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Hierarchical control strategies for energy management of connected hybrid electric vehicles in urban roads

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ABSTRACT

This paper presents a fuel efficient control strategy for a group of connected hybrid electric vehicles (HEVs) in urban road conditions. A hierarchical control architecture is proposed in this paper for every HEV, where the higher level and the lower level controller share information with each other and solve two different problems that aim at improving its fuel efficiency. The higher level controller of each HEV is considered to utilize traffic light information, through vehicle to infrastructure (V2I) communication, and state information of the vehicles in its near neighborhood, via vehicle to vehicle (V2V) communication. Apart from that, the higher level controller of each HEV uses the recuperation information from the lower level controller and provides it the optimal velocity profile by solving its problem in a model predictive control framework. Each lower level controller uses adaptive equivalent consumption minimization strategy (ECMS) for following their velocity profiles, obtained from the higher level controller, in a fuel efficient manner. In this paper, the vehicles are modeled in Autonomie software and the simulation results are provided in the paper that shows the effectiveness of the proposed control architecture.

1. Introduction

Connected vehicle technology proposed by the Intelligent Transportation Systems Joint Program Office (ITS-JPO) of the United States Department of Transportation addresses some of the issues associated with the current transportation system. In the connected vehicle system, vehicles are capable of communicating with other vehicles (vehicle to vehicle communication (V2V)) and transportation infrastructure (vehicle to infrastructure communication (V2I)) via wireless communications such as dedicated short range communications (DSRC). In the current transportation system, the major areas of concern are mobility, environmental impacts and safety. The primary aim of the envisioned connected vehicle technology/systems is to improve safety of the transportation system since it has been reported that V2V and V2I communication addresses almost 79% of all vehicle crashes (Najm et al., 2010). According to the ITS-JPO website, traffic congestion costs 87.2 billion on the U.S. economy, with 4.2 billion hours and 2.8 billion gallons of fuel spent sitting in traffic. Moreover, deterioration of mobility affects the environment since it has been seen that vehicles that are stationary, idling, and traveling in a stop-and-go pattern due to congestion emits more greenhouse gases than those traveling in free-flow conditions.

Hybrid electric vehicles (HEVs) have attracted a lot of attention in the last decade because of their fuel efficiency and emission. HEVs improve fuel efficiency by using power from both the energy storage systems (batteries) and the engine,

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and by using regenerative braking. At any time, the power split between the engine and the battery is required to be optimized to improve fuel efficiency while satisfying the driver power request. The control strategies for HEVs available in the literature can be categorized as dynamic programming based approach (Lin et al., 2001; Brahma et al., 2000), artificial intelligence based approach (Salman et al., 2000) and methods based on electric power to equivalent fuel conversion (Paganelli et al., 2001, 2000; Onori et al., 2010). It has been pointed out in Brahma et al. (2000) that knowledge of future driving profile further improves vehicle fuel efficiency. Some of the literature considering future driving behavior and road conditions for HEVs as well as for plug-in electric vehicles are available in Vogel et al. (2012), Zhang and Vahidi (2011), Zhang et al. (2010, 2009), Gong et al. (2008), and Sun et al. (2015). Authors in Zhang and Vahidi (2011), Zhang et al. (2010, 2009) have developed energy management strategies for both HEVs and plug-in electric vehicles that uses real-time road grade and trip information.

Future driving behavior prediction using historical data is available in Vogel et al. (2012), Gong et al. (2008), and Sun et al. (2015), where a reinforcement learning based driver model is developed in Vogel et al. (2012) to predict future driving behavior while data driven trip information is developed in Gong et al. (2008) and Sun et al. (2015) that predicts future vehicle velocities for plug-in electric and plug-in hybrid electric vehicles respectively. The future velocities in Gong et al. (2008) and Sun et al. (2015) are predicted using average road velocity data and the power split is performed using dynamic programming and model predictive control strategy respectively. The predicted velocities in Gong et al. (2008) and Sun et al. (2015) are approximate average vehicle velocities that are computed at a macro level of the transportation system and do not consider micro level details such position of preceding vehicles that influences vehicle velocities to a great extent (collision avoidance). Most of these research only focus on controlling the power split between the engine and the battery and do not consider controlling the driver behavior. In this paper, we present a novel hierarchical control architecture for HEVs in urban road conditions in a connected vehicle scenario that uses both V2V and V2I communication to develop fuel efficient control strategies by controlling both the vehicle driving behavior as well as lower level power split.

