Coasting on Highways – Potentials and Realization

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1. Perspectives of Coasting

Automobile development and usage can contribute further to minimize consumption of resources and to limit the emissions of climate relevant pollutants such as CO$_2$. The legislation of the EU set up a heavy cornerstone by calling 95 € per g CO$_2$ emissions. This creates a strong drive to follow even elaborate approaches at any vehicle subsystem. This work deals with some measures to optimize the primary vehicle function, driving from A to B.

The still valid basis of passenger car (PC) certification in the EU, the MNEDC, focuses on vehicle operation with very limited longitudinal dynamics, rather long periods of halts and quite low mean velocities. The US FTP75 cycle is more dynamic, though at low medium speed. Both cycles rely on a completely flat drive.

Even in the extra-urban part of the MNEDC with a mean velocity of just 62 km/h, there is a poor representation of much of the typical long distance travel with passenger cars in developed countries, utilizing interstate or fast track roads without intersections. Furthermore, a significant percentage of the geography in Europe and the entire world consists of highways with a hilly profile. This should be specified herein as a rather high part of traveling on slopes between 1 % to 6 % up- and downhill. Additionally, these long distance highways are built mainly with elevated curve radii, such that a traveling speed between 80 and 140 km/h is common and safe. These conditions are especially met on motorways. A high percentage within the total transport service performed by PCs follows such modes of operation, hence giving a significant potential to minimize CO$_2$ emissions.

It is basic knowledge, that an integration of coasting phases can reduce the fuel consumption of a motor vehicle over driven distance, e. g. [Mark12]. In fuel-saving competitions, for instance the ‚Michelin Challenge Bibendum‘, coasting strategies are widely applied. In the US the general public knows such activities as „pulse&glide“ or „hypermiling“ [wife13]. Many of these approaches focus on hybridized powertrain concepts [Lee09]. Other implementations are made in modern HD trucks. There, special conditions dominate as a high weight to power ratio, where optimizations improve shifting strategy [Joac10]. However, with state-of-the-art motorizations of PC there are rather few occasions requiring to shift down from top gear in overland driving under the guideline of fuel efficiency. Another principle difference for HD trucks is the ubiquitous upper speed limits while low acceptable spreads in velocity due to tough economics of transportation business. In contrast, though speed limits are widely imposed also for PC overland travel, many drivers do not stick as close to these
speed limits as HD professionals must do. Therefore the fuel saving potential for a temporarily lowered speed in coasting phases is to be quantified.

‘Pulse and Glide’ on flat roads yields a velocity profile of saw tooth function type, which does not seem broadly applicable in car traffic. If the coasting phases were placed at downhill slopes, they could obtain a significant share of the total vehicle operation without entailing too high speed deviation that would not be reasonable for the driver and the traffic environment.

Much of the work published in this field focusses on strategies to implement driver assistance systems showing fuel savings on a statistical basis [Henn12], [Mark12]. However, these potentials may often not been reduced to physical parameters and their variations with first order vehicle operation values such as average speed, vehicle weight or engine efficiency. In a first paper fuel savings of PCs in hilly overland travel could be derived simulating a hill model with constant slopes [KoGr12]. Even with the engine idling upon coasting, reductions of 3 to 5 % were found, although fuel is consumed without any power output for rather extended portions of the driving (>30%). The savings can be derived from the fuel needed to overcome all the internal losses the engine’s rpm. Usually this effort is expressed as mean friction power \( P_{mr} \). \( P_{mr} \) does never contribute by definition to the ‘effective’ engine output, which drives the car. On the other hand, \( P_{mr} \) increases with engine rpm usually with an exponent slightly higher than one. Thus, even idling saves fuel due to engine operation at lowest possible rpm compared to its rpm with engaged top gear. Dr. Rohde-Brandenburger of VW showed this dependency in his work quantifying fuel savings [RoBr96], applying it to subsequent tasks such as the effects of reducing vehicle weights on fuel consumption [RoBr12]. Later in this paper, figure 2b depicts this reasoning as a Willans-Diagram: The reference car consumes at 120 km/h / 2700 min\(^{-1}\) 1.9 l/h, i. e. 1,58 l/100km just to keep its engine running, not contributing to the energy for driving the car.

