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Comprehensive Energy Management—Eco Routing & Velocity Profiles

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Contents

Introduction

Bernhard Brandstätter[1] and Daniel Watzenig[1] on Behalf of the Cluster of 4th Generation Electric Vehicles

This book is organized in two volumes (the contents of both volumes are listed at the end of this introduction):

- Volume 1: "Comprehensive Energy Management—Eco Routing & Velocity Profiles"
- Volume 2: "Comprehensive Energy Management—Safe Adaption, Predictive Control and Thermal Management"

Comprehensive Energy Management

Energy management plays a central part in today's vehicles, especially for battery electric vehicles, where a limited number of charging possibilities and time-consuming charging processes lead to range anxiety of the users. This can be considered as an important factor (apart from the increased cost of electrical vehicles compared to conventional ones) that prevents larger number of fully electric vehicles on the road.

Thus comprehensively treating energy and controlling it is of uttermost importance.

This book provides findings of recent European projects in FP-7 grouped in a cluster named "Cluster of 4th Generation Electric Vehicles" but also gives insight into results from ongoing H2020 projects related to energy management.

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Since fuel cell technologies are gaining more attraction again, the last section of the book gives an overview of the state of the art in this field what PEM[2] fuel cells is concerned.

Cluster of 4th Generation Electric Vehicles

The Cluster “4th Generation EV” was set up late 2013 by the European projects INCOBAT, iCOMPOSE and eDAS, with the purpose to synchronize and cojointly promote the R&D topics on electric vehicles. By growing to a total of six projects with the FP7 projects Batteries2020, IMPROVE and SafeAdapt, the cluster also enlarges its networks and range of influence on the European electric vehicle community (Fig. 1).

The projects within the cluster are focusing on the following goals:

- Batteries 2020+: improve performance, lifetime and total cost of ownership of batteries for EVs
- eDAS: Holistic energy management for 3rd and 4th generation EVs.
- iCOMPOSE: Integrated Control of Multiple-Motor and Multiple-Storage Fully Electric Vehicles.
- INCOBAT: Innovative Cost Efficient Management System for Next Generation High Voltage Batteries.
- IMPROVE: Integration and Management of Performance and Road Efficiency of Electric Vehicle electronics.
- SAFEADAPT: enrich networked embedded systems in e-vehicles.

Uniting more than 40 partners from 12 countries all over Europe, including 7 OEMs, with an overall budget of more than 36 million Euros, the impact of the cluster on the next generation of electric vehicles keeps on growing.

The “4th Generation EV” cluster is organized around the three following working groups:

- Comprehensive energy management
- Central computing platform
- Potential of electrification

[2]Proton exchange membrane

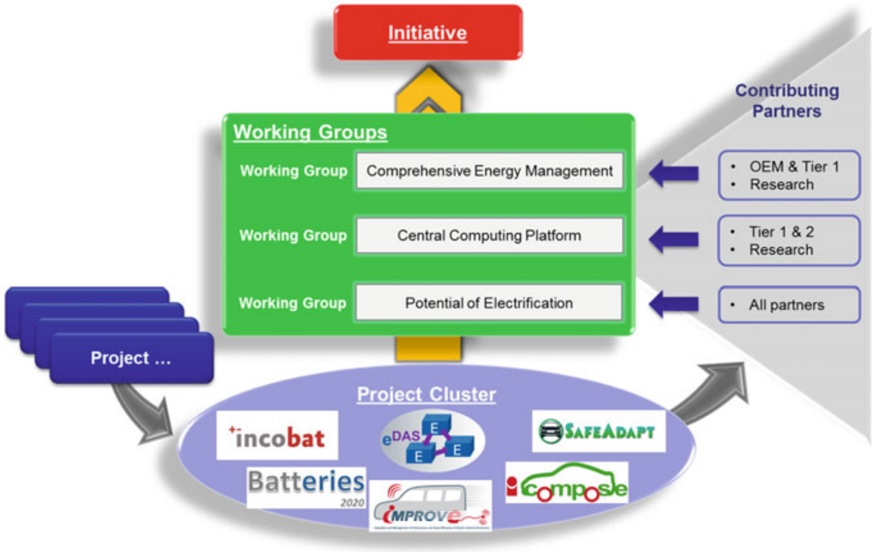

Fig. 1 Cluster of 4th Generation Electric Vehicles

Some of the cluster projects will end in 2016 but bridging to H2020 projects has already begun. As an example the H2020 project OPTEMUS can be mentioned, where the comprehensive energy aspect is widened by new technologies like heating panels and energy harvesting technologies with strong focus on thermal comfort sensation inside the cabin (which plays a very important role in overall energy consumption).

Organization of this Book

The chapters of this book are organized under five different groups: ECO driving and ECO routing covers different approaches for optimal speed profiles for a given route (mostly interconnecting with cloud data); model-based functional safety and fault-tolerant E/E architectures; advanced control making use of external information (from a cloud) as well; thermal management as a central part for energy optimization and finally some aspects on fuel cells.

These subject areas with their chapters (chapter titles in italic) are listed below:

Volume 1:

- ECO Driving and ECO Routing
  - *Aspects for Velocity Profile Optimization for Fleet Operated Vehicles*: on-board and off-board optimization including cloud communication

- *Semi-Autonomous Driving Based on Optimized Speed Profile*: different controllers including model predictive control
- *Design of Vehicle Speed Profile for Semi-Autonomous Driving: energy consumption optimization for different driving conditions*
- *Energy-Efficient Driving in a Dynamic Environment*: considers energy optimal velocity profiles in the presence of other traffic participants and overtaking possibility
- *Model-Based Eco-Routing Strategy for Electric Vehicles in Large Urban Networks*: energy consumption model that considers accelerations and road infrastructure

Volume 2:

- Safety Aspects
  Addressing fault-tolerant approaches of automotive energy-efficient E/E architectures and model-based functional safety engineering in
  - *Safe Adaptation for reliable and Energy-Efficient E/E Architectures*
  - *Model-based functional safety engineering*
- Advanced Control
  - *Model predictive control of highly efficient dual mode energy storage systems including DC/DC converter*
  - *Predictive energy management on multi-core systems*: first approach to solve a reference speed tracking problem on a multi-core platform in real time
- Thermal Management
  - *Holistic thermal management strategies for electric vehicles*: including some rudimentary cabin comfort issues
  - *Heat pump air conditioning systems for optimized energy demand of electric vehicles*
- Fuel Cells
  - *Thermal management of PEM fuel cells in electric vehicles*

The aspects within the field of comprehensive energy management are too numerous that all of them could have been addressed in this book (aerodynamics and adaptive control of aerodynamic features could be mentioned in this context as an example). We think, however, that important key enabling elements for optimal energy management taking the environment and context into account have been collected in this book.

We cordially acknowledge all authors and co-authors for their efforts and looking forward to next steps in future projects.

Graz, Austria
December 2016

Daniel Watzenig
Bernhard Brandstätter

The Design of Vehicle Speed Profile for Semi-autonomous Driving

3

Zdenek Herda, Pavel Nedoma and Jiri Plihal

3.1 Optimal Speed Profile Design

3.1.1 Basic Assumptions

The algorithm recommends optimal levels of throttle pedal, brake pedal and gear shift. This is based on a several factors. The decisive part is focused on the driving horizon rather than maximizing speed in the next route section. In this horizon the key point is selected (decisive point) which presents the largest decrease of speed. Given this point we optimize the change of speed in the closest time frame. The algorithm decides whether it is necessary to change parameters from the previous step based on the change of speed in that previous step. If it is necessary the algorithm makes a decision with respect to the current driving mode.

