Abstract
This study quantifies fuel savings and conditions for the application of coasting phases, i.e. the vehicle rolling without traction force in an automated driving strategy, herein named economic cruise control ECC. Under the presumption of a driver input lead velocity and a limit of acceptable delta speed deviation, fuel savings can achieve values of 5% to just above 10% on highways traveling with a conventional, non-hybridized powertrain, assuming that the ICE is stopped upon coasting. Lower mean speed driving yields relatively higher savings. Reference is constant speed driving at the identical mean velocity, such that an ECC function may obtain somewhat higher savings in real traffic environment. For a first version of driving and powertrain control strategy it could be shown, that the fuel economy of a hybridized powertrain can benefit from coasting, too.

For the initiation of the coasting phase, a criterion has been derived by defining a ‘coasting preview length’ CPL function, which can be analytically calculated at each point of the road, if its altitude profile is known. Since downhill coasting seems to be the naturally acceptable case, the CPL function shows a rather sharp increase when approaching the hill summit. The point of inflection of the CPL function was identified as criterion for the earliest reasonable point to start coasting.

Introduction
Though fuel prices showed certain intermediate decreases in the past due to modern methods of hydrocarbon exploitation and global economic developments, a general tendency to rising fuel costs can be expected for the future. Hence efficiency will remain a crucial requirement for any product of the automotive industry. Furthermore a strong drive to minimize fuel consumption is brought about by legal limitations such as the ‘Corporate Average Fuel Economy’ in the US or the 95 € imposed by the European Union monetarising each g CO\textsubscript{2} emissions. Classical approaches such as more efficient powertrain systems and designs for reduced vehicle weight and drag stay promising and receive considerable investments. However, non-conventional measures such as systems assisting drivers to employ more efficient ways of driving become more attractive for industry, consumers and researchers. Often they are referred to as ‘eco-drive’ or similar.

The traditional test procedures to measure fuel consumption such as the NEDC in Europe or the US FTP do not capture all relevant driving conditions: For instance, considerable parts of engine loads and vehicle velocities are excluded or only integrated in minor percentages. There is recently a global development towards more realistic or demanding test procedures, either nationally or with the aspect of global standardization, leading to a WLTP. However, these advanced test procedures continue to be defined on flat road profiles. Thus, the considerable percentage of road traffic having uphill and downhill stretches will not be included explicitly. This study should contribute to quantify positive effects on fuel consumption, if the road profile was integrated reasonably into the driving strategy.

The basic idea is to apply phases of coasting on downhill parts of the road. Here coasting is understood as the vehicle rolling without any positive (=driving) or negative traction force. Some recent contributions from automotive industry deal with coasting as a part of future strategy to improve users’ fuel economy, e. g. [1] and [2]. With conventional, non-hybridized ICE-driven powertrains actually in series, coasting means the ICE idling at low rpm due to the powertrain disengaged either by the clutch or neutral gear. This coasting operation is to separate from overrun conditions with engaged gear and the ICE at higher rpm defined by the total transmission ratio and the vehicle speed.

Start-stop-systems are widely common today, which shut off an ICE at or close to zero vehicle speed. And the electrification of auxiliaries is coming up providing many perspectives. Thus conventional powertrain systems which may stop an ICE also
at higher speed are announced for the near future, 2014 [3]. Furthermore, for manual transmission systems dominating some passenger car markets, development is ongoing to establish clutch-by-wire technology [4], which would enable an automated coasting strategy without taking off the established MT handling from the car. On the other hand, widespread automatic transmissions have already realized a disengagement of the powertrain and even ICE stop, introduced in their hybrid versions in today’s series [2].

Criteria for Coasting

Methodology and Assumptions
Modeling calculations in this study are performed either by the commercial software “CRUISE” of AVL List GmbH or by calculation in a personal computer based spreadsheet. A step width of 10 m was applied and regarded sufficient since fuel efficient driving at highway speeds above 70 km/h can be reduced to the use of highest gear and entails rather low longitudinal dynamics, herein commonly below 1 m/s².

Reference Vehicle
This research project “ECC” includes on-road vehicle testing as it has been documented in [5]. So the simulation results of this contribution are basing on a virtual car of the same type: Ford (of Europe) Focus Sedan 5-door with 1, 6 T ecoBoost 110 kW 6-speed MT model year 2012. It is equipped with a modern turbo-charged 4 cylinder gasoline DI-engine as moderate downsizing concept. This motorization provides decent power reserves at the regarded traveling speeds of 70 to 130 km/h and road gradients.

