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A two-level stochastic approach to optimize the energy management strategy for fixed-route hybrid electric vehicles

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ABSTRACT

Many hybrid electric vehicle (HEV) energy management strategies are developed and evaluated under fixed driving cycles. However in the real-world driving, vehicles are very unlikely to keep running under a fixed known cycle. Instead, a lot of vehicles run on fixed routes. Unfortunately, human driving data collected on a driving simulator shows that it is very difficult to select or create a determined typical driving cycle to represent the fixed-route driving due to the uncertainties in traffic light stops and driver behaviors. This paper presents a two-level stochastic approach to optimize the energy management strategy for fixed-route HEVs. The historical data on the fixed route are utilized and a road-segment-based stochastic HEV energy consumption model is built. The higher-level energy optimization problem is solved by stochastic dynamic programming (SDP). The SDP computation uses the vehicle model and historical driving data on the fixed route and it can be conducted offline. The result of SDP is a 2-dimension lookup table of parameters for lower-level control strategy therefore this approach can be easily real-time implemented in practice. The developed stochastic approach is compared with three strategies using the data collected on the driving simulator: the optimal energy consumption by assuming all trip information is known in advance and solved via dynamic programming (DP), a determined energy management approach using typical trip data of the fixed-route driving, and a simple strategy which does not require any route data. Simulation results show that the proposed stochastic energy management strategy consumes 1.8% more energy than the optimal result after 24 trips on the fixed route and considerably outperforms the other two real-time HEV energy management strategies.

1. Introduction

Hybrid electric vehicle energy management strategies have been widely researched as they are the keys to improve the HEV operational energy efficiency and lower the emissions. Some optimal control methods including dynamic programming [1] and Pontryagin's minimum principle (PMP) [2,3] can be used to calculate the optimal control strategy if the complete driving cycle information, which is usually described as a speed-time table, is known in advance. But it can hardly be directly implemented in real world driving because it is impossible to exactly predict the future information for the whole trip. There are several practical energy management strategies, including heuristic rules [1,4], fuzzy logic [5], and equivalent consumption minimization strategy (ECMS) [2], which do not require future driving information thus can be applied in the real-world driving. However, most of these strategies are designed, tuned or evaluated based on some driving cycles. While the real driving scenario can be quite different from the standard driving cycle, there is no guarantee of the performance of these strategies in the real driving scenarios. Model predictive control (MPC) and some other preview-based energy management strategies, which predict the future trip information (usually in a relatively short time period for HEV applications) and optimize the strategy over the prediction horizon iteratively, can also be applied to the HEVs [6–16]. Some studies show that the well-tuned MPC and ECMS have good performance, as their energy consumption is very close to the DP result [6,15]. However, the tuning is dependent on the driving cycle and the comparison is only made under that specific driving cycle.

In the real-world driving, though it is impossible that a vehicle strictly follows a fixed and known driving cycle, a lot of vehicles run on fixed routes. For example, the public transportation buses, some utility vehicles, and personal cars for commuters all run on fixed routes. The undiscovered information in the fixed-route driving can definitely help improving the control strategies of HEVs, because in general the more information we have for the entire trip, the better we can design the energy management strategies. Some research has been conducted on exploring the potential for fixed-route HEVs. A method to online predict the future speed profiles for vehicles operating in fixed-route service is presented in [17]. In [18] a clustering method to study distance-based driving pattern and energy

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management strategy for fixed-route driving are proposed. In [19] the energy consumption of an HEV is optimized using a pre-defined speed profile and an online adjustment scheme that compensates for the difference between the actual speed profile and the pre-defined profile is provided. In [20] an approach to select the most representative trip is presented and DP is applied to optimize the energy consumption of the trip while the uncertainty in route length is considered. Then the battery state of charge (SOC) result from DP is used to design a real-time HEV control strategy for commuter vehicles. Most of the essential ideas of the aforementioned research are based on deriving a fixed driving cycle as a typical trip of the fixed-route driving, and then designing an energy management strategy and a compensation scheme around the fixed cycle.

