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An extended car-following model considering vehicular gap fluctuation

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ABSTRACT

To explore and evaluate the effects of vehicular gap fluctuation on roadway traffic mobility, fuel economy and exhaust emissions, we first analyzed the linkage between vehicular gap fluctuation and the following car's acceleration or deceleration with the measured car-following data, and then developed an extended car-following model considering vehicular gap fluctuation based on the full velocity difference model. Finally, numerical simulations are conducted to explore how vehicular gap fluctuation affects car's velocity, acceleration, vehicular gap, fuel consumptions and exhaust emissions. The results show that vehicular gap fluctuation has significant effects on the dynamic characteristics, fuel consumptions and exhaust emissions of traffic flow, and that considering vehicular gap fluctuation in modeling traffic flow system can improve the stability of traffic flow, increase fuel efficiency and reduce exhaust emissions.

1. Introduction

Various theories are employed to describe the car traffic flow system. Car-following theory is one class of such theories, which is based on the follow-the-leader concept. Rules of how a driver follows her\his immediate leading vehicle have been studied for many years based on both experimental observations and theoretical analyses, which include the early linear models proposed by Chandler et al. [1], the early nonlinear models presented by Reuschel [2], Pipes [3], Gazis et al. [4] and Newell [5], the recent remarkable work of Bando et al. [6], Helbing and Tilch [7] and Jiang et al. [8] and some others in the literatures [9–45]. The optimal velocity model proposed by Bando et al. [6] is one of the favorable car-following models because of its distinctive feature in describing many properties of traffic flow such as the instability of traffic flow, the evolution of traffic congestion and the formation of stop-and-go waves. To overcome the shortcoming of the optimal velocity model, Helbing and Tilch [7] proposed the generalized force model by considering the negative velocity difference. Jiang et al. [8] put forward the full velocity difference model by considering both the negative and the positive velocity differences. Subsequently, many efforts have been made based on the optimal velocity model or the full velocity difference model by considering vehicular gap in different combinations.

Ge et al. [46] put forward an extended car-following model considering an arbitrary number of cars ahead on a single-lane highway with the following differential equation:

$$\frac{dx_n(t+\tau)}{dt} = V\left(\Delta x_n(t), \Delta x_{n+1}(t), \ldots, \Delta x_{n+j-1}(t)\right), \tag{1}$$

where $x_n(t)$ is the position of car n at the time t; $V(\cdot)$ is the optimal velocity function; $\Delta x_n(t)$ is the vehicular gap

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between car n and car $n+1$; $\Delta x_{n+j-1}(t)$ is the vehicular gap between car $n+j-1$ and car $n+j$ at the time t.

Jiang and Wu [47] studied the night driving behaviors in the car-following model under periodic boundary conditions based on the full velocity difference model by redefining the optimal velocity function, which is formulated as follows:

$$V(\Delta x_n(t)) = \begin{cases} \tanh(\Delta x_n(t) - x_c) + \tanh(x_c), & \Delta x_n(t) < x_{c1}, \\ a - \Delta x_n(t), & x_{c1} < \Delta x_n(t) < x_{c2}, \\ b, & \Delta x_n(t) > x_{c2}. \end{cases} \quad (2)$$

where x_{c1} and x_{c2} are the critical vehicular gaps, a and b are constants.

Tang et al. [48] proposed a new car-following model with consideration of the driver's memory, which is formulated as follows:

$$\frac{dx_n(t+\tau)}{dt} = \beta_1 V(\Delta x_n(t)) + \beta_2 V(\Delta x_n(t-\tau)), \quad (3)$$

where $x_n(t)$ is the position of car n at the time t; $V(\cdot)$ is the optimal velocity function; $\Delta x_n(t)$ is the vehicular gap between car n and car $n+1$; τ is the memory step; β_1 and β_2 are sensitivity parameters.

Peng et al. [49] presented a new optimal velocity difference model for a car-following theory based on the full velocity difference model, which is presented as follows:

$$\frac{dx_n(t)}{dt} = \kappa[V(\Delta x_n(t)) - v_n(t)] + \lambda \Delta v_n(t) + \gamma[V(\Delta x_{n+1}(t)) - V(\Delta x_n(t))], \quad (4)$$

where $[V(\Delta x_{n+1}(t)) - V(\Delta x_n(t))]$ is the optimal velocity difference of car n at the time t; κ, λ and γ are sensitivity parameters.

Tang et al. [50] developed a new car-following model with consideration of the driver's forecast effect, which takes the following form:

$$\frac{dx_n(t+\tau)}{dt} = \beta_1 V(\Delta x_n(t)) + \beta_2 V(\Delta x_n(t+\tau)) \quad (5)$$

where τ is the forecast step; β_1 and β_2 are sensitivity parameters.

Jin and Wang [51] presented a new car-following model by incorporating the effects of front traffic situation, which is formulated as follows:

$$\frac{d^2 x_n(t)}{dt^2} = \alpha\left\{(1-\rho)V[\Delta x_n(t)] + \rho V\left[\frac{1}{m}\sum_{j=0}^{m-1}\Delta x_{n+j}(t)\right] - v_n(t)\right\} + \lambda \Delta v_n(t), \quad (6)$$

where $x_n(t)$ is the position of car n at the time t; $V(\cdot)$ is the optimal velocity function; $\Delta x_n(t)$ is the vehicular gap between car n and car $n+1$; $\frac{1}{m}\sum_{j=0}^{m-1}\Delta x_{n+j}(t)$ is the average vehicular gap of the front j cars; α and ρ are sensitivity parameters.

Yu and Shi [52] proposed an extended car-following model by considering vehicular gap changes with memory, which is formulated as follows:

$$\ddot{x}_n(t) = \kappa[V(\Delta x_n(t)) - v_n(t)] + \lambda \Delta v_n(t) + \gamma[\Delta x_n(t) - \Delta x_n(t-\delta)], \quad (7)$$

where $[\Delta x_n(t) - \Delta x_n(t-\delta)]$ is the vehicular gap difference at the time t; κ, λ and γ are sensitivity parameters.

On the one hand, although the above-mentioned car-following models in the literatures [8,46–52] can be used to describe many properties of the real traffic flow, they were proposed from the qualitative perspective. It needs a lot of field observations and data mining analysis on the real traffic flow before modeling process essentially.

On the other hand, a driver has memory if his speed at a later time depends on his speed at the previous time. Zhang [53] developed a continuum macroscopic model arising from a car-following model with driver memory and found that the driver's memory in car-following behaviors can lead to viscous effects in continuum traffic flow dynamics. Tang et al. [48] put forward an extended car-following model considering the driver's memory and found that considering driver's memory in modeling car-following behaviors can improve the traffic flow stability. Yu and Shi [52] proposed an extended car-following model by considering vehicular gap changes with memory and found that considering vehicular gap changes with memory in designing the adaptive cruise control system can improve the traffic flow stability and reduce fuel consumptions.

Under the above perspective, we further investigate the car-following model considering driver's memory in this paper, the field data of car-following behaviors are measured to explore the relationship between vehicular gap fluctuation and the following car's acceleration or deceleration, and then an extended car-following model considering vehicular gap fluctuation is developed for further analysis.

2. Data mining analysis and modeling

2.1. Data collection and mining analysis

In this section, we select the Jingshi Road/Shanshi East Road intersection of Jinan in China as the data collection cite and use digital camera to obtain the measured car-following data and conduct data mining analysis.

It is supposed that car 1 follows car 2 and the difference between vehicular gap at time t and the mean value of vehicular gaps of the last cycle is defined as the fluctuation of vehicular gap between car 2 and car 1 by using the method of window moving in real time. The cycle length is equal to the time window length.

By using frame differential method [54,55], the field data of car-following behaviors of every 1 s are extracted, which contain each car's velocity, acceleration, velocity difference, the relative distance and vehicular gap fluctuation with different time window length. We only obtain the measured data of car-following behaviors with the maximum time window length of 4 s for the time being due to the limitation of visual angle. Partial measured car-following data are listed as shown in Tables 1–3.

The gray correlation analysis [56,57] is considered to be an analysis of the geometric similarity between the