This paper aims at quantifying possible fuel savings by coasting on real road profiles and to verify it in vehicle tests. For this goal traffic circumstances are explicitly reduced to overland speeds and disregard necessary brakings, which evidently favor hybrid concepts able to recover parts of dissipated energy. Previous publications dealt with disturbances from the traffic environment, e. g. [Albe10], [Neun06]. Also under those conditions, the fuel consumption at necessary speed reduction phases profit often from letting the car roll instead of engine overrun or employing the wheel brake. So coasting will have a considerable fuel saving potential for the economic, widely used passenger cars with conventional drivetrain, too.
2. Coasting in Practice

2.1 Potential Vehicle Implementation

Coasting (ambiguously the German term established is „Segeln“, literally „sailing“) can be realized by opening the clutch or putting in neutral gear in a conventional PC with manual transmission (MT). This may be applied by conscious drivers as it was done in the vehicle testing described below. However, this approach has only a limited scope from the point of view of usability and safety, especially in denser traffic.

In the world PC market, only a minority is equipped with MT. Notably the dual clutch transmissions, which market share is rising, do not need additional hardware components to implement an automated driving strategy with coasting. Many modern series cars offer freewheel systems to save fuel, which open the transmission instead of engine overrun when driver’s load request is zero meaning foot off the accelerator pedal, e. g. VW Passat bmt, Daimler B-class and Porsche as ACC InnoDrive [Mark12]

Nowadays start-stop-systems are state-of-the-art, which stop the engine at vehicle standstill. The increasing electrification of auxiliaries such as power steering and brake boosters will allow to stop the engine in a running car, too. Implementation in series PCs are expected in the near future.

2.2 Reference vehicle

![Reference vehicle with work group](Picture 1: reference vehicle with work group)
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This work is part of the research project „ECC – Economic Cruise Control“. This acronym stands for the goal to develop further the common cruise control (CC) function: the command variable vehicle speed is allowed to vary within set limits in order to minimize fuel consumption.

This project includes the proof of a coasting driving strategy in a demonstrator-vehicle. Due to its high market share, the compact „B“ class of PCs was chosen with a decent powerful motorization, since it is more common in cars with high percentages of long distance trips, for instance used by field and service professionals.

The choice fell on a Ford 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 gasoline DI-engine, representing moderate downsizing. This motorization provides decent power reserves also uphill at the regarded traveling speeds of 80 to 140 km/h. The car is equipped with a series ACC system.

The reference data of table 1 enters the following simulations, unless stated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
<th>unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Power</td>
<td>110</td>
<td>kW</td>
<td>bei 5700 min⁻¹</td>
</tr>
<tr>
<td>Max. Torque</td>
<td>240</td>
<td>Nm</td>
<td>at 1600 bis 4000 min⁻¹ constant</td>
</tr>
<tr>
<td>Displacement</td>
<td>1596</td>
<td>cm³</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>1362</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>Drag</td>
<td>0,678</td>
<td>m²</td>
<td></td>
</tr>
<tr>
<td>Top Speed</td>
<td>210</td>
<td>km/h</td>
<td></td>
</tr>
<tr>
<td>Transmission Ratio</td>
<td>2,636</td>
<td>-</td>
<td>0,69 x 3,82: 43,7 km/h at 1000 min⁻¹</td>
</tr>
<tr>
<td>Consumption MNEDC</td>
<td>5,9</td>
<td>l/100 km</td>
<td>combined (137 g CO₂/km)</td>
</tr>
<tr>
<td></td>
<td>7,6</td>
<td>l/100 km</td>
<td>urban</td>
</tr>
<tr>
<td></td>
<td>4,9</td>
<td>l/100 km</td>
<td>extra-urban</td>
</tr>
<tr>
<td>Idle fuel cons.</td>
<td>0,6</td>
<td>1 / h</td>
<td>From bord computer and logger</td>
</tr>
</tbody>
</table>