Before initiating braking or accelerating, the algorithm verifies the track profile between the current location and the key point. It modifies parameters of the braking distance and optimal speed based on the inclination. The following action is decided after this modification. The action flow diagram is shown in Fig. 3.1 and described later in Sect. 3.1.3.

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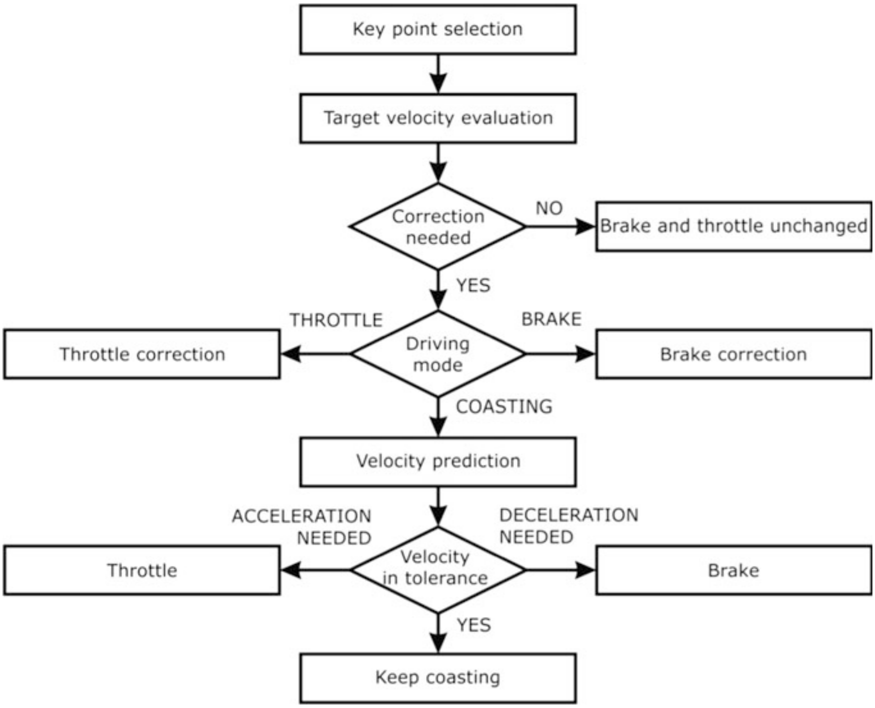

Fig. 3.1 The scheme of brake and throttle motion

3.1.2 Target Velocity

Achieving the optimal speed in one step of the algorithm would not be effective and it could cause repeated corrections of the vehicle dynamics. As a basic preposition the algorithm takes respect to the part of the track in the distance H (hundreds of meters). This enables the assignment of milestone to points on the track with respect to the discretization step of the road for example 20 m. The current location is then marked as 1. Variables are then indexed by these milestones, i.e., optimal speed v_i^{opt}, distance x_i, etc.

The point which represents the largest decrease of speed in the discretization step is selected as the key point with respect to the traffic density and changed legal limit. The key point is based on the topology of the road and road features. In case all points have assigned a larger speed than the actual vehicle's speed v then the maximum decrease can be interpreted as the minimum increase. The mathematical representation follows:

$$r_i = \frac{v - v_i^{opt}}{x_i - x}, \tag{3.1}$$

$$k = \operatorname{argmax}_{i \in H}(r_i). \tag{3.2}$$

The goal of the algorithm is to achieve the speed v_k^{opt} in the following path of the vehicle. With respect to the theoretical discretization of vehicle's movement, e.g. $\Delta t = 0.2$ [s], we can determine the traveled distance as $\Delta s = \Delta t * v/3.6$ [m]. Given the ratio between this distance and the distance to the key point the algorithm modifies the target speed change:

$$\Delta v_{NEXT} = (v - v_k^{opt}) \frac{\Delta s}{x_k - x}. \tag{3.3}$$

3.1.3 Vehicle's Movement Dynamic Correction

The algorithm works iteratively. It modifies value of speed v, throttle p and brake b from the previous step $(v_{LAST}, b_{LAST}, p_{LAST})$ in every time step instead of computing new values again every time. The change of speed in the last step is given by

$$\Delta v_{LAST} = v - v_{LAST}. \tag{3.4}$$

The planned speed change (3.3) and the last speed change (3.4) are compared to decide the necessity of intervention. For this comparison coefficient C was defined which is basically the size of hysteresis.

$$\Delta v_{KOR} = \Delta v_{NEXT} - \Delta v_{LAST}. \tag{3.5}$$

If $|\Delta v_{KOR}| < \mathrm{C}$, it is not necessary to intervene. Brake b and throttle p remains unchanged: $b = b_{LAST}$ and throttle $p = p_{LAST}$. The next step of the algorithm is based on the current driving mode—brake, throttle and coasting.

(a) Brake:

In this mode the vehicle deceleration is controlled. If $\Delta v_{KOR} \leq -C$, it is necessary to apply more deceleration than the vehicle is currently doing. In opposite if $\Delta v_{KOR} > C$, it is necessary to apply less deceleration. The correction of braking force is in both cases based on the following formula:

$$b = b_{LAST} - \beta \Delta v_{KOR}. \tag{3.6}$$

The coefficient β modifies the magnitude of the braking force change with respect to the natural change of speed in the comfort driving. When the value of b decreases below a certain level b_{min} (*based on the adhesion limit and vehicle assistant system activation*) the process of braking is terminated ($b = 0$).

(b) Throttle:

In this mode the acceleration of the vehicle is controlled. The principle is similar to brake mode. If the value of $\Delta v_{KOR} \leq -C$, it is necessary to accelerate more than the current acceleration is. In opposite if $\Delta v_{KOR} > C$, the required acceleration is lower. The correction of throttle is in both cases based on the following formula:

$$p = p_{LAST} - \gamma \Delta v_{KOR}. \tag{3.7}$$

The coefficient γ modifies the magnitude of the throttle position change with respect to the comfort driving. When the value of p decreases below a certain level p_{min} the acceleration process is terminated ($p = 0$).

(c) Coasting:

During coasting mode the algorithm predicts vehicle velocity in coasting mode and considers if the predicted velocity fits into the defined limits like maximal deviation form speed limit and safety limit in curves. If the velocity fits the coasting mode remains unchanged. If not the coasting is canceled and algorithm switches the state into the throttle or brake based on need for acceleration or deceleration.

3.1.4 Shifting Gears

The most important fact for gear shifting is engine revolutions and load, but also the inclination of the road had to be considered. The need for shifting with electric motor is based on engine efficiency which depends on revolutions and load. The efficiency map will be presented later in Sect. 3.2.3. The recommended area of revolutions for each gear can be defined by 4 key points (see Fig. 3.2): minimal acceptable revolutions A, minimal revolutions for shifting down B, minimal revolutions for shifting up C, maximal acceptable revolutions D.

This approach breaks down the need for gear shifting into five basic intervals. The behavior for all intervals follows:

(1) $\langle 0, A \rangle$—Downshift.
(2) $\langle B, C \rangle$—No shifting required.
(3) $\langle D, D+ \rangle$—Upshift.
(4) (A, B)—Algorithm considers downshift. This is done only if one of the following conditions occurs:

Fig. 3.2 Key points for gear shifting

- The gas pedal is pressed further than in the previous step ($p_{LAST} < p$). In this case the gear remains the same.
- Large uphill climbing is not expected and simultaneously the acceleration is not active ($p = 0$). In this case the current shift is removed coasting-down is active. It is canceled in the moment when ($p > 0$). In this moment the previous shift is reengaged.

