrid control strategy includes more rules but also simpler ones. In order to capture as much braking energy as possible the electric machine (EM) is allowed to operate in overload in the recuperation mode. An I^2t counter as presented in [22] is implemented in order to limit charging current in braking situations. During the propulsion of the vehicle the EM is working under nominal conditions in order to lower the load point of the ICE. In contrast to [22] the hybrid control strategy used in the simulation model for this paper doesn't feature a predictive function.

The mentioned development of the control strategies for the hybrid powertrain and the gearbox based on literature sources, as well as the usage of the efficiency maps (also based on literature sources), lead to a certain inaccuracy of the simulation results. Nonetheless the reduction of fuel consumption indicated by the simulation model is in accordance with the published reduction potential [24] [25].

3 Results

The results of the comparative life cycle analysis show that HEVs have a significant contribution to energy and CO_{2eq} emission reduction. Referring to the questions defined in section 2.1, the difference in environmental impact is large. From Figure 4 can be concluded, that in total the HEV saves about 4,34 t CO_{2eq} per ton cargo compared to the ICEV over lifetime. The environmental impact due to the production of the HEV drivetrain components is with 0.07 gCO_{2eq} / tkm very small compared to the use phase with 4.41 gCO_{2eq} / tkm.

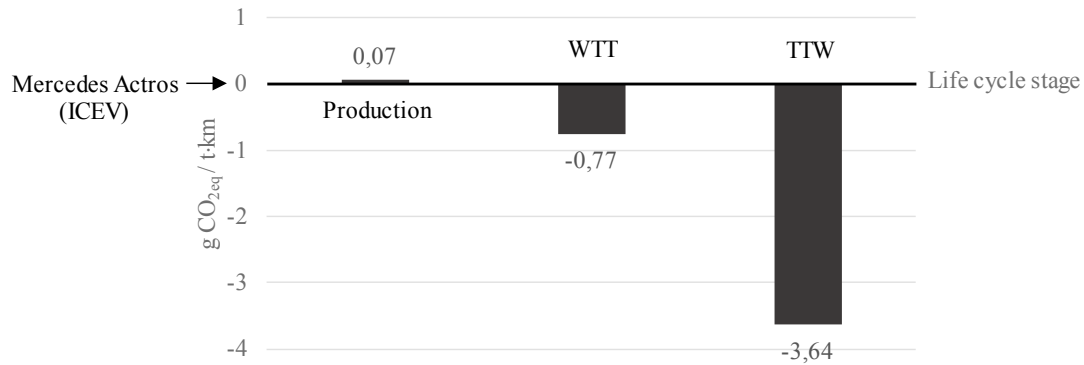


Figure 4: CO_{2eq} emission reduction potential of HEV compared to ICEV

This large share of the use phase on the overall life cycle (about 98 %) results from the fact that the annual mileage assumed in this study of 130,000 km is very large. According to [6] passenger cars in Germany drive annually in average about 14,259 km which leads to the fact, that the share of the hybrid drive train production on the vehicle life cycle increases despite possibly smaller sized hybrid systems as presented in this paper. This correlation is presented in many studies, e.g. in [26].

The results of the break-even analysis (Figure 5) indicate that the larger CO_{2eq} emissions resulting from the HEV drivetrain production are compensated at a mileage of about 15,800 km (about 1,5 months) due to the more efficient energy conversion and the capability of energy recuperation.