The reference data of table 1 enters the following simulations.

Table 1. Data of reference vehicle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Power</td>
<td>110 kW @ 5700 min⁻¹</td>
</tr>
<tr>
<td>Max. Torque</td>
<td>240 Nm from 1600 to 4000 min⁻¹ constant</td>
</tr>
<tr>
<td>Displacement</td>
<td>1596 cm³</td>
</tr>
<tr>
<td>Mass</td>
<td>1362 kg (including driver and fuel)</td>
</tr>
<tr>
<td>Drag</td>
<td>0,678 m² (Cw x A crosssec. 0,30 x 2,26 m²)</td>
</tr>
<tr>
<td>Air density</td>
<td>1,2 kg/m³</td>
</tr>
<tr>
<td>Rolling friction factor</td>
<td>0,01 independent of velocity</td>
</tr>
<tr>
<td>Total efficiency powertrain</td>
<td>0,95</td>
</tr>
<tr>
<td>Transmission Ratio 6ₜ, Gear</td>
<td>2,636 = 0,59 x 3,82; 43,7 km/h @ 1000 min⁻¹</td>
</tr>
<tr>
<td>Rotational masses factor lambda</td>
<td>1,03</td>
</tr>
<tr>
<td>Top Speed</td>
<td>210 km/h</td>
</tr>
<tr>
<td>Consumption MNEDC</td>
<td>5,9 l/100km (combined: 137 g CO₂/km)</td>
</tr>
<tr>
<td></td>
<td>7,6 l/100km (urban)</td>
</tr>
<tr>
<td></td>
<td>4,9 l/100km (extra-urban)</td>
</tr>
<tr>
<td>Low Idle fuel consumption</td>
<td>0,57 l/h</td>
</tr>
</tbody>
</table>

Fuel Consumption Map
This study is based on a generic map of fuel consumption such that it can be easily adapted to different motorizations. This approach is following studies of Rohde-Brandenburger [7, 8]:

\[
\hat{V}_{zeroP,1L} = 6 \cdot 10^{-8} \cdot rpm^2 + 2 \cdot 10^{-4} \cdot rpm + 1,6 \cdot 10^{-1}
\]

(1)

The absolute term has been increased for this study from 1,29·10⁻¹ l/h in order to fit the data taken from the reference vehicle. This value \(\hat{V}_{zeroP,1L}\) is essential to understand why coasting may save fuel even when the engine is idling: For this engine operating at 3000 rpm, already 2,1 liter of fuel is consumed just to keep the engine at its speed, without yielding any mechanical output power. Hence, lowering the engine speed to an ordinary low idling just below 800 rpm reduces this part of fuel consumption to 0,57 l/h, such that the effect of fuel cut-off by overrun operation is often over-estimated, while overrun constantly draws energy out of the running vehicle. This expresses the well-known fact, that any ICE tends to operate with diminishing efficiency at high rpm and low loads.

Following [8], many gasoline engines show a fixed value of 0,27 l/h per kW for the fuel consumption just for the increase of power output, shown as the constant gradient curves in the Willans line diagram. Since Rohde-Brandenburger focused on NEDC operation at low engine loads, he limited his analysis to this linear characteristics. This study, however, requires engine operation also at higher loads. So it has been chosen an additional third order approach leading to

\[
SFC = \left(\frac{\hat{V}_{zeroP,1L}}{P_c} + 2,7 \cdot 10^{-1} \cdot \frac{l}{h \cdot kW} \right) \cdot \rho_{fuel} + 3 \cdot 10^{-3} \cdot \frac{g}{kWh \cdot bar^3} \cdot P_{me}^3
\]

(2)
This equation leads to the SFC values as shown in the isoline diagram in figure 2 for the relevant rpm area. Key values are given in table 2.