(5) (C, D)—Algorithm considers upshift. It occurs when the gas pedal is partially released ($p_{LAST} > p$).

The iterative system of changing action inputs of gas and brakes introduces the feeling of real driving into the model. It considers wider conditions such as inclination and rolling resistance. It allows choosing the system reaction more precisely and thus reduces the amount of corrections. Also, by setting the toleration area, it is possible to modify the amount of interventions and thus regulate the fluency of driving. The system of changing gears includes the possibility of coasting-down, when the vehicle uses the declining road or redundant speed to shift to the neutral gear. This leads to energy savings. The transition between the state where brakes are active and the state where the gas pedal is active is done by values $b = p = 0$, which prevents from pressing both pedals at once.

The proposed algorithm does not allow exceeding the maximum allowed speed which leads to the safe driving. Simulated energy consumption with and without shifting will be shown later on Table 3.2.

3.1.5 Model Approach

In the next procedure was for experimental verification used the optimal speed profile algorithm modelled by the Bayes approach described by the equation:

$$P(Y|X_1X_2...X_n) = \frac{P(X_1X_2...X_n|Y)}{P(X_1X_2...X_n)}P(Y) \tag{3.8}$$

The probability occurrence of dependent quantity Y in a specific category is the same as the joint probability distributions of these quantities evaluated for this category and multiplied by the probability of this category. Consider that $X_1X_2...X_n$ are measured quantities and Y is the probability occurrence of quantities $X_1X_2...X_n$. Y is normalised by the joint distribution of measured quantities. The shape of the distribution function is not limited, its selection should respect the empirical distribution of measured data and the nature of estimated quantities.

The joint distribution $P(X_1X_2...X_n|Y)$ for each category of velocity and energy consumption priority may be extracted from the driving test measurements together with the distributions of each marginal distribution. This enables the evaluation of probability distribution of estimated quantity in a given category and either select the most likely category in a given time or focus on the probability of appearance in one of the risky categories.

For better illustration the progress of described algorithm is shown on Figs. 3.4, 3.5, 3.6 and 3.7 where the priority coefficient alpha represents gain function as a weighted sum of two contradicting criteria—travel time and energy consumption. Higher value means higher average velocity (shorter travel time) and lower value means lower energy consumption.

3.1.6 Outputs from the Vehicle Speed Profile Model

This chapter is concerned with the optimal speed package tool. This tool is created to find optimal driving profiles for a car driving along a known path from point A to point B with a certain gain function. This function can take various forms and in our case it provides weighted optimisation of two contradicting criteria: time consumption and energy consumption. The goal is to provide an optimal leading speed and acceleration/deceleration signals to maximise the gain (i.e. minimise the loss in terms of travelling time):

$$con = t * \left(c_{p0} * k\right) \tag{3.9}$$

where k is a control input ([1,10] accelerating, [−1, −10] decelerating), t is time spent driving with such control input and c_{p0} is parameter. This parameter is fitted form data and applies according to the quality of the fit. Please note that even with no control input there is some consumption present.

The approach to achieve the above stated goal lies in the use of Bayesian Networks in the form of decision graphs. We profit from the decomposability property of this type of graph and Bellman's principle leading to the possibility of local solutions. The path is traversed backwards obtaining optimal profiles leading to the next point in each step. When the algorithm reaches the start of the track, the forward pass constructs the optimal solution profile.

The model was learned to be able to work with a different drive type (electric) and the use of the neutral gear was heavily revised. Herein is present the overview of the current status with two different drives at the end.

The most important aspects of the model are functions modelling the vehicle and its consumption. So far we are using functions which were fitted from observed experimental data. It is necessary to point out that these data are of small volume. Due to a previous discretisation step some intervals of values were not treated properly. This behaviour led to varied results for different discretisation steps while all remaining variables stayed the same. The most apparent problem was in the discretisation of the acceleration. This behaviour was removed by the fix. For a better illustration of the algorithm progress we present a comparison with its different versions in the form of plots.

Circuit around Mlada Boleslav around 38 km in length, consisting of highway, primary roads and local roads.

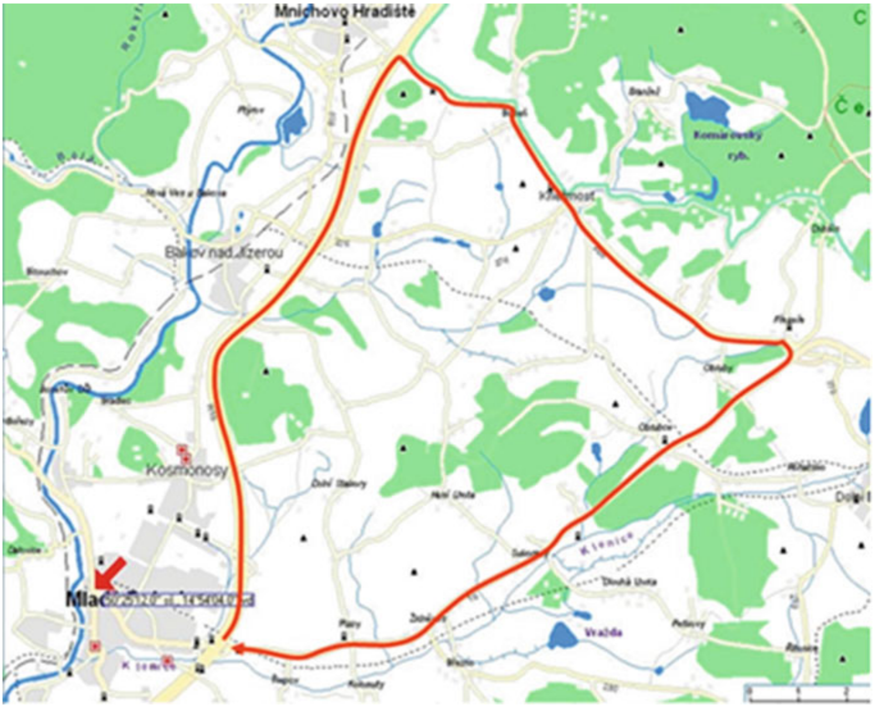

Fig. 3.3 Test course near Mlada Boleslav

The circuit was measured repeatedly, after verification and regularisation of metrics, correlations of the road surface parameters and dynamic features were assessed from the vehicle demonstrator Skoda eRapid FEV, see Fig. 3.3.

Results from testing the vehicle demonstrator Skoda eRapid on two testing tracks in the proximity of Mlada Boleslav, see Figs. 3.4, 3.5, 3.6 and 3.7.

The output from the final version of the algorithm without the coasting-down mode for different coefficient alpha shows Fig. 3.8. Theoretical average speed and energy consumption for these speed profiles are in Table 3.1.