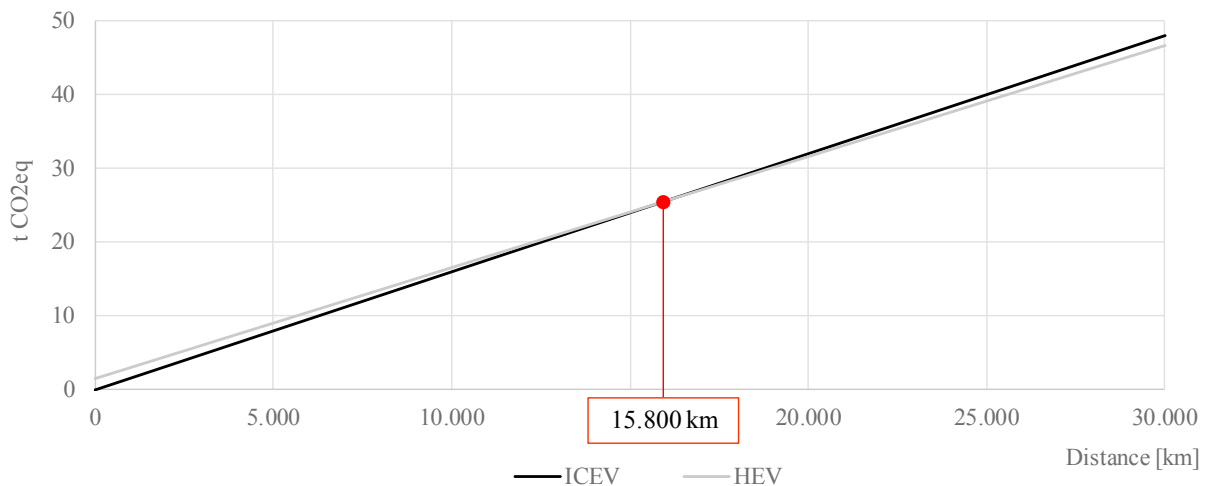


Figure 5: Break-even analysis (ICEV vs. HEV)

A sensitivity analysis is conducted to examine the variation of different parameters on the break-even point (see Figure 6). The variation of each parameter is represented on the x-axis, the effect of this, the increase or decrease of break-even distance, is shown on the y-axis. The origin represents the break-even point of 15,800 km based on the assumptions presented in chapter 2.

First, the effect of using different fuels compared to conventional diesel is studied. Therefore, the difference in well-to-wheel (WTW) emissions for production (WTT) and combustion (TTW) of 1 MJ final fuel are taken into account. Replacing diesel by Syndiesel (brown dot), the primary energy demand increases by 6 % and the break-even distance decreases, since the production of Syndiesel is more energy demanding than conventional diesel [18]. Using biodiesel (green dots) instead of conventional diesel leads to an increase of break-even distance. The reduction of WTW emissions by 86 % (fatty acid methyl ester (FAME)), 44 % (rapeseed methyl ester (RME)) and 36 % (HVO (hydrotreated vegetable oil)) shifts the break-even point by 79 %, 600 % and 64 %, respectively. For these types of biodiesel it is assumed that during combustion no CO_{2eq} emissions are released [18]. Neglecting this assumption, the primary energy demand for the production of these 3 biofuels increases, results in a positive parameter variation and a decrease in break-even distance.

The standard conditions for the energy consumption calculation (TTW) are based on a driving cycle with many acceleration and deceleration intervals as well as uphill and downhill sections. These conditions are available in Germany but these are not standard conditions. Considering different driving cycles (blue dots) reduces the energy savings (parameter variation) by 26 % (typical long-haul on motorway), respectively by 59 % (rural road). Taking a driving cycle without hills into account, the fuel consumption of the HEV increases slightly above the level of the ICEV. In this special case there is no intersection of the ICEV and HEV curve.

