

Consumption Optimization in Battery Electric Vehicles by Autonomous Cruise Control using Predictive Route Data and a Radar System

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ABSTRACT

This paper presents an autonomous cruise control for battery electric vehicles. The presented approach is based on the usage of predictive route data which is extracted out of a digital map and a wide range radar system in order to capture vehicles in front.

By using the predictive route data and the information of the radar system, the autonomous cruise control can control the vehicle's speed over a wide range of driving situations without any driver interaction.

The main aim of the presented autonomous cruise control is to optimize the battery electric vehicle's energy consumption. The main idea is to use predictive route data in order to calculate a consumption optimal vehicle speed trajectory by means of online optimization. The benefits of the autonomous cruise control are shown by means of real test drives and measured data evaluation. Also, this paper gives an outlook how energy consumption can be further optimized by using an automatic transmission in the battery electric vehicle in combination with a predictive gear selection strategy.

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INTRODUCTION

The automotive mechatronics department of the Institute of Automotive Engineering and Vehicle Engines Stuttgart (FKFS) carries out research on the issue of range prediction and range optimization in battery electric vehicles (BEVs) by using different approaches. In several government-funded and industry projects diverse research is carried out using a holistic approach to generate fast and sustainable solutions. The FKFS offers and uses several facilities such as a fleet of different category electric vehicles equipped with measurement systems for power flow and vehicle dynamics [1], a test bench for electric and hybrid power trains [2,3] as well as batteries and cells [4], a driving simulator for the development of advanced driver assistance systems [5,6,7] and a research charging station capable of different kind of AC, DC and inductive charging, see Figure 1.

For a successful market introduction of BEVs, their range must be increased towards a consumer accepted degree. To achieve this aim, car manufacturers spend much effort to increase battery capacities and to decrease the vehicle's energy consumption. While on the one hand, efficiency improvement of power train components and the reduction of driving resistances depict the focus, on the other hand,

consumption reduction by means of intelligent driver assist systems is regarded to be a major key.

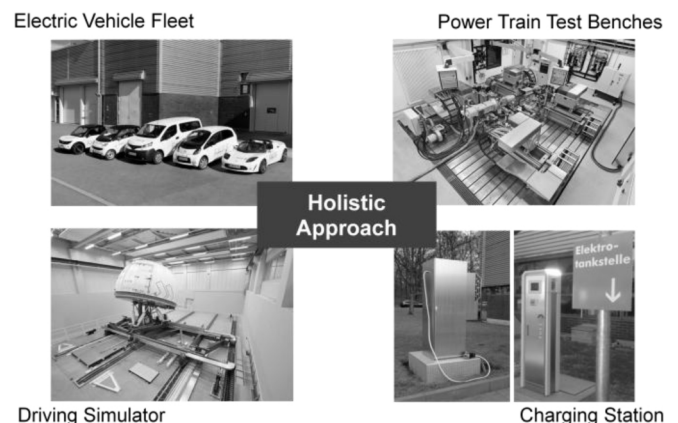


Figure 1. FKFS facilities for diverse BEVs research issues

In this context, especially cruise controls are considered to have great potential to achieve significant energy consumption savings since they can take over control of the vehicle's power train and thus directly influence the energy consumption. These cruise controls can be further improved

if predictive information of the route in front is used [8,9,10,11]. The predictive route information can be provided by digital maps or by self-learning route data storages [12].

Besides the target of optimizing the vehicle's energy consumption by means of applying an appropriate speed trajectory, also the issue of driver comfort and acceptance plays a major role for developing effective and frequently used driver assist systems [13].

This paper presents an implementation of such a cruise control in a real BEV. The main ingredients for the proposed control are a wide range radar sensor system and a digital map. The proposed cruise control was introduced in [8]. This paper aims to present an extension of the existing control scheme which considers the calculation of the applied vehicle speed trajectory by means of online optimization. The target of the online optimization is to calculate a speed trajectory for a certain length horizon of the route in front by minimizing the required energy consumption for the regarded route horizon under several constraints. Thereby, the topological property of the route in front is the main influencing variable for the vehicle speed optimization.