Table 1: Data Reference Vehicle

Fuel consumption was measured by an on board drive recorder type M-LOG of project partner Ipetronik. The data is taken in 1 Hz from the OBD interface, since the reference vehicle is equipped by a series ECU without any further access to its hard- and software. The values of air mass flow and actual air to fuel ratio (lambda) yield the fuel consumed. This approach was established employing the silver scan tool by partner RA-Consult. The measurement and simulation results give evidence that this method’s accuracy in route based fuel consumption is sufficient to show savings of only a few percent.
2.3 Vehicle Testing on Reference Route

From the simulation work at an artificial hill profile [KoGr12] it was learned that coasting downhill could reduce the fuel consumption around 5%. A proof of these rather small quantities requires a reduction of all ‘disturbance factors’ to a minimum: At first all comparisons must base on the same values of mean velocity. Additionally all drives with significant use of the brake were omitted since the dissipated energy cannot be quantified and the vehicle is not hybridized. Braking can be completely avoided in surprisingly many drives by decent anticipation, even in German workday’s daytime situations. This statement is valid within the applied motorway speed range from 80 to 140 km/h. Nor faster drives are much relevant because of a evidently lacking acceptance to save fuel by coasting, neither a creeping drive at truck speeds gives a realistic perspective for PCs overland travel.

Furthermore statistics are used to quantify fuel savings by repeated driving on a reference route. On Germany’s motorway A81 between the cities of Stuttgart and Heilbronn, a stretch of ~28 km was selected with a certain hilly characteristic. Figure 1a gives an example reference drive, mainly at constant speed by ACC, only occasionally lowered due to traffic disturbances. The difference between set point 125 km/h and driven speed just below 120 km/h can be attributed to the driver’s expectations of a speedometer showing a small surplus to the real velocity. The engine load is scaled such that a value of ~12% represents idling as well as overrun. The curve shows the dominance of slopes and accelerations for high output, having at each point still reserves though. The green line gives the hilly profile, here taken from the GPS tracker’s altitude. This signal undergoes points of unsteadiness due to changes in satellite tracking so it has been filtered. Reasonable coincidence was found by comparing it to a high resolution altitude profile from the geodetic office of Baden-Württemberg (LGL).

Figure 1b shows the reference route driven with a manually realized ECC driving strategy: the black curve shows phases of coasting (rolling in neutral gear), which sum up to 40,0 % per distance or 41,3 % time. This difference is coming from the lower average speed in the phases of coasting.
Figure 1a: Reference Route northward with (adaptive) cruise control operation

Figure 1b: Reference Route northward with manual coasting strategy
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The total average speeds are very close: the ACC125 drive gave $v_{\text{mean}}$ of 118.6 km/h, whereas the ECC drive of fig. 1b yielded 117.1 km/h. The fuel consumption was measured to 5.71 l/100 km and 5.44 l/100 km, respectively. This represents a fuel saving of 4.7%. Remarkably the readings from the bord computer were quite consistent with a small delta (5.6 l/100 km for ACC125 @ av. 120 km/h and 5.4 l/100 km for ECC @ av. 119 km/h). Both measurements were performed within one hour in sequence at a stable weather situation, including backwinds around 18 km/h in this direction (weather office data). Another reason for the low absolute values of fuel consumption is the total descent: the altitude of the endpoint is 70 m lower than the start. Driving in the opposite direction, the absolute values rise significantly due to total altitude increase and the headwind this day.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>A81 north 28km -70m $\Delta h_{\text{tot}}$</th>
<th>A81 south 28km +70m $\Delta h_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$v_{\text{mean}}$ Fuel C. Coast</td>
<td>$v_{\text{mean}}$ Fuel C. Coast</td>
</tr>
<tr>
<td>ACC125</td>
<td>118.6 5.71 0</td>
<td>118.7 6.86</td>
</tr>
<tr>
<td>ECC</td>
<td>117.1 5.49 40,0</td>
<td>117.6 6.78 31,2</td>
</tr>
<tr>
<td>ECC ES</td>
<td>117.1 5.25 40,0</td>
<td>117.6 6.64 31,2</td>
</tr>
<tr>
<td>Fuel Saving</td>
<td>6.8 %</td>
<td>2.4 %</td>
</tr>
<tr>
<td>ACC125 BC</td>
<td>120 5.6 0</td>
<td>120 6.9 0</td>
</tr>
<tr>
<td>ECC BC</td>
<td>119 5.4 -</td>
<td>119 6.7 -</td>
</tr>
</tbody>
</table>

