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A trajectory smoothing method at signalized intersection based on individualized variable speed limits with location optimization

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ABSTRACT

Traffic signals on urban highways force vehicles to stop frequently and thus causes excessive travel delay, extra fuel consumption and emissions, and increased safety hazards. To address these issues, this paper proposes a trajectory smoothing method based on Individual Variable Speed Limits with Location Optimization (IVSL-LC) in coordination with pre-fixed traffic signals. This method dynamically imposes speed limits on some identified Target Controlled Vehicles (TCVs) with Vehicle to Infrastructures (V2I) communication ability at two IVSL points along an approaching lane. According to real-time traffic demand and signal timing information, the trajectories of each approaching vehicle are made to run smoothly without any full stop. Essentially, only TCVs' trajectories need to be controlled and the other vehicles just follow TCVs with Gipps' car-following model. The Dividing RECTangles (DIRECT) algorithm is used to optimize the locations of the IVSLs. Numerical simulation is conducted to compare the benchmark case without vehicle control, the individual advisory speed limits (IASL) and the proposed IVSL-LC. The result shows that compared with the benchmark, the IVSL-LC method can greatly increase traffic efficiency and reduce fuel consumption. Compared with IASL, IVSL-LC has better performance across all traffic demand levels, and the improvements are the most under high traffic demand. Finally, the results of compliance analysis show that the effect of IVSL-LC improves as the compliance rate increases.

1. Introduction

As is shown in Fig. 1(a), traffic signals at-grade intersections of highways inevitably force vehicles to stop and wait frequently and cause stop-and-go waves in proceeding traffic in traditional traffic operations. Such stop-and-go waves considerably compromise traffic efficiency due to the loss time in starting from a full stop, dramatically increase vehicle fuel consumption and emissions due to frequent and abrupt accelerations and decelerations, and likely cause safety hazards due to large speed discrepancies in the same traffic stream.

Signalized intersections generally are responsible for the most frequent and restrictive bottlenecks on urban streets. Due to the importance of signalized intersections for urban road traffic efficiency, a lot of studies have focused on how to control, adjust and optimize signal control strategies to improve the passing capacity (Koonce et al., 2008, Cai et al., 2009, Zhao et al., 2011, Li et al., 2014a, Khamis and Gomaa, 2014, Zhu et al., 2015). Although providing proper signal control could help greatly increasing the capacity of a signalized intersection, it still cannot eliminate full stops and oscillatory trajectories of vehicles approaching, which

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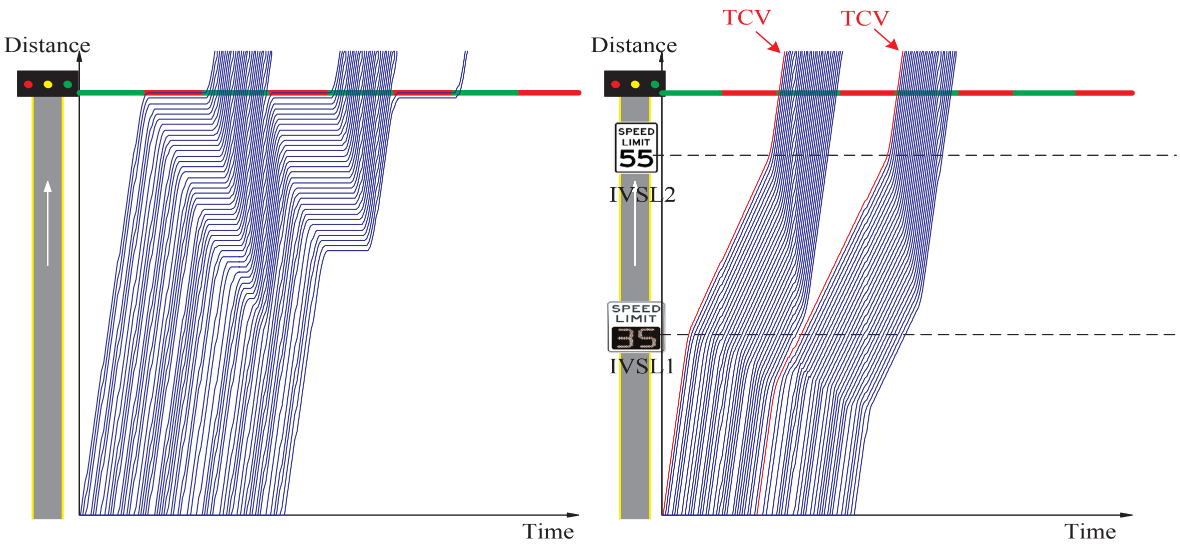

(a) Vehicle trajectories in the traditional case. (b) Vehicle trajectories with IVSL-LC.