The remainder of this paper is organized as follows: Based on the results of a huge test person study carried out by the FKFS, the first section gives an overview about the energy consumption in BEVs and the influencing variables. In the following two sections first the experimental BEV which serves as a platform to test and evaluate the considered controls is briefly described and subsequently the outline for the autonomous cruise control [8] resumed. The following section presents the extension of the existing control scheme by a speed trajectory calculation using online optimization and predictive route data as well as measured results to show the achieved benefits. This paper concludes with an outlook and a summary.

ENERGY CONSUMPTION IN BATTERY ELECTRIC VEHICLES AND INFLUENCING VARIABLES

Several research studies on the issue of energy consumption in vehicles conclude that the required energy for a certain route underlies heavy distributions [1,14,15]. The measured results for the electric power train energy consumption in study [1] are shown in Figure 2. In the considered study, a representative collective of 42 test persons drove a 60 km driving cycle with statistically confident parts of urban, extra urban, federal highway and freeway sections in Stuttgart area with five different class BEVs which were equipped with special measurement devices.

As can be seen, distributions in power train consumption can reach more than 30 %. Since all drives were done on the same route, the distributions are caused by varying traffic situation or by the test persons' individual driving style.

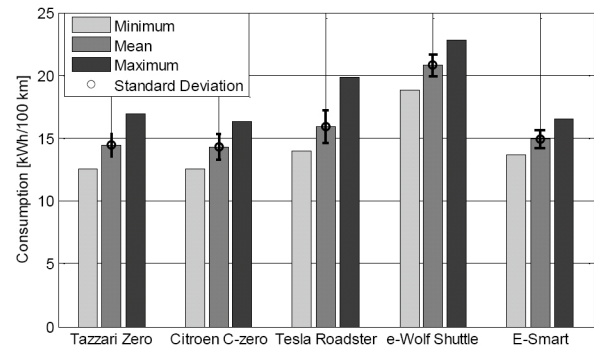


Figure 2. Measured electric power train energy consumption in five different class BEVs in the study of [1]

The Figure 3 shows the electric power train consumption as a function of the mean speed during the drives.

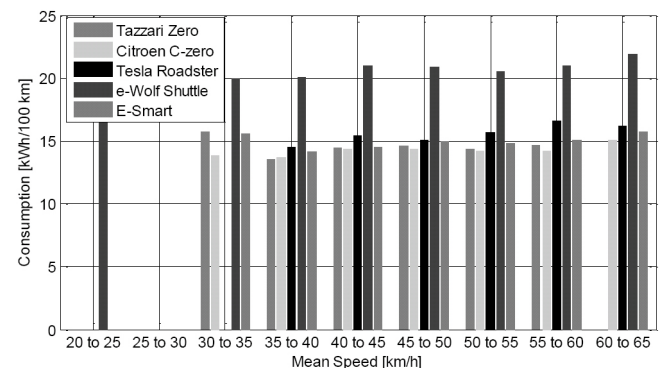


Figure 3. Measured electric power train energy consumption as function of the achieved mean speed [1]

From Figure 3 can be concluded that there is no evident relation between mean speed and electric power train consumption. This finding is astonishing since higher mean speed indicates increased energy consumption for driving resistances, especially the air resistance.

To explain this finding, the Figure 4 shows exemplarily for the E-Smart the electric power train consumption separated by the driving resistances and the power train losses for the test person with the lowest and the test person with the highest achieved mean speed. Thereby, it cannot be answered if the big difference in the mean speeds originates mainly from a very different traffic situation during the two drives or from a very different driving style of the two test persons. Since the results were achieved on a driving cycle with same start and stop position, the potential energy can be neglected.

