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A novel lattice hydrodynamic model considering the optimal estimation of flux difference effect on two-lane highway

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HIGHLIGHTS

- A new lattice model is proposed by considering optimal estimation of flux difference effect on two-lane highway.
- The effect of optimal estimation of flux difference on two-lane highway is deduced from linear stability analysis.
- The kink–antikink soliton solution for two-lane highway is obtained through nonlinear analysis.
- The consequence of optimal estimation of flux difference on traffic flow dynamics is investigated through simulation.

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ABSTRACT

The optimal estimation of flux difference effect is introduced to construct a new lattice hydrodynamic model for two-lane highway. Through linear stability analysis, it is found that the new consideration plays an important influence upon the stability of two-lane traffic flow. Moreover, the mKdV equation near the critical point is derived from nonlinear analysis, which describes the propagation behavior of traffic jam in two-lane traffic system. Simulation results show that the stability of two-lane traffic system can be increased and the emergence of traffic jams are effectively relieved by the optimal estimation of flux difference effect, which is in good agreement with theoretical analysis.

1. Introduction

Traffic jam has attracted a considerable number of scholars' attention since it seriously hinders the development of economic activity and people's travel. Traffic modeling is an effective method to investigate the properties of traffic jams mathematically. Generally, the existing traffic models are divided into microscopic models and macroscopic models. The microscopic models, which include the cellular automaton models [1] and the car-following models [2–11], mainly revealed the dynamic evolution of individual drivers' behavior. While the macroscopic models, which cover gas kinetic models [11], the continuum models [12–22] and the lattice hydrodynamic models [23–47], mainly reflect the macroscopic traffic characteristics of the road. Among these macroscopic models, the lattice hydrodynamic model firstly proposed by Nagatani [23,24] is one of vigorous macro models and is inspired by the devotion of scholars. Therefore, many mathematical models [25–44] have been proposed to describe the nature of traffic jams with the consideration of various traffic factors in lattice hydrodynamic model on single lane more realistically. Furthermore, Nagatani [45] incorporated the effect of lane changing to establish the lattice hydrodynamic model for two-lane traffic system. Subsequently, a few traffic factors [36–55]

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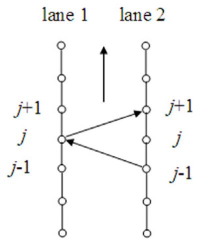

Fig. 1. The schematic model of traffic flow on a two-lane highway.

were introduced into the lattice hydrodynamic model of two-lane traffic flow. To a certain extent, it is easier to suppress the jams of the traffic system in above lattice models mentioned for two-lane highway. However, the difference between estimation optimal and current flux (EOCFD) has not been investigated in the lattice hydrodynamic model on two-lane highway. In real traffic, with the development of vehicle to vehicle communication (called for V2V), a driver can acquire the difference between expected optimal flux and observed actual flux under lane changing, which contributes to adjusting his/her velocity to approach the optimal state as soon as possible. That is to say, the EOCFD effect may have an inevitable influence on two-lane traffic flow. Accordingly, in the following section, we will take the EOCFD effect into account in the lattice hydrodynamic model when lane changing is allowed. After this, linear stability analysis and nonlinear analysis will be explored to describe the jamming transition. Also, numerical simulation is applied to validate the theoretical analysis.

2. The extended model

In two-lane system, the behaviors of lane changing often occur. To solve this traffic appearance, Nagatani [45] presented the original lattice hydrodynamic model for two-lane highway by considering lane changing behaviors. Fig. 1 shows the circumstances in the original two-lane lattice model of traffic flow. The continuity equations were described for two-lane highway as follows [45]:

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

where $\gamma \left|\rho_0^2 V'(\rho_0)\right| (\rho_{2,j-1} - \rho_{1,j})$ represents the lane changing rate from lane 2 to lane 1 when the density at site $j-1$ on lane 2 is higher than that at site j on lane 1. where γ means the rate constant coefficient with dimensionless. Similarly, when the density at site j on lane 1 is higher than that at site $j+1$, the lane changing rate is equal to $\gamma \left|\rho_0^2 V'(\rho_0)\right| (\rho_{1,j} - \rho_{2,j+1})$ from lane 1 to lane 2. Then, By combining Eqs. (1) and (2), we obtain the continuity equation as below:

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

where ρ_0, ρ_j and v_j represent the average density, the local density and local velocity on two lanes, respectively. $\rho_j = (\rho_{1,j} + \rho_{2,j})/2$, $\rho_j v_j = (\rho_{1,j}v_{1,j} + \rho_{2,j}v_{2,j})/2$. At the same time, the evolution equation of the two-lane traffic was given as

$$\partial_t[\rho_j(t)v_j(t)] = a[\rho_0 V(\rho_{j+1}) - \rho_j(t)v_j(t)] \tag{4}$$

where $a = 1/\tau$ is the sensitivity of a driver. $V(\rho)$ shows the optimal velocity function [42] described by

$$V(\rho) = (v_{\max}/2)[\tan\ \mathrm{h}(1/\rho - 1/\rho_c) + \tan\ \mathrm{h}(1/\rho_c)] \tag{5}$$

where ρ_c means the safety density. However, the EOCFD effect has not been explored in the lattice models of two-lane traffic flow up to now. Based on evolution equation (4), here we take this new consideration into account for the evolution equation as below:

$$\partial_t[\rho_j(t)v_j(t)] = a[\rho_0 V(\rho_{j+1}) - \rho_j(t)v_j(t)] + ak[\rho_0 V(\rho_0) - \rho_j(t)v_j(t)] \tag{6}$$

where k is the reaction coefficient of the EOCFD effect term $[\rho_0 V(\rho_0) - \rho_j v_j]$. Making the difference of Eq. (6), we get

$$\rho_j(t+\tau)v_j(t+\tau) = \rho_0 V(\rho_{j+1}) + k[\rho_0 V(\rho_0) - \rho_j(t)v_j(t)] \tag{7}$$

Then, both Eqs. (3) and (7) are the form of new lattice hydrodynamic model. By eliminating the velocity in Eqs. (3) and (7), one obtains the density evolution as below:

$$\begin{aligned}&\rho_j(t+2\tau) - \rho_j(t+\tau) + \tau\rho_0^2[V(\rho_{j+1}) - V(\rho_j)] + k[\rho_j(t+\tau) - \rho_j(t)]\\&-\tau\gamma \left|\rho_0^2 V'(\rho_0)\right| (\rho_{j+1}(t+\tau) - 2\rho_j(t+\tau) + \rho_{j-1}(t+\tau)) = 0\end{aligned} \tag{8}$$