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Predictive intelligent driver model for eco-driving using upcoming traffic signal information

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HIGHLIGHTS

- The intersection constraint considered in the IDM is regarded as a dummy preceding vehicle at red light and no barriers at green light to extend ACC application to the road with intersections.
- An intersection passing decision is made based on model prediction with large time scale steps to forecast the arrival time with downstream queue discharge time under consideration.
- A speed reduction strategy is proposed to reduce idling time at signalized intersection by solving the combined constraints of the SPaT and the vehicle status.

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ABSTRACT

Without accounting for the signalized intersection constraints in the design of adaptive cruise control (ACC) system, the ACC-equipped connected vehicle (CV) traveling on signalized roadway should be taken over by driver at signalized intersection frequently and speed variations increase significantly. Aiming at addressing this issue, a predictive intelligent driver model (IDM) for eco-driving based on V2X communication is proposed by using upcoming traffic signal information, which can be regarded as the upper controller of ACC system. The intersection signal constraints considered in IDM is treated as a dummy preceding vehicle at red light and no barriers at green light to cope with the application extending problem. To reduce idling time at signalized intersection, an intersection passing decision is presented with model prediction to forecast the arrival time with downstream queue discharge time under consideration, and an eco-driving model with speed reduction strategy is proposed by solving the combined constraints of the signal phase and timing (SPaT) and the vehicle status. Numerical simulations show that taking the speed profile generated by eco-driving model as speed advisor can reduce idling times and fuel consumption levels in the vicinity of signalized intersection.

1. Introduction

The ACC system can make the vehicle smart in freeway to keep itself safe from rear-end collision and conserve fuel consumption via reducing unnecessary speed variations. However, without receiving upcoming traffic signals' phase and

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timing (SPaT) information, the ACC-equipped vehicle traveling on signalized roadway may break traffic regulations and have to be taken over by driver to make itself idling at red light. Thus speed variations as well as energy consumption would increase in highly interacting urban traffic [1,2]. Considering inter-vehicle communication can improve drive safety, traffic efficiency and fuel economy by forecasting upcoming traffic states among vehicles [3], thus modifying the upper control strategy of the ACC under vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication conditions has the potential to address the eco-driving issue of ACC-equipped connected vehicles.

For the sake of fuel economy by guiding vehicle catch intersection at green light, Asadi et al. [4] planed a reference speed model based on the map of traffic light over space and time utilizing upcoming traffic signal information in ACC system to reduce idling time at red lights and improve fuel economy. With the help of model predictive control (MPC), this proposed scheme can make the ego vehicle timely arrival at green light with minimal use of braking, maintaining safe distance between vehicles, and cruising near set speed. To drive a vehicle efficiently on roads containing varying traffic and signals at intersections, Kamal et al. [5] presented a continuation and generalized minimum residual based MPC system to reduce fuel consumption level by measuring relevant information of current road and traffic, anticipating future states of preceding vehicle, and calculating optimal control input by trade off fuel economy and safe performance. To track the reference speed given by Asadi et al. [4], Xia et al. [6] proposed a trigonometric accelerate and decelerate speed profile model to investigate dynamic eco-driving in an arterial with traffic signals, where SPaT information of traffic lights is offered to vehicle for adjusting its speed profiles in advance while traveling through the corridor during the green phase of the signal to minimize fuel consumption and emissions. Taking the driver's behavior adaptability into account, Xiang et al. [7] developed a closed-loop speed advisory model with coasting for eco-driving, which can uses vehicle coasting to supplement cruising to avoid oscillations. To address energy consumption issue of electrical vehicle (EV) in urban road when approaching traffic light, Zhang and Yao [8] focused on the EV eco-driving via linear speed variation planning for the upstream and downstream of the signalized intersections with the support of cooperative vehicle infrastructure system (CIVS) technologies. To increase the willingness of the drivers to follow the recommended speed, the driver's preferences should be considered. Butakov and Ioannou [9] proposed a personalized speed optimization algorithm for approaching and passing signalized intersections, which uses the driver's preferences and characteristics knowledge to calculate that improves fuel economy, reduces waiting time, and addresses the driver's preferences. In order to improving fuel economy significantly and keeping drivability being not sacrificed simultaneously, Wan et al. [10] put forward a speed advisor system (SAS) for pre-timed traffic signals using sub-optimal fuel minimal driving strategy, and showed that not only the ego car's fuel economy is improved, but also the platoon fuel consumption decreases with the increment of percentage of SAS-equipped vehicles. To consider impacts from queues at intersections on eco-driving, He et al. [1] proposed an optimal vehicle speed trajectory on a signalized arterial with queue taking into account, which is given by taking both vehicle queue and traffic light status into account to establish a multi-stage optimal control formulation to obtain the optimal vehicle trajectory on signalized arterials. Kamalanathsharma and Rakha [2] developed an eco-cooperative adaptive cruise control (ECACC) based on a moving horizon dynamic programming approach, by using V2I communication to receive SPaT data, predicting future traffic signal and queue constraints on a vehicle's trajectory, and optimizing its speed profiles to minimize fuel consumption level via modified A-star algorithm. To ensure that the vehicle arrives at intersection stop bar just as the last queued vehicle is discharged, Yang et al. [11] developed an ECACC algorithm that computes the fuel-optimum vehicle trajectory via a rarefaction wave and shock wave based queue estimation at intersections.

To solve the optimal speed profile problem with non-convex constraints coming from the traffic lights, Nunzio et al. [12] provided a sub-optimal solution to minimize energy consumption, travel through a sequence of signalized intersections and always catch a green light. This sub-optimal solution is implemented by pruning algorithm, graph approximation, best path identification and crossing times optimization. Later on, Jiang et al. [13] proposed a Pontryagin's Minimum Principle based eco-driving system for an isolated signalized intersection under partially connected and automated vehicles (CAVs) environment, and showed that the proposed system is able to attenuate the shock wave caused by signal controls.

To control vehicle catch intersections at green light, Li et al. [14] focused on eco-departure operations of CVs with V2X communication at signalized intersections, and showed that by guiding the acceleration of the leading vehicles, the following vehicles are controlled via a bolza-type optimal control methodology when departing from a signalized intersection. Jin et al. [15] proposed a power-based longitudinal control algorithm for a connected eco-driving system, which considers the vehicle's brake specific fuel consumption map, roadway grade, traffic condition ahead and traffic signal status of the upcoming intersection in the calculation of an optimal speed profile in terms of energy conservation. Considering the drivers may not be able to precisely follow the recommended speed profiles, Altan et al. [16] developed a partially automated vehicle system with an eco-approach and departure feature, which can receive dedicated short range communication (DSRC) message sets from the intersection and automatically follow recommended speed profiles. Aiming at minimizing energy expenditure and maximizing energy regeneration for EV, Akhegaonkar et al. [17] investigated a longitudinal eco-adaptive cruise controller base on dynamic programming for a smart and green autonomous vehicle.

To reveal the relationship between the driving behaviors and the fuel consumptions, Kesting et al. [18] presented an adaptive cruise controller design for active congestion avoidance, by using IDM to represent ACC-equipped vehicles and three parameters of the IDM to model driving style. Ubiergo and Jin [19] used a car-following model (CFM) and an emission model to simulate the behavior of vehicles at signalized intersections, and proposed a hierarchical green driving strategy to smooth stop-and-go traffic through V2I communication. Yu et al. [20,21] proposed CFMs to investigate the impacts of velocity difference changes (VDC) with memory and relative velocity difference (RVD) with memory on the dynamics