Electrification of tractor trailer vehicles – Niche or mainstream?

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Abstract

Recently commercial vehicles with hybrid electric drivetrains found their way into commercial markets. On one hand, they offer fuel saving potential in different driving situations and on the other hand it is possible to keep emissions within the future legal requirements. For example, in future it may be necessary to drive in pedestrian areas without any emissions. Nevertheless, these new drivetrain topologies also offer new challenges for engineers.

Control strategies must be developed to reduce fuel consumption and to secure the limitation of emissions specified by law. Before a hybrid vehicle is engineered, an analysis should be done to verify the highest possible fuel saving potential that is reachable for an implemented, causal hybrid operation strategy. This helps to evaluate hybrid energy management controls.

The following article explains a method to determine the maximum fuel saving potential of hybrid vehicles. It is also shown, that fuel consumption

of tractor semi-trailer vehicles, driven in their daily long haul application area, can theoretically be reduced with a parallel hybrid drivetrain.

The high usable power of Li-Ion batteries and electric motors extends the current possibilities of the driven auxiliaries, too. A combination of intelligent controllers and auxiliaries or the integration of the auxiliary operation strategy into the vehicle energy management system can lead to further fuel consumption reductions.

Introduction

Hybridization becomes more and more important in passenger cars and so commercial vehicle developers shouldn’t ignore this technological step. But there will be some difference in research between commercial vehicles and passenger vehicles because of their different application cases. Therefore, trucks with hybrid propulsion systems have different advantages in different driving situations. The following paper describes the potentials of hybrid heavy duty vehicles in their environments, the highways. The first chapter contains the generated vehicle model which is used for optimization in the further chapter. In the second chapter an optimization method for energy management of a hybrid vehicle will be presented. The simulation results which are made with this optimization are figured in chapter three. The potential of electrically driven auxiliaries in long haul vehicles is shown in the fourth chapter. Last but not least a summary and also an outlook will be given in the concluding chapter.

Modelling

To calculate the potential of fuel consumption reduction of heavy duty hybrid truck, a so-called backward or quasi-static model [1] is used. In a quasi-static model, torque demand and vehicle speed demand is defined at every time step in the simulation because these variables result from the predefined driving cycle.

The advantage of such a model is its simplicity and results can be generated very fast. This is necessary, because an optimization function would call the specific backward vehicle model very often. Hence, the calculation time will be reduced. Another advantage of the quasi-static approach (Figure 1) is that a driver's influence is eliminated. Without this driver's model influence the simulation results can be compared much easier. The single mass model is described in equation **(1)**

$$\begin{aligned} m_{Veh} \cdot \dot{v}_{Veh}(t) = F_{Trac}(t) - F_{AirRes}(t) - \\ - F_{ClimbRes}(t) - F_{RollRes}(t) \end{aligned} \tag{1}$$

where

$$F_{Trac}(t) = \frac{T_{Gbx,in}(t) \cdot i_{Axl} \cdot i_{Gear}(t) \cdot \eta_{Gear} \cdot \eta_{Axl}}{r_{Tir,dyn}} \tag{2}$$

$$F_{AirRes}(t) = \frac{\rho_{Air}}{2} \cdot A_{Veh} \cdot c_w \cdot v_{Veh}^2(t) \tag{3}$$

$$F_{ClimbRes}(t) = m_{Veh} \cdot g \cdot \sin(\alpha_{Climb}(t)) \tag{4}$$

$$F_{RollRes}(t) = m_{Veh} \cdot g \cdot a_{Roll} \cdot \cos(\alpha_{Climb}(t)) \tag{5}$$

are the traction and resistance forces.

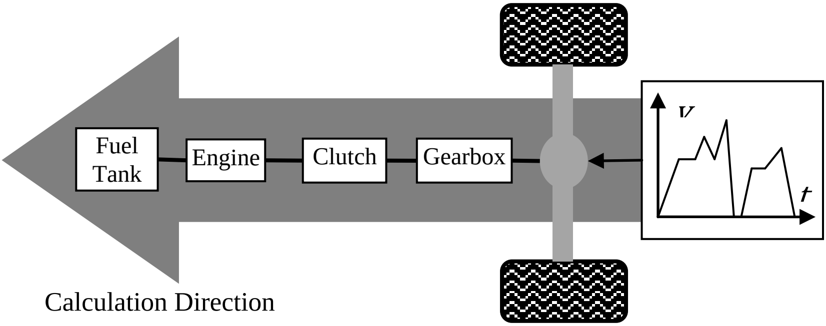


Figure 1: Backward Model

In case of a conventional model, the gearbox input torque ($T_{Gbx,in}$) is equal tothe engine crankshaft torque (T_{Eng}) presupposed the clutch is closed. The gearbox input torque ($T_{Gbx,in}$) of a parallel hybrid electric powertrain combines the engine torque (T_{Eng}) and the electric motor torque (T_{EM}):

$$T_{EM}(t) = u(t) \cdot T_{Gbx,in}(t) \tag{6}$$

$$T_{Eng}(t) = (1 - u(t)) \cdot T_{Gbx,in}(t) \tag{7}$$

with *u(t)* as the torque distribution coefficient which is furthermore needed in the optimization chapter. The maximum and minimum torque values of the engine and electric motor are limited, depending on their rotational speed values:

$$T_{EM,min}(n_{EM}) \leq T_{EM}(t) \leq T_{EM,max}(n_{EM}) \tag{8}$$

$$T_{Eng,min}(n_{Eng}) \leq T_{Eng}(t) \leq T_{Eng,max}(n_{Eng}) \tag{9}$$

As a result of an engine consumption map, the specific or absolute fuel consumption of a driving cycle can be calculated:

$$b_e(t) = f(T_{Eng}(t), n_{eng}(t)) \tag{10}$$

The aim of the optimization is minimum fuel consumption at a specific driving cycle.

The electric motor efficiency map couples the electrical power and the mechanical power of electric motors:

$$\eta_{EM}(t) = f(T_{EM}(t), n_{EM}(t)) \tag{11}$$

Hence, the electric current which charges or discharges the battery is defined as:

$$I_{EM}(t) = \begin{cases} \frac{T_{EM}(t) \cdot n_{EM}(t)}{U_{Bat}(t) \cdot \eta_{EM}(t)}, & \text{for } T_{EM}(t) \geq 0 \\ \frac{T_{EM}(t) \cdot n_{EM}(t) \cdot \eta_{EM}(t)}{U_{Bat}(t)}, & \text{for } T_{EM}(t) < 0 \end{cases} \tag{12}$$

where

$$I_{Bat}(t) = \begin{cases} \frac{I_{Aux}(t)+I_{EM}(t)}{\eta_{Bat,dischrg}} \text{ for } I_{EM}(t) >= -I_{Aux}(t) \\ (I_{Aux}(t) + I_{EM}(t)) \cdot \eta_{Bat,chrg} \text{ else} \end{cases} \quad \textbf{(13)}$$

$$U_{Bat}(t) = f(SOC(t), I_{Bat}(t)) \quad \textbf{(14)}$$

is the battery voltage depending on the load current (e.g. auxiliaries and electric motor, shown in equation

(13**)**) and the state of charge (SOC).

One bottle neck of a hybrid vehicle is the low energy saving capacity of the battery. Therefore the SOC of the battery must be monitored by every hybrid operation strategy. In most cases, this SOC is only allowed to move between small limits:

$$SOC_{min} \leq SOC(t) = \frac{Q_{Bat}(t)}{Q_{0,Bat}} \leq SOC_{max} \quad \textbf{(15)}$$

where Q_{Bat} is the actual capacity and $Q_{0,Bat}$ is the nominal capacity of the battery. The last equation needed for vehicle modelling is the relation between the battery capacity and the battery current:

$$\frac{dQ_{bat}(t)}{dt} = I_{Bat}(t) \quad \textbf{(16)}$$

These vehicle model equations are necessary for the following optimization.

Optimization

The next step after modelling is to combine the model with the optimization algorithm. Because of the huge amount of optimization parameters (for every time step, an optimal power distribution factor hast to be found), the Dynamic Programming Method (DPM) seems to be the most efficient way in an acceptable computation time. Therefore a modified DPM is used, shown in the equations **(17)** to **(23)**:

$$\min_{u(t)} J(u(t)) \tag{17}$$

s.t.

$$\dot{x}(t) = f(x(t), u(t), t) \tag{18}$$

$$x(0) = x_0 \tag{19}$$

$$x(t_{end}) \in [x_{end,min}\ ,\ x_{end,max}] \tag{20}$$

$$x(t) \in \mathcal{X}(t) \tag{21}$$

$$u(t) \in \mathcal{U}(t) \tag{22}$$

where

$$J(u(t)) = G(x(t_{end})) + \int_0^{t_{end}} H(x(t), u(t), t)dt \tag{23}$$

is the cost functional.

The reason for the modifications is that a problem must be discretized to use the standard DPM. But in case of a hybrid vehicle, states like *SOC(t)* or *u(t)* continuous and discretization produces aberrations. To minimize such aberrations of the problem’s limits, the DPM algorithm is extended. No further details will be explained in this paper of the DPM itself, because the extended DPM is documented in [2], [3] and [4].

In the one-dimensional optimization problem, described by equations **(17)** to **(23)**, the vehicle model can be found in equation **(18)** where *x(t)* is the current SOC of the battery. This model is discretised in the time *t*, power distribution factor *u(t)* and *SOC(t)* domain. The cost functional, whose result value should be minimized, is the cumulated fuel consumption calculation. Hence, the last time step has its own SOC limits because a comparison of fuel saving potential is valid, if SOC at the beginning is nearly equal to SOC at the end of the driving cycle. In the chapter “Simulation Results” the graph of the SOC limits can be seen.

