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Optimal speed advisory for connected vehicles in arterial roads and the impact on mixed traffic ☆

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ABSTRACT

Connected Vehicles (CV) equipped with a Speed Advisory System (SAS) can obtain and utilize upcoming traffic signal information to manage their speed in advance, lower fuel consumption, and improve ride comfort by reducing idling at red lights. In this paper, a SAS for pre-timed traffic signals is proposed and the fuel minimal driving strategy is obtained as an analytical solution to a fuel consumption minimization problem. We show that the minimal fuel driving strategy may go against intuition of some people; in that it alternates between periods of maximum acceleration, engine shut down, and sometimes constant speed, known in optimal control as bang-singular-bang control. After presenting this analytical solution to the fuel minimization problem, we employ a sub-optimal solution such that drivability is not sacrificed and show fuel economy still improves significantly. Moreover this paper evaluates the influence of vehicles with SAS on the entire arterial traffic in micro-simulations. The results show that SAS-equipped vehicles not only improve their own fuel economy, but also benefit other conventional vehicles and the fleet fuel consumption decreases with the increment of percentage of SAS-equipped vehicles. We show that this improvement in fuel economy is achieved with a little compromise in average traffic flow and travel time.

1. Introduction

Connected Vehicles (CV) are able to access and share information wirelessly with each other and with the infrastructure in real time through vehicle-to-vehicle and vehicle-to-infrastructure communication protocols. Informed by this rich "ambient" data, connected vehicles can adjust their movements in coordination with other vehicles and traffic control systems and enhance their safety, energy efficiency, and mobility. Research on the technology and applications of connected vehicles has been ongoing for many years around the world; an example is the large testbed with thousands of connected vehicles that has been deployed in the city of Ann Arbor, Michigan (Krueger and Fehr, 2013). In 2014, the U.S. Department of Transportation (DOT) issued advance notice of proposed rule-making to begin implementation of vehicle-to-vehicle communications technology in new vehicles (Howden, 2015). Therefore it is expected that in near future new vehicles in the US have the communication capability to communicate with each other and perhaps with intelligent infrastructure such as traffic signals.

A large body of research has been done on developing driving strategies that improves fuel economy. For example in Li et al. (2015a) the authors proposed a fuel optimized operating strategy, they concluded that the optimal operating strategy is periodic because of the S-shaped engine fueling rate. In Eben Li et al. (2013), the authors propose a headway control

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algorithm to reduce fuel. In Hellström et al. (2010, 2009), the authors propose look-ahead control algorithms which take upcoming road topography into account to reduce fuel consumption. These approaches assume that vehicles are not communicating among each other. With CV technologies, new approaches are emerging rapidly. In Bhavsar et al. (2014), the authors propose energy saving strategies for plug-in hybrid electric vehicles using upcoming traffic signal timing and headway information.

A Speed Advisory System (SAS) that aids in reducing idling near traffic signals is one of the applications of CV technology, which has been proposed by our research group (Asadi and Vahidi, 2009, 2011; Mahler and Vahidi, 2014) and various other researchers across the world (Koukoumidis et al., 2011; Mandava et al., 2009; Rakha and Kamalanathsharma, 2011; Wollaeger et al., 2012). Vehicles equipped with a Speed Advisory System (SAS) can utilize upcoming traffic signal information predictively and manage their speed in advance to reduce idling at red lights. SAS relies on vehicle connectivity to obtain traffic Signal Phase and Timing (SPaT). The technology for transmitting traffic signal information to subscribing vehicles has been demonstrated in several research projects (Koukoumidis et al., 2011; Xia et al., 2012). The SPaT information may be directly transmitted to vehicles within range using Dedicated Short Range Communications (DSRC) technology (Koukoumidis et al., 2011) or may become available by the traffic control center through cellular and Wi-Fi networks. Alternative means of inferring SPaT information via on-board cameras (Koukoumidis et al., 2011) and via crowd-sourcing (Fayazi et al., 2015) have also been proposed.