Table 2: Data Vehicle Testing

The fuel saving values have been corrected for the small difference in mean velocity with a factor of 0.05 (l/100km) per km/h, derived from steady state simulations. Since the fuel savings are of limited quantity it is of crucial importance to compare them only on the basis of identical mean velocities. Other test drives on the same reference route yielded similar percentages of coasting phases from 30 to 42 %, even in the “uphill” direction southward. The values given in table 2 are not singularly optimized results, but achieved in everyday traffic around the year, omitting just drives with traffic congestions.
3. Optimization of Coasting Strategy

3.1 Simulation Setup

With the sum of driving resistances for drag, rolling friction, climbing/descent and acceleration, the simulation tool calculates at each step of 10 m either the resulting acceleration and speed from a command variable engine load, or it selects the required engine load for a given vehicle velocity. Parameters are set according table 2:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Density</td>
<td>$\rho_{\text{air}}$</td>
<td>1,2</td>
<td>kg/m³</td>
<td></td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>$f_R$</td>
<td>0,01</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Dynamic Wheel Radius</td>
<td>$r_{\text{dyn}}$</td>
<td>0,312</td>
<td>m</td>
<td>for 215/55R16</td>
</tr>
<tr>
<td>Rotating Mass Factor</td>
<td>$\lambda_{\text{rot}}$</td>
<td>0,03</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Efficiency Powertrain</td>
<td>$\eta_{\text{PT}}$</td>
<td>0,95</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Fuel to restart engine</td>
<td>$V_{\text{f.start}}$</td>
<td>0,4</td>
<td>ml</td>
<td>for warm engine</td>
</tr>
</tbody>
</table>

Table 3: Values for Simulation

Any vehicle fuel consumption simulation relies much on the efficiency of the internal combustion engine. Usually it is visualized in an engine SFC map of the so called “shell type”. Figure 2a shows a zoomed section for the fitted reference engine, since no engine map of the reference vehicle is available. The reference data was measured at a different EU4 type turbo charged DI gasoline engine. As alternative a second type of modern SFC characteristic is shown as engine “gasoline2”: It represents a SFC best point at higher load and less increase in SFC above. The absolute SFC values at the best and low load reference point 2 bar were kept unchanged.

Table 2 documents values at key points of the map. The values with * give the best points of SFC. Since the regarded speed range from 80 to 140 km/h cover a limited spread from 1793 rpm to 3137 rpm (no slip), the dependence of SPC on engine speed could be neglected.

<table>
<thead>
<tr>
<th>Engine Load</th>
<th>2 bar</th>
<th>8,0 bar</th>
<th>12,2 bar</th>
<th>15,2 bar</th>
<th>18,9 bar p.me</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Type</td>
<td>10,6 %</td>
<td>42,3 %</td>
<td>64,4 %</td>
<td>80,4 %</td>
<td>100 % load</td>
</tr>
<tr>
<td>Gasoline (ref)</td>
<td>394,0</td>
<td>247,1</td>
<td>237,7*</td>
<td>241,4</td>
<td>255,7</td>
</tr>
<tr>
<td>Gasoline 2</td>
<td>394,0</td>
<td>252,7</td>
<td>239,6</td>
<td>237,4*</td>
<td>240,3</td>
</tr>
</tbody>
</table>

Table 4: Specific Fuel Consumption Values in g/kWh
3.2 Velocity Spread Variations

In order to get a comparable evaluation, the simulation was applied to the same part of the reference motorway A81 as in the vehicle testing. As it was learned from the previous simulation of an artificial hill profile [KoGr12], coasting would save more if its time share could be maximized. Thus, a first approach for an optimized ECC strategy is based on the guideline to start coasting whenever the slope becomes negative, i. e. downhill, and to end it by acceleration at defined engine load if the slope changes sign.

