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Fuel consumption optimization for smart hybrid electric vehicle during a car-following process

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A B S T R A C T

Hybrid electric vehicles (HEVs) provide large potential to save energy and reduce emission, and smart vehicles bring out great convenience and safety for drivers. By combining these two technologies, vehicles may achieve excellent performances in terms of dynamic, economy, environmental friendliness, safety, and comfort. Hence, a smart hybrid electric vehicle (s-HEV) is selected as a platform in this paper to study a car-following process with optimizing the fuel consumption. The whole process is a multi-objective optimal problem, whose optimal solution is not just adding an energy management strategy (EMS) to an adaptive cruise control (ACC), but a deep fusion of these two methods. The problem has more restricted conditions, optimal objectives, and system states, which may result in larger computing burden. Therefore, a novel fuel consumption optimization algorithm based on model predictive control (MPC) is proposed and some search skills are adopted in receding horizon optimization to reduce computing burden. Simulations are carried out and the results indicate that the fuel consumption of proposed method is lower than that of the ACC+EMS method on the condition of ensuring car-following performances.

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1. Introduction

Environment pollution and petroleum problems have become more and more serious, which pushes vehicle technologies into the aspects of energy conservation and environment protection [1]. Wherein, hybrid electric vehicles (HEVs) provide large potential to save fuel consumption and reduce pollutant emission [2,3]. An HEV is a vehicle driven by more than one power source, and usually refers to a combination of internal combustion engine (ICE) and electric motor (EM). It has various driving mode under different conditions, such as ICE driving alone, EM driving alone, ICE and EM driving together, EM regenerative braking and so on, which makes it easily to adjust IEC operation points in a high-efficiency area [4–6]. On another side, intelligence and net-connection of vehicles are a trend, which can bring out great convenience and safety for drivers [7–10]. Advanced driver assistant system (ADAS) is being applied in passenger vehicles gradually, which contains adaptive cruise control (ACC), automatic parking, lane-change assistance, etc. [11]. By combining these two vehicular technologies, vehicles may achieve excellent performances in terms of dynamic, economy, environmental friendliness, safety, and comfort. Therefore, in this paper, a smart hybrid electric vehicle (s-HEV) is selected as a platform to study a car-following process with optimizing fuel consumption.

Many works have given a deep insight in the energy management strategy (EMS) for HEVs and the car-following control which is a kind of ACC for intelligent/smart vehicles. Hu et al. studied energy efficiency of a series plug-in hybrid electric bus

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(PHEB) with different EMSs and battery sizes based on the tank-to-wheel (TTW) analysis [12]. Li et al. proposed a correctional DP-based EMS of PHEB, which improved the economic performance in a city-bus-route [13]. A MPC-based EMS is put forward to solve the fuel consumption optimization which is formulated as a nonlinear constrained optimal control problem in [14]. Besides, an adaptive energy management was proposed for a PHEV based on driving pattern recognition and dynamic programming [15]. Among all the approaches, MPC-based method is one of most popular kind of EMSs [14,16]. Meanwhile, MPC is also the most common method to realize ACC. For example, Sarkouri et al. used a nonlinear MPC to realize an automated switching to cruise control [17], and Li et al. proposed a fast online computation of MPC and applied it to a fuel economy-oriented ACC [18]. Besides, supervised adaptive dynamic programming was also used for a full-range ACC problem [19], and a method of kernel-based least squares policy iteration was proposed for a self-learning cruise control [20]. In addition, the controls of vehicle dynamics, such as anti-brake system (ABS), traction control system (TCS), electronic stability control (ESC), and tire force analysis, are also supposed to be considered in ACC [21–23].

However, most of studies are focused on EMS or ACC alone. As for the car-following of an s-HEV, it is a multi-objective optimal problem, which has more restricted conditions, optimal objectives, and system states. Kural et al. integrated an ACC into EMS for HEV to estimate the look-ahead battery energy and if necessary apply pre-discharge strategies to fully benefit the recuperation energy during deceleration manoeuvres [24]. Luo et al. proposed a multi-objective decoupling hierarchical strategy [7] and a coordinated control of tracking ability, fuel economy, and ride comfort [9]. The first method has a clear structure and each control hierarchy uses a practical algorithm so that it can be applied in a real electric control unit. The second method uses a multistep offline dynamic programming optimization and an online lookup table to realize the real-time control, which obtains better performance than the first one. In fact, the solution of the problem is not supposed to simply add an EMS to an ACC in series (an ACC+EMS method). An ACC+EMS method can solve the problem but is not optimal, because an ACC just considers dynamic car-following performances and then an EMS can only decide the torque distribution of ICE and EM according to the desired vehicle acceleration. It is worth noting that two different sequences of desired acceleration may achieve similar ACC performances but have great differences in EMS results. Therefore, a deep fusion method with ACC and EMS is needed to solve the problem. The contributions and novelties of this paper are as follows: 1) a car-following problem with optimizing fuel consumption for s-HEV is formulated; 2) a novel fuel consumption optimization algorithm based on nonlinear MPC is proposed; 3) some search skills are used in preceding horizon optimization to reduce the computing burden.

The rest paper is organized as follows. System dynamic models of an s-HEV are built in Section 2. Then, Section 3 introduces and formulates the problem. Next, an optimal fuel consumption control method is designed in Section 4. In Section 5, simulations are carried out and results are analyzed. Finally, Section 6 concludes the paper.

2. System dynamic models

In this paper, a single-shaft parallel s-HEV equipped with an AMT is selected as the study platform, whose powertrain structure is shown in Fig. 1. The powertrain system mainly contains a gasoline engine, an automated dry clutch, an electric motor (EM), a power battery, a five-speed AMT, and a braking system [25]. The engine and EM can provide traction independently for the vehicle, and the EM can also provide braking force coordinated with the braking system. The clutch can connect or disconnect the engine with the powertrain to ensure that the engine can operate in high-efficiency area, but the dynamics of clutch engagement and disengagement are not considered in this paper. The AMT can adjust operation points for the engine and EM via changing transmission ratio [26].

The key parameters of the HEV are shown in Table 1, which are obtained from ADVISOR, and following text will introduce and build simplified models of each part. Simplified models may neglect some dynamic characteristics of system parts, but in this paper we emphasize the dynamics of the whole system far more than that of each part. Therefore, it is proper and convenient using the simplified models to reflect system dynamics because the detailed dynamics of each part have little effect on that of the whole system.

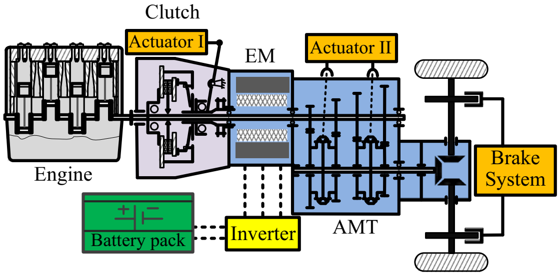

Fig. 1. Schematic graph of the single-shaft parallel HEV powertrain structure.

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