Figure 2. Map isolines for specific fuel consumption in the relevant range of ICE operation

Table 2. Key values of specific fuel consumption SFC map

<table>
<thead>
<tr>
<th>Operation point</th>
<th>SFC in g/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>(rpm / bar p_{\text{bar}})</td>
<td></td>
</tr>
<tr>
<td>2000 / 2</td>
<td>287,6</td>
</tr>
<tr>
<td>2000 / 6</td>
<td>296,6</td>
</tr>
<tr>
<td>2000 / 10</td>
<td>244,7</td>
</tr>
<tr>
<td>2000 / 14 (best)</td>
<td>239,5</td>
</tr>
<tr>
<td>2000 / 18</td>
<td>243,0</td>
</tr>
<tr>
<td>3000 / 2</td>
<td>402,8</td>
</tr>
<tr>
<td>3000 / 6</td>
<td>271,7</td>
</tr>
<tr>
<td>3000 / 10</td>
<td>247,7</td>
</tr>
<tr>
<td>3000 / 14,5 (best)</td>
<td>241,6</td>
</tr>
<tr>
<td>3000 / 18</td>
<td>244,7</td>
</tr>
</tbody>
</table>

These characteristics may underestimate the SFC increases under maximum engine load operation due to fuel enrichment, especially for downsized turbo-charged engines. For the purpose of a fuel efficient driving strategy this operation area has to be avoided anyway. According to previous studies with varying SFC mappings [6] the best fuel consumptions are achieved with accelerations around 60% of maximum engine loads i.e. effective torques, which has been chosen as the standard value for vehicle accelerations within this study.

Reference Road Profiles

The use of navigation data, especially altitude profiles, for improving fuel efficiency has been dealt with previously, e.g. [9]. This study aims at a quantification of the effect of coasting on downhill road passages under defined circumstances. Hence two profiles have been chosen as references, displayed in figure 3. One hill is named “flat” with maximum slopes of 2,5 % and a total altitude difference of 27,2 m over a length of 4 km. The top of this hill is exactly at half the total length. The other “steep” hill reaches gradients up to 6,2 % with an altitude difference of 41,4 m. This hill profile is complete at its starting altitude after 2330 m. In this study the reference track named “steep hill” is extended by a flat track to the equal total length of 4 km.

Both reference hills were composed symmetrically by mirroring a real profile from hilly German motorway A81 between exits Heilbronn-Untergruppenbach and Pleidelsheim north of Stuttgart, basing on data from the LGL (office for geoinformation of the state of Baden-Württemberg). This three lane motorway had been completely rebuilt in the 1980s, such that its profile may be taken as a sample applying modern highway tracing. This selection should enable the deduction of general principles for the use of downhill coasting phases to save fuel: roads with steeper gradients exist, especially in mountainous areas. They would require additional braking to limit driving speeds to safe values, thus going beyond the scope of this work. Many international multi-lane long distance freeways tend to limit their maximum gradients to these values around 6 % with few exceptions. The “flat” hill shows potentials for coasting at typical road profiles for hilly areas.

Assumptions for the Validation of Driving with Coasting

Scope of this study is the field of long distance driving with passenger cars or light duty vehicles. Therefore two reference velocities are chosen: 120 km/h (74,6 mph) should represent travelling on a multi-lane freeway type road, whereas 90 km/h (55,9 mph) stands for overland driving on single lane highways under limited speed conditions. In order to derive conclusions for the pure effect of integrating coasting phases into the driving strategy, this study relies on this quite ideal environment. Real circumstances such as occasions of necessary decelerations due to speed limits, road curvature or traffic situations will pose additional conditions. However, if a coasting strategy were once integrated in the general driving strategy it can be deduced that coasting can as well contribute to fuel efficiency at situations of externally required decelerations. This consideration is valid for the slower traffic in congested urban areas, too, especially if communications car-to-infrastructure or car-to-car were taken into account. The quantification of coasting benefits under these conditions goes beyond this study, too.

The higher average travelled distances for those vehicles of the population, which are dominantly used in freeway and overland riding, render an improved fuel efficiency to contribute considerably to the integrative progress of slowing down
depletion of resources and emission of greenhouse gases. Furthermore, an efficient use of coasting may benefit the fuel efficiency of hybrid vehicles especially in highway conditions, where their advantage today shows to be less impressive than in urban driving. Lee [10] showed perspectives in this field, though he did not take the road gradient profiles into account.

