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An extended heterogeneous car-following model accounting for anticipation driving behavior and mixed maximum speeds

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ABSTRACT

The optimal driving speeds of the different vehicles may be different for the same headway. In the optimal velocity function of the optimal velocity (OV) model, the maximum speed $v_{\max}$ is an important parameter determining the optimal driving speed. A vehicle with higher maximum speed is more willing to drive faster than that with lower maximum speed in similar situation. By incorporating the anticipation driving behavior of relative velocity and mixed maximum speeds of different percentages into optimal velocity function, an extended heterogeneous car-following model is presented in this paper. The analytical linear stable condition for this extended heterogeneous traffic model is obtained by using linear stability theory. Numerical simulations are carried out to explore the complex phenomenon resulted from the cooperation between anticipation driving behavior and heterogeneous maximum speeds in the optimal velocity function. The analytical and numerical results all demonstrate that strengthening driver's anticipation effect can improve the stability of heterogeneous traffic flow, and increasing the lowest value in the mixed maximum speeds will result in more instability, but increasing the value or proportion of the part already having higher maximum speed will cause different stabilities at high or low traffic densities.

1. Introduction

With the economy growth and rapid development of the owning amount of automobile, traffic jam is becoming more and more severe, and it is an imperative problem what kinds of traffic control and guidance methods can be applied to lighten it and effectively improve traffic systems efficiency. Research on the traffic flow has been receiving increasing attention in the world [1–4]. When the traffic flow is seen as a compressible fluid on traffic mean speed and density, many macroscopic traffic models have been proposed to reveal the traffic features [5], such as lattice hydrodynamic models [6–12], gas kinetic models [13], and the continuum models [14–18]. Besides the macroscopic models, the cellular automata model [19], intelligent driver model (IDM) [20, 21] and the car-following model [22] are also developed to reveal many real traffic phenomena such as traffic congestion, stop-and-go traffic waves, traffic jamming transition and local cluster effect.

Due to the convenience describing the individual vehicle movement, the car-following models have drawn continuous research attention [23–26]. Under the assumption that a car will turn its velocity to that of proceeding car, Reuschel presented the earliest car-following model [27]. Based on construction of an optimal velocity function on the headway and the assumption that a car should adjust its velocity to the optimal velocity, Bando et al. proposed the famous optimal velocity model (OVM) [28] in 1995, which can be used to explain the qualitative characteristics of the actual traffic flow, such as the stop-and-go phenomenon, traffic instability and the congestion evolution and so on. To overcome the unrealistic deceleration and acceleration rates in OVM, Helbing and Tilch [29] developed a generalized force model by adding the influence of negative relative velocity. And then by adding the positive relative velocity into generalized force model, Jiang et al. presented the full velocity difference model (FVDM) [30]. Based on the OVM or FVDM, many new car-following models have been proposed by considering various factors and information, such as optimal velocity difference [31], multiple headway [32], regenerative energy [33], traffic jerk [34], anticipation optimal velocity [35]. Based on car-following model, Tang et al. studied the factors of sig-

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nal light on the fuel consumption and emissions [36], trip costs of a traffic corridor [37] and vehicle's safety envelope [38]. By adding the effect of anticipation driving behavior of relative velocity on the headway in the optimal function, Zheng et al. developed an improved car following model considering anticipation driving behavior [39].

Accounting for the difference in driving skill or vehicle type, driving strategy of each vehicle traveling on the lane is not exactly the same. The homogeneous traffic models may not well simulate the mixed traffic flow characteristics. Then some researchers pay much attention on the heterogeneous traffic. Ward presented a mathematical approach to analysis the linear stability of heterogeneous traffic model [40]. Tang developed a macroscopic heterogeneous traffic model [41]. Replacing $v_{\max}$ in the original Bando model with heterogeneous maximum speeds, Yang et al. developed a heterogeneous car-following model with heterogeneous maximum speeds [42,43]. They mainly focused on the performance of four types of car-truck following combinations. Yang et al. also proposed cellular automata based traffic flow model to investigate the characteristics of car-truck heterogeneous traffic flow [44]. Two styles of self-stabilizing control in historical velocity difference are investigated by Li et al. [45]. Tang et al. studied the impact of state of battery charge on car-following characteristics in the heterogeneous traffic system [46]. Liu et al. studied the car-truck heterogeneous traffic flow based on the IDM [47]. The second-order macroscopic continuum model was applied to study the heterogeneous traffic flow by Mohan [48]. Li studied the heterogeneous traffic with two kinds of sensitivities [49].

