METHODS AND ALGORITHMS IN CONTROL OF HYBRID POWERTRAINS

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Abstract

The main ambition of this paper is to give an overview of the development of methods and algorithms for an energy-efficient (fuel saving) operation of vehicle power trains. At first general influencing factors of the vehicle's energy efficiency are analyzed. Beside conventional development objectives like lightweight construction, combustion engine efficiency, air drag reduction two newly considered main energy efficiency influencing factors are the driver behavior and the power train control/ balancing (of hybrid vehicles). Those two factors are investigated within different research projects at the Vehicle Mechatronics Department at Dresden University of Technology. One project presented in this paper aims to develop a prototype driver assistance information system for a fuel-efficient and safe approaching and crossing of vehicles at traffic light controlled intersections by influencing/ informing the driver (chapter 3). The second project deals with the supervisory control of hybrid power train. An overview of control methods and basic design steps for a predictive control scheme of a parallel hybrid power train are given (chapter 4).

1. Introduction

The development of energy-efficient vehicles is one of the main issues in (auto-) mobility research and political discussion, to meet the requirements for fuel consumption reduction and strict emissions standard achievements. To increase energy efficiency different measures for designing new vehicles can be taken into account. Those measures can be grouped into two fields - passive and active energy management. Whereas measures of the passive energy management include constructive and component-oriented design steps, the active energy management increases vehicle efficiency during the operation phase. An overview and analysis is given in chapter 2.

Two active energy management measures – the impact on the driver's behavior and the supervisory control (operational mode management) of the hybrid drive train system are presented and discussed in this paper. The common denominator of those active design measures is the use of predictive data provided by vehicle-internal status and surround information sensors to forecast the driving progress within a certain horizon or to analyze the current and forthcoming driving situation. Those predictive data is utilized for both

(1) as driving information that is brought to the driver via a human machine interface (e.g. speed recommendations within the vehicle instrument panel) or
(2) as input value(s) for a supervisory control algorithm (e.g. MPC-model predictive control) that determines the optimal balance between the power torques of the combustion and electrical engines in the drive train according to the current and forthcoming driving situation.

Case (1) is investigated by a research project presented in chapter 3. An implementation of driver assistance/ information system based on an ad-hoc-network communication system connecting an advanced traffic light controller module attached to a standard intersection control unit and a vehicle controller unit mounted in the vehicle approaching the intersection is described. Based on traffic light timing information, vehicle geographic positioning and dynamics data as soon as information on vehicle-surrounding traffic (preceding vehicle platoons) a situation-adaptive, time- and energy-optimal driving strategy is calculated that is brought as approaching speed recommendation to the driver.
Case (2) is discussed in detail in chapter 4. Different methods for the supervisory control of (parallel) hybrid power trains are presented and compared. Exemplary results of simulation-based investigation of the potential of predictive vehicle operation (assuming ideal predictability of forthcoming driving situations) are given.

2. Methods for an Efficient Energy Management in Vehicles

Legal and customers' requirements are constantly increasing for vehicles in terms of emission standards, fuel reduction goals and comfort and safety functionality.

Therefore an optimization of the efficiency of new cars is essential. One possibility is the so called passive energy management. It is based on an analysis and optimization in parallel to the development of existing and new technical subsystems in vehicles. The main topics and measures are [Lan06]:

- optimization of internal combustion engines
- integration of new materials and production processes to reduce the vehicle mass
- improving the aerodynamics
- development of alternative dynamics

Based on progress of digital computer sciences (increased computing functionality) and the increasing power and functional range of mechatronic systems it is possible to control actively the energy flow in cars, called active energy management. Here, all the methods for situation-adaptive vehicle operation by adapting component use and by ensuring an efficient provision of energy are combined. Three main possibilities can be considered [Lie10]:

- calculating an economical route (avoid traffic jams)
- supporting the driver by information (enhance foresighted driving)
- optimization of supervisory control (balance use of drive train components)

Figure 1 shows the complete system with the main subsystems driver, vehicle, environment and route. On the one hand the driver might be supported by an information system, to control the vehicle. On the other hand, a vehicle controller might control the vehicle subsystems autonomously. The first one is defined by choosing the most economical route (1) and the driver information system to support a foresighted, efficient control of the car (2), further information are given in chapter 3. An optimization of the on-board supervisory control is the third possibility (3). Here the degree of efficiency is maximized by pre-conditioning the reversible on-board energy storages (e.g. batteries, storage of the air conditioner,…). This is shown in detail in chapter 4.

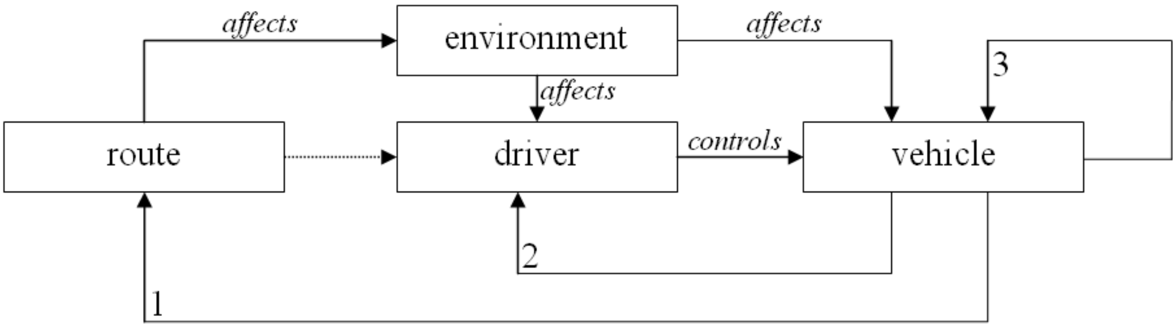

Figure 1: System driver-vehicle-environment

The use of predictive data analyzing the current and forthcoming driving situations is the common denominator for all of the three possibilities. The chosen route depends on a current driven route prediction containing all route elements between start and destination point. In comparison the support of the driver for an optimization of the vehicle control needs a shorter horizon of the prediction data, since the driver needs information just on the forthcoming driving situation. For supervisory control strategies the range of prediction is depending on the architecture of vehicle and the energy storages (for bigger energy storage capacities, an increased prediction data horizon is useful).

Table 1: Comparison of different information sources for driving states prediction

	surround sensors			**Global Positioning Systems (GPS)**		**car-2-x systems**
	radar	lidar	video	route known	route unknown	
detection range horizontal angle distance	5°-40° 40m-200m	~270° 150m	~50° 100m	360° theoretic. unlimited	360° theoretic. unlimited	360° Ad-Hoc up to 1000m
adverse weather performance	++	-	--	++	++	++
sensor costs	-	--	-	0	0	-
precision	++	++	++	+	0	++
information content	object distance, curves	object distance, curves	objects, traffic signs, scenario interpretation	global traffic network, road type, traffic information		traffic scenario information

To obtain predictive data for the vehicle driving states different information sources that are technically available in vehicles now or in the near future can be used. Table 1 gives a compact overview [Cas07].

3. Car-to-Traffic light Communication based Driver Information System

One important measure in the field of active energy management of vehicles is the impact on the driver's behavior. The complexity of especial intra-urban driving situations with numerous driver-influencing factors such as surrounding vehicles, pedestrians, traffic sign/ light based regulations motivates the development of driver-influencing information systems to enhance a foresighted driving. One of the biggest potentials for informing the driver can be seen for driving situations in the range of traffic light controlled intersections. Due to missing knowledge of the traffic light timing inefficient driving profiles and vehicle operation modes occur (e.g. (1) driver accelerating some hundred meters in front of intersection at green traffic light - followed by hard braking due to traffic light switching to red, (2) running engines at red traffic lights). To open up potentials of supporting drivers during those situations information systems ("off-board" sensors) based on cooperative vehicle to vehicle or vehicle to infrastructure communication systems (V2V, V2I) are increasingly considered to be introduced in vehicular technology in the near future (1), (2).