On a vehicle with manual transmission such as the reference car of this project, coasting with the engine idling can be realized by shifting to neutral in many circumstances without endangering the traffic environment. Some cars in series production with conventional powertrains, e. g. VW Passat blue motion technology with dual clutch gearbox, offer coasting features such that the engine does not go to overrun when the driver releases the acceleration pedal completely but disengages the powertrain and make the car coast [11]. Also on widespread torque converter type automatic gearboxes coasting functions may be integrated, being reality in their hybridized vehicle applications, e. g. Daimler’s S350 hybrid [2].

Beyond the driver dependent initiation of coasting the main focus of this project is to investigate possibilities of an automated driving strategy, herein named ECC for Economic Cruise Control. This work should contribute by establishing criteria when and how to realize this ECC idea for maximum benefit.

One main assumption is related to the aspect of velocity variation. Unlike classical cruise control CC known for decades, any reasonable ECC function will have to include a certain variation of its actual speed. Nowadays this is state of the art because ACC functions with radar based distance sensing are common which automatically decelerate and accelerate the car, too.

The basic idea for an ECC function still starts with a setpoint value for vehicle speed, either manually set by the driver or imposed by autonomous sensing systems such as traffic sign identification, distance radar, navigation or even car-to-car or cloud data.

Additionally the straightforward approach for any ECC functionality appears to set maximum delta values for the speed variation. One central argument is the acceptance of such a function: if the driver set the command velocity to 100 km/h, it may be assumed that a speed variation between e. g. 103 km/h and 95 km/h would be accepted in most cases. Presumption thereby is the low dynamics of acceleration in top gear and deceleration by coasting. A car varying autonomously its speed between 60 km/h and 130 km/h when the setpoint speed was 100 km/h, unless forced to by traffic circumstances, will presumably not gain positive reactions by owners. Hence, the values of speed deviation seem to be a crucial parameter for ECC function development.

As shown in the preliminary studies within this research project [5], [6] and by other authors, e. g. [1] fuel savings by coasting are around 5 % in many cases. Savings can reach values above 10 % under favorable circumstances. These values appear limited or even marginal. Comparing to the efforts of reducing energy losses or weight of vehicle components, the expenditures to realize an ECC functionality seem to be still well worth considering.

These limited values of realistic fuel saving by coasting lead to the conviction that this study as engineering/physical quantification of fuel savings must be based on constant mean velocity cases, since saving fuel by driving less fast is a trivial fact. Table 3 quantifies this dependency for the reference cases of this study: Around 90 km/h, 5 % deviation in mean velocity gives almost 5 % change in fuel consumption, while the same relative change from the mean velocity even alters fuel consumption by more than 6 %. Values for the hill type “steep” differ very little from the values shown here. So fuel savings of some percent may only be proven if it is certain that the mean speed remains constant.

<table>
<thead>
<tr>
<th>profile</th>
<th>v.mean / km/h</th>
<th>FC in l/100km</th>
<th>delta FC %</th>
</tr>
</thead>
<tbody>
<tr>
<td>hill „flat“</td>
<td>86,5</td>
<td>4.244</td>
<td>- 4,6%</td>
</tr>
<tr>
<td>hill „flat“</td>
<td>90</td>
<td>4.444</td>
<td>0</td>
</tr>
<tr>
<td>hill „flat“</td>
<td>94,5</td>
<td>4.656</td>
<td>+ 4,8%</td>
</tr>
<tr>
<td>hill „flat“</td>
<td>114</td>
<td>5.702</td>
<td>- 6,0%</td>
</tr>
<tr>
<td>hill „flat“</td>
<td>120</td>
<td>6.066</td>
<td>0</td>
</tr>
<tr>
<td>hill „flat“</td>
<td>126</td>
<td>6.450</td>
<td>+ 6,3%</td>
</tr>
</tbody>
</table>

On the other hand it should not be precluded as second order effect that any eco-drive function such as ECC might entail a certain slowing down as additional contribution to the perceived fuel savings, being crucial for the acceptance and economic success of such a function. This question, however, goes well beyond the engineering focus of this study to questioning aspects of traffic psychology.

**Scenarios of Coasting**

**Starting Point Optimization for Coasting without Prior Boost Acceleration**

The first criterion to be identified is the point of starting the coasting phase. Figure 4 shows possible velocity profiles on the flat reference hill for a mean velocity of 90 km/h, varying from starting well ahead of the summit at 2000 m to points already on the downhill stretch of the hill profile. Outside the coasting phase the vehicle speed has been maintained constant. The value has been taken as degree of freedom in order to fulfill the requirement of identical mean velocity. Hence, for the shorter coasting phase at the earliest starting point 1800 m this constant speed is somewhat lower.

