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A speed guidance strategy for multiple signalized intersections based on car-following model

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HIGHLIGHTS

- A speed strategy is incorporated into a car-following model.
- The leading vehicle's feasible trajectories are calculated when it runs across multiple intersections.
- The impacts of the speed strategy on each vehicle's driving behavior are studied.
- The effects of the speed strategy on the fuel consumption are studied.

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ABSTRACT

Signalized intersection has great roles in urban traffic system. The signal infrastructure and the driving behavior near the intersection are paramount factors that have significant impacts on traffic flow and energy consumption. In this paper, a speed guidance strategy is introduced into a car-following model to study the driving behavior and the fuel consumption in a single-lane road with multiple signalized intersections. The numerical results indicate that the proposed model can reduce the fuel consumption and the average stop times. The findings provide insightful guidance for the eco-driving strategies near the signalized intersections.

1. Introduction

With the rapid increase of the number of vehicles, traffic system has caused much loss of energy and efficiency [1]. A signalized intersection plays an important role in relieving traffic pressure, but it causes high fuel consumption and emissions due to frequent starting and braking [2,3]. Meanwhile, the attributes of signal lights (including the cycle, green split and operational strategies) simultaneously affect the driving behavior and the related energy consumption [4,5]. Hence, researchers have proposed many models to explore how to reduce the travel time, fuel consumption and emissions, and how to enhance the traffic safety and the operational efficiency [6–8].

In fact, each driving behavior plays an important role on traffic flow [9–13]. The studies [6–8] show that each reasonable driving behavior can reduce the energy consumption and emissions (especially near signalized intersection), i.e., eco-driving behavior has turned a feasible and effective solution because it can reduce the energy consumption and emissions by reasonably adjusting the driving behavior [14–16]. Thus, some eco-driving strategies were proposed to optimize the fuel consumption, signal timing and operational efficiency [17–19]. With the development of ITS (intelligent transport

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system), V2X (vehicle to everything) technology can provide SPAT (signal phase and timing) [20] and CV (connected vehicle) technology can transmit information in a vehicle fleet [21]. Rakha et al. [22] applied V2I (vehicle-to-infrastructure) technology to develop an eco-driving to reduce the fuel consumption and CO_2 emission at an isolated intersection. Wu et al. [23] proposed a speed guidance model to study the driving behaviors at a signalized intersection, and found that their model can reduce the delay at the intersection. Zhao et al. [24] developed a dynamic signal timing optimization strategy based on the vehicle's type (e.g., electric vehicle, EV), used VISSIM to carry out numerical tests, and found that the strategy can reduce the energy consumption and delay. Tang et al. [25] proposed a car-following model with the remaining green time to explore the driving behaviors at an intersection, and found that the proposed model can reduce the fuel consumption and enhance the safety and operational efficiency. Except for the above models, there are other traffic flow models based on some new technologies [26–29]. However, the models [22–29] cannot describe the driving behaviors on a road with multiple signal lights. Likely, reasonable driving behaviors can reduce the energy consumption and emissions and enhance the operation efficiency. In fact, each vehicle's driving behaviors between two signal lights influence the time and speed that it reaches the next intersection, so its fuel consumption and travel time between the two signal lights vary according to its motion behaviors. Li et al. [30] used the adaptive dynamic programming and reinforcement learning to design a new signal control strategy (that considers the performance of local intersection and the neighboring intersections), and found that the strategy can reduce the delay. Sun et al. [31] developed a speed guidance model to describe each vehicle's movement on a road with multiple signal lights, and found that the proposed model can reduce the stop time, fuel consumption and emission. Mahler and Vahidi [32] utilized some data collected on a road with multiple signal lights to construct a signal-phase prediction model, and found that the prediction model can enhance the use efficiency of fuel consumption. Wu et al. [33] utilized the signal timing and the speed to propose an AIRS (adaptive intelligent routing system) model, and found that the proposed model can relieve the congestion.

The above models focus on developing some eco-driving strategies to reduce the fuel consumption and emissions on a road with signal light. In fact, besides the above models, many car-following models are used to study the driving behaviors [34–42]. For example, Gipps [34] developed a car-following model accounting for acceleration/deceleration rate. Bando et al. [35] proposed an OV (optimal velocity) model; Sasaki and Nagatani [36] used the OV model to explore the effect of signal light on traffic flow. Helbing and Tilch [37] proposed a GF (generalized force) model. Jiang et al. [38] developed a FVD (full velocity difference) model, which was extended to study the effects of some traffic factors (e.g., interruption [39], signal light [40,41], speed guidance [42]) on the driving behaviors from different perspectives, but the models cannot reproduce the impacts of multiple signal lights on the driving behavior since they did not consider multiple signal lights.

Based on the car-following model, we in this paper propose a speed guidance strategy to study the effects of multiple signal lights on the driving behavior and the fuel consumption during the process that each vehicle runs across multi-intersections. In comparison with the existing models, the proposed model has two contributions, i.e., (1) it can reproduce the effects of multi signal lights on each vehicle's driving behaviors, and (2) it can reduce the total fuel consumption and average stop time during the process that each vehicle fleet passes through multi-intersections.

2. Model formulation

In this section, we first introduce some related car-following models and fuel consumption models, and then propose a speed guidance strategy to achieve eco-driving behavior on a road with multi signalized intersections. Next, we incorporate the speed guidance strategy into a car-following model, and finally propose a car-following model with speed strategy guidance.

2.1. Car-following model

The generalized car-following model on a single lane can be reduced as follows:

$$\frac{\mathrm{d}v_n}{\mathrm{d}t} = f\left(v_n, \Delta x_n, \Delta v_n, \ldots\right), \tag{1}$$

where v_n, Δx_n, Δv_n are respectively the nth vehicle's speed, headway and relative speed; f is a stimulus function. If we define Eq. (1) as different functions, we can obtain different car-following models. For example, the FVD model [38] can be expressed as follows:

$$\frac{\mathrm{d}v_n(t)}{\mathrm{d}t} = \kappa\left(V\left(\Delta x_n\left(t\right)\right) - v_n\left(t\right)\right) + \lambda\Delta v_n\left(t\right), \tag{2}$$

where κ, λ are reaction coefficients that can be defined as follows:

$$\kappa = 0.41, \lambda = \begin{cases} 0, & \text{if } \Delta x_n \geq 100 \\ 0.5, & \text{otherwise.} \end{cases} \tag{3}$$

$V\left(\Delta x_n\right)$ in Eq. (2) is the nth vehicle's optimal velocity that can be defined as follows:

$$V\left(\Delta x_n\right) = \frac{v_{\exp}}{2}\left(\tanh\left(\Delta x_n - x_c\right) + \tanh\left(x_c\right)\right), \tag{4}$$