3.2 Efficiency Driving Using Optimal Speed Profile and Coasting-Down

3.2.1 Coasting Mode Strategy

Consider the optimal speed profile with a balanced average speed and energy consumption due to selected coefficient *alpha* described in the previous text. It seems that the energy consumption cannot be further reduced, but there is still

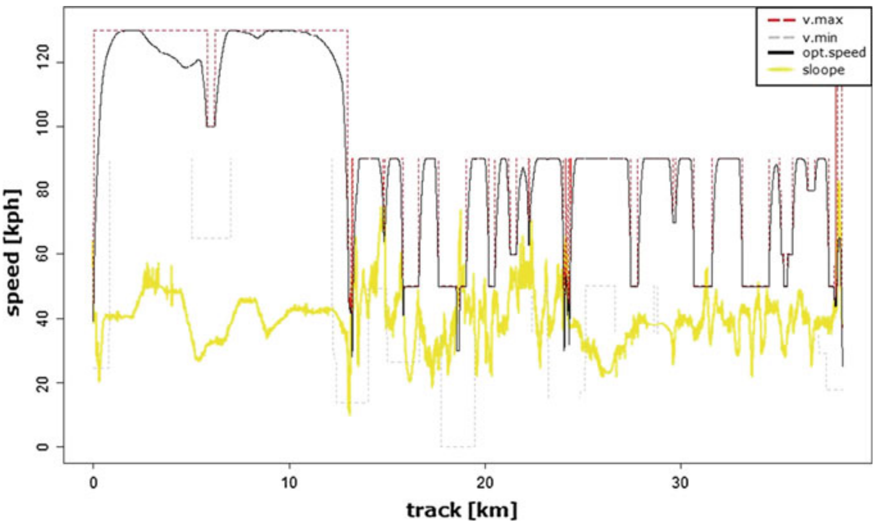

Fig. 3.4 Model outputs, energy consumption 10.854 kWh, travel time 28.16 min, alpha 0.6, 38 km long track, without using coasting-down strategy

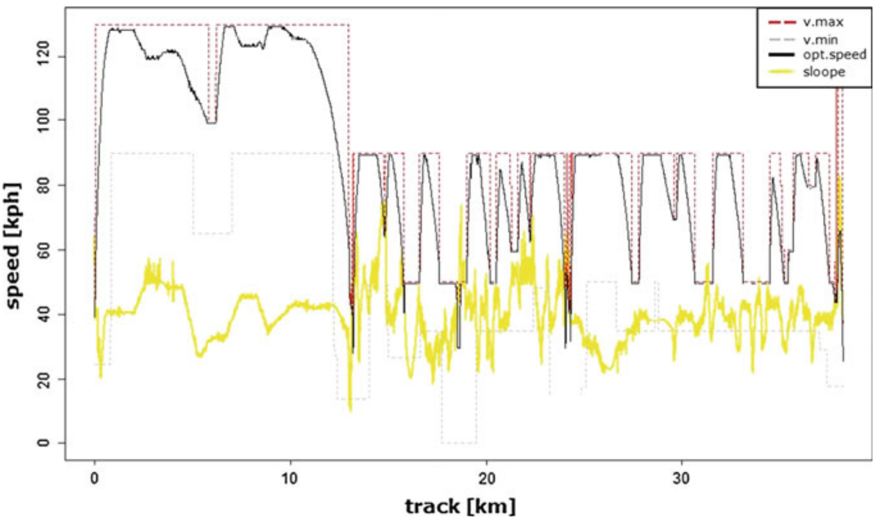

Fig. 3.5 Model outputs, energy consumption 10.011 kWh, travel time 29.54 min, alpha 0.6, 38 km long track, with using coasting-down strategy

another option known as coasting. The original idea was to apply this mode directly to the optimal speed profile algorithm, but it was not suitable for a driver option to deactivate this mode during driving because the coasting behaviour affects the shape of the speed profile so it cannot be simply deactivated. In this case a different

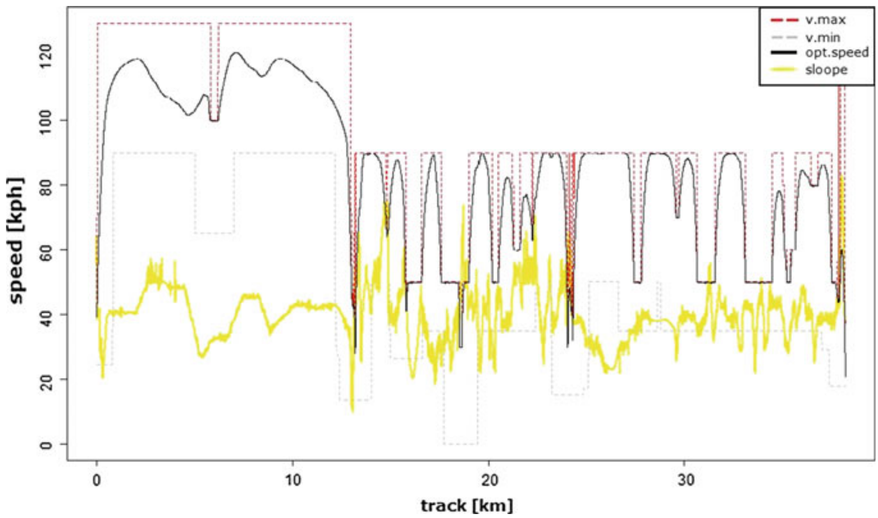

Fig. 3.6 Model outputs, energy consumption 10.234 kWh, travel time 29.6 min, alpha 0.4, 38 km long track, without using coasting-down strategy

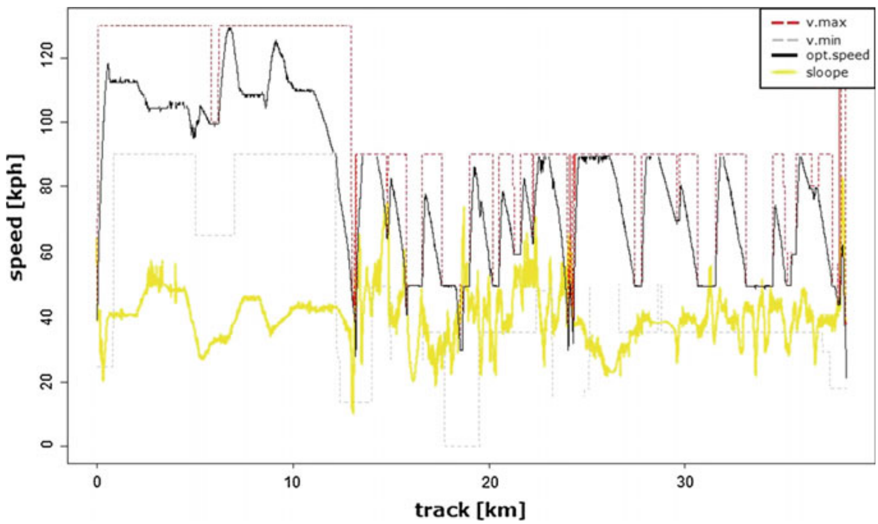

Fig. 3.7 Model outputs, energy consumption 9.282 kWh, travel time 31.54 min, alpha 0.4, 38 km long track, with using coasting-down strategy

algorithm had to be designed only for this mode which can be applied on-line during driving.

