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An extended car-following model accounting for the average headway effect in intelligent transportation system

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HIGHLIGHTS

- A new car-following model is proposed by considering the average headway effect of preceding vehicles group in ITS environment.
- Linear analysis is carried out to study the stability of traffic flow.
- The mKdV equation can be derived by using the reductive perturbation method to describe the density wave of traffic jam.
- The results show that the average headway effect can efficiently suppressed the emergence of traffic jamming.

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ABSTRACT

In this paper, an extended car-following model is proposed to simulate traffic flow by considering average headway of preceding vehicles group in intelligent transportation systems environment. The stability condition of this model is obtained by using the linear stability analysis. The phase diagram can be divided into three regions classified as the stable, the metastable and the unstable ones. The theoretical result shows that the average headway plays an important role in improving the stabilization of traffic system. The mKdV equation near the critical point is derived to describe the evolution properties of traffic density waves by applying the reductive perturbation method. Furthermore, through the simulation of space–time evolution of the vehicle headway, it is shown that the traffic jam can be suppressed efficiently with taking into account the average headway effect, and the analytical result is consistent with the simulation one.

1. Introduction

In recent years, the traffic jam problem has become a serious issue and attracted considerable attention of scholars due to its complex mechanism [1–3]. Many traffic flow models have been proposed to study various complex traffic phenomena, such as phase transition, instability and stop-and-go waves in traffic flow [4–7]. Generally, these models can be classified into the macroscopic models and the microscopic models. The macroscopic models (e.g., hydrodynamic models [8–12]) regard the whole road traffic system as compressible fluid formed by vehicles and the traffic features are revealed through analyzing the relationship among density, velocity and flow. The microscopic models (e.g., cellular automaton models [13–20] and car-following models [21–45]) treat each individual vehicle as a particle and regard the vehicle traffic as a system of interacting particles driven far from equilibrium.

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Among these models, the car-following models are widely discussed for their convenience to describe the driver's individual behavior. In 1995, Bando et al. [27] proposed the well-known optimal velocity (for short, OV) car-following model, which has successfully revealed the dynamic evolution of traffic jam in a simple way. Subsequently, many improvements have been done to make it conform to actual observations. Helbing and Tilch [28] conducted a calibration for the OV model by using the empirical data and developed a generalized force (for short, GF) model to overcome the shortcomings of high acceleration and unrealistic deceleration occurring in the OV model. In 2001, Jiang et al. [29] found that the GF model is poor in anticipating the kinematic wave speed at high density and the delay time of car motion and proposed a more realistic full velocity difference (for short, FVD) model. The study shows that the FVD model is in agreement with the field data better than OV and GF models.

Recently, with the rapid development of intelligent transportation system (for short, ITS), drivers can easily receive more and accurate information of other vehicles on road by inter-vehicle communication (for short, IVC), and then adjust their driving behavior. In this aspect, many scholars successively developed some extended multiple car following models considering the traffic information of other vehicles based on OV model or FVD model in an environment of ITS. Nagatani [30] proposed an improved car-following models taking into account the next-nearest-neighbor interaction in front. Hasebe et al. [31,32] presented an extended OV model applied to a cooperative driving control. Ge et al. [33] developed an improved car following model by taking into account an arbitrary number of vehicles ahead on a single lane highway. Tang et al. [34,35] put forward two new car-following models with consideration of inter-vehicle communication. Zhang et al. [36] established an extended car-following model considering the multiple drivers' desired velocities. Ngoduy [37] investigated the instabilities of heterogeneous intelligent traffic flow. Sun et al. [38] constructed an improved car-following model considering the average velocity effect of preceding vehicles group in the transportation cyber–physical system. In addition, some researchers advised other generalized traffic flow models by introducing multiple information of headway [39–42] or relative velocity [43–45], and so on. Stability analysis in these aforementioned models all proved that the traffic jam could be effectively suppressed and the stability of traffic flow is greatly improved.

As we know, the information of average headway on road is also easy to obtain by using information and communication technologies in ITS environment. With this information, drivers can anticipate the state of traffic flow on the road ahead and adjust their driving behavior quickly. Therefore, the average headway of preceding vehicles group has a significant impact on the driver's anticipation driving behavior during car following. It is necessary to consider this effect for the traffic flow modeling. However, to our knowledge, the average headway effect of preceding vehicles group on the micro driving behavior and the formation mechanism of density wave of traffic jam have not been explored in the car-following models up to now.

In view of the above reason, a new car-following model is proposed by considering the average headway effect of preceding vehicles group in ITS environment. In the following section, the new car-following model is constructed. In Section 3, the linear stability analysis is conducted to obtain the neutral stability condition. The mKdV equation is obtained by applying the reductive perturbation method, and the evolution feature of traffic jam is described by the kink–antikink wave in Section 4. In Section 5, numerical simulations are performed to validate analytic results, and the intrinsic mechanism of the corresponding phase transition is explored. Finally, some conclusions are drawn in Section 6.

2. Model

In 1995, Bando et al. [27] firstly proposed the optimal velocity (OV) model to describe the car-following behavior on a single-lane highway. The motion equation is given as follows:

$$\frac{\mathrm{d}v_n(t)}{\mathrm{d}t} = a\left[V\left(\Delta x_n\left(t\right)\right) - v_n(t)\right] \tag{1}$$

where $x_n(t)$ and $v_n(t)$ are the position and the velocity of the nth vehicle at time t, respectively. a denotes the sensitivity of a driver, $\Delta x_n(t) = x_{n+1}(t) - x_n(t)$ is the headway of two successive vehicles and $V\left(\Delta x_n(t)\right)$ is the nth vehicle's optimal velocity, which depends on the headway $\Delta x_n(t)$. The basic idea of the model is the acceleration of the nth vehicle is determined by the velocity $v_n(t)$ and the headway $\Delta x_n(t)$.

However, the empirical data show that the OV model may appear too high acceleration and unrealistic deceleration. In order to overcome the deficiency, Jiang et al. [29] proposed the full velocity difference (FVD) model by considering the relative velocity between the leading vehicle and the following vehicle as:

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

where $\Delta v_n(t) = v_{n+1}(t) - v_n(t)$ is the velocity difference of two successive vehicles and λ is the responding factor to the velocity difference. Compared with the OV models, the results show that the FVD model is more realistic, but high deceleration also occurs in the FVD model.

To further investigate the nature of traffic more realistically, some extended OV models [39–45] were proposed by considering the motion information of many preceding or following vehicles as well as using other vehicles' traffic data provided by the application of ITS. These models can be summarized as the following generalized equation:

$$\frac{\mathrm{d}v_n(t)}{\mathrm{d}t} = f\left(v_n(t), \Delta x_n(t), \Delta x_{n+1}(t), \ldots, \Delta x_{n+k}(t), \Delta v_n(t), \Delta v_{n+1}(t), \ldots, \Delta v_{n+k}(t)\right) \tag{3}$$