The data rich environment developed through the process of V2V and V2I communication can be used to improve not only safety but also various other aspects of the transportation system, such as mobility and fuel economy. In recent years, a lot of research in automotive engineering and intelligent transportation systems has focused in the development of fuel economic control strategies for conventional vehicles (Kamal et al., 2010, 2013; Chang and Morlok, 2005; Yang and Jin, 2014; Mensing et al., 2014). The fuel efficiency of a vehicle can be improved through a number of different ways such as improvement of engine characteristics, vehicle structure against aerodynamic drag, and powertrain system. Apart from these factors, fuel efficiency of vehicles has also been seen to depend on the driving behavior as explained in Van Mierlo et al. (2004). The general trend in developing fuel efficient control schemes is to minimize sharp vehicle accelerations while some literatures (Kamal et al., 2010, 2013) consider approximate fuel consumption models, as a function of vehicle velocity and acceleration, or vehicle's internal characteristics (Chang and Morlok, 2005). Authors in Yang and Jin (2014) provided an eco-driving approach by using velocity smoothing technique while an approach improving vehicle fuel efficiency and emission is provided by the authors in Mensing et al. (2014).

A number of literatures consider traffic light information for developing fuel efficient control strategies in urban roads (Asadi and Vahidi, 2011; Mahler and Vahidi, 2014; De Nunzio et al., 2013; He et al., 2015; Mandava et al., 2009). Authors in Mandava et al. (2009) provided an algorithm that minimizes acceleration profile and avoids stopping at red lights. A model predictive control strategy minimizing red light idling and sharp accelerations is shown in Asadi and Vahidi (2011) while a probabilistic approach is used in Mahler and Vahidi (2014) considering noisy traffic light conditions. A multi stage optimal control approach considering vehicle queue for multiple intersections is presented in He et al. (2015). Authors in De Nunzio et al. (2013) provided a pruning and graph discretization method for energy minimization of electric vehicles.

Most of the literature in fuel economic or energy efficient control of vehicles consider single vehicle scenario and do not consider multiple vehicles in the road where behavior of one vehicle affects the other. Although some literature considers congested traffic (Treiber et al., 2000), they are mostly focused on safety rather than fuel economy or energy efficiency. In this paper, an effort has been made to develop fuel efficient control strategy for the individual vehicles considering congested traffic and traffic lights which are common in urban road conditions. In one of our previous research in HomChaudhuri et al. (2015), we have developed fuel economic control strategies for a group conventional vehicles in urban road conditions. In this paper, we extend our work to HEVs and develop a hierarchical control strategy that improves the performance of the group of connected HEVs in urban road conditions.

In our proposed hierarchical control architecture, the higher level controller develops the optimal velocity profile of a HEV in a model predictive control framework utilizing recuperation efficiency information from its lower level controller, and traffic light conditions (V2I information) and neighboring vehicle information (V2V communication). The optimal velocity profile (developed by the higher level controller) focuses on minimizing the average tractive energy consumption of the vehicle and the improvement of vehicle mobility by reducing red light idling. The lower level controller tracks the velocity profile obtained from the higher level controller by optimally splitting power between the vehicle engine and the battery by using an adaptive equivalent consumption minimization strategies (Sciarretta and Guzzella, 2007; Onori et al., 2010). In this way, both the controllers work together in improving vehicle fuel efficiency. Charge sustaining parallel HEVs are considered in this paper and the software Autonomie (Michaels et al., 2010) has been used for modeling and simulation purposes.