The design goal of the prototype communication and information system at TUD Department of Vehicle Mechatronics is to build a universal basis for the implementation of several functions (numbered applications [1], [2], [3]) for driver assistance/ support in the range of traffic light intersections. The following figure gives an overview of the distributed system architecture consisting of a single, central traffic light controller module (TL-C) and multiple vehicle controller modules (Veh-C).

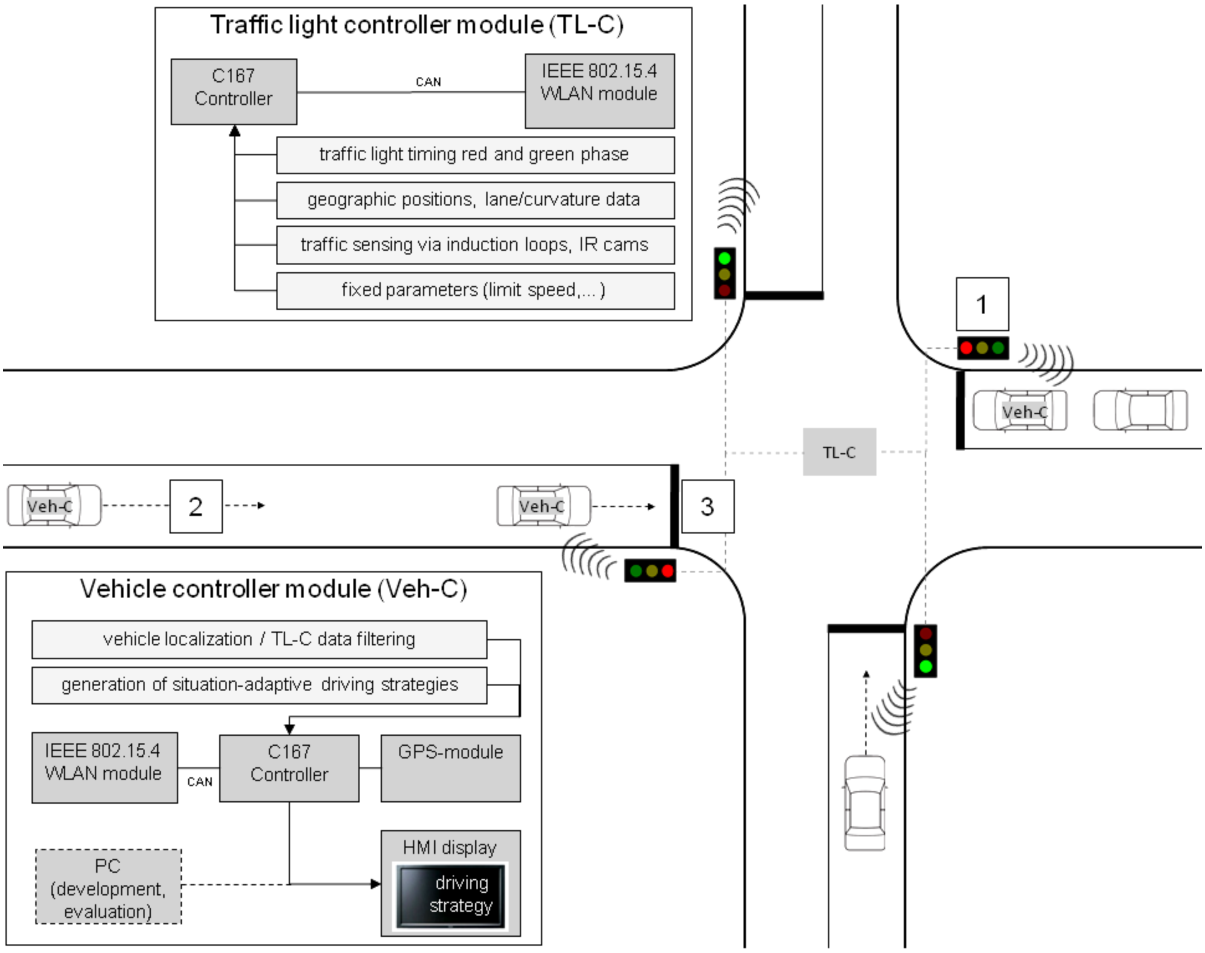

Figure 2: Overview of system design and illustration of use-cases, numbered 1, 2, 3

The considered driver supporting functions are described shortly in the following.

