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Author(s):
Onder, Christopher H.; Ott, Tobias; Guzzella, Lino

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How Much Fuel Can a Hybrid Electric Vehicle Save?

Author and co-author(s) name(s)
Tobias Ott tobias.ott@idsc.mavt.ethz.ch
Prof. Dr. Lino Guzzella guzzella@idsc.mavt.ethz.ch
Dr. Christopher Onder christopher.onder@idsc.mavt.ethz.ch

Affiliations, author and co-author(s)
ETH Zurich, Institute for Dynamic Systems and Control

Abstract
A method is presented to calculate the lower bound for the achievable fuel consumption of a hybrid electric vehicle. The resulting minimal fuel consumption for various drive cycles is calculated and compared to a conventional vehicle. The influence of an increasing degree of hybridization is investigated and it is shown, that most of the fuel saving potential is achieved with a relatively low hybridization ratio of 20%.

Introduction
Hybrid electric vehicles (HEV) combine the excellent efficiency of electrical powertrains with the excellent travelling range of liquid or gaseous fuel combustion engines. They offer the potential to substantially reduce the fuel consumption and will therefore play an important role in the mobility of the future. This paper gives a detailed analysis on the fuel saving potential of HEV’s.

In a first step, the lower boundary for the achievable fuel consumption of a HEV is derived based on an idealized theoretical concept of a hybrid electric powertrain. The calculated fuel consumption for various drive cycles is compared to the consumption of a conventional powertrain.

In a second step, a more detailed model of a parallel hybrid powertrain is assumed. The influence of the various additional energy losses is investigated and the achievable fuel consumption is compared to the idealized case from the first part.

Minimum Fuel Consumption of a HEV

Vehicle driving resistances
The traction force ($F_T$) which is necessary to let the vehicle follow a given speed profile consists of four parts:

$$ F_T = \frac{1}{2} \cdot \rho_a \cdot A_f \cdot c_d \cdot v(t)^2 + c_r \cdot m_v \cdot g + m_v \cdot g \cdot \sin(\alpha) + m_v \cdot \frac{d}{dt} v(t) $$

The first part describes the aerodynamic drag where $\rho_a$ is the density of air, $A_f$ the frontal area of the vehicle, $c_d$ the aerodynamic drag coefficient and $v(t)$ the vehicle speed. The second part describes the rolling friction where $c_r$ is the rolling friction coefficient, $m_v$ the vehicle mass and $g$ the gravitational constant. The third part describes the uphill driving force where $\alpha$ is the road inclination angle. The last part describes the inertial forces.

It is important to notice, that the first two forces are dissipative, which means that energy is lost. In the case of uphill driving force energy is converted to potential energy and in the case of inertial forces,
the energy is converted to kinetic energy. The latter two forces are therefore not directly linked to an energy loss.

**Fuel saving mechanisms of a HEV**

The effects which lead to a lower fuel consumption of a HEV compared to a conventional vehicle can be separated into two main categories:

- **Recuperation**
  
  Kinetic and potential energy can be recuperated by the electric motor and stored in the battery for later use. Use of the friction brakes which would lead to an energy loss can be avoided.

- **Shifting of engine operating point towards higher efficiencies**

  The operating point of the engine can be shifted either to higher loads, by storing the additional energy in the battery or to lower loads which means to switch the engine off and drive purely electric.

  Due to the additional electric power, the internal combustion engine can be downsized while still meeting the peak power demand. This also leads to a shifting of the operating points towards higher loads.

  Elimination of idling losses can also be regarded as a shifting of the engine operating point.