Fig. 1. Vehicle trajectories at the upstream of a signalized intersection.

could incur many negative effects, e.g., high pollution/emissions, low traffic efficiency, safety hazards, etc.

With the emergency of intelligent transportation systems technologies connected vehicle (CV) (Talebpour et al., 2015, Lee and Park, 2012) and connected autonomous vehicle (CAV) (Talebpour and Mahmassani, 2016, Gong et al., 2016), control strategies on trajectory smoothing and speed harmonization from the vehicle perspective have been proposed for both freeways and signalized arterials. On the freeway side, Variable Speed Limits (VSL) (Chen et al., 2014, Yang and Jin, 2014, Khondaker and Kattan, 2015, Han et al., 2017) or Speed Advisory Control (SAC) (Mensing et al., 2013, Jin et al., 2016, Hu et al., 2016) methods have been extensively studied in the past several decades. It is believed to be efficient for reducing accident probability, improving traffic flow efficiency, and bringing down fuel consumption and emissions due to speed reduction and harmonization.

This paper focuses on the speed control strategies on signalized arterials. Different from the research on freeway, the speed control strategies on signalized arterials have to adapt to signal timing to minimize stops at signalized intersections while smoothing vehicle trajectories. Some studies developed Optimal Speed Advisory (OSA) and Green Light Optimal Speed Advisory (GLOSA) to decrease stop times and fuel consumption (Mahler and Vahidi, 2012, Wan et al., 2016, Katsaros et al., 2011, Nguyen et al., 2016, Wu et al., 2015). Vahidi designed an OSA with connected vehicle (CV) based on probabilistic prediction of traffic signal timings to reduce idling and fuel consumption (Mahler and Vahidi, 2012). Later, he considered the impact on mixed traffic (Wan et al., 2016). Wu utilized energy-optimal speed control to save energy for Electric Vehicle (EV) (Wu et al., 2015). Katsaros proposed a GLOSA strategy with CV to decrease fuel consumption and stop times (Katsaros et al., 2011). And Nguyen improved GLOSA to an efficient and reliable one for autonomous vehicles (AV), which considered the traffic mobility (Nguyen et al., 2016). A number of researchers investigated Eco-driving for improving fuel economy, mobility and safety (Rakha and Kamalanathsharma, 2011, Li et al., 2016, Jung et al., 2016, Jiang et al., 2017). Rakha used Eco-driving with an explicit optimization objective of reducing fuel consumption for CV, and presented the erroneous of simplified objective functions (Rakha and Kamalanathsharma, 2011). Then, Barth focused on Eco-Approach and Departure with CV to enhance the safety, mobility and environmental sustainability at signalized intersections (Li et al., 2016). Park developed a Bi-level optimization consisted of an Eco-driving algorithm and a traffic signal optimization process (Jung et al., 2016). And Jiang utilized Eco-driving under partially CAV to prioritize mobility before improving fuel efficiency (Jiang et al., 2017). In addition, several studies solved optimal fuel saving speed profiles with Eco-Cooperative Adaptive Cruise Control (ECACC) (Kamalanathsharma and Rakha, 2012, Yang et al., 2016a, Rakha et al., 2016). Rakha integrated Eco-driving with the CACC system to select the fuel optimal trajectory, considering the effect of queueing. Field tests were implemented to demonstrate the improvement of mobility and fuel efficiency (Kamalanathsharma and Rakha, 2012, Yang et al., 2016a, Rakha et al., 2016). Others studied VSL (Ubiergo and Jin, 2016) and trajectory smoothing design (Zhou et al., 2017, Ma et al., 2017) to improve traffic performance. Jin presented an Individual Advisory Speed Limit (IASL) for CV to simulate the mobility and environment improvement of signalized intersections (Ubiergo and Jin, 2016). Li designed a platoon of CAVs with parsimonious shooting heuristic algorithm before signalized intersection to yield the optimal traffic performance on mobility, environment and safety (Zhou et al., 2017, Ma et al., 2017). Integrated signal-timing and trajectory control has also been investigated in recent studies (Yang et al., 2016b, Li et al., 2014b).

While CAV technologies can control detailed vehicle trajectories in high resolution (Zhou et al., 2017, Ma et al., 2017, Jiang et al., 2017, Rakha et al., 2016, Nguyen et al., 2016), they are relatively future technologies and may not be comprehensively deployed in near future. Instead, this paper focuses only on connected vehicles without automation capabilities. In other words, vehicles in this study are controlled by human drivers, though with assistant from individual vehicle based information provided by the connected