Coasting can be applied to any car by using the neutral position of the gearbox. For our car demonstrator with an asynchronous electric engine it is possible to do in

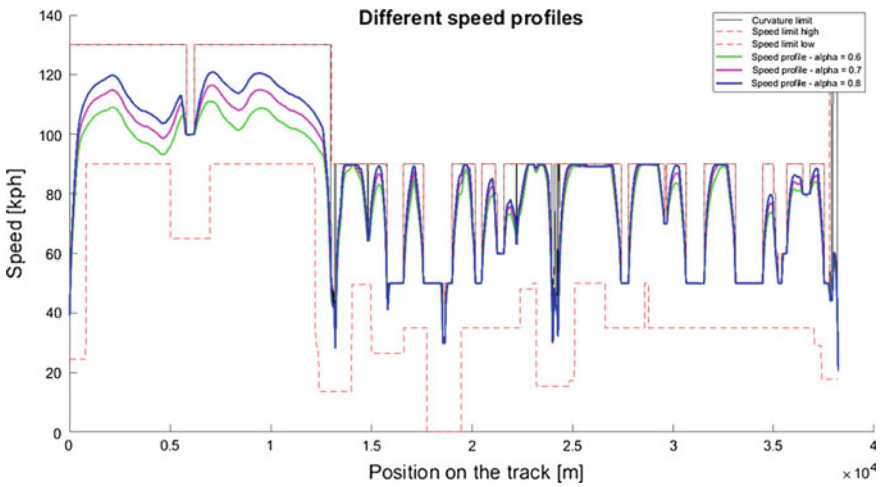

Fig. 3.8 Model outputs for different coefficients alpha = 0.6, 0.7, 0.8

Table 3.1 Theoretical energy consumption/regeneration and average speed of designed profiles

Alpha	Energy per track [kWh]			Average speed [kph]
	Consumed	Regenerated	Total	
0.6	8.3964	0.4434	7.953	80.6228
0.7	8.6789	0.5088	8.1702	83.1274
0.8	8.9555	0.5765	8.3789	85.294

the electric way instead of using the neutral position. And how does it work? The principle is very simple. Accumulated kinetic energy of the car is used to continue driving with small deceleration which is more effective than keeping a higher velocity and then decelerating with recuperation. Of course coasting should only be applied at a suitable position on the track like highway exits, deceleration before curves and speed limits. The suitable areas are identified on-line using the model based prediction of the car velocity. The model structure is described in Sect. 3.2.3.

An example of coasting is shown on the speed profile calculated for coefficient *alpha* = 0.7 (see Fig. 3.9). The red line shows the speed profile without coasting and the blue line shows deceleration with coasting at suitable parts of the track. A detailed description of deceleration with coasting is shown on the highway exit (see Fig. 3.10). For a better comparison both pictures also show total consumed and regenerated energy (integration of actual energy consumption).

For the coasting algorithm must be defined some allowed offset from the original speed and minimal length of track during coasting. The exemplified coasting was calculated with the offset from the original velocity +1, −15 kph and minimal length 50 m. The coasting strategy in the example follows:

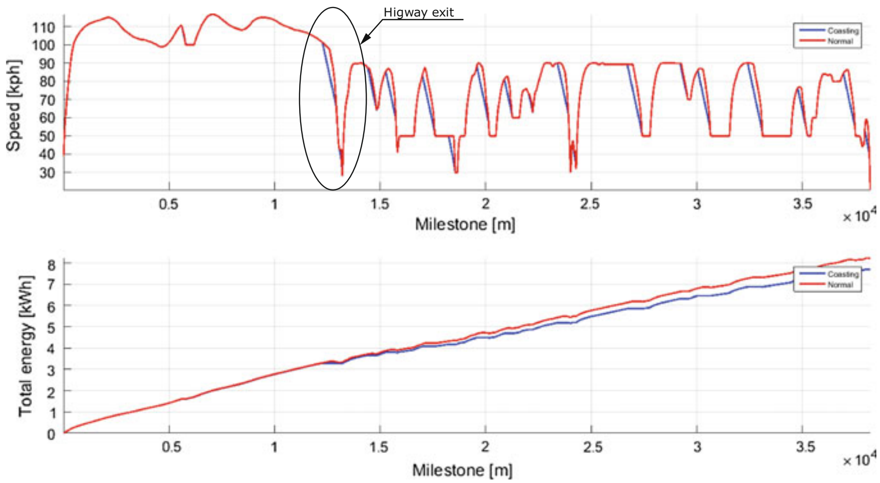

Fig. 3.9 Optimal speed profile calculated for alpha = 0.7, *red*—speed profile without coasting, *blue*—deceleration using coasting

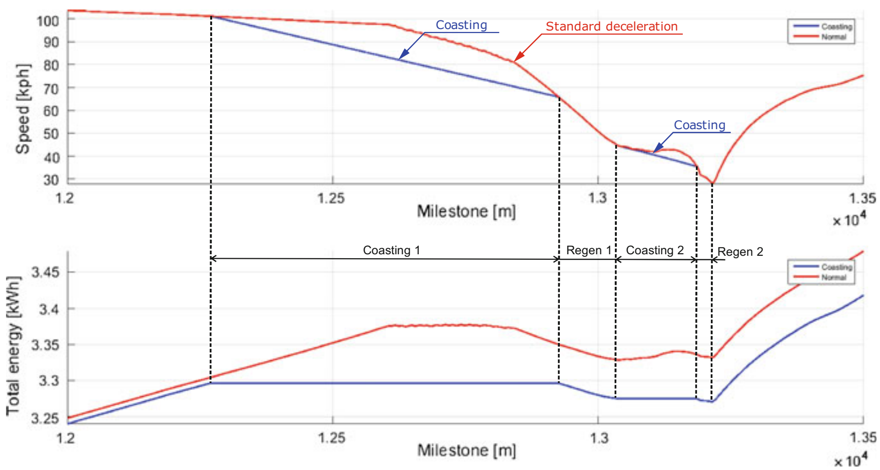

Fig. 3.10 Detailed deceleration on highway exit using coasting

- Coasting 1—Apply coasting when described conditions are accomplished.
- Regen 1—Coasting deceleration is not enough, regeneration breaking must be used.
- Coasting 2—Conditions are accomplished again.
- Regen 2—Final regeneration breaking.

Coasting calculated for different offsets from the original speed (+1, −10, −15 and −20 kph) is a little different due to the original speed profile because not all

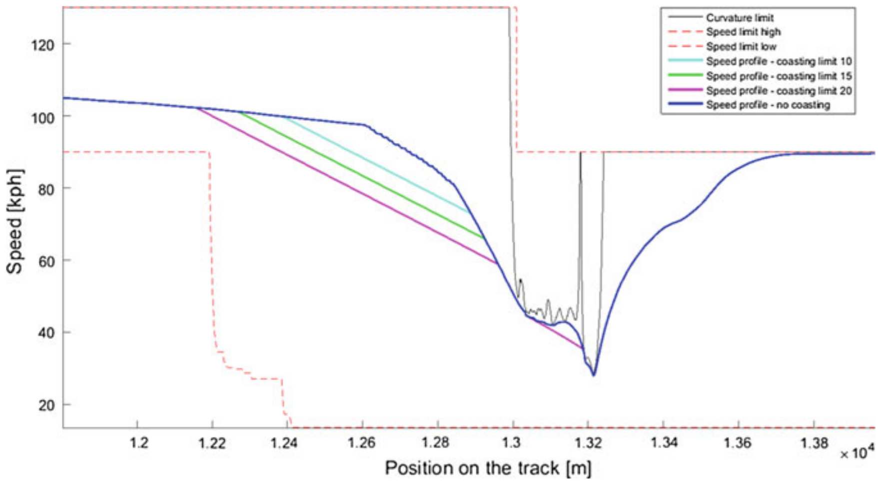

Fig. 3.11 Coasting calculated for a different offset: −10, −15, −20 kph

decelerations are possible to use for the example maximal offset −20 kph. This example is also shown on highway exit (Fig. 3.11). The first deceleration using coasting is possible to make with all three defined offsets, but the last coasting deceleration no because of speed profile shape. It only allows one chance for coasting and all three calculated coastings are in cover so it looks like only one design.