Due to the differences of the vehicle type or driving skills, the optimal driving speeds of the different vehicles may be different for the same headway. The optimal velocity function of OVM is constructed from the hyperbolic tangent function with regarding the maximum velocity $v_{\max}$ as the upper bound. Thus, the maximum speed $v_{\max}$ is an important parameter determining the optimal driving speed. When using the optimal velocity function in OVM, a car's maximum speed $v_{\max}$ reflects the driver's aggressive driving degree. A vehicle with higher maximum speed $v_{\max}$ is more willing to drive faster than that with lower maximum speed in similar situation. In addition, driver often adjust his speed according his anticipation by observing the traffic condition in real traffic. Existing research seldom take into account the influence of the cooperation between the driver's anticipation effect and heterogeneous maximum speeds on the traffic flow.

In this paper, incorporating the anticipation driving behavior of relative velocity into Bando's model, an extended heterogeneous car-following model is presented with consideration of the combined effect of the driver's anticipation effect and heterogeneous maximum speeds with different percentage in optimal velocity function. This extended model can reveal the phenomenon to some extent that different vehicles have different aggressive driving degrees and optimal driving velocities for same headway. The analytical linear stable criterion for this extended heterogeneous traffic model is studied by using linear stability theory. Numerical simulations are carried out to explore the complex phenomenon resulted from the combined influence of driver's anticipation behavior and heterogeneous characteristics. The different effects on the traffic stability are also discussed when changing the intensity of driver's anticipation and the value or proportion of the heterogeneous maximum speeds at high and low traffic densities.

2. The extended heterogeneous car-following model

Bando et al. [27] proposed the optimal velocity model (OVM) as follows:

$$\frac{dv_n(t)}{dt} = a\big[V(\Delta x_n) - v_n(t)\big], \tag{1}$$

where a indicates the driver's sensitivity coefficient, $\Delta x_n = x_{n+1} - x_n$, x_{n+1} and x_n represent respectively the position of the preceding vehicle $n+1$ and the following vehicle n, v_n is the velocity of the vehicle n, and the optimal velocity function $V(\Delta x_n)$ is defined as [27]

$$V(\Delta x_n) = \frac{v_{\max}}{2}\big[\tanh\big(\Delta x_n(t) - h_c\big) + \tanh(h_c)\big], \tag{2}$$

where $v_{\max}$ and h_c denote the maximum speed and the safety distance respectively.

To overcome the unrealistic deceleration and acceleration rates in OVM, by adding the influence of negative relative velocity, Helbing and Tilch [29] developed a generalized force model. And then by adding the positive relative velocity into generalized force model, Jiang et al. [30] presented the full velocity difference model (FVDM) as

$$\frac{dv_n(t)}{dt} = a\big[V(\Delta x_n) - v_n(t)\big] + \lambda \Delta v_n(t), \tag{3}$$

where $\Delta v_n = v_{n+1} - v_n$ denotes the relative velocity difference between the preceding vehicle $n+1$ and the following vehicle n, the λ is the response coefficient to the velocity difference.

On account of the driver always adjusting their driving speed based on the dynamic estimation information, then by adding the factor of anticipation driving behavior of relative velocity into the optimal velocity function, Zheng et al. [39] developed an extended anticipation driving car-following model as follows:

$$\frac{dv_n(t)}{dt} = a\big[V(\Delta x_n + T\Delta v_n) - v_n(t)\big] + \lambda \Delta v_n(t), \tag{4}$$

where T denotes the forecast time, $T\Delta v_n$ is the anticipation space headway for the next moment.

Due to the differences of the vehicle type and driving skills, the optimal driving speeds of the different vehicles may be different for the same headway. In the optimal velocity function of OVM, the maximum speed $v_{\max}$ is an important parameter determining the optimal driving speed. Different vehicles may have different maximum speeds. In addition, the driving behavior is often affected by the driver's anticipation of the relative velocity. Thus, the heterogeneous traffic system with mixed features and driving anticipation effect may well model the real complex traffic flow.

In this paper, we focus on the heterogeneous traffic system combining the effect of driver's anticipation and mixed maximum speeds. Thus, based on the model containing anticipation driving behavior in the optimal velocity function, an extended heterogeneous car-following model is presented with consideration of both driver's anticipation driving behavior and mixed maximum speeds of different percentages as follows:

$$\begin{cases} \dfrac{dv_n(t)}{dt} = a\big[V(\varepsilon_n, \Delta x_n + T\Delta v_n(t)) - v_n(t)\big], \\ \text{for vehicles having the maximum speed } \varepsilon_n \\ \quad \text{with a percentage } p_n, \end{cases} \tag{5}$$

where ε_n is the maximum speed of car n reflecting the degree of aggressive driving, a vehicle with higher ε_n prefers to drive faster than that with lower ε_n in the same situation. $V(\varepsilon_n, \Delta x_n)$ is the optimal velocity function, related to the maximum speed ε_n and headway Δx_n, defined by

$$V(\varepsilon_n, \Delta x_n) = \frac{\varepsilon_n}{2}\big[\tanh(\Delta x_n - h_c) + \tanh(h_c)\big]. \tag{6}$$

Then using Taylor expansion, the improved heterogeneous traffic model containing anticipation driving behavior and mixed maximum speeds can be rewritten as follows:

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