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Driving-behavior-aware stochastic model predictive control for plug-in hybrid electric buses

Liang Li [a,*], Sixiong You [a], Chao Yang [a], Bingjie Yan [a], Jian Song [a], Zheng Chen [b]

[a] The State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China
[b] The Faculty of Engineering, University of Technology, Sydney, NSW 2007, Australia

HIGHLIGHTS

- The novel approximated global optimal energy management strategy has been proposed for hybrid powertrains.
- Eight typical driving behaviors have been classified with *K*-means to deal with the multiplicative traffic conditions.
- The stochastic driver models of different driving behaviors were established based on the Markov chains.
- ECMS was used to modify the SMPC-based energy management strategy to improve its fuel economy.
- The approximated global optimal energy management strategy for plug-in hybrid electric buses has been verified and analyzed.

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ABSTRACT

Driving cycles of a city bus is statistically characterized by some repetitive features, which makes the predictive energy management strategy very desirable to obtain approximate optimal fuel economy of a plug-in hybrid electric bus. But dealing with the complicated traffic conditions and finding an approximated global optimal strategy which is applicable to the plug-in hybrid electric bus still remains a challenging technique. To solve this problem, a novel driving-behavior-aware modified stochastic model predictive control method is proposed for the plug-in hybrid electric bus. Firstly, the *K*-means is employed to classify driving behaviors, and the driver models based on Markov chains is obtained under different kinds of driving behaviors. While the obtained driver behaviors are regarded as stochastic disturbance inputs, the local minimum fuel consumption might be obtained with a traditional stochastic model predictive control at each step, taking tracking the reference battery state of charge trajectory into consideration in the finite predictive horizons. However, this technique is still accompanied by some working points with reduced/worsened fuel economy. Thus, the stochastic model predictive control is modified with the equivalent consumption minimization strategy to eliminate these undesirable working points. The results in real-world city bus routines show that the proposed energy management strategy could greatly improve the fuel economy of a plug-in hybrid electric bus in whole driving cycles, compared with the popular charge depleting–charge sustaining strategy and it may offer some useful insights for realizing the approximate global optimal energy management for the plug-in hybrid electric vehicles.

1. Introduction

DUE to the urgent demand for energy conservation and emission reduction, the potential of hybrid electric vehicles (HEV) has been extensively explored in the past few decades. The configuration of HEV provides great potential of energy saving, and the single-shaft parallel plug-in hybrid electric buses (PHEBs) with automated mechanical transmission (AMT) has been very popular in some countries for its compact structure and high transmission efficiency. Since the internal combustion engine (ICE) and electric machine (EM) are combined in the same shift via clutch, the torque split control is adopted. But this configuration cannot always guarantee the optimal performance with the existing control strategies, such as charge-depleting and charge-sustaining (CD–CS) and other simple strategies. Still, as the real driving conditions of PHEBs are fixed, the historical information of driving cycles can be used for the foundation of the stochastic driver models, through which the driver behaviors could be predicted more accurately [1,2]. And once the driver models are precise enough, the vehicle performance, including fuel economy,

* Corresponding author.

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could be improved greatly and the near optimal solution can be obtained.

Since there are two main power sources in a PHEB, the extra degree of freedom is good for the flexible distribution of the demand torque between ICE and EM to improve the efficiency of the power sources [3–5]. Furthermore, as the driving condition of city bus is repetitive, some of the parameters such as road slopes, total distance and the statistic traffic information of the whole driving cycles can be obtained in advance to enhance the energy efficiency of a plug-in hybrid vehicle [6]. Therefore it is a meaningful research work to seek an effective energy management strategy for a PHEB.

The energy management strategies for HEV may essentially be optimization-based strategies with necessary constrains of many kinds, such as the powertrain configuration [7]. Considering the unique features of multisource vehicles, many studies have been conducted on this potential optimization problem. In order to get the theoretical global optimal energy management strategy, dynamic programming (DP) algorithm-based energy management strategy was designed [8,9]. In addition, Pontryagin's Minimum Principle (PMP)-based power management was also adopted and the efficiency of the propulsion system can be improved significantly [10]. However, without the complete knowledge of future driving cycle, the global optimization could not be applicable. Given that lots of information about the future driving behaviors cannot be obtained such as the vehicle speed and driver inputs, the equivalent consumption minimization strategy (ECMS) based on Pontryagin's Minimum Principle was developed [11]. Considering the practicability of energy management strategy, the fuzzy logic-based energy management system was proposed and experiment tests were done [12]. As the model predictive control (MPC) had been applied to many fields with excellent results [13,14], the MPC had been applied to the energy management [15]. The ECMS focusing on the optimization at the present moment may improve the performance of the rule-based energy management strategy. However, it still fails to take the future energy demands into account. Different from the above energy management strategies, the energy management strategies which are concerned with the efficiency of tank-to-wheel have also been proposed, this may offer some useful insights for the current strategies to get higher fuel economy [16]. As the fuel economy should not be the only goal for optimization, the influence of battery health has also been considered [17]. In addition, to achieve the optimal energy allocation for the engine-generator, a novel adaptive energy management strategy has been proposed, and the results were verified [18].