[1] Vehicle - Traffic light communication for an optimized combustion engine (ICE) auto start stop function / motor turn-off recommendation for the driver – based on transmission of the remaining red light timing the ICE start stop function can be activated earlier during braking phases or can be disabled for very short red traffic light stops (stop time less than amortization time).

[2] Vehicle - Traffic light communication and vehicle localization for the generation of situation-adaptive, time- and energy-optimal driving profiles – in this case traffic red and green light timing information of current and following phases are evaluated and distance to intersection or backing-up queue length point is calculated. Based on path-time equations the optimal driving strategy can be determined, illustrated in figure 3. Exemplary driving strategies – standstill avoidance strategy and strategy with standstill are shown in the diagrams in figure 4 including the implemented HMI design for driver information.

[3] Vehicle - Traffic light communication and vehicle localization for traffic red light crossing warning/ prevention – based on reliable vehicle odometry (wheel speed, acceleration) and highly precise vehicle localization data, the deceleration behavior of the extended analysis of driver situation awareness.

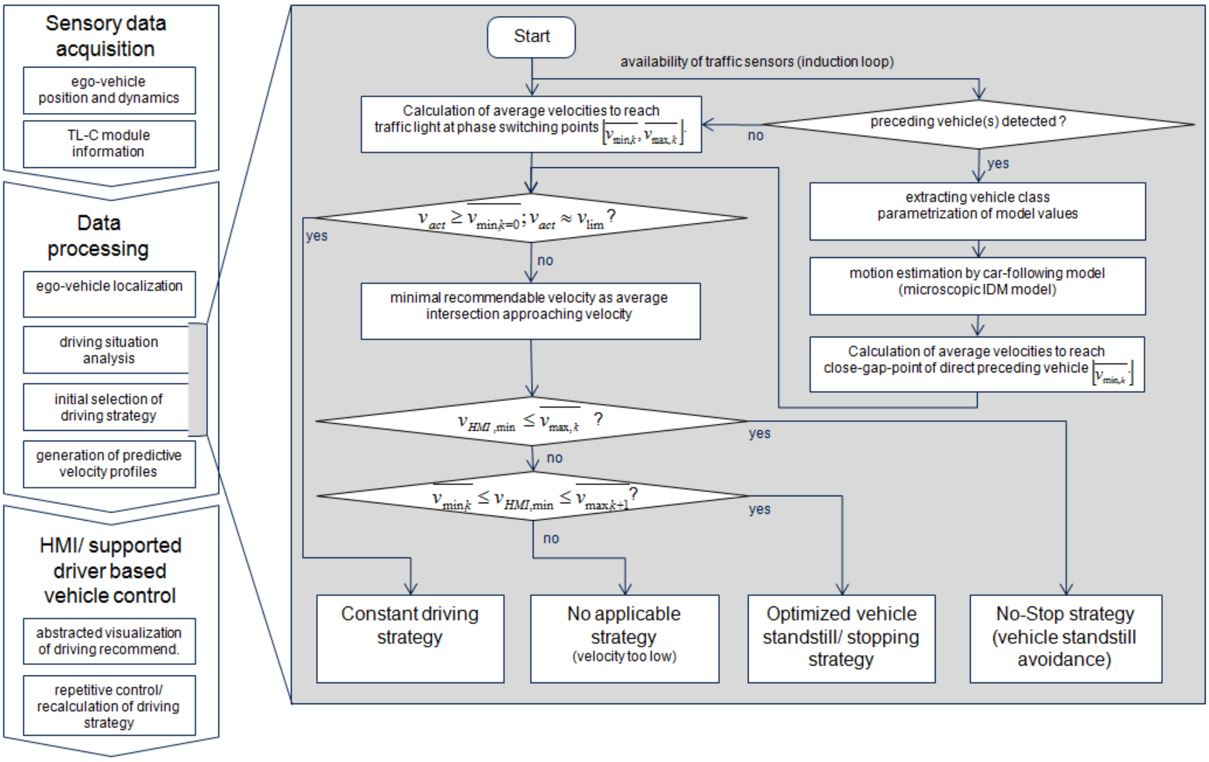

Figure 3: Overview of system data processing steps (left); flow chart of situation analysis/ driving strategy decision, based on path-time equations (right)

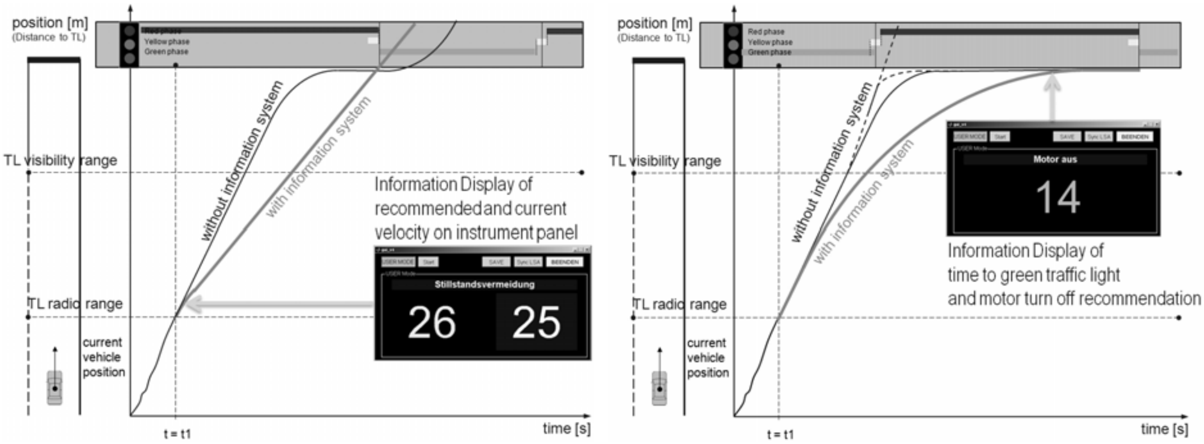

Figure 4: Calculated time- and energy efficient velocity profiles for two driving strategies – left: optimal velocity recommendation to follow a standstill avoidance strategy; right: velocity profile for optimized strategy with standstill and ICE turn off recommendation for stop time greater than amortization time

4. Supervisory Control of Hybrid Power Trains

Hybrid drive trains in vehicles are one approach for the realization of an efficient mobility. Their importance rises in connection with current political discussions on decreasing fossil fuel resources and emission reduction. A combination of electric drive and combustion engine seems to be a suitable solution to open up fuel saving potentials. The advancement for the energy efficiency of the conventional power train arises from the possibility of using the bidirectional flow of energy in hybrid vehicles. Further potentials can be seen in the reduction of component wear during the whole vehicle life cycle, the reduction of emissions and an increasing driving performance. There are three main architectures of hybrid power trains, series, parallel and power split.

Parallel and power-split hybrid power train structures of two propulsion engines offer great potentials for developing highly energy-efficient (depending on the current driving situation) vehicle operating methods. The speed/torque curves of the components combustion engine (ICE), electric motor (EM) and mechanical brake are very important for the used areas of the vehicle operation modes. They can be used for an evidence to find the best control strategy of the power train. The chosen gear, the current state of charge (SOC), the currently active vehicle speed and for example the requested torque by the driver has a direct influence to the drive characteristics. The main aim of supervisory control schemes explained in this paper is to find the most energy-efficient decision to set the operation parameters (torque of the electric motor and combustion engine, as well as the shifted gear) on the basis of different input values. The increase of torque, raised by combustion engine, to realize higher energy storage in the energy accumulator is called assist here. The choice of the parameters is also qualified as so called control strategy. There are existing three main approaches/ methods:

Online-Optimized Strategies

One control scheme is the so called Online-Optimization. At first an assessment of values in the form of a cost function is necessary. In this application the cost function is set up by fuel consumption and the level of the current SOC. The solution of the cost function has to be minimized for every time step (if there is no prediction) or for the complete predicted horizon (1).

$$f(\alpha_1, \alpha_2, ...\alpha_n) = \min\left(\frac{\sum_{i=1}^{n} w_i \cdot \alpha_i}{\sum_{i=1}^{n} w_i}\right) \qquad \alpha_1(SOC), \alpha_2(\eta_{EM}), \alpha_3(\eta_{ICE}), ... \qquad (1)$$

The advantage is the achievement of high power train efficiency, near to the global optimum. Disadvantage is the required computing power.

Heuristic-Operation Strategies

Secondly, hybrid power train control scheme can be based on heuristic strategies by optimizing fuel consumption using expertise of developers. Here the developer has to define a couple of rules. The construct of rules may decide online (during vehicle operation) which operation mode (e.g. electric driving, shifting the operating point of combustion engine in hybrid mode or conventional driving only with combustion engine) is chosen. Important rule parameters can be pre-calculated in offline simulations. This variant of control strategy is qualified for simplified implementation and low calculation capacity in the vehicle, but results concerning fuel consumption and efficiency (depending on operational profile) are partial far away from the global optimum. Predictive data is not needed for this approach.

Optimal-Control Strategies

A possibility to handle this intricate problem is the use of a predictive horizon to determine the forthcoming future driving states of the vehicle. On the basis of this predictive horizon the best split of the driving power can be calculated. This type of control scheme of a hybrid vehicle is called online optimal control.

The implementation of the online optimal control – in combination with the widely used Dynamic Programming (DP) method – leads to the global optimum of vehicle efficiency, but requires high computing resources; consequently this method is rarely found in related applications yet [Bac05]. Further on, the online-optimal control scheme strongly relies on predicted driving states information that must have a certain steadiness within the prediction horizon to obtain a clear advantage compared to the other two control scheme approaches.

Optimal-Control strategy can be used to calculate the possible reference consumption for a given operational profile. Figure 5 shows the results of a quasi-static simulation of a full-hybrid-car (parallel hybrid, assuming ideal prediction data) in comparison to the same online optimal control strategy using no predictive information. The analysis is done for the New European Driving Cycle (NEDC). The fuel saving potential with a prediction for the simulated parallel hybrid electric power train and battery storage is around 5%.

The quality of the online optimal control strategy using predictive information depends directly from the correctness of prediction data. The predictive strategy may turn worse than a non-predictive strategy for wrong predictions of forthcoming driving situations. Hence, it is essential to use adequate prediction data sources, cp. Table 1. A distinction is drawn between probabilistic-, nominal- and worst-case-prediction.