Figure 5 displays the effect on fuel consumption in two curves: the higher one gives the values if the ICE was kept idling in the coasting phase. The minimum FC of 4,28 l/100km is equivalent to a fuel saving of 3,8 %. The lower red curve shows fuel consumption with the assumption of an engine start-stop system including 400 μl fuel needed to restart the warm engine. Its minimum reaches 4,09 l/100km, meaning 8,0 % of fuel saving compared to the fuel consumption at constant speed of 4,44 l/100km.
Interestingly these savings do hardly depend on the point where the coasting phase was initiated. The minimum in fuel consumption has a very flat characteristic. Only if coasting is started too early, here at 1800 m, the fuel economy is significantly worse. This mostly quite plane curve enables to apply an automated ECC driving strategy such that the initiation of coasting may be taken as a certain degree of freedom, for instance letting it depend on traffic circumstances, without trading in much of the saving benefit.

This statement remains unchanged, regarding driving a lot faster over the "steep" reference hill with otherwise identical circumstances, given in figure 6. The minimum fuel consumption follows once again has a very low curvature, so any automation may profit of this degree of freedom. Only in case the coasting starts too early, the fuel consumptions show a step characteristic trading in all saving potentials.

In figures 5 and 6, values of the relative length of the coasting phase are depicted, too. For the flat hill in figure 5, the length of coasting phase yields a good correlation to the fuel consumption: the longer the car is coasting at low idle or engine stop, the less fuel is consumed by the part needed to keep the ICE at the higher rpm without creating power output. For the steep hill, shown in figure 6, this tendency prevails only for the late starting point of coasting. If it was initiated to early, the fuel consumption slightly increases although the coasting phase reaches the highest values.

Figure 6 is showing the velocity profiles of the case of figure 6. It gives an explanation for this effect: the long coasting phases starting early (curve for 1020 m) require a significantly increased constant speed value for the other parts of the model hill, depicted as higher velocity split values in figure 6, too. Once again this higher speed level is derived from the requirement to drive the 4 km stretch at constant mean velocity. Hence, these increased speed parts lead to more than proportional increased driving resistances due to the velocity squared dependency of the drag.

Figures 6 and 7 depict a special feature of the steep hill drive: For the starting points at 970 m and before, the coasting phase ends even before the steepest downhill parts are reached, where the rolling car gets accelerate just by gravity. With this short coasting phase, the controlled constant speed outside the coasting phase remains lower. However, shown in figure 6, the fuel saving effect is drastically reduced.

These findings strengthen the general tendency that an extension of coasting phases to its maximum benefits the fuel saving potential.
Coasting Preview Length CPL as Criterion to Initiate Coasting Phases

From the previous paragraph it was learned that there is a rather determined point before which a coasting phase should not be initiated. For an application of an automated ECC function under the condition of a known road profile, a general ‘rule’ to identify this point would be a key criterion. A further demand will be that such a rule would not require much of the calculation resources in any ECU, since they are still limited in spite of tremendous power enhancements because of broadened functionalities, e. g. for OBD purposes.

A simplified energy balance of the vehicle rolling without tractions force may be taken as basis for such a rule:

\[
\int F_{res} ds = \frac{1}{2} m_j \left( v_f^2 - v_i^2 \right) + m g \left( h_f - h_i \right) \tag{3}
\]

With the driving resistances

\[
F_{res} = m \cdot g \cdot f_r + \frac{P}{2} \cdot c_w \cdot A \cdot v^2 = k_r + k_d \cdot v^2 \tag{4}
\]

and the kinetic Energy (\( m_j \) stands for the mass increased by the factor \( \lambda \) accounting for the rotating masses)

\[
\Delta E_{kin} = \frac{1}{2} m_j \left( v_f^2 - v_i^2 \right) = \frac{1}{2} m_j \cdot \Delta v \cdot \left( v_f + v_i \right) = m_j \cdot \Delta v \cdot v_{max} \tag{5}
\]

It leads to a differential equation

\[
ds = \frac{m_j \cdot \Delta v \cdot v + m \cdot g \cdot dh}{k_r + k_d \cdot v^2} \tag{6}
\]

which is solved by stepwise numerical integration to yield

\[
CPL = s_{CP} - s_0 \tag{7}
\]

Coasting preview length CPL is determined at each point \( s_0 \) under the boundary conditions of known velocity \( v(s_0) \) and altitude function \( h(s) \) and limited by a given maximum value of \( \Delta v \). [11] In praxis this maximum speed deviation \( \Delta v \) is determined as a minimum speed value: As shown in the previous paragraph, longer coasting phases support fuel savings, whereas the lowest speed where to finish the coasting phase appears to be crucial parameter for the acceptance of driving strategy with coasting.