It is obvious that coasting makes the average speed lower and it is necessary to find a good compromise between the average speed and saved energy during coasting. In the shown example the original speed profile average speed is 83.13 kph and with coasting 81.58 kph.

Simulated energy consumption for different speed profiles and different limits for coasting algorithm is shown on Table 3.2. The benefit of coasting in comparison with the same speed profile without coasting is almost 6%. An interesting comparison is also between the speed profile for alpha = 0.6 without coasting and alpha = 0.7 with coasting using tolerance +1, −15 kph. The average speed of profile 0.6 is 80.62 kph and the average speed of profile 0.7 is 81.58 kph. Although the average speed of profile 0.7 is higher the total consumed energy is 7.69 kWh which is less than 7.95 kWh for profile 0.6. This is the proof of higher efficiency of coasting in comparison with regeneration breaking.

3.2.2 Real Road Measurement Using Semiautonomous Driving with and Without Coasting Mode

As was already mentioned Semiautonomous driving could run in two different modes. The first is without coasting and second with coasting. The Optimal speed

Table 3.2 Simulated results for different speed profiles and driving modes

Driving mode			Energy per track [kWh]				Average speed [kph]	Shifting benefit [%]	Coasting benefit [%]
Alpha	Shifting	Coasting	Tolerance	Consumed	Regenerated	Total			
0.6	on	off	–	8.3964	0.4434	7.953	80.6228	1.3018	–
	on	on	+1 −10	7.7364	0.1431	7.5934	79.7072	1.2998	4.5216
	on	on	+1 −15	7.5768	0.0789	7.4979	79.181	1.2694	5.7224
	on	on	+1 −20	7.5023	0.0488	7.4535	78.891	1.2311	6.2806
	off	off	–	8.4908	0.4329	8.0579	80.6228	–	–
	off	on	+1 −10	7.8283	0.135	7.6934	79.7072	–	4.5235
	off	on	+1 −15	7.6674	0.0732	7.5943	79.181	–	5.7534
	off	on	+1 −20	7.5919	0.0455	7.5464	78.891	–	6.3478
0.7	on	off	–	8.6789	0.5088	8.1702	83.1274	1.3452	–
	on	on	+1 −10	7.9993	0.192	7.8073	82.2357	1.3433	4.4418
	on	on	+1 −15	7.7958	0.108	7.6878	81.5808	1.2942	5.9044
	on	on	+1 −20	7.6865	0.0639	7.6226	81.1781	1.2604	6.7024
	off	off	–	8.7783	0.4966	8.2816	83.1274	–	–
	off	on	+1 −10	8.0946	0.181	7.9136	82.2357	–	4.4436
	off	on	+1 −15	7.8894	0.1008	7.7886	81.5808	–	5.9530
	off	on	+1 −20	7.779	0.0591	7.7199	81.1781	–	6.7825
0.8	on	off	–	8.9555	0.5765	8.3789	85.294	1.2330	–
	on	on	+1 −10	8.262	0.2453	8.0167	84.4485	1.2211	4.3228
	on	on	+1 −15	8.0306	0.1475	7.8831	83.7536	1.1858	5.9172
	on	on	+1 −20	7.8716	0.0834	7.7882	83.1585	1.1386	7.0499
	off	off	–	9.0462	0.5627	8.4835	85.294	–	–
	off	on	+1 −10	8.3478	0.2319	8.1158	84.4485	–	4.3343
	off	on	+1 −15	8.1151	0.1373	7.9777	83.7536	–	5.9622
	off	on	+1 −20	7.9544	0.0765	7.8779	83.1585	–	7.1386

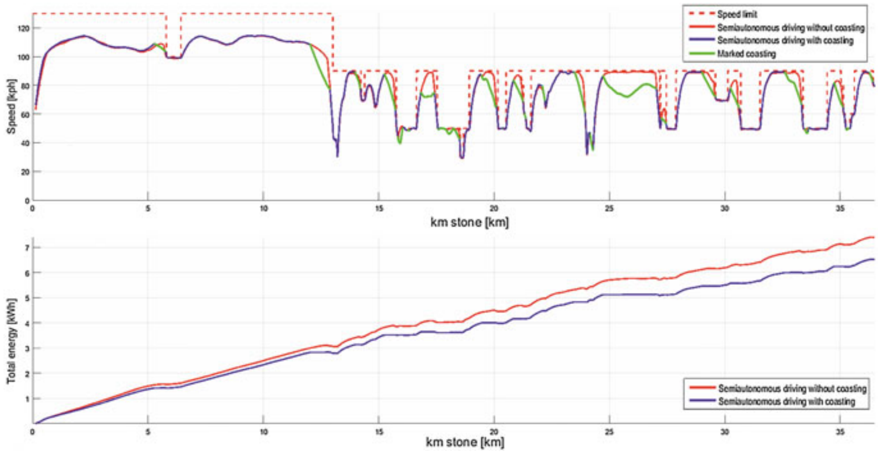

Fig. 3.12 Semiautonomous driving with and without coasting

profile, which is an input to the system, is always designed without coasting and coasting algorithm is a part of the car speed controller so it can be simply activated or deactivated. This was done to see different energy consumption on the track in both modes. The coasting mode makes the average speed of the vehicle a little lower than the mode without coasting but it has the significant benefit of lower energy consumption. This benefit is higher than using regenerative breaking, because energy regeneration is not as effective as driving and due to two energy conversions.

The first conversion is from battery to kinetic and potential energy (driving) and the second conversion from kinetic and potential energy into battery (regeneration). Both conversions have some efficiency which means two energy losses. Coasting has in a principle much better efficiency, because there is only one energy conversion from battery to kinetic and potential energy.

The second conversion from kinetic and potential energy to battery is missing and accumulated kinetic and potential energy is used only to overcome car driving resistance. Comparison of both driving modes is shown in Fig. 3.12 and measured results like real average speed and energy consumption are listed in Table 3.3.

3.2.3 Simple Vehicle Energy Consumption Model

The goal was to find a simple vehicle model which describes energy consumption of the car and is suitable for on-line calculations in automotive control units. This model is based on the balance of forces in longitudinal direction of driving (Fig. 3.13) and torque balance in the centre of the front wheel (Fig. 3.14).

