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Effects of signal light on the fuel consumption and emissions under car-following model

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HIGHLIGHTS

- A car-following model is used to study the fuel consumption and emissions on a road with signal light.
- The effects of signal light on the fuel consumption are studied.
- The effects of signal light on emissions are explored.

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ABSTRACT

In this paper, a car-following model is utilized to study the effects of signal light on each vehicle's fuel consumption, CO, HC and NO_X. The numerical results show that each vehicle's fuel consumption and emissions are influenced by the signal light and that the effects are related to the green split of the signal light and the vehicle's time headway at the origin, which can help drivers adjust their micro driving behavior on the road with a signal light to reduce their fuel consumption and emissions.

1. Introduction

With the rapid increase of the number of vehicles, the traffic energy consumption and emissions have become more and more serious [1–6], so researchers have been attracted to propose various models (to explore the traffic energy consumption and emissions) and control strategies (to solve or relieve the traffic energy consumption and emissions) [7–23]. Roughly speaking, the existing traffic energy consumption/emission models can be sorted into the micro models [7–10] and the macro models [11–16], where the micro models [7–10] study a single vehicle's energy consumption and emissions from the microscopic perspective and the macro models [11–16] study the traffic energy consumption and emissions from the macroscopic perspective. The control strategies [18–23] propose the effective methods to solve or reduce the traffic energy consumption and emissions from the perspective of eco-driving. The above studies can describe some complex traffic phenomena relevant to the energy consumption and emissions, but they do not explore the effects of signal light on the energy consumption and emissions under car-following model. As for the complex phenomena occurring near a signal light, most researchers studied the effects of signal light on the driving behavior and the capacity of intersection [24–31] and did not explore the effects of signal light on the energy consumption and emissions (especially under car-following model). In this paper, we use a car-following model to investigate the effects of a signal light on the fuel consumption, HC, CO and NO_X on a road with open boundary condition.

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2. Model

The generalized car-following model in a single-lane system can be reduced as follows [32–36]:

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

where v_n, Δx_n, Δv_n are respectively the nth vehicle's speed, headway and relative speed If we define Eq. (1) as different expression, we can obtain different car-following model, e.g., OV (optimal velocity) model [32], GF (generalized force) model [33], FVD (full velocity difference) model [35], the car-following model with the consideration of the traffic interruption probability [36]. In this paper, we use the model [36] to study the effects of a signal light on each vehicle's fuel consumption and emissions due to the following reasons:

(i) some traffic interruptions occur during the red light period.
(ii) this model explicitly considers the traffic interruption probability.
(iii) Tang et al. [36] utilized numerical tests to testify that this model can perfectly reproduce the complex traffic phenomena that were resulted by the traffic interruption factors.

The car-following model [36] can be formulated as follows:

$$\frac{\mathrm{d}v_n}{\mathrm{d}t} = \kappa\left(V\left(\Delta x_n\right) - v_n\right) + \lambda_1 p_{n-1}\left(-v_n\right) + \lambda_2\left(1 - p_{n-1}\right)\Delta v_n, \tag{2}$$

where $V(\bullet)$ is the nth vehicle's optimal speed determined by Δx_n, p_{n-1} is the $(n-1)$th vehicle's interruption probability, κ, λ_1, λ_2 are three reaction parameters. Here, $V(\Delta x_n)$ is defined as follows [35]:

$$V\left(\Delta x_n\right) = V_1 + V_2 \tanh\left(C_1\left(\Delta x_n - l_c\right) - C_2\right), \tag{3}$$

where l_c is the vehicle's length, V_1, V_2, C_1, C_2 are four parameters. In this paper, V_1, V_2, C_1, C_2, l_c are defined as follows [35]:

$$V_1 = 6.75\ \mathrm{m/s}, \qquad V_2 = 7.91\ \mathrm{m/s}, \qquad C_1 = 0.13\ \mathrm{m}^{-1}, \qquad C_2 = 1.57, \qquad l_c = 5\ \mathrm{m}. \tag{4}$$

For simplicity, we here define the parameters κ, λ_1, λ_2 as follows [35,36]:

$$\kappa = 0.41, \qquad \lambda_1 = \lambda_2 = \begin{cases} 0.5, & \text{if } \Delta x_n \le 100\ \mathrm{m} \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

As for the parameter p_n, we here define it as follows:

$$p_n = \begin{cases} 1, & \text{if the nth vehicle is interrupted by the signal light} \\ 0, & \text{otherwise.} \end{cases} \tag{6}$$

Next, we should introduce the vehicle's fuel consumption model and emission model. As for the two topics, researchers proposed many related models (e.g., VT-Micro model, MOVES model, etc.) and the models can describe many complex traffic phenomena related to the vehicle's energy consumption and emissions [1–23], but we here use the VT-Micro model to study the impacts of traffic light on the vehicle's fuel consumption and emissions since the car-following model is used to describe each vehicle's motion and this model is formulated by the vehicle's instantaneous speed and acceleration, where the VT-Micro model can be reduced as follows [7,9]:

$$\ln\left(\mathrm{MOE}_e\right) = \sum_{i=0}^{3}\sum_{j=0}^{3} \kappa_{i,j}^{e} v_n^{i}\left(\frac{\mathrm{d}v_n}{\mathrm{d}t}\right)^{j}, \tag{7}$$

where MOE_e is the nth vehicle's fuel consumption rate whose unit is ml/s, i, j are respectively the speed power and the acceleration power, and $k_{i,j}^{e}$ is the regression coefficient. Ahn et al. [9] pointed out that Eq. (7) can be used to explore each vehicle's CO, HC and NO_X if reasonably redefining $\kappa_{i,j}^{e}$, so Eq. (7) can be used to explore the vehicle's CO, HC and NO_X. Ahn et al. [9] used the experimental data (that were collected at the Oak Ridge National Laboratory) to calibrate the parameters $\kappa_{i,j}^{e}$ of the vehicle's fuel consumption, CO, HC and NO_X (see Table 1). The purpose of this paper is to qualitatively explore the influences of signal light on the vehicle's fuel consumption, CO, HC and NO_X, so we here use $k_{i,j}^{e}$ defined in Table 1 and do not calibrate them by experimental data. Note: if applying other model determined by the vehicle's instantaneous speed and acceleration to study the fuel consumption, CO, HC and NO_X, we can obtain similar results.

3. Simulation

In this section, we use Eqs. (2) and (7) to study the effects of a signal light on the vehicle's fuel consumption, CO, HC and NO_X on a road with open boundary condition. Before studying the effects, we should give the numerical scheme of Eq. (2) because it is difficult to obtain the analytical solution of Eq. (2). Eq. (2) has many difference schemes, but the numerical