A problem that must be solved in every truck drivetrain simulation is the gear shift strategy. The chosen gear depends on the vehicle mass which varies between curb vehicle weight (CVW) and gross vehicle weight (GVW). A factor up to five or even more between these two reference weights can occur. So the shifting strategy and therefore the engine operation points differ very much in a driving cycle, depending on the additional load. Hence, a second optimization problem occurs. A compromise between a fast calculation and a shifting strategy which is similar to the real driver's gear choice has to be found. The fast optimization is necessary because this gear ratio minimizing is an optimization in the DPM. Therefore, the highest possible gear that fulfils the current driving state seems to be a good compromise. Another option for choosing the gear ratio is to find the most efficient operating point in the engine's consumption map. This strategy needs much more time during the optimization operation and cannot be used in the hybrid vehicle if it is driven by the electric motor which has a lower maximum torque. One example is the gearbox which input speed can be lower than engine's idle speed at driveaway in a hybrid vehicle. The chosen shifting strategy can be used in case of driving with the electric motor or the engine, by only changing the optimization limits. These calculated gear ratios often result near the best engine or electric motor efficiency points and hence the disadvantage compared to the shown gear shift strategy is reduced. The equations for describing the optimization problem are:

$$\min_{i_{Gear}(t)} i_{Gear}(t) \qquad \textbf{(24)}$$

$$\begin{aligned}
&\text{s.t.} && \\
\frac{T_{Gbx,out}(t)}{i_{Gear}(t)} &\leq && \begin{cases} T_{Eng,max}(n_{Eng}(t)) \text{ for } n_{Gbx,in} \geq n_{Eng,idle} \\ T_{EM,max}(n_{EM}(t)) \text{ else} \end{cases} && \textbf{(25)} \\
0 &\leq && n_{Gbx,in}(t) = n_{Gbx,out}(t) \cdot i_{Gear}(t) \leq n_{Eng,max} && \textbf{(26)} \\
\frac{T_{Gbx,out}(t)}{i_{Gear}(t)} &\geq && T_{EM,min}(n_{EM}(t)) && \textbf{(27)}
\end{aligned}$$

Simulation Results

Simulation results are created for two cycles with a tractor trailer vehicle. One is the heavy-duty urban dynamic driving schedule (HUDDS) and the other is a part of a measured highway driving cycle (MHDC). Both cycles are simulated with CVW and GVW. The main vehicle parameters are described in Table 1.

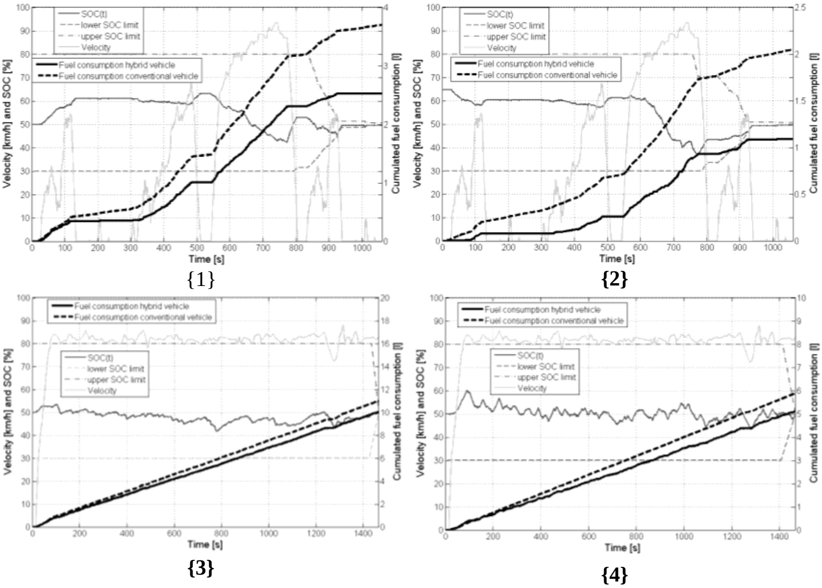
The following diagrams in Figure 2 show the SOCs and cumulated fuel consumptions over driving cycles with different weights. As mentioned, there is also fuel reduction potential in a long haul vehicle driven on the highway. The highest possible fuel reduction though is in the urban driving cycle without load due to bad engine operation points of the conventional drivetrain. In this case, the electric motor raises the engine operation points to a better efficiency area and its excessive power is stored in the electric energy storage system. Another advantage in the urban driving cycle is the possibility to use start/stop functionality, which avoids idle losses of the engine. The energy saving potential of such driving efforts is between 32% (GVW) and 47% (CVW) (see Figure 3)

	Conventional Drivetrain	Hybrid Drivetrain
GVW	40 to	
CVW	8 to	
Engine Power max	350 kW	
Motor/Battery Power Max (Motor Mode)	-	120 kW
Motor/Battery Power Min (Generator Mode)	-	-100 kW

Battery Energy Content Max / useable	-	4.7 kWh / 1 kWh
Gear Ratios * Rear Axle Ratio	[10.37 8.43 6.49 5.27 4.18 3.4 2.48 2.02 1.55 1.26 1 0.81] * [3.73]	

Table 1: Simulated vehicle parameters

The fuel consumption reduction at the MHDC results from the engine's phlegmatic behaviour. Hence, the engine operates in its most efficient range and the electric motor equalizes the difference between the power demand of current driving state and this efficient engine state. Energy saving potential at such application scenarios lies between 9% (GVW) and 14% (CVW). Because of long haul driving situation this relative small fuel reduction potential can reduce fuel costs measurably.



{1}

{2}

{3}

{4}

Figure 2: Driving Cycles:
{1} HUDDS GVW; {2} HUDDS CVW; {3} MHDC GVW, {4} MHDC CVW

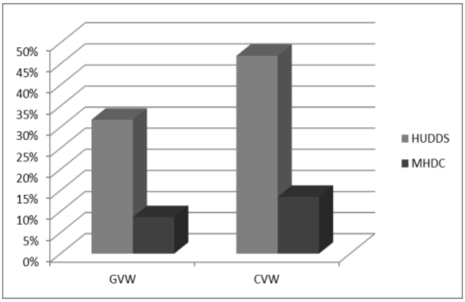


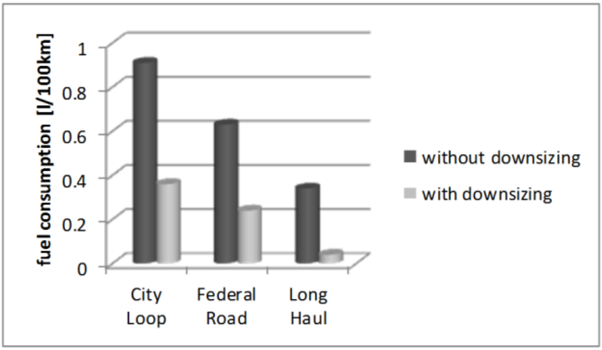
Figure 3: Fuel consumption reduction between conventional and hybrid vehicle

Auxiliaries

The high voltage level of the traction battery makes it possible to drive powerful auxiliaries electrically. Such auxiliaries are the hydraulic steering pump, the cooler fans, air compressor and A/C compressor. There is a high potential of fuel consumption reduction because of the additional degree of freedom for control (rotational speed), especially on highway cycles.

The following section of the paper takes a closer look at the hydraulic steering pump. By using a demand oriented control algorithm for the pump speed it is possible to reduce the hydraulic power of the system to a maximum value of 2.2 kW what makes it possible to operate the steering pump on the 24V electrical system of the hybrid-electric vehicle. The great advantage of the system’s downsizing – also for the use in a hybrid-electric vehicle equipped with a high-voltage on board power supply – is a reduced number of requirements regarding high-voltage safety. Furthermore the downsizing leads to potential savings regarding fuel consumption as shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

A detailed analysis on energy reduction of an electrified hydraulic steering pump and an electrified air compressor is given in [5]. The fuel saving potential of the electrified hydraulic steering pump is up to 0.5l/100km when driving on highway [5]. A similar result is published with air compressor results. In such a case, the benefit is about 0.9l/100km during a highway cycle.



Summary and Outlook

With this method it is shown that a hybrid tractor vehicle has a high theoretical energy reduction potential even during highway driving applications. The full fuel reduction result can normally not be realized but some driving states like recuperation on low downhill grades make energy recovery possible during long haul application. In general literature you can find a potential of 4-6 % fuel also for long haul applications with electric hybridization [6]. With the extended DPM it is shown that there is a bigger possible, theoretical gain of up to 9%. Because of high driving distances carried out with such vehicles, this amount of fuel savings leads to high cost reductions. In addition to an optimized and causal operation strategy for tractor trailer vehicles the energy reduction potential of the electrified auxiliaries reduces fuel consumption even more.

Further research will look for energy saving potentials due to electrification of other auxiliaries, like A/C-compressor and cooling fan. Nowadays cooling fans are coupled with the engine by a hydraulic clutch. This clutch generates losses due to slip and the fan speed is limited to the engine speed.

Similar problems occur at the A/C-compressor whose operation speed depends on the engine speed, too. Hence, these both auxiliaries have also potential for fuel consumption reductions, if they could be powered electrically, which is a lesser problem in a hybrid vehicle.

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