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Optimal energy management strategy for parallel plug-in hybrid electric vehicle based on driving behavior analysis and real time traffic information prediction☆

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ABSTRACT

Conclusive evidence has justified great importance of energy management strategies in the performance and economy of plug-in hybrid electric vehicles (PHEVs). This article pays attention to improve adaptive equivalent consumption minimization strategy (A-ECMS) for parallel PHEV based on driving behavior recognition and real time traffic information prediction. Three main efforts have been made to distinguish our work from exiting research. Firstly, a hierarchical driving behavior model is constructed, providing in-depth knowledge about behavior generation, transmission, and consequence. Secondly, an online driving behavior classification method is designed. The proposed method is the coefficient result of offline driving behavior study based on self-report driving behavior questionnaire (DBQ) and online driving behavior discrimination by BP neural network. Thirdly, an improved adaptive equivalent consumption minimization strategy (IA-ECMS) is formulated based on identified driving behavior and predicted real time traffic information. The IA-ECMS can realize equivalent factor tuning instantaneously and reasonably. The simulation results indicate the proposed energy management strategy holds potential in fuel economy improvement than A-ECMS.

1. Introduction

The crisis of global warming, environment pollution and natural resource shortage calls for the development of novel energy saving and environment friendly technologies. Plug-in hybrid electric vehicles (PHEVs) have drawn much attention for excellent fuel economy and less exhaust emission. Compared with hybrid electric vehicles (HEVs), PHEVs take advantage over larger capacity battery and evolved engines, obtaining better performance. In other words, PHEVs can consume less fuel without scarifying drivability by rationally utilizing energy from engine and battery. The flexible energy distribution between engine and battery puts forward higher requirement on energy management problem. Therefore, the energy management strategies of PEHVs have aroused general concern.

1.1. Literature review

1.1.1. PHEV management strategies

A plethora of complicated control methods have been utilized to provide optimal control policies, managing power flow between engine and battery. The proposed energy management strategies can be divided into three types: Heuristic methods [1–5], Instantaneous control methods [6–10], and Global optimization methods [9,11,12]. The preceding works have been proved to be effective under certain conditions. Among them, the equivalent consumption minimization strategy (ECMS) have drawn a lot attention as an instantaneous strategy [6]. ECMS is originally derived from Pontryagin Minimum Principle (PMP), which can be applied in real practice [7].

In ECMS, equivalence factor is the key factor that determines effect of ECMS, requiring instantaneous adjustment [8]. By equivalence factor, the total fuel consumption can be achieved by converting electric energy consumption into equivalent fuel consumption. And the optimal control candidates are those who result the minimum total fuel consumption. Generally speaking, equivalence factor can be affected by energy consumption of driving cycle ob-

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viously [13], leading to the proposal of A-ECMS. In some A-ECMS methods [7,14–16], equivalence factor is tuned according to identified type of driving cycles, assigning a pre-calculated value. This method can realize adjustment while it cannot guarantee accurate adjustment. In some newly developed method [17,18], future travel information prediction is applied for obtaining more accurate energy consumption in whole driving cycle, adjusting equivalence factor more reasonably. Except energy consumption of driving cycle, driving behavior can also produce an effect on equivalence factor adjustment.

1.1.2. Driving behavior analysis

Humans have been proved to be an essential role in manipulating human-machine systems, i.e. vehicles [19]. As a result, human behaviors in driving are suggested to be deep investigated to improve vehicle performance. In automatic vehicles or advanced driving assistant systems (ADASs), driving behaviors have been carefully studied to improve system performance [20–22]. These studies can be driving behavior models building [20,21], driving behavior classification [22], etc. A series of considerable driving behavior models have been developed based on different theories of human behavior in [23–25], focusing on different aspects of driving task, and providing intuitive knowledge of driving behaviors. Some methods of driving behavior classification have been proposed in [26–28], the identified driving behavior can be applied in differentiation design of ADASs and traffic systems.