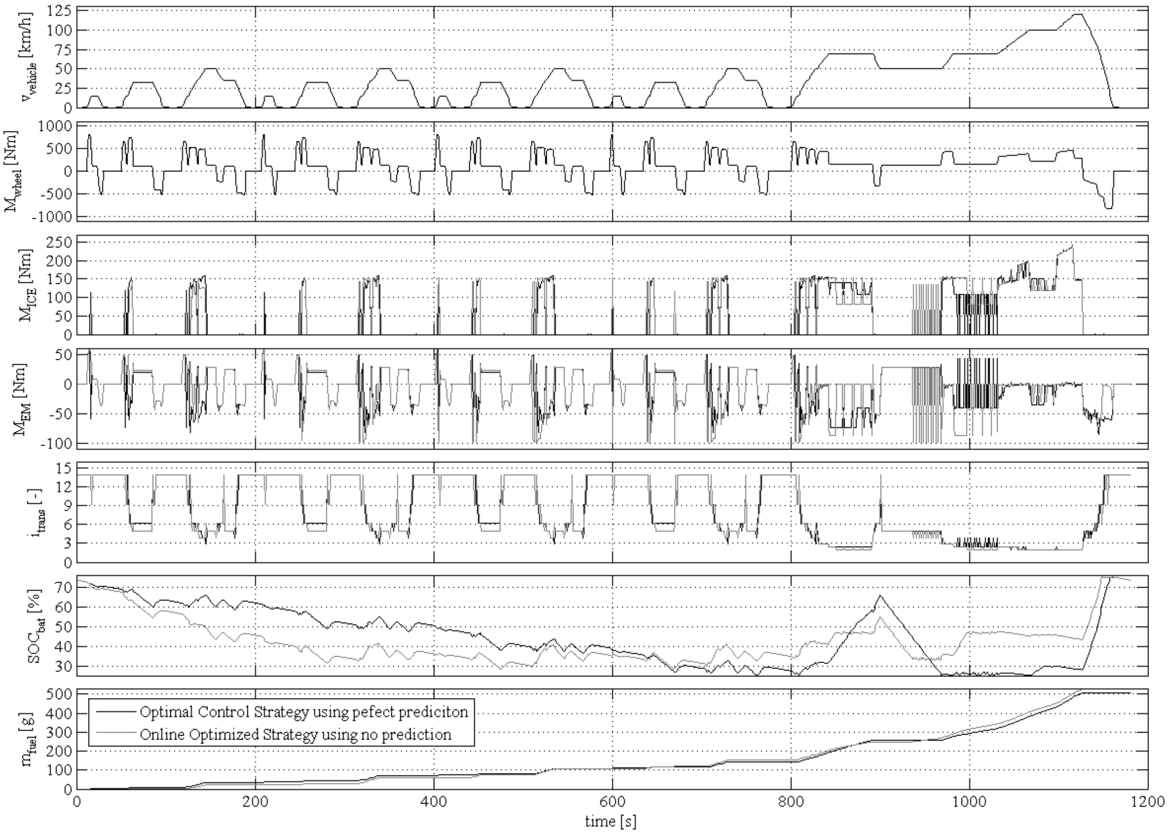

Figure 5: Non-predictive (grey) vs. predictive control strategy under assumption of ideal prediction data (black)

Using prediction-based control-strategies the foresighted time (horizon length) has to be in a range of several minutes. The usage of information describing the vehicle's surroundings (provided by on-board radar or video sensors) is not suitable in this case. The application of navigation-data (for static information), car2x-data (for dynamic information) seems to be promising (qualified for nominal-prediction). Another interesting data-source are historic vehicle journeys, i.e. recorded profiles of vehicles dynamic parameters that depend on influence of dynamic environment parameters (e.g. traffic lights against the time of day) and on the driver characteristics in different driving situations (qualified for probabilistic-prediction).

5. Conclusions / Outlook

New requirements and guidelines for fuel saving, decreasing emissions and the customer requirements for more driving performance are reasons for the development of measures in the field of passive and active energy management of vehicle design. Two active energy management measures were described in detail in this paper.

Based on advanced traffic light (predictive) information transmitted via a wireless communication protocol the development of a prototype information system to support the driver (as first active energy management measure) during intersection approaching and crossing situation was presented. Necessary design steps concerning driving strategy decision, HMI design were addressed in an overview. Further investigation is directed towards automation of intersection approaching velocity profiles by implementing extended adaptive cruise control (ACC) functions.

The choice of certain control strategies of hybrid power train (as second active energy management measure) has a big influence on the energy efficiency of vehicles. Different schemes for power train control strategies were discussed. The greatest potentials are given by the so called predictive online optimal control strategy. Further investigation objectives can be seen in providing reliable prediction data by combining different information and sensor sources from the traffic telematics and an implementation of this control scheme on a hardware-in-the-loop test bench or in a real hybrid vehicle.

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