However, due to the different traffic conditions, traffic light changes, weather conditions, even driver's emotions, the fixed-route vehicles cannot be considered as being driven under a fixed cycle. The actual speed and torque demand can vary substantially among each trip even on the same route by the same driver. Those attempts to describe or approximate the fixed-route driving as a fixed cycle cannot guarantee the optimal energy consumption result. More details about this phenomenon will be discussed later in Section 2. Some studies try to use stochastic approaches to describe the uncertain trip information and design an HEV energy management strategy based on stochastic models [6,7,9,14,15,16,21,22]. These previous studies use short-time-scale stochastic models, usually sampled at about 1 Hz (some varies from about 0.2 Hz to 5 Hz). These stochastic models cannot capture the long-term behavior if the total trip length is more than thousands of seconds. For example, a point-wise pedal Markov model sampled at 1 Hz can hardly provide enough information about the future state after thousands of steps. The methods described in the previous studies are not suitable for the long-term behavior description because of their structures and their target of predicting the point-wise speed and torque demands. Most of these models do not consider the road environment (e.g. local or highway, uphill or downhill) except [22]. But [22] only provides an example of using two different driving patterns (urban and extra-urban), which may be too simple especially for the fixed-route case where much more valuable information is available. None of these models can take into account the uncertainties in the traffic light signals.

Unlike a point-wise model, a road-segment-based model [23,24] is more suitable for long-term prediction. This is because it extends the length in each prediction step thus fewer steps are required for longer prediction, and it can also distinguish some key road environment factors such as local or high way, and uphill or downhill. In this paper, a two-level control structure is used: in the lower level, a practical HEV energy management controller is implemented, but the key parameters in the controller will be determined in the higher level where a stochastic method is used based on the road-segment model. In this two-level structure, the higher level takes the advantage of long-term stochastic prediction and gives "strategic-level" command, while the lower-level control focuses on the local operational control.

In this paper, it is assumed that the interested vehicles only run on a fixed route, or the vehicles run on a fixed route frequently and the controller is able to recognize it (for more information regarding route prediction and recognition, please refer to [25,26]). It is also assumed that the historical driving data of the fixed-route driving, including the speed and torque demand, are recorded and available.

In this research, the fixed-route driving data for analysis are gathered on a driving simulator. A stochastic approach is used to derive an optimized energy management strategy for fixed-route HEVs. First, the route is divided into a series of segments. A stochastic model on fuel and electricity consumption over each segment is built based on historical data. The battery SOC change and fuel consumption over each road segment are considered as random variables whose probability distributions can be affected by the parameters of the lower-level controller. Then the higher-level control strategy is obtained by stochastic dynamic programming to optimize the lower-level controller parameters, while any practical HEV controller with tuning parameters can be chosen as the lower-level controller. All the optimization computation can be conducted off-line and the SDP result can be presented as a 2-dimensional map of parameters for lower-level controller which can be applied in real-time implementation. The developed strategy is validated in simulation on a plug-in vehicle and compared with several other strategies.

Fig. 1. The driving simulator platform.

The paper is structured as follows. Following the introduction section, the fixed-route driving data characteristic analysis is given in Section 2. The stochastic optimization problem formulation and solution for HEV energy management strategy optimization are presented in Section 3. Section 4 provides the simulation studies. Conclusions are given in Section 5.

2. Fixed-route driving data analysis

In this section, the driving simulator used for fixed-route driving behavior study will be introduced first. Then the data collected on the driving simulator will be analyzed to show that fixed-route driving cannot be represented by a fixed cycle, and the ideas on how the fixed-route information data can be used will be given.

2.1. Driving simulator platform

Fig. 1 is a picture of the driving simulator. The vehicle model used in the simulator is based on a mid-size passenger car with a 3.2 L Diesel engine and 6-speed automatic transmission. The vehicle dynamic model is a 3-degree-of-freedom vehicle body model with four 4-degree-of-freedom tire models based on the Magic Formula tire model [27] with load transfer considered. A map-based engine model and a pedal-speed-map-based transmission shifting strategy are used in the simulator. A 12-kilometer track, which is demonstrated in Fig. 2, is designed as a combination of both local roads and highways. Road slopes are considered in the road model and vehicle model, which means there are some uphill and downhill in the trip. There are multiple stop signs and traffic lights on the local road. Some detailed track parameters are shown in Table 1. The driver is required to drive following the speed limits, stop signs, traffic light signals, and other traffic regulations. In the test, a test driver has driven on the track for 24 times, at the frequency of once or twice a day, to simulate a normal commuter behavior. An overview of the test trips is shown in Table 2.

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