Figure 8 shows the CPL as function of \( s_0 \) in the relevant area over the flat reference hill. For a constant speed of 90 km/h when starting to coast, different graphs depict the influence of allowed minimum speeds. Evidently the coasting phase becomes longer with decreasing minimum speed. And there is a maximum in coasting lengths slightly advancing from points behind the top of the hill.

Most helpful, however, appears to be the sharp rise in CPL values before its maximum. This coincides with the drastically increasing coasting lengths in the velocity profiles of figure 4 and the relative coasting times shown in figure 5, providing the earliest starting point for the coasting phase to yield good fuel savings. Regarding the comparable CPL curve for a minimum speed value of 80 km/h in figure 8, the optimum point to trigger the coasting appears to be the point of inflection of the CPL function. The change of gradient in stepwise on-board calculation of CPL is judged as easily being identified.

Figure 9 gives the CPL curves for the higher average velocity of 120 km/h, with adapted minimum speed values. The global characteristics prevail: The maxima of CPL increase and move forward for increasing velocity deltas. Once again, for each assumed minimum speed there is a well identifiable point of deflection in the CPL curve, with good coincidence to the earliest starting point where a coasting phase would pay off.

Figure 10 displays the case of fast driving over the steep hill, where the characteristic is somewhat strengthened, showing sharp rises of the CPL curves. Their deflection point coincides with the point of early starting the coasting phase, as discussed the values around 1000 m at figure 7.
Besides the starting point the CPL function seems to yield a criterion whether it would be worthwhile to start coasting at all: if the downhill stretch was short and with little road gradient, the first derivative dCPL/ds would stay small such that a limit on its value may serve as borderline, in order not to stress vehicle components or drivers with too many short coasting phases.

**Velocity Delta Dependency**

In the first paragraph varying the starting point of the coasting phase already different velocity deltas were observed due to the prerequisite that the mean velocity must be kept constant. However, the minimum speed was not changed. In figure 11 the velocity profiles are depicted depending on this parameter: lower minimum speeds entail longer parts coasting at rather low velocities. To maintain the mean speed this has to be balanced by considerable increased constant speeds beyond the coasting phase, reaching a value above 100 km/h already for 70 km/h as minimum speed.

**Benefits of Boost Accelerations Before Coasting**

In figure 13 different realizations of a boost before coasting is displayed, identified by their minimum velocities, whereas figure 14 gives their fuel consumption results. First of all it is found that with the help of boosting the constant speed entering and leaving the hill drive can be set to the desired mean speed and still the coasting reduces the fuel consumption noticeably: for a limited velocity delta, taking 80 km/h as minimum speed, the fuel consumption is reduced by 8.7%.

A further point must be discussed about figure 11: the assumed constant speed values outside the coasting area may be contradicting drivers’ expectancy as well: for a mean velocity object of 90 km/h, referring to the classical cruise control function, it will not be convincing to be forced to travel outside the coasting phase with significantly higher speed. Though this deviation would be lower if the considered distance was extended to more than 4 km, it seems reasonable to compensate in the direct environment of the coasting phase for the parts of coasting at speeds below the mean value. This leads to the point whether it would be useful to accelerate just before initiating a coasting phase. This approach is referred to as ‘boosting’ within this study.
Figure 14. Fuel consumption, relative coasting time for coasting with preceding boosting

As it has been observed before with no boosting, lowering the velocity split by increasing the minimum speed, the fuel economy deteriorates. Even the additional idea of a subsequent second boosting and coasting phase does not seem completely convincing. Though the fuel savings improve, as the coasting part riding with low idling or zero rpm increases, a higher frequency of changing coasting and boosting must be seen critical: will drivers accept this behavior, even though the zigzag characteristics of the speed do not mean uncomfortable and shaky driving because of the low dynamics of deceleration and acceleration in the top gear at 60% engine load, which is comparable to established accelerations in automated cruise control systems? Besides the aspect on the passenger cars, vehicle subsystems such as starter motors and exhaust gas treatment would profit not only in lifetime, if they were started and shut down less often.

