The automotive industry is facing significant pressure to drastically reduce in emissions in the near future in order to meet evolving legal requirements for fuel efficiency and CO2 emissions. Alternative drivetrains, such as plug-in hybrid electric vehicles (PHEVs), are regarded as a promising technology to help meet these challenges. The energy management is a crucial factor for achieving low emissions and high fuel efficiency. In current HEVs, mostly rule-based operation strategies are used to determine the power distribution between both propulsion units - the internal combustion engine (ICE) and the electric motor/generator (EMG). Despite its intuitive and simple implementation, a rule-based strategy is generally not the optimum with respect to fuel consumption especially for distances longer than the all-electric driving range (AER).

A more efficient operation strategy can be implemented when the upcoming driving route with its speed is predicted and adapted to the certain driving style. The usage of the estimated information in long-term and short-term results in an overall optimal fossil fuel consumption (Figure 1).

Since real-time capability is a prerequisite for vehicle implementation, special attention is given to enhance the computation efficiency. Besides the proper determination of the discretisation grid resolution of the solution space also a time-efficient vehicle model structure and a multi-level controller structure, compare Figure 2, are introduced. The innovative operation strategy is designed for a parallel HEV drivetrain layout configuration where the EMG is mounted between the starting clutch and the gearbox. The investigated PHEV offers a maximum overall system power of about 200 kW.

The proposed intelligent energy management controller is able to concurrently increase the overall fuel efficiency and enhance the longitudinal vehicle performance by efficiently maintaining the energy content of the battery over the entire driving route. Compared to state-of-the-art rule-based operation strategies fuel saving up to 11.7 % are possible (with almost similar energy content at the end of the trip) depending on the real-world driving cycle. The anticipatory and driving style adapted planning of the energy content of the battery simultaneously ensures sufficient energy reserves to instantly provide the total vehicle system power over the entire driving route. Compared to state-of-the-art rule-based operation strategies fuel saving up to 11.7 % are possible (with almost similar energy content at the end of the trip) depending on the real-world driving cycle. The anticipatory and driving style adapted planning of the energy content of the battery simultaneously ensures sufficient energy reserves to instantly provide the total vehicle system power over the entire driving route.

The novel holistic energy management controller (Figure 4) is based on the basic layout in Figure 2 and the combined data collected while driving. It considers three different information levels, depending on the data available. If no additional information about the route ahead is available, a simple rule-based operation strategy is used. If a frequently driven route is recognised, the stored data about the route is used to enable additional fuel saving potential. If input data from a navigation system and GNSS signals are available, the advanced prediction and adaptation (P&A) algorithm further enhances the fuel efficiency of PHEVs. If both GNSS with digital map data and stored routes are available, the advanced operation strategy combines both data. For all routes within the AER, the electric drive mode is used. The route recognition algorithm detects characteristic data during driving and compares that data with the stored routes. The structure of the energy management controller enables the use of other information from advanced communication technologies, such as intelligent transportations systems (ITS) or geographic information system (GIS). Nevertheless, this additional information is not necessary in order to improve the fuel efficiency. The output of the holistic energy management controller is the requested power distribution between both propulsion units the EMG and the ICE which ensures an energy-efficient vehicle operation near to its optimum.

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The presented thesis includes three main innovations. First fixed-location information, e.g., intersection or speed limits is augmented with the driver's individual driving behaviour. Moreover, methods for approximating the driver's individual driving style (e.g., the acceleration/deceleration behaviour or the maximisation rate of vehicle acceleration) are incorporated with fixed-position information. This enables the innovative energy management controller to increase the prediction accuracy. Second, a novel holistic energy management controller is proposed, which is able to account for different trip scenarios, such as trips both within and beyond the AER. Third, all effects of the innovative real-time capable operation strategy are explicitly tested in an advanced dynamical vehicle model, which yields more realistic conditions regarding fuel savings and improvement of the longitudinal vehicle dynamics.

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The presented research work provides an in-depth analysis of PHEVs, and especially their operation strategies. The introduced innovative energy management controller, based solely on the vehicle, the driver's past trip data and GNSS signals, can remarkably enhance fuel efficiency by maintaining the energy content of the battery in an efficient manner. The operation strategy enables a high level of vehicle performance and comfort, while keeping fossil fuel consumption at a low level. The proposed operation strategy can effectively help to achieve current and future CO2 targets, even in a real-world driving cycle. Even high-performance vehicles (>200 kW) are able to approach the goal of an average of 95 g/CO2 across the entire vehicle fleet by 2020. This will lead to improved customer acceptance and thus higher market share for HEVs, along with reducing GHG emissions, should be the primary goal of developing operation strategies for HEVs.

**Results**

The proposed intelligent energy management controller is able to concurrently increase the overall fuel efficiency and enhance the longitudinal vehicle performance by efficiently maintaining the energy content of the battery over the entire driving route. Compared to state-of-the-art rule-based operation strategies fuel saving up to 11.7 % are possible (with almost similar energy content at the end of the trip) depending on the real-world driving cycle. The anticipatory and driving style adapted planning of the energy content of the battery simultaneously ensures sufficient energy reserves to instantly provide the total vehicle system power over the entire driving route.

**Innovation**

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**PhD Thesis Development of an operation strategy for plug-in Hybrid Electric Vehicles – long-term prediction and adaptation based on past vehicle and driver data**

**Dr. Harald Kraus, Graz University of Technology, Institute of Automotive Engineering**

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