**Perfect hybrid**

To determine the minimal achievable fuel consumption of a HEV, the concept of a “perfect hybrid powertrain” is introduced. It is characterized by the following properties

- The power of the electric motor is unlimited.
- The battery is unlimited both in capacity and power.
- The hybridization does not increase the mass of the vehicle.
- All electric components are perfect (efficiency of 1)

As a consequence, any energy spent for acceleration of the vehicle can be fully recuperated, the same holds for energy spent for driving uphill. The energy demand does therefore only depend on the dissipative parts of the driving resistances which are aerodynamic drag and rolling friction. Due to the unlimited power of the electric components and the unlimited capacity of the battery, operating point shifting of the internal combustion engine is unlimited and will therefore only be operated at its best efficiency point. If recharging of the battery from the electric grid is not considered, the fuel consumption is related to the energy simply by the peak efficiency of the internal combustion engine ($\eta_{\text{max}}$) and the lower heating value of the fuel ($H_l$).

For a given drive cycle which is characterized by its speed profile $v(t)$, the resulting fuel consumption per distance ($FC_{\text{Perfect Hybrid}}$) can simply be calculated by:

$$
FC_{\text{Perfect hybrid}} = \frac{1}{H_l \cdot \eta_{\text{max}}} \cdot \left( \frac{1}{2} \cdot \rho_a \cdot A_f \cdot c_d \cdot \frac{\int v(t)^3 \cdot dt}{\int v(t) \cdot dt} + c_r \cdot m_v \cdot g \right)
$$
Comparison of the perfect hybrid and a conventional powertrain

The concept of the "perfect hybrid" allows evaluating the potential of an electric hybridization for various driving situations. For all the following investigations, a compact car is assumed which is characterized by:

- vehicle mass \( m_v \): 1150 kg
- aerodynamic drag coefficient \( c_d \): 0.315
- frontal area \( A_f \): 2.05 m²
- rolling friction coefficient \( c_r \): 0.012
- Downsized and supercharged gasoline engine with a peak power of 80 kW and a peak efficiency \( \eta_{\text{max}} \) of 35%
- Dual-clutch gearbox with 7 gears.

The resulting fuel consumption for the MVEG-95, the “Common Arthemis Drive Cycle” (CADC) and for driving at a constant speed (50 / 80 / 120 km/h), can be seen in figure 1.

![Fuel consumption comparison](image)

**Figure 1: Fuel consumption comparison**

The length of the blue bar indicates the fuel consumption of the “perfect hybrid” whereas the length of the total bar indicates the fuel consumption of the vehicle with the conventional powertrain.

The fuel-saving potential of the hybrid vehicle is strongly dependant on the driving pattern. The largest reduction can be achieved in the urban parts of the drive cycles, which are characterized by a low average speed and frequent accelerations and decelerations. Compared to that there is almost no potential at a constant speed of 120 km/h.

The fuel consumption of the “perfect hybrid” is strongly dependant on the driving pattern. The consumption at a constant speed of 120 km/h for example is twice as high as the fuel consumption on the MVEG-95.

It has to be mentioned, that the concept of a “perfect hybrid” is idealized and purely theoretic, the calculated fuel consumption can never be reached by any real hybrid powertrain. However it serves as a lower bound and indicates the potential and limitations of electric hybridization.
Detailed Powertrain Model

To compare the results of the “perfect hybrid” with a more realistic hybrid powertrain, a more detailed model of a full parallel hybrid powertrain is assumed. Figure 2 schematically shows the investigated topology. It is a parallel hybrid powertrain with an additional clutch which allows decoupling the combustion engine from the powertrain. The gearbox is a 7 speed dual-clutch gearbox.

Figure 2: Topology of the Hybrid powertrain (Taken from [2], with modifications)

Additional losses

Compared to the idealized model of the “perfect hybrid” there are several additional sources of losses:

- **Non-optimal operating point of the internal combustion engine**
  The internal combustion engine is not always operated at its peak efficiency point. This causes additional fuel consumption.

- **Losses in the Battery**
- **Losses in the electric motor and the power electronics**
- **Losses due to conventional braking (friction brakes)**
  Due to the limited Power of the electric Motor and the battery and due to the limited capacity of the battery, kinetic and potential energy cannot always be fully recuperated.

- **Miscellaneous**
  There exist several other sources of additional losses. (Friction in the gearbox and the final drive, losses in the clutches …)

All these losses lead to an increased fuel consumption compared to the “perfect hybrid”, where all these components are assumed to be perfect.