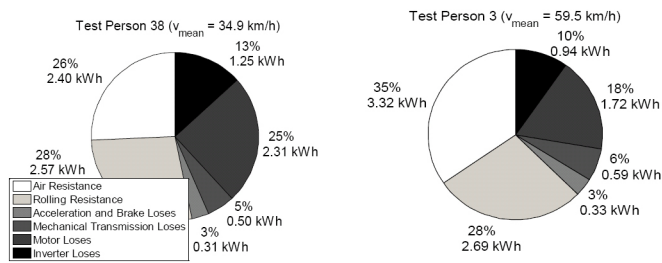


Figure 4. Electric power train consumption analysis for E-Smart for the lowest mean speed (left) and the highest mean speed (right) test person

According to Figure 4, the test person with the highest mean speed spent much more energy to overcome air resistance compared to the test person with the lowest mean speed. But on the other side, the lowest mean speed test person had much more losses in the electric power train to overcome such that the overall consumption result is nearly equal and displays a total difference of less than 2 %.

In conclusion, if considering a certain route, a speed profile with a high mean speed causes an increased consumption for especially air resistance while a speed profile with a low mean speed leads to increased electric power train losses. This issue is further analyzed in the Figure 5 which shows in the left diagram the time slices for the vehicle acceleration states in the two test drives discussed in the Figure 4 as well as the related efficiency map of the E-Smart electric power train including inverter and electric motor in the right diagram.

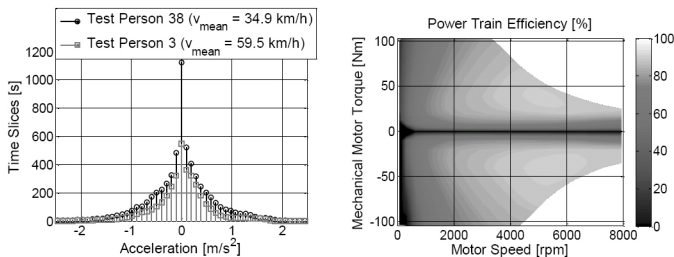


Figure 5. Vehicle acceleration time slices during the discussed test drives (left) and E-Smart electric power train efficiency map

As can be seen, the test person with the lowest mean speed displays more time slices at high acceleration and deceleration rates. Thus, this test person had to accelerate and brake more often and stronger. Accordingly, the driven speed profile of the lowest mean speed test person is less steady compared to the speed profile of the highest mean speed test person.

Since high acceleration and deceleration indicate for high torque request and considering at the same time that the power train efficiency is decreasing with increasing torque request at lower speeds, see the power train efficiency characteristics in the right diagram in Figure 5, the test person

with the lowest mean speed had to overcome much more power train losses than the test person with the highest mean speed who was driving with a smoother speed profile at higher speeds.

As a main result of this analysis follows that a smooth speed profile, i.e. less acceleration and deceleration phases, is preferably. It will lead to a higher mean speed and consequently to a decreased traveling time. The energy consumption for a smooth speed profile is nearly equal compared to a less steady speed profile with a lower mean speed. In the first case, the energy consumption for driving resistances will dominate, in the second case, the electric power train losses will be increased.

Furthermore, the amount and the distribution of electric power train losses is very noticeable. In the case of the lowest mean speed test person electric power train losses amount 38 % related to overall consumption, in the case of the highest mean speed driver it amounts 28 %.

Considering the cruise control design which is discussed in this paper, the following targets can be identified:

- Avoiding unnecessary acceleration and braking by means of using predictive information of the route in front and information about vehicles in front provided by the radar system.
- Incorporating the electric power train efficiency characteristics in the process of set speed calculation in order to optimize electric power train losses.

EXPERIMENTAL ELECTRIC VEHICLE

This section briefly describes the experimental BEV which serves as a platform to test and evaluate the presented controls [16]. The considered experimental vehicle is a Smart ForTwo 450 CDI which was converted to a BEV, see Figure 6.



Figure 6. E-Smart experimental BEV (left) and its control system (right)

The main BEV characteristics are summarized in the Table 1. The vehicle is equipped with several rapid control prototyping units which are used to implement diverse control functions and an extensive set of sensors to measure all relevant vehicle dynamics variables, driver interaction variables as well as electric variable. By means of a set