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An improved lattice hydrodynamic model considering the driver's desire of driving smoothly

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HIGHLIGHTS

- Considering driver's desire of driving smoothly, a new lattice hydrodynamic model is proposed.
- By using the linear analysis method, the stability condition is obtained.
- The modified KdV equation is derived to describe the propagating behavior of traffic jams.
- The valid of the analytical results and the effect of the driver's desire of driving smoothly are numerically verified.

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ABSTRACT

Besides the forward vehicles' traffic situation, driving behaviors may be influenced by the driver's desire of driving smoothly, which is embodied by the fact that many drivers like to adjust current traffic situation to the optimal steady state. With the consideration of the effect of driver's desire of driving smoothly, an improved lattice hydrodynamic model is proposed in this paper. The analytical stability criterion is derived by the linear analysis method. And then the modified KdV equation is deduced to describe the characteristic of traffic jams near the critical point. In addition, the numerical simulations are presented to investigate the effect of the factor contained herein on the traffic stability. The analytical and numerical results all show that traffic jams can be effectively relieved when the factor of driver's desire of driving smoothly is incorporated into the traffic model.

1. Introduction

With the increase in the number of private cars, the traffic jam problem is extremely severe in our city. Many researchers have devoted much time to uncover the underlying mechanism of traffic jams [1–8]. A considerable number of traffic models have proposed to investigate the complex traffic phenomena, such as the car-following model [9–18], lattice hydrodynamic models [19–22], intelligent driver model (IDM) [23,24], cellular automata model [25,26], continuum models [27–29], gas kinetic models [30].

Nagatani firstly presented the lattice hydrodynamic model by combining the continuum model and the idea of the car following model [31,32]. There are only discrete spatial and continuous temporal variables in the lattice hydrodynamic model. It can conveniently describe the dynamical phase movement on the freeway. Following Nagatani's model, many extended lattice models are presented.

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Tian et al. investigated the effect of the density difference on the stability of lattice model [33]. Sun et al. also discussed the impact of optimal flux difference [34]. The factors of the anticipation effect of potential lane changing [35], the anticipate optimal current [36], and the interruption probability in the optimal current difference [37] are considered by Pent et al.. Gupta et al. presented a multi-phase lattice hydrodynamic model [20] with the consideration of three-phase optimal velocity function. Ge et al. [38] derived the stability condition of the control method for lattice hydrodynamic model. By considering the density change rate [39], Li et al. incorporated the delay feedback control into the lattice model. