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Integrated optimal eco-driving on rolling terrain for hybrid electric vehicle with vehicle-infrastructure communication

Jia Hu [a], Yunli Shao [b], Zongxuan Sun [b,*], Meng Wang [c], Joe Bared [a], Peter Huang [a]

[a] *Office of Operation Research and Development, Federal Highway Administration, United States*
[b] *Department of Mechanical Engineering, University of Minnesota, United States*
[c] *Department of Transport & Planning and Department of BioMechanical Engineering, Delft University of Technology, The Netherlands*

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ABSTRACT

This research presents an integrated optimal controller to maximize the fuel efficiency of a Hybrid Electric Vehicle (HEV) traveling on rolling terrain. The controller optimizes both the vehicle acceleration and the hybrid powertrain operation. It takes advantage of the emerging Connected Vehicle (CV) technology and utilizes present and future information as optimization input, which includes road topography, and dynamic speed limit. The optimal control problem was solved using Pontryagin's Minimum Principle (PMP). Efforts were made to reduce the computational burden of the optimization process. The evaluation shows that the benefit of the proposed optimal controller is significant compared to regular HEV cruising at the speed limit on rolling terrain. The benefit ranges from 5.0% to 8.9% on mild slopes and from 15.7% to 16.9% on steep slopes. The variation is caused by the change of hilly road density.

1. Introduction

Transportation sector accounts for about 28% of greenhouse gas emissions in the United States (U.S. Department of Transportation) and for 25% of the total energy consumption in developed countries (World Energy Council). It has become a major source of environmental pollutants that could lead to global warming and human health problems. Reducing emissions and improving fuel efficiency have become a vital problem to solve. Many researchers have investigated this topic from various angles: innovations in engine/vehicle design (Mendez and Thirouard, 2008); interference from human factor's perspective (Enomoto et al., 2009); and strengthening policy regulation (Portney et al., 2003). In this work, the research team explores the potential of introducing vehicle automation and connectivity to improve fuel efficiency.

Connected Vehicle (CV) technology is gaining attention around the world. In the United States, the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) has released an advance notice regarding implementing the CV technology (NHTSA, 2014). In Europe, the first connected vehicle has already hit the road in 2015. It is predicted that the worldwide penetration of the CV technology in new vehicles will increase from 10% in 2018 to 70% in 2027 (Nelson, 2014).

Under a CV context, sensors are installed on vehicles to collect data and communication devices are equipped to transmit information among vehicles and nearby infrastructures. Measurements not available in the past become available now,

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* Corresponding author.

E-mail addresses: Jia.Hu@dot.gov (J. Hu), shaox176@umn.edu (Y. Shao), zsun@umn.edu (Z. Sun), m.wang@tudelft.nl (M. Wang), Joe.Bared@dot.gov (J. Bared), Peter.Huang@dot.gov (P. Huang).

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including: vehicle speeds, positions, arrival rates, rates of acceleration and deceleration, approaching terrain and the like. This newly available information is valuable since it enables transportation entities to perform more intelligently in response to the present and future traffic conditions. For instance, traffic control device could extend green light for the coming high volume traffic, or vehicles could adjust their speeds to travel through a signalized intersection based on the signal timing information provided.

Past studies have investigated eco-oriented automated vehicles that take advantage of the CV technology. They can typically be classified into two categories. The first category focuses on the vehicle level control where vehicle acceleration is optimized. Vehicles are designed to operate with minimized fuel consumption and maximized mobility. Several examples are as follows: intelligent merging (Dafflon et al., 2015; Scarinci and Heydecker, 2014; Jin and Orosz, 2014; Chen et al., 2014; Liu et al., 2010); platooning (Wang et al., 2014a, 2014b; Huang et al., 2014; Milanés and Shladover, 2014; Hall and Chin, 2005); eco-approach (Hu et al., 2015, 2014; Guler et al., 2014) and Cooperative Adaptive Cruise Control (CACC) (Wang et al., 2014a, 2014b; Nyitchogna et al., 2014; Niihara, 2013; Ioannou, 2003). The second category zooms into the automobile and optimizes powertrain control to maximize fuel efficiency (Sun and Zhu, 2014; Mohd Zulkefli et al., 2014; Wang et al., 2013; He et al., 2012; Girault, 2004). For regular vehicles, the optimization target is the gear position. Power-split Hybrid Electric Vehicle (HEV) has battery as the second power source compared to regular vehicles. Its optimization targets are two folds, one is engine operating points, and the other is power-split between the internal combustion engine (ICE) and the battery.