1.2. Motivation and contribution

Despite that the methods discussed in literature review have been proved to be effective under certain conditions, there are several problems remain to be optimized to govern energy flow better. First, numerous proposed energy management strategies cannot bring their capability into full play without pre-knowledge about future driving cycle. Second, driving behavior studies related to energy management still need more endeavor. The driving behavior generation mechanism, reasonable classification method are all benefit to formulate more efficient strategy with better adaptability.

The main purpose of this study is to improve the performance of A-ECMS by tuning equivalence factor instantaneously based on driving behavior analysis and travel information prediction. The driving behavior analysis and travel information prediction provide foundation to realize equivalence factor adaptive adjustment. Three main contributions have been made in this study. To begin with, a hierarchical driving behavior model is established. This model can provide intuitive knowledge about generation, transmission, and consequence of driving behavior, making preparation for incorporating driving behavior into energy management strategy design for PHEV. Secondly, an online driving behavior identification method is developed. Compared to conventional driving behavior identification methods, this online method is the result of offline multivariate statistical analysis on self-report DBQ and online BP neural network discerning, possessing justified classification basis and online implementation effect. Thirdly, the IA-ECMS is proposed. The IA-ECMS can accomplish energy distribution in real time with driving behavior analysis and traffic information prediction.

1.3. Outline of the paper

The reminder of the paper is organized as follows: the constructed driving behavior model is described in Section 2. The online driving behavior identification method is designed in Section 3 with offline and online two processes. The IA-ECMS is proposed in Section 4 with details about how to integrate the identified driving behavior information and predicted traffic information into equivalence factor adjustment. The evaluation of proposed IA-ECMS is carried out in Section 5, and conclusions are provided in Section 6.

2. Hierarchical driving behavior model

Driving behavior is the essential factor that could make difference on traffic and vehicle performance [29], which deserves to be deeply investigated. A number of driving behavior studies on vehicle performance mainly try to address following basic questions for further application [23–25]:

a. *How does driving behavior generate, transform and make difference?*
b. *What is the degree of heterogeneity in driving behaviors in real driving environment?*
c. *To what extent do driving behavior of different drivers vary due to personal features, environment and social factors?*

To excavate answers to these basic questions, driving behavior models which can reproduce various driving behaviors or reveal inner mechanism of human performance are highly recommended.

2.1. Hierarchical driving behavior model

Generally, driving behavior can be described as consisting following one or several tasks [29]:

a. *Perceiving stimulation in traffic environment, and making suitable response according to stimulation and inner psychology activity.*
b. *Implementing responses as actual behavior.*
c. *Monitoring the consequence of actions and, if need, making adjustment.*

In accordance with tasks included in driving behavior, it can be divided into several stratified process before driving behavior comes into being, which are perception and decision-making, action establishment, and action implementation. The perception and decision-making process is mainly responsible for driving behavior preliminary generation, which is determined by driver's inner psychological activities and perception to environment. The inner psychological activities can be: attitude towards trip (travel time, travel pleasure level, travel speed, etc.), attitude to environment and social pressure (competition for speed, obeying rules, etc.), global goals and needs (destination, economy, etc.), local goals and needs (car following, lane switching, etc.) and risk assessment. The perception to environment is connected with status awareness (current traffic status and future traffic status, vehicle status, etc.). To the action establishment stage, it is directly related to maneuvering control by following the order from perception and decision-making level, which is the actual driving behavior establishment. For instance, acceleration for passing by other vehicles ordered by local goal. To the action implementation, they are direct operation on vehicles, such as operation on acceleration pedal, etc., leading to final consequence. Therefore, a hierarchical driving behavior model can be built in Fig. 1 to characterize driving behavior accordingly. According to Fig. 1, driving behaviors can exert influence by establishing actions and then operating on vehicles according to global and local goals and needs determined by psychology and status awareness. In addition, psychological activities and environment factors can influence each other, which is also true with global and local goals and needs. In this hierarchical driving behavior model, the mental model is in charge of unscrambling order from upper level and distributing workload for multithreading capability of humans. Moreover, adjustment is indispensable for some complex behaviors. The mathematic control loop of this hierarchical driving behavior model is illustrated in Fig. 2. In