Figures 2: Specific fuel consumption maps

Fig 3a: v.min = 100 km/h
Fig 3b: v.min = 110 km/h
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Figures 3: simulated ECC drive for $v_{\text{mean}}$ of 120 km/h and 60% engine load

The second borderline is the minimum speed. When the velocity drops below a set value, the virtual car starts to accelerate, until it reaches the maximum speed value. There another coasting phase is initiated if this point occurs on a negative slope or the maximum speed is maintained by lowering the engine load, as a cruise control function would do.

For the set minimum value, the maximum speed is subsequently identified by a solving algorithm such that the mean speed target is met for the complete route.

Figures 3 illustrate this driving strategy for an engine load value of 60%: within the first 11 km of overall downhill driving, the virtual car just changes between acceleration and coasting, the later mainly on the downhill slopes. The resulting velocity profile, the blue line of zig-zag type, appears to be quite uncomfortable and hardly acceptable for a normal driver. However, the accelerations never exceed 0.6 m/s². This value is equivalent to employing 4.6 s for a speed change of 10 km/h, hence it is far not dynamic or uncomfortable, because in many normal traffic situations much higher decelerations occur at breaking or accelerating speed changes, not regarding any sudden or emergency situations.

At the lowest parts of the profile, around 11 km to 14 km, rather flat stretches lead to CC driving at constant speed for some phases, entailing engine operation at higher values of specific fuel consumption.

Figure 4: Fuel Consumptions and ECC parameters over minimum speed
Figure 3b shows the ECC strategy when the minimum speed limit is increased to 110 km/h. The maximum velocity derived is 125.2 km/h. Thus the range of driven speed is much lower than in the case of figure 3a, varying from 100 to 133 km/h. This velocity spread is presumably a crucial parameter for driver’s acceptance of ECC strategy. The advantage of lower velocity spread is counteracted by an increased number of coasting phases and engine starts.

Figure 4 gives an overview for varying the minimum speed: At the right corner constant speed driving at 120 km/h renders the highest fuel consumption of 5.72 l/100km, with no coasting and engine starts, off course.

Applying the ECC strategy, the fuel consumption lines show significant decreases: The higher curve regards the engine idling when coasting whereas the lower values account for the stopped engine and its restarts with a fuel volume of 400 µl each. For this case the minimum fuel consumption value is 5.18 l/100km, yielding a best case saving of 9.3 %.

Further parameters are given in fig. 4 for evaluation purposes: The number of coasting phases, equal to engine restarts, shows a strong increase with low speed variation. This is quantified as a velocity spread parameter: it is given in % of mean velocity as double amplitude: for instance, the value 20 % of 120 km/h gives a variation from v.min 105 km/h to v.max 129 km/h.

Figure 4 shows that the fuel saving by ECC driving can be achieved almost completely in a rather wide field of velocity spreads. Hence, it remains more a question of proper driver information and assistance to maximize the acceptance of this strategy.

### 3.3 Engine Load Variations

![Simulation Reference Motorway A81: Engine Load Variations](image)

Figures 5a and 5b: simulated ECC strategy for 45 % and 90 % engine load
Another central parameter of ECC application is the engine load for acceleration phases. Figures 5a and 5b show two rather extreme variations of engine power, the reference has been given in figure 2a: With the low value of fig.5a, at the end of the route the part of CC driving has to be extended to assure that the end speed is identical to the starting such that no loss or gain in kinetic energy would distort the result. Figures 6 sum up the accelerations load variations: a clear minimum in fuel consumption around 60% is found.

For low engine loads, the increased time to regain speed entails a significant reduction in coasting duration and less fuel savings due to higher integral ‘friction’ losses for higher mean engine rpm.