At the opposite side regarding large delta speed, figures 13 and 14 show rather little effect by varying the point of boosting start: The values for the minimum speed of 71, 9 km/h and 72, 5 km/h, respectively, do not mean significant differences in fuel savings, although the later starts boosting already at 1720 m, 270 m earlier than the standard starting point.

Hybridization Modeling and Simulation Results

The objective of the hybrid vehicle simulation study presented in this section is to give a first outline for additional benefits considering coasting at hybrids. The downhill potential energy can be either used to charge the battery by an electric machine, e.g. the operation strategy BMW ActiveHybrid 5 [13], or directly used to overcome the driving resistance by coasting [12] which is supposed to be more efficient due to the higher efficiency in the powertrain. For that case a preliminary coasting strategy is simulated herein.

Hybridization Modeling

The reference vehicle Ford Focus is virtually hybridized by adding the electrical drive axle on the vehicle rear axle. Figure 15 shows the configuration of this hybridization. An additional clutch connects the ICE and one electric machine “Generator”, which enables the battery charging by ICE. The other electric machine “E-Motor” is directly connected with the rear axle, which can either deliver the traction power or charge the battery by braking energy recuperation.

Figure 15. Hybridized reference vehicle powertrain configuration

The characteristics of the main additional powertrain components are given in Table 4. The two electric machines share the same specification.

Table 4. Characteristics of the additional hybrid components

<table>
<thead>
<tr>
<th>Component</th>
<th>Main Characteristics</th>
</tr>
</thead>
</table>
| Generator/E-Motor | Type: asynchronous machine (ASM)  
max. Rotational speed: 7500 1/min  
max. Torque: 240 Nm @ 3000 1/min |
| Battery | Type: NiMH  
Capacity(cell): 5 Ah  
Nominal voltage(cell): 7.2 V  
Number of cells per row: 40  
Number of rows: 7 |

Simulation Method

The “steep” hill profile is simulated in AVL Cruise for two average driving velocities, 120 km/h and 90 km/h. The road profile is divided into three sections: section 1 uphill, section 2 downhill and section 3 flat. As shown in Figure 16, 10 cases are simulated, which consider different hybrid operation modes in the three sections. Case 1 is a simulation of the conventional Ford Focus. Case 2 is pure electric vehicle driving simulation. In Case 3 to 8 the vehicle power is delivered either only from ICE or from E-Motor in one complete section. In section 3 of case 9 the ICE mode is involved for the battery SOC balance. And the coasting is considered in case 10. The Case 1 to 9 are constant velocity driving. In case 10 there is velocity variation due to the coasting.

The hybrid vehicle operation modes and corresponding ICE and electric machines ON/OFF states are shown in Table 5. The operation point shifting strategy is applied in the ICE mode. If the desired ICE load is less than the optimal load at current rotational speed, the operation point is shifted to the optimal operating line with the same rotational speed. This is also called “load point increase”. In this case, the ICE output torque is increasing. The ICE takes over all the propulsion power and deliver additional power to charge the battery via the Generator.
Simulation Results

The simulation results of the hybridized Ford Focus are summarized in Table 6, which lists the fuel consumption (FC), battery electrical energy consumption (EC) and equivalent fuel consumption (eq. FC) of each case. The equivalent fuel consumption is calculated by the sum of actual ICE fuel consumption and the converted ICE fuel consumption for battery charging to cover the electrical energy consumption. Equation 8 shows this fuel consumption conversion.

\[ \text{eq. } FC = \frac{EC}{\eta_G \cdot \eta_B} \cdot \frac{SFC_{opt}}{\rho_f \cdot D} \cdot 100 \]  

(8)

Where \( \eta_G \) is the efficiency of the Generator, \( \eta_B \) is the efficiency of the battery, \( SFC_{opt} \) is the engine optimal specific consumption, \( \rho_f \) is the fuel density (0.76 kg/L for gasoline), and \( D \) is the distance (4km).