Table 3.3 Results of semiautonomous driving with and without coasting

Measured energy consumption for driving mode with and without coasting					
Driving mode	Average speed [km/h]	Energy per track [kWh]			Energy consumption [kWh/100 km]
		Consumed	Regenerated	Total	
Without coasting	77.31	7.9962	0.5815	7.4146	20.39
With coasting	75.54	6.5263	0.2482	6.5263	17.94
Benefit of coasting [%]					12.02

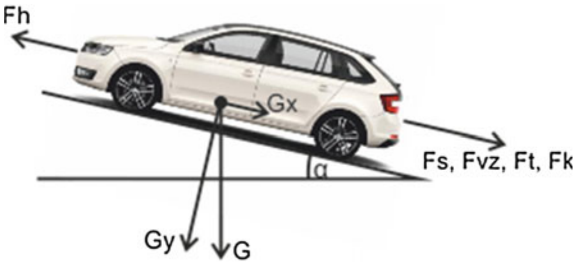

Fig. 3.13 Balance of forces in longitudinal direction

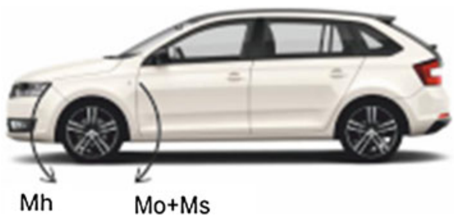

Fig. 3.14 Torque balance in the center of the front wheel

$$F_h = F_s + F_{vz} + F_v + G_x + F_k \tag{3.10}$$

where

F_h driving power
F_s inertia force
F_{vz} air resistance
F_v rolling resistance
G_x part of gravity force
F_k wheel resistance during cornering

$$M_h = M_o + M_s \tag{3.11}$$

$$M_h = (F_s + F_{vz} + F_v + G_x + F_k) * R + M_s \tag{3.12}$$

$$M_h = \left(m * v' + \frac{1}{2} * v^2 * \rho * C_w A + m * g * \cos\alpha * \xi + m * g * \sin\alpha + F_k \right) * \\ * R + J_p * \omega_k' \tag{3.13}$$

where

M_h driving torque
M_o resistance torque
M_s powertrain inertia torque
R wheel radius
m vehicle mass
ρ air density
$C_w A$ product of drag coefficient C_x and front surface of the car
g gravity acceleration
ξ rolling resistance coefficient (speed dependent)
α slope angle
J_p powertrain moment of inertia
ω_k wheel angular velocity
v vehicle speed

Differential Eq. (3.13) is our basis for the vehicle energy consumption model. The last step is to calculate engine torque and power using gear ratio and powertrain efficiency (3.14) and finally to consider engine efficiency (3.15) (Fig. 3.15). With this model it is possible to calculate the energy consumption of the vehicle from inertial data and the actual vehicle state (speed, acceleration, slope angle, etc.) and with a small modification of the equation it is also possible to predict the speed of the car which was used in the coasting detection algorithm.

$$M_{mot} = \frac{\frac{M_h}{i_c}}{\eta_p} + M_{s\_mot} \tag{3.14}$$

$$P = \frac{M_{mot}}{\eta_{mot}} * \omega_{mot} \tag{3.15}$$

where

M_{mot} engine torque
M_h driving torque
M_{s_mot} engine inertia torque

ω_{mot}	engine angular velocity
P	input power (energy consumption)
i_c	gear ratio
η_p	powertrain efficiency (gearbox, joints, etc.)
η_{mot}	engine efficiency

The model coefficients were identified on the same amount of measured data as for the optimal speed profile algorithm. The identification process was based on a deceleration test in three different modes:

(1) Free wheel mode—identification of rolling resistance and rotational inertia mass without engine (disconnected cutch).
(2) Free wheel mode with cornering—wheel resistance during cornering.
(3) Different shifted gears—engine inertia identification.

Example identification results are shown in Fig. 3.16. This simple model structure could be identified on-line in the vehicle during suitable maneuvers (coasting) for the adaptation to change some parameters during the life of the vehicle like increasing resistance in bearings etc.

3.2.4 Optimal Gearbox Shifting Map Design

In a real vehicle the automatic gearbox shifting is controlled by a shifting map. This map should be designed considering the vehicle dynamics and fuel/energy consumption. For a combustion engine it is possible to say when we need low fuel consumption the engine should make as low revolutions as possible. On the opposite side when we need a dynamic this engine should work at high revolutions because the power is increasing with the engine speed.

For an electric engine it is not so clear because of its behaviour. Consider the efficiency map for our asynchronous engine (see Fig. 3.15). This motor has the best efficiency between 3500 and 4500 rev/min and from 2200 rev/min has almost constant power—torque is decreasing with increasing revolutions. Due to this fact it is not possible to design a shifting map as same as for a combustion engine, but it is necessary to consider engine efficiency and power for various engine speeds and loads.

Consider the engine load only affected by a throttle position (driver command) and the engine speed as a function of the vehicle speed and selected gear ratio. With these conditions it is possible to calculate the shifting points to keep a higher engine efficiency or vehicle dynamics. Table 3.4 shows one example of shifting map where till 50% of throttle the shifting points are designed to keep higher efficiency and up to 50% to keep better vehicle dynamics. Numbers in Table 3.4 means the vehicle speed in kph. The green shifting points were designed for efficiency, blue points for dynamics, orange points were manually tuned for a smooth connection between efficiency and dynamics, red points are the speed limits of the map and black points are hysteresis for shift down.

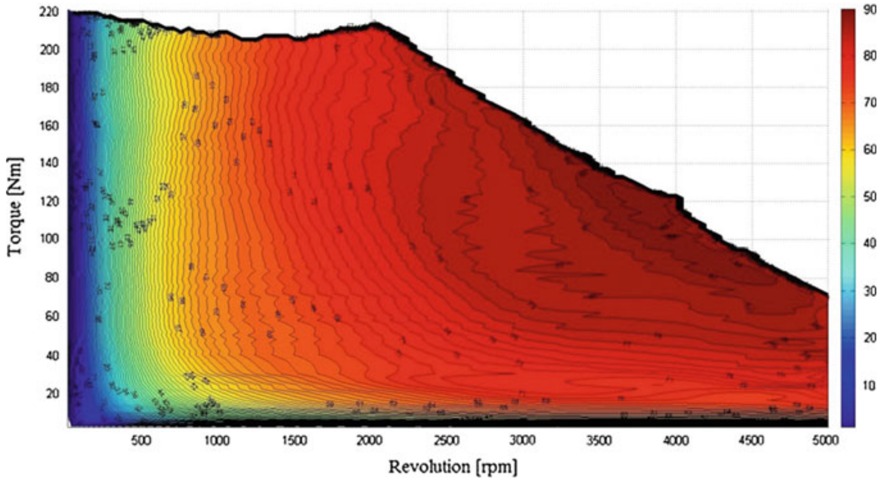

Fig. 3.15 Powertrain efficiency map

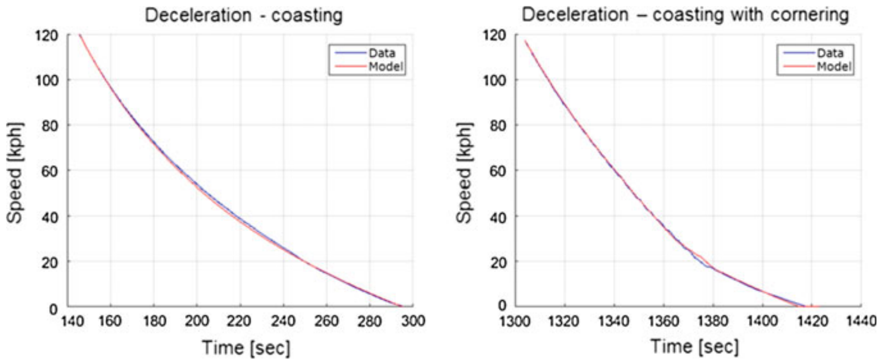

Fig. 3.16 Example identification results

For a better description we show two shifting point calculations from 3rd to 4th (a) for throttle = 38% and (b) for 63%. For shifting point (a) the engine efficiency for 3rd gear is better up to vehicle speed 84 kph and from this speed it is a more effective 4th gear (Fig. 3.17). When the max engine revolution or torque limit is reached the efficiency and torque on wheel is shown with its last value. The torque on wheels (affects vehicle dynamics) is always higher for 3rd gear up to maximal revolution so this point is designed for efficiency.