Fuel consumption for a varying hybridization ratio

To investigate the influence of the hybridization, the fuel consumption is calculated for various hybridization ratios. The Hybridization ratio is defined as [3]:

$$HR = \frac{P_{\text{max electric path}}}{P_{\text{max ICE}} + P_{\text{max electric path}}}$$

The total Power, which is the peak power of the internal combustion engine plus the peak power of the electric motor, is kept constant at 80 kW. This ensures that the driving performance of the vehicle is kept constant.
The energy management strategy is determined using dynamic programming. This ensures that the minimum fuel consumption for any given hybridization ratio is obtained such that a “fair” comparison is possible. More details on dynamic programming can be found in [4]. Dynamic programming for vehicle applications is described in more details in [1, 3].

![Figure 3: Fuel consumption on the MVEG-95 for a varying hybridization ratio](image)

The results of the calculations for the MVEG-95 can be seen in Figure 3. The figure shows the fuel-consumption for a varying hybridization ratio. The consumption is split up into the consumption of the “perfect hybrid” and all the additional losses as described above. Two additional cases are calculated, namely the conventional powertrain and the conventional powertrain equipped with an additional start/stop-system.

For an increasing hybridization ratio, the fuel consumption can be reduced substantially. The minimum achievable fuel consumption is approximately 25% higher than the fuel consumption of the “perfect hybrid”. It can be seen, that the most important effect is the shifting of the operating point of the internal combustion engine. Recuperation of kinetic energy is less important in the MVEG-95. Some of the savings of these two effects are compensated by increasing losses in the electric motor and the battery.

The results of the calculations show, that most of the fuel saving potential is exploited with a rather small hybridization ratio of approximately 20%. For the given vehicle this leads to an internal combustion engine with a peak power of 64kW and an electric motor with a peak power of 16kW. A further increase of the hybridization ratio does only slightly reduce the fuel consumption, for hybridization ratios above 60%, the fuel consumption even increases.

![Figure 4: Engine operating points on the MVEG-95 for various hybridization ratios](image)
The resulting engine operating points for the conventional powertrain and three different hybridization ratios can be seen in Figure 4. The four figures show engine torque versus engine speed as well as the iso-efficiency lines. The resulting mean efficiency of the internal combustion engine is also indicated at the bottom.

The mean efficiency of the internal combustion engine in the conventional powertrain is already rather high. This is due to the fact, that the engine is downsized and supercharged, which has proven to be an effective way to improve the mean efficiency of an internal combustion engine [2]. As expected, the mean efficiency increases with an increasing hybridization ratio. The largest increase is observed for the first 10% of hybridization. The reason is that most of the operating points at very low load, where the efficiency is low, can already be avoided by driving purely electrically in these situations.

**Fuel consumption on the drive cycles**

It has been shown, that most of the fuel-saving of a HEV can already be achieved with a rather low hybridization ratio of 20%. In Figure 5 the fuel consumption for this hybridization ratio is compared with the fuel consumption of the conventional vehicle and with the fuel consumption of the “perfect hybrid”. The drive cycles which are considered are the same as in Figure 1.

![Figure 5: Fuel consumption for the hybrid powertrain. (Hybridization ratio 20%)](image)

In most cycles, the consumption of the hybrid with 20% hybridization ratio comes relatively close to the consumption of the “perfect hybrid”. The concept of the “perfect hybrid” is therefore a good method to estimate the potential of an electric hybridization.

**Conclusion**

The fuel saving potential of hybrid electric vehicles is strongly dependant on the driving pattern. For urban driving conditions the potential is large, whereas it is almost zero at highway conditions.

In the MVEG-95, shifting of the engine operating point is more important than the capability of energy recuperation.

Most of the fuel saving potential of an electric hybridization is achieved with a relatively low hybridization ratio of 20%.

The concept of the “perfect hybrid” has proven to be a good method to estimate the fuel-saving potential and limitations of an electric hybridization.
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