The battery will be charged to high SOC level or even overcharged if the vehicle was powered by ICE more than one section, see case 4, 6, and 7. Due to the less energy requirement of velocity 90 km/h comparing with 120 km/h, the battery is also at relative high SOC level by ICE operating in the longest section 3, see case 8. However, only one section ICE powering causes an amount of battery discharging energy, see case 2, 3, and 5. In that case, the vehicle is set to the ICE mode for section 1 and part of section 3 to balance the battery SOC, see case 9 and 10. The fuel consumption improvements comparing with conventional vehicle (Case 1) are shown in Figure 17. The remarkable improvement is given by Case 6. Comparing with the ICE, the E-Motor has higher efficiency in downhill section due to the low desired traction torque. Furthermore, in order to balance the battery SOC, the reduced ICE mode operating time is applied in Case 9, which has relative high fuel consumption improvement. As it was shown in the first paragraphs of this study, the conventional vehicle fuel consumption benefits from downhill coasting. Case 10 involves a coasting mode in the downhill section, which shows more fuel consumption improving potential also for the hybrid vehicle.

The simulation detailed results of case 9 and case 10 with average velocity 120 km/h are taken to be the example. The velocity variation and the torque maps of engine and two electric machines are shown in Figure 18.
As it is shown in Table 6 and Figure 17, for 120 km/h average velocity the coasting improved the fuel consumption up to 6.49%, which is 3 % more than for constant driving (Case 9). And the improvement for lower average velocity 90 km/h driving is as high as 10.52 %.

From the hybrid simulation result the following conclusions:

- Traction by the E-Motor during high torque demand causes high equivalent fuel consumption due to the low efficiency of the energy path, which from ICE to battery and then further to electric machine.
- The potential energy of the downhill road offers the benefit to fuel consumption improvement of the hybrid vehicle. It is more efficient to use this potential energy by coasting than by energy recuperation.
- Comparing with the 120km/h, the lower average velocity 90km/h can benefit more from the downhill coasting.

Conclusions

1. By coasting on highways passenger cars can achieve fuel savings up to 10 % at a constant mean velocity of 90 km/h.
2. ECC, name of the driving strategy in this study, use downhill parts of the road for coasting in order to achieve drivers’ acceptance and fuel savings.
3. With higher mean velocity, the relative savings decrease. So coasting tends to be most beneficial at overland travelling with medium speeds in hilly area.
4. The point to initiate the coasting phase yields a rather flat minimum of fuel consumption, leading to a considerable degree of freedom enabling to make the start point depend on traffic circumstances without spending the fuel saving potential significantly.
5. From a simplified energy balance of the rolling vehicle, a CPL function (coasting preview length) can be calculated, setting a maximum admissible delta velocity with respect to the actual speed. This CPL function shows a sharp increase and well defined deflection point when approaching the hill summit, which can be taken as criterion to initiate a coasting phase.
6. Increasing velocity deltas, allowing the vehicle to cruise down to relatively low minimum speeds, benefits the fuel savings up to a certain limit. This approach, however, has to be balanced to denial of acceptance for instantaneous vehicle velocities too much off the desired speed.
7. The introduction of a boosting phase just prior to the coasting period enables to limit the area of deviations from the desired speed. The benefits in fuel economy do mainly prevail, such that boosting seems to be a proper approach for an acceptable realization of an ECC strategy.
8. The downhill coasting offers a benefit to fuel consumption also for a hybrid vehicle. This improvement can amount to 2 % to 3% with respect to a hybrid vehicle at constant velocity driving and 6.5 % to 10.5 % compared to a conventional vehicle. Coasting on the downhill section appears to be more efficient than energy recuperation via the electrified drivetrain.
9. Future work needs to cover further optimization, especially for the multidimensional hybrid load distribution.
References


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Definitions/Abbreviations
ACC - Adaptive Cruise Control
CPL - Coasting preview length
ECC - Economic Cruise Control, as title of this research project acronym for the optimized driving strategy applying cruising phases
ECU - Electronic Control Unit
FC - Fuel Consumption
ICE - Internal combustion engine
NEDC - New European Driving Cycle according RL 70/220/EWG
MT - Manual Transmission
OBD - On-Board Diagnosis
PC - Passenger Car
SFC - Specific Fuel Consumption
WLTP - Worldwide harmonized Light vehicles Test Procedures