At higher engine loads from 70% to 100% the fuel consumptions increase more and more: On one hand this is due to the increase in specific fuel consumptions as it was given in figure 2. The SFC appears a relevant factor as the comparison of fig. 6a to 6b reveals: The alternative engine ‘gasoline2’ was characterized by a minimum SFC at higher load, such that its increase in fuel consumption is lower. Since there is an increase of fuel consumption starting at loads below its SFC best point though, figure 6b proves that it is not only the SFC characteristics leading to the fuel consumption rising with faster accelerations.

On the other hand this can be derived from the increased time share of driving in CC mode at constant speed. This effect is shown in figure 5b at the phases of varying intermediate engine loads. This entails reduced efficiency due to higher SFC values at engine loads much below the best points (ref. figure 2).
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3.4 Mean Speed Variations

Further simulations quantify the effect of different mean velocity. At 140 km/h, the fuel consumption driving constant speed becomes 7.01 l/100km. An ECC drive can reduce the fuel consumption by just 3.5%. On the other hand at v.mean of 100 km/h the CC value of 4.67 l/100 km could be reduced with the coasting ECC strategy by an impressive maximum of 14.8%. However, in dense traffic of central Europe, velocities getting low to those of trucks seem critical from the point of view of acceptance.

3.5 Route Profile Variation

The reference profile chosen in this work is characterized by a mean slope of 0.25 % downhill, i.e. 70 m over 28 km. A glance at different profiles is obtained by driving the virtual reference car at mean speed of 120 km/h in the opposite direction. Table 6 sums up the simulation results, maintaining the other parameters such as 100 km/h minimum speed and 60 % engine load:

<table>
<thead>
<tr>
<th>Strategy</th>
<th>A81 north 28km -70m Δh&lt;sub&gt;tot&lt;/sub&gt;</th>
<th>A81 south 28km +70m Δh&lt;sub&gt;tot&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>v.mean</td>
<td>Fuel C.</td>
<td>Restarts</td>
</tr>
<tr>
<td>120km/h</td>
<td>l/100km</td>
<td>-</td>
</tr>
<tr>
<td>ACC</td>
<td>5.72</td>
<td>0</td>
</tr>
<tr>
<td>ECC idle</td>
<td>5.41</td>
<td>0</td>
</tr>
<tr>
<td>ECC ES</td>
<td>5.19</td>
<td>14</td>
</tr>
<tr>
<td>Fuel Saving&lt;sub&gt;ES&lt;/sub&gt;</td>
<td>9.3 %</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Data Simulation Results for opposite direction

The “uphill” direction results in fewer possibilities to coast. Hence, the fuel saving potential gets reduced, but is still noticeable.

4. Conclusions

a. An ECC economic cruise control driving strategy applying coasting phases with stopped engine could reduce the fuel consumption 5 to 10 % with respect to constant speed (CC) driving.

b. Even with the engine idling upon coasting less fuel is consumed in most cases.

c. On a hilly reference route of 28 km German motorway fuel savings by coasting were found both in vehicle testing and simulations consistently.
d. For an optimized strategy it is important to maximize the time share of coasting, since running at idle or zero rpm saves the fuel used to overcome the total friction losses at higher rpm.

e. A certain spread in velocity must be accepted to obtain the fuel savings. A trade-off is encountered between increased number of coasting phases / engine restarts and a higher velocity spread.

f. A choice of parameters for ECC driving must take driver’s acceptance into account, beyond the scope of this work basing in engineering physics.

g. This work regards just one reference route, apparently typical for motorways in hilly countryside. Though quantitative differences would be found for different profiles, the general tendencies shown in the work will prevail.

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- IPETRONIK GmbH & Co. KG, D-76532 Baden-Baden
- RA Consulting GmbH, D-76646 Bruchsal

Acronyms

ACC       Adaptive Cruise Control
BMBF      Bundesministerium für Bildung und Forschung
           (German Federal Ministry of Education and Research)
ECU       Electronic Control Unit
FC        Fuel Consumption
OBD       On-Board Diagnosis
PC        Passenger Car
MNEDC     Modified New European Driving Cycle according RL 70/220/EWG
MT        Manual Transmission
SFC       Specific Fuel Consumption
Literature and other Sources


