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Eco-driving advisory strategies for a platoon of mixed gasoline and electric vehicles in a connected vehicle system

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ABSTRACT

As electric vehicles (EVs) have gained an increasing market penetration rate, the traffic on urban roads will tend to be a mix of traditional gasoline vehicles (GVs) and EVs. These two types of vehicles have different energy consumption characteristics, especially the high energy efficiency and energy recuperation system of EVs. When GVs and EVs form a platoon that is recognized as an energy-friendly traffic pattern, it is critical to holistically consider the energy consumption characteristics of all vehicles to maximize the energy efficiency benefit of platooning. To tackle this issue, this paper develops an optimal control model as a foundation to provide eco-driving suggestions to the mixed-traffic platoon. The proposed model leverages the promising connected vehicle technology assuming that the speed advisory system can obtain the information on the characteristics of all platoon vehicles. To enhance the model applicability, the study proposes two eco-driving advisory strategies based on the developed optimal control model. One strategy provides the lead vehicle an acceleration profile, while the other provides a set of targeted cruising speeds. The acceleration-based eco-driving advisory strategy is suitable for platoons with an automated leader, and the speed-based advisory strategy is more friendly for platoons with a human-operated leader. Results of numerical experiments demonstrate the significance when the eco-driving advisory system holistically considers energy consumption characteristics of platoon vehicles.

1. Introduction

1.1. Background and motivation

The automotive industry has introduced alternative fuel vehicles and innovative vehicle control strategies to reduce the dependency on fossil fuels, enhance energy efficiency, and promote sustainable transportation. The development of alternative fuel vehicles, including electric vehicles (EVs), fuel cell vehicles, natural gas vehicles, aims at reducing petroleum use by removing the conventional gasoline vehicles (GVs) from the road. As one type of alternative fuel vehicles, EVs (including plug-in hybrid EVs and battery EVs) have enjoyed an increasing market penetration over the past decade. Governments around the world have aggressive plans to accelerate the removal of GVs to achieve their emission reduction goal. The European Union has drafted a stipulation to remove half of internal combustion engine vehicles from the road by 2030 and totally ban their usage by 2060 (European

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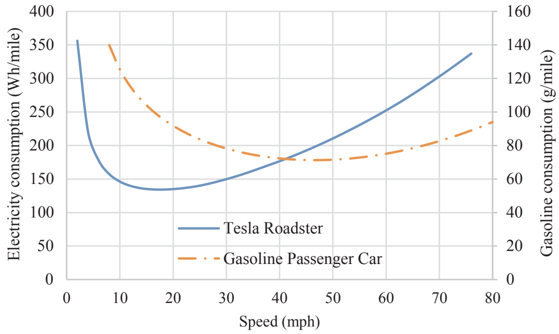

Fig. 1. Vehicle energy economy at different speeds (Tesla Roadster energy economy data is from Van Haaren (2011) and the fuel economy data of gasoline cars is from Sobrino et al. (2016).)

Commission White Paper, 2011). Other countries have set targets for adopting alternative fuel vehicles, for example, U.K. and France have announced that they will stop selling gasoline and diesel cars by 2040 (Petroff, 2017). According to the U.S. Energy Information Administration (EIA, 2017), the total number of electric cars in the U.S. reaches 3.1 million by the end of 2016. Randall (2016) predicts that by 2022 the cost of EVs will be close to the conventional GVs due to the advances in battery technology. As battery cost reduces, demand for EVs will rise significantly. The U.S. EIA projects that over 30 million (24%), passenger cars on U.S. roads will be electricity powered by 2040. Randall (2016) predicts that 35% of new light-duty vehicle sales will be EVs by 2040. As more and more EVs will share urban roads with GVs, it will be common to observe the mixed traffic of EVs and GVs in the future.

Another approach for fuel consumption reduction aims at enhancing the energy efficiency through the control of vehicle dynamics. Speed advisory, or variable speed limit, is one of vehicle control solutions to improve energy efficiency, especially for stop-and-go traffic and vehicles approaching signalized intersections. The rationale behind the speed advisory lies in the fact that vehicles consume more energy (either fossil fuels or electricity) when accelerating. Providing optimal speeds to vehicles approaching a queue or red signal can reduce the energy consumption by preventing vehicles from unnecessary acceleration and braking. It is critical to note that, due to the vehicle-specific mechanical characteristics, vehicles should apply different speeds to minimize their energy consumption under the same traffic and signal conditions. In particular, the electricity consumption of EVs differs significantly from the fuel consumption of conventional GVs, partly due to the equipped regenerative braking system that can recharge a portion of the kinetic energy to the battery during deceleration.

As demonstrated in the literature, vehicle's energy consumption is highly correlated to vehicle travel speed. Conventional GVs reach their best fuel efficiency at speed higher than the best energy-efficient speed of EVs. Fig. 1 shows the fuel economy of conventional gasoline cars based on the highway energy assessment methodology (Sobrino et al., 2016). It illustrates that the gasoline cars achieve their best fuel economy at speed between 40 and 50 mph. By contrast, battery EVs typically reach the best electricity consumption at a relatively low speed. For example, Fig. 1 shows Tesla Roadster can reach the lowest electricity consumption rate at speed between 15 and 20 mph. As a result, the energy-optimal speed trajectory of a battery EV will differ from that of a conventional GV under the same travel conditions. Our previous studies (He et al., 2015; Wu et al., 2015b) have demonstrated this difference. Therefore, in the mixed traffic condition, it is challenging to control each vehicle to follow its energy-optimal speed trajectory, especially under the congested traffic condition.

Another energy-efficient vehicle control solution is platooning, which shows good potential for enhancing fuel economy. In a platoon, vehicles are controlled to follow one another with a small space headway to reduce air resistance and energy consumption. The recent advances in sensor and communication technologies facilitate the formation of platoons on urban roads. For instance, the commercially available adaptive cruise control systems built upon radar, Lidar, or ultrasonic sensors enable drivers to follow a lead vehicle with a small space headway. In the future, the cooperative adaptive cruise control (CACC) systems, which leverage the connected vehicle technology, can enable vehicles to travel with a much closer headway based on more accurate vehicle controls developed upon the information shared among neighbor vehicles. With connected vehicle technology and necessary infrastructure ready, vehicle platoons will be common on urban roads to enjoy the benefits of increasing road capacity and travel comfort, in addition to reducing energy consumption.

As mixed traffic platoons are prevailing on the road, the different energy consumption characteristics and the constraints induced by the interactions among platoon vehicles entail a holistic consideration of the optimal speed to minimize the overall energy consumption. The energy-optimal speed for each platoon vehicle is a local minimum that would be difficult to implement due to the spatiotemporal constraints imposed by neighbor vehicles. For instance, when a traditional GV tends to approach a red signal at an energy-optimal speed 45 mph, its preceding EV may prefer traveling at 20 mph that is energy optimal to the EV. Such a scenario entails the question: What is the speed profile for a platoon of vehicles consisting of GVs and EVs, to achieve the best energy economy? This study aims to answer this question by developing analytical models for an eco-driving advisory system oriented to mixed traffic platoons.

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