The shifting point (b) it is better to design for dynamics considering the torque on wheels. The dynamics for the 3rd gear is better up to 82 kph and from this speed is better to use the 4th gear (Fig. 3.18).

Table 3.4 Example shifting map for 7 speed automatic gearbox

	Throttle position																
Shifting	0	6	13	19	25	31	38	44	50	56	63	69	75	81	88	94	100
1 -> 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1 -> 2	20	20	23	23	24	27	28	29	35	35	34	33	31	30	30	30	30
2 -> 1	12	12	15	15	16	19	20	21	27	27	26	25	23	22	22	22	22
2 -> 3	36	36	38	45	45	59	59	58	58	58	55	53	51	49	49	49	49
3 -> 2	28	28	30	37	37	51	51	50	50	50	47	45	43	41	41	41	41
3 -> 4	49	49	50	62	64	68	84	87	92	88	82	79	77	77	77	77	77
4 -> 3	41	41	42	54	56	60	76	79	84	80	74	71	69	69	69	69	69
4 -> 5	84	84	87	91	93	128	131	135	128	122	114	110	106	106	106	106	106
5 -> 4	76	76	79	83	85	120	123	127	120	114	106	102	98	98	98	98	98
5 -> 6	112	112	112	113	117	126	157	160	164	154	147	144	135	135	135	135	135
6 -> 5	104	104	104	105	109	118	149	152	156	146	139	136	127	127	127	127	127
6 -> 7	140	141	143	145	147	148	180	213	202	190	180	172	165	165	165	165	165
7 -> 6	132	133	135	137	139	140	172	205	194	182	172	164	157	157	157	157	157
7 -> 7	255	255	255	255	255	255	255	255	255	255	255	255	255	255	255	255	255

Shifting point legend: efficiency, dynamics, manually adjusted for smooth connection of different designs, hysteresis, limits

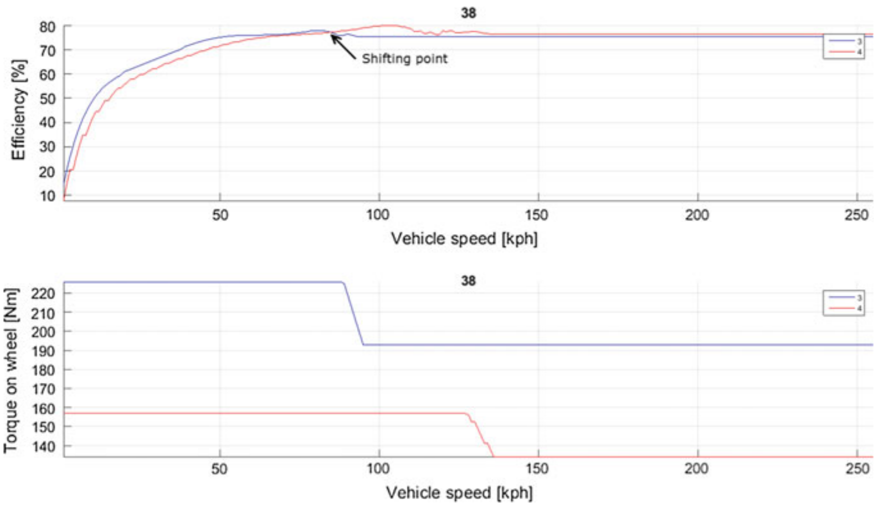

Fig. 3.17 Shifting point from 3rd to 4th gear for throttle 38%

In this way it is possible to design the whole shifting map which is shown in Table 3.4. This shifting map was uploaded to a real gearbox and tested in defined cycles NEDC (Table 3.5) and WLTP (Table 3.6) in comparison with the constant gear realised with the same gearbox, but with a constantly shifted 4th gear. Tables 3.5 and 3.6 shows energy consumption for both cycles using shifting and without shifting.

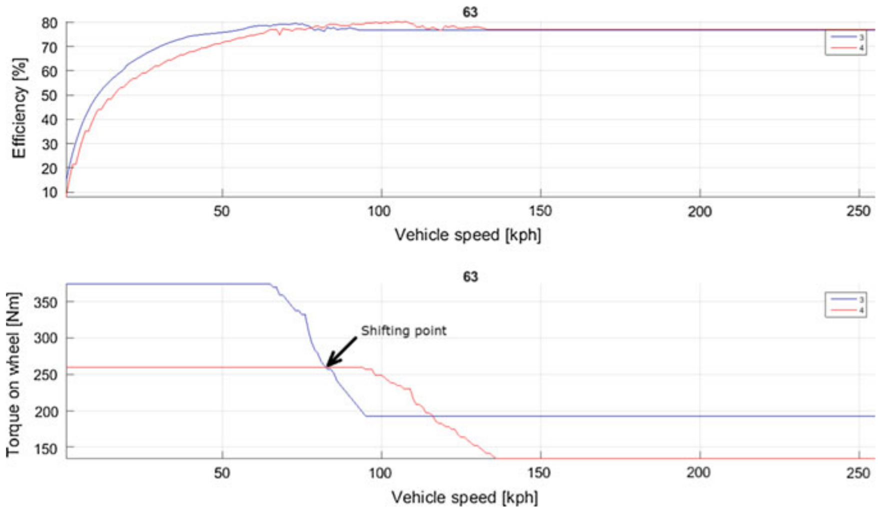

Fig. 3.18 Shifting point from 3rd to 4th gear for throttle 63%

Table 3.5 Results of NEDC cycle

NEDC				
Mode	Average speed [kph]	Energy pre cycle [kWh]		
		Consumed	Regenerated	Whole
Constant gear 4.	34.62	1.96	0.14	1.82
Shifting (1–6)	34.33	1.81	0.15	1.66
Benefit of gearbox [%]		7.43	12.89	8.94

Table 3.6 Results of WLTP cycle

WLTP				
Mode	Average speed [km/h]	Energy pre cycle [kWh]		
		Consumed	Regenerated	Whole
Constant gear 4.	46.81	4.28	0.32	3.96
Shifting (1–6)	46.88	4.14	0.37	3.78
Benefit of gearbox [%]		3.16	15.29	4.63

3.3 Conclusion

During this work an algorithm for Optimal speed profile was designed and verified. This algorithm is independent to the type of vehicle, is optimal for a selected priority between energy consumption and average speed, considers safety limits and is applicable for advanced driver assistance systems and also for autonomous driving.

The demonstrated principle of coasting was also verified with a real car where the benefit of coasting for energy saving could be up to 12%, which of course it depends on the track.

The disadvantage of this principle is a very high sensitivity to track/map data quality because inputs to the Optimal speed profile design and model for speed predictions are track curvature, slopes and speed limits. In this case similar kinds of driver assistant systems should be connected with a well updated source of data and online information about traffic situations which could cause a speed limitation like road works.

For our goals, it was also necessary to design a new shifting map to consider an electric motor's behaviour because the Optimal speed design algorithm is not applicable on-line now and pre-designed shifting only cannot be used for real driving due to other unpredictable interruptions of driving like avoiding manoeuvers, breaking, etc. The benefit of shifting in comparison with a constantly selected gear in defined cycles NEDC (8.94%) and WLTP (4.63%) was also evaluated. The benefit for the real track near Mlada Boleslav was only simulated and it is approx. 1.3%. It is not so big a benefit because engine efficiency in 4th gear with an average speed over 80 kph is very high. Benefits also depend on driving cycles and the biggest benefit of shifting is expected in the cities where the FEVs make sense.

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