Different from the ECMS, the predictive control strategies can benefit from the future information. Besides, considering the random characteristics of the total system, such as vehicle speed and driver behaviors, the stochastic dynamic programming (SDP) was also developed for PHEV to realize an improved fuel economy [19]. Furthermore, in recent years, the stochastic model predictive control (SMPC) has been intensively/widely studied, and some significant progress was obtained [20,21]. Due to the characteristics of SMPC, this method has been firstly introduced into the energy management of HEV, which benefits from the statistics of the uncertainties to improve fuel economy [2,22,23]. As the driving conditions and traffic conditions have a significant influence on the driver behaviors, some proper researches had been conducted for HEV [24,25]. And the driving behaviors classification seems to be an effective method to solve this problem. In addition to classification of driving behaviors, the road slopes, which has some influence on driver behaviors, should also be taken into consideration.

Considering that the driving conditions of PHEBs in this paper are fixed and repeatable, the SMPC could be fit for this problem, in which the driver behaviors could be taken as the stochastic disturbance inputs. Given the nonlinearity of the vehicle system, linearization of this system might influence the performance on fuel economy [11]. Thus the nonlinear equation of state could be adopted for SMPC. Moreover, because current driver inputs could be quantified as finite types independent of the past values, the Markov chain might be adopted to establish the driver models for different driving behaviors [26]. Since the goal of the SMPC at each step is to obtain the minimum fuel consumption (FC), taking tracking the reference battery state of charge (SOC) into consideration in the finite predictive horizons, the results of optimization are the local optimal solution, which cannot always guarantee the efficiency of current working point. . The instantaneous optimization of ECMS might make it favorable to correct these kind of inputs.

Therefore, in this paper the driver-behavior-aware modified SMPC (MSMPC) based energy management strategy is proposed, in which the unknown driver inputs in the prediction horizon are taken as the stochastic disturbance inputs. Altogether, three main contributions are made: (1) the *K*-means is adopted for driving behaviors classification, and the stochastic drivers models are established based on it; (2) combined with the stochastic driver models, the energy management strategy based on SMPC is proposed for the single shaft PHEBs; (3) the MSMPC is proposed, in which the ECMS is used to modify the SMPC to improve its fuel economy. With the energy management strategy mentioned above, the fuel economy is improved compared with the standard charge-depleting and charge-sustaining (CDCS) energy management strategy, DP, SMPC and MPC. In addition, the proposed approximated global optimal energy management strategy is suitable for the city bus driving conditions and is able to be converted to the online control.

This paper is organized as follows. In Section 2, the configuration and mathematical models of the hybrid powertrain are given and the problem is described in the second part. In Section 3, the driving-behavior-aware MSMPC is introduced. In Section 4, the results are shown and analyzed. Finally, conclusions are presented in Section 5.

2. Powertrain model and problem description

2.1. Hybrid powertrain model

The configuration of a single-shaft PHEB with AMT is shown in Fig. 1, where the engine and EM are placed at either end of the clutch, and the EM can work as electric motor or generator alternately. And due to the configuration of this hybrid system, they could only output torques on the same driving shaft, thus this kind of configuration is called coaxial parallel configuration. What's more, in order to improve the dynamic performance and economic performance of the PHEBs, the automated mechanical transmission (AMT) is added between the differential mechanism and the clutch, and via proper shift strategy, the vehicle performance can be further improved [27]. The main parameters of the studied PHEB are listed in Table 1.

The mathematical model of a PHEB can be described as follows.

Because only the longitudinal dynamics of the vehicle is considered for fuel consumption, the vehicle longitudinal dynamics model is applied to get the demand torque, and the driving torque of the wheel can be written as [28]:

$$T_w = \eta_T \cdot i_{AMT} \cdot i_d (T_e + T_m) + T_b \tag{1}$$

where T_w is the wheel torque, T_e and T_m is the torque of engine and torque of EM respectively. η_T is the transmission efficiency, i_d and i_{AMT} is the gear ratio of the differential gear and AMT respectively.