Motion planning or trajectory planning problems can be formulated as optimal control problems (Katrakazas et al., 2015). Past research has formulated the speed advisory problem as optimal control problems and obtained the optimal speed trajectory. In Asadi and Vahidi (2011) and Kamal et al. (2010, 2013) Model Predictive Control (MPC) approaches have been used to obtain near optimal trajectories while considering traffic signals. In He et al. (2015) the authors propose to obtain speed trajectories considering queue pattern and signal timings. In Mahler and Vahidi (2014), Kamalanathsharma and Rakha (2013), Kamalanathsharma et al. (2015), and Ozatay et al. (2014), the authors propose Dynamic Programming (DP) approaches to solve the optimal control problem. Unfortunately, these methods are costly in terms of CPU and memory use and often cannot be executed in real time. In Ozatay et al. (2012), the authors use a linearized model of a vehicle's longitudinal dynamics and solved the fuel minimization problem analytically with given boundary conditions. This analytical method is computationally less expensive and by which the approach proposed in our paper is inspired. The solution we propose maintains the nonlinearities in vehicle dynamics, relaxes the boundary conditions to the minimum required information, and solves the optimal control problem relying on Pontryagin's Minimum Principle (PMP) and kinematic constraints. We show that the optimal solution requires switching between maximum engine torque (boost) and engine shut-down (glide) and occasionally includes a period of constant speed (sustain). Similar conclusions can be found in Li and Peng (2011) and Li et al. (2012). We then argue that the resulting speed profile, while fuel optimal, is uncomfortable to drivers and may also be disruptive to surrounding traffic. We then resort to modified suboptimal speed profiles and still show improvement in fuel economy as a result of avoiding red lights.

Equipped with analytical solutions, we then evaluate the impact on fuel economy in mixed traffic conditions. SAS can significantly reduce energy consumption of individual vehicles and improves their ride comfort, yet it decreases the average speed of equipped vehicles and increases their travel time. It is not difficult to analyze the effect on each equipped vehicle itself (Asadi and Vahidi, 2011; Mahler and Vahidi, 2014; Rakha and Kamalanathsharma, 2011; Boyle and Mannering, 2004; Manzie et al., 2007). However, the SAS technology is unlikely to be implemented in every vehicle in the near future. Therefore it is essential to evaluate the influence of equipped vehicles on other vehicles in mixed traffic flow. There are many papers aiming at evaluating the impact of adaptive cruise control in mixed traffic (Kesting et al., 2010; Ioannou and Stefanovic, 2005), or the impact of vehicle-infrastructure cooperation (Farah et al., 2012). However, to the authors' best knowledge, there are few papers discussing the impact of SAS on mixed traffic for multiple intersections. For instance in Kamalanathsharma et al. (2015) and in Xia et al. (2013) the authors evaluate the influence of eco-driving or eco-speed control only on vehicles equipped with such a system, or only on the surrounding traffic. Another example in Mensing et al. (2014) only discusses impacts of eco-driving on ego-vehicle's pollutant emission and fuel consumption. In Boyle and Mannering (2004) the authors only discuss impacts of speed advisory to driving behavior. In this paper, we evaluate the influence of SAS-equipped vehicles on each other as well as on conventional vehicles. Moreover, in this paper we evaluate the system when traveling across multiple intersections.

It is currently prohibitively difficult to do in the field experiments of a large number of connected vehicles in mixed traffic. Therefore it is necessary to choose a simulation tool to conduct simulations under different traffic situations. In this paper we use the microscopic traffic simulation tool *Paramics*. Paramics is able to simulate a large number of vehicles in a complex traffic network. Moreover, it is easy to set percentages of different types of vehicles and adjust traffic demands. A direct result is measurement of instantaneous speed and acceleration values that influence driving comfort as well as fuel consumption. Vehicles equipped with SAS aim to avoid sharp braking and/or stopping at traffic signals, which improves their fuel efficiency. We will use a fuel consumption model to calculate the fuel economy of each vehicle based on its velocity and acceleration profile. From velocity trajectories we also evaluate travel time of each vehicle. In Paramics it is possible to install virtual sensors to also measure traffic flow. We use these virtual measurements to evaluate the side effects of the proposed SAS technology.

The rest of this paper is organized as follows: Section 2 presents the optimal control framework for obtaining analytical solutions for the optimal speed trajectory of individual vehicles. Section 3 introduces the simulation environment, parameters, and various test setups. The results are summarized in Section 4 followed by conclusions in Section 5.