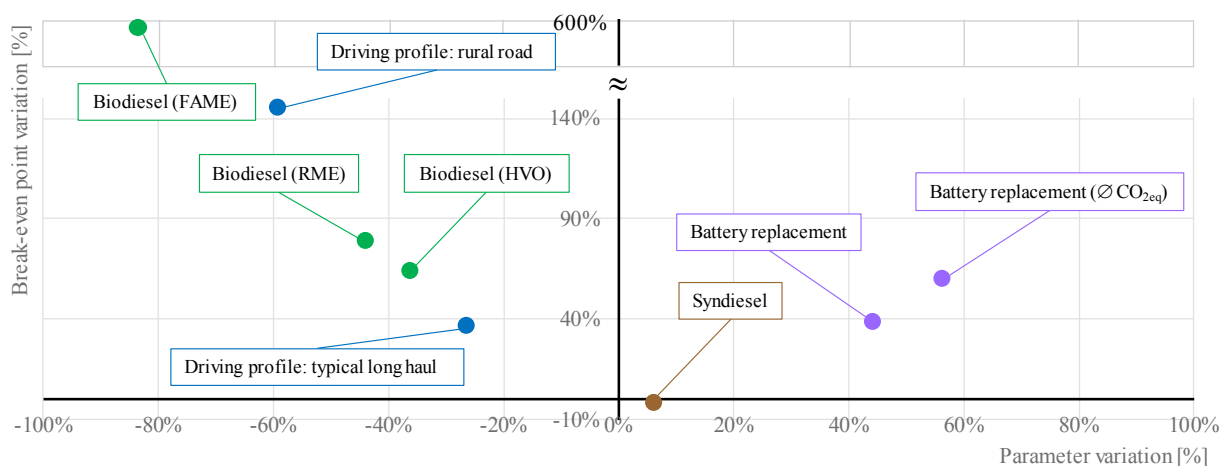


Figure 6: Sensitivity analysis of break-even distance

Assuming one battery replacement during lifetime (purple dots), the CO_{2eq} emissions released during production increase (parameter variation) by 44 % and the break-even point shifts by 39 %. Compared to literature, the specific CO_{2eq} emission resulting from the battery production (kg CO_{2eq}/kWh) listed in the ecoinvent 3.2 database are relatively small. Taking an average value (ØCO_{2eq}) into account, the break-even distance is reached at about 25,300 km. Due to the fact that the capacity of the selected battery is relatively small in relation to the vehicle mass, the effect of the replacement on the overall life cycle CO_{2eq} emission is small, as well. Evaluating this, it has to be considered, that this hybrid drive train setup has been specially designed for this application (addition of torque, electric motor and diesel engine acting simultaneously during acceleration phases, no pure electric driving).

The study shows that for all parameter variations the larger CO_{2eq} emissions of the HEV drivetrain production are compensated within the first year of use with exception of Syndiesel and motorways without hills.

Several assumptions were made within this life cycle analysis, which may lead to uncertainties of the results. In order to model the drive train components production, the material composition is linearly scaled by mass because life cycle inventory data for these components are not available. In reality, material composition is not only a function of mass but of several other parameters. Furthermore, the increase in vehicle weight due to the additional hybrid drive train components was not taken into account. The overall mass of semitrailer trucks in Germany is limited to 40 tons. By increasing the tractor mass, the transport capacity decreases and the specific CO_{2eq} emissions per ton increase.

4 Conclusion

In this study a comparative life cycle analysis of conventional and hybrid heavy-duty trucks is presented. The large contribution of HDV to greenhouse gas emissions in German traffic offers a large reduction potential. The results confirm this potential: the larger CO_{2eq} emissions due to the production of the HEV drive train are already compensated by a better energy conversion efficiency and a well-defined control strategy within the first months of operation at a mileage of 15,800 km. Compared to the ICEV, the HEV saves 4,34 g CO_{2eq} per transported ton and kilometre during use. To examine the effect of different parameter variations on the results, a sensitivity analysis of the break-even point has been conducted. The variation of almost all parameters results in an increase in break-even distance but the larger HEV production emissions are still compensated within the first year of operation.

Ecologically, the hybrid heavy-duty truck represents a better alternative to conventional vehicles powered by internal combustion engines. How far they are economically competitive remains to be examined in future.

Acknowledgments

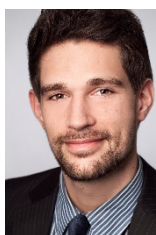
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