However, most of the aforementioned studies only deal with CV applications on a level road. This is not always a reliable assumption. For example, the intelligent merging application may require a ramp vehicle to accelerate to join a platoon on an uphill. Instead of saving fuel from reducing waiting time and unnecessary stop-and-go, this acceleration maneuver actually causes excessive fuel consumption and greenhouse gas emissions. Hence, it is essential to take account of the road topography information. In addition, there is more room to improve fuel efficiency on rolling and mountainous terrain. Past research demonstrated that a 6% increase in a roadway grade leads to 40–94% increase in fuel consumption (Park and Rakha, 2006). Another study confirmed that the fuel economy on flat routes is superior to that on rolling or mountainous routes by approximately 15–20% (Boriboonsomsin and Barth, 2009).

Before enhancing various CV applications with road topography information, the first step is to realize it on a single vehicle. Several such systems have been proposed. Most researchers investigated the speed level optimization only (Ahn et al., 2013; Rakha et al., 2012; Kamal et al., 2011; Mensing et al., 2013, 2012; Hooker, 1988). These eco-driving systems allow vehicles to travel within a range of speed as opposed to driving at a fixed speed (speed limit). As a result, vehicles are able to make use of the energy gained from downhill sections and apply it to overcome grade resistance from uphill sections. Few studies were focused on integrated optimization of vehicle speed and powertrain optimization. A minimum fuel driving control method was developed by Saerens and Bulck for a light duty passenger vehicle (Saerens and Van den Bulck, 2013). However, this study only considered constant slope scenario, therefore is not ready for real world implementation. A similar minimum fuel controller was also proposed for heavy diesel trucks (Hellström et al., 2010). Both studies optimized gear position together with speed. However, their controllers are computational intensive and are not suitable for real-time CV applications.

To summarize, past studies suggest that fuel efficiency can be improved at two levels: vehicle level and powertrain level. The majority of the previous studies focused on only one level. Seldom did researchers conduct combined optimization for two levels. No one has performed an integrated optimization for real-time applications, nor for hybrid vehicles. Nevertheless, it is expected that integrated optimization on a hybrid vehicle would produce the highest fuel efficiency. It is crucial to develop such a vehicle controller that uses road topography information to improve CV applications for fuel saving. This will lead to a series of research, while its foundation can start from a single vehicle. Therefore, the objective of this study is to design a vehicle controller that:

- Minimizing fuel consumption on rolling terrain for a Hybrid Electric Vehicle.
- Integrating vehicle level and powertrain level optimization.
- Taking advantage of the Connected Vehicle technology.
- Reducing computational burden in preparation for future on-road experiments.

The reminder of the paper is organized as follows: Section 2 ‘Control structure’ provides the high-level description of the control structure; Section 3 ‘Control design’ presents the optimization problem formulation and the associated solution; Section 4 ‘Simulation evaluation’ identifies all the specifics of the simulation and presents its results and findings; and finally, Section 5 ‘Conclusion’ discusses the conclusions and contributions.

2. Control structure

In this section, the structure of the integrated optimal controller is presented in Fig. 1. The system considered from the perspective of an individual free-cruising HEV vehicle, of which the state $\boldsymbol{x}$ can be described by the vehicle’s position, speed and battery state-of-charge (*SOC*). The control structure is based on the assumption that the vehicle is equipped with vehicle-to-infrastructure (V2I) communication device. Communication is assumed to be reliable, that is no communication issues