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Analysis of two-lane lattice hydrodynamic model with consideration of drivers' characteristics

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HIGHLIGHTS

- A new lattice hydrodynamic model for two-lane traffic system is proposed by considering drivers' timid or aggressive characteristics.
- Theoretical analysis and computer simulation are carried out to reveal the influence of drivers' characteristics on traffic stability.
- Aggressive drivers are much more prompt than timid drivers in stabilizing traffic flow.

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ABSTRACT

A new lattice hydrodynamic model for two-lane traffic system is proposed with consideration of drivers' timid or aggressive characteristics. The effect of drivers' timid or aggressive characteristics on the stability of traffic flow is studied via linear analysis theory and nonlinear reductive perturbation method. The linear analysis results show that the stable region for aggressive drivers is much larger than that for timid drivers, which means that aggressive drivers are much more prompt than timid drivers in stabilizing traffic flow. Moreover, we derive the mKdV equation near the critical point and obtain its kink–antikink soliton solution to describe the feature of traffic jamming transition. The good agreement between numerical simulations and analytical results reveals that drivers' characteristics have an important role in the stability of traffic flow and traffic jamming transition in two-lane traffic system.

1. Introduction

Traffic jam is a serious problem in our modern society in term of traffic safety, traffic efficiency and energy consumption. Lots of traffic models have been developed to uncover the underlying mechanism of traffic congestion. Basically, the existing traffic models can be divided into the microscopic models and the macroscopic models. The microscopic models such as the car-following models [1–5] and the cellular automata models [6–8] treat each individual vehicle as a particle and regard traffic as a system of interacting particles driven far from equilibrium. The microscopic models are widely used for their convenience to describe the movement of individual vehicles. The macroscopic models, including the continuum models [9–14], the gas kinetic models [15,16] and the lattice hydrodynamic models [17–40], treat the whole traffic flow as compressible fluid formed by vehicles and reveal traffic properties through analyzing the relation among traffic flow, mean

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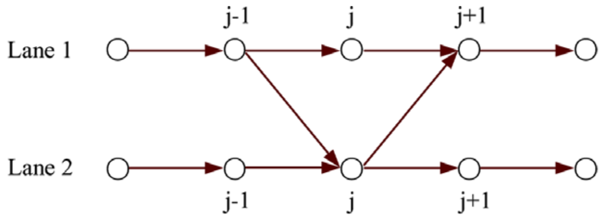

Fig. 1. The schematic model of traffic flow on a two-lane highway.

speed and traffic density. Many important real traffic phenomena like the stop-and-go traffic waves, local cluster, traffic congestion and traffic jamming transition can be reproduced in these models.

In 1998, Nagatani [17] presented the first lattice hydrodynamic model to describe traffic density waves on a single lane highway. The fundamental idea of Nagatani's model is that a driver adjusts the vehicle's velocity in view of the density of the preceding lattice. Later, many extended researches have been performed to improve the performance of Nagatani's model more realistically. Among them, some were developed by introducing the flux difference effect [18–21], the density difference effect [22–24], the multi-lattices effect [25,26], and the others were extended by considering drivers' physical delay [27], drivers' anticipation effect [28–31] and drivers' memory effect [32].

However, the above mentioned researches cannot be employed to reveal the characteristics of two-lane highway. Actually, two-lane or multi-lane roads are widespread in real traffic networks. For this reason, Nagatani [33] extended his single lane lattice hydrodynamic model to two-lane system and investigated the impact of lane changing on traffic stability. After that, some modifications have been made by considering various traffic factors [34–40].

Even some of the aforementioned models have taken drivers' individual behavior into account, they are unable to explain the influence of drivers' characteristics (timid or aggressive) on traffic flow. In fact, different drivers' characteristics would result in different influence on traffic flow. Timid drivers are conservative and they usually want to maintain a large distance with the preceding vehicle, so their perceived headway is larger than the actual headway and then the corresponding perceived downstream density is smaller than the real downstream density as the traffic density equals the inverse of headway. To the contrary, aggressive drivers often tend to keep a close distance with the preceding vehicle and over-estimate the downstream traffic density. That is to say, the impacts of aggressive or timid driving behaviors on traffic evolution are different. In order to reveal the impacts of different drivers' characteristics on traffic jamming transition explicitly, a new lattice hydrodynamic model with consideration of drivers' characteristics for two-lane highway is proposed. The new two-lane lattice hydrodynamic model is put forward in the following section. Section 3 relates to the linear stability analysis of the new model. In Section 4, the mKdV equation near the critical point is derived by using nonlinear reductive perturbation method and its kink–antikink soliton solution is also obtained to depict the propagating behavior of traffic density waves. Numerical simulations are carried out to verify the analytical results in Section 5 and finally, a conclusion is given in Section 6.

2. The new model

The schematic of traffic flow on a two-lane highway proposed by Nagatani [33] is shown in Fig. 1. If the density at lattice $j-1$ on the first lane is higher than that at lattice j on the second lane, then lane changing will occur from the first lane to the second lane with a rate $\gamma\left|\rho_0^2V'(\rho_0)\right|(\rho_{1,j-1}(t)-\rho_{2,j}(t))$, where γ is a dimensionless constant coefficient; ρ_0 is the average density; V denotes the optimal velocity function and $V'(\rho_0)$ is the first-order derivative of V at ρ_0; $\rho_{1,j}(t)$ and $\rho_{2,j}(t)$ indicate the densities at lattice j on the first and second lane, respectively. The constant $\left|\rho_0^2V'(\rho_0)\right|$ is introduced to be dimensionless. Similarly, lane changing will occur with the rate $\gamma\left|\rho_0^2V'(\rho_0)\right|(\rho_{2,j}(t)-\rho_{1,j+1}(t))$ from the second lane to the first lane if the density at lattice j on the second lane is higher than that at lattice $j+1$ on the first lane. Therefore, the continuity equations for the first lane and the second lane are formulated respectively as follows:

$$\partial_t\rho_{1,j}+\rho_0(\rho_{1,j}v_{1,j}-\rho_{1,j-1}v_{1,j-1})=\gamma\left|\rho_0^2V'(\rho_0)\right|(\rho_{2,j-1}-2\rho_{1,j}+\rho_{2,j+1}), \tag{1}$$

$$\partial_t\rho_{2,j}+\rho_0(\rho_{2,j}v_{2,j}-\rho_{2,j-1}v_{2,j-1})=\gamma\left|\rho_0^2V'(\rho_0)\right|(\rho_{1,j-1}-2\rho_{2,j}+\rho_{1,j+1}). \tag{2}$$

By adding Eq. (1) to Eq. (2), one obtains the following continuity equation for two-lane traffic system

$$\partial_t\rho_j+\rho_0(\rho_jv_j-\rho_{j-1}v_{j-1})=\gamma\left|\rho_0^2V'(\rho_0)\right|(\rho_{j-1}-2\rho_j+\rho_{j+1}), \tag{3}$$

where $\rho_j=(\rho_{1,j}+\rho_{2,j})/2$, $\rho_jv_j=(\rho_{1,j}v_{1,j}+\rho_{2,j}v_{2,j})/2$ and time variable t is omitted for simplicity.

In addition, Nagatani [33] assumed that the evolution equation of traffic flow on each lane is not affected by lane changing and gave the evolution equation for two-lane traffic system as

$$\rho_j(t+\tau)v_j(t+\tau)=\rho_0V(\rho_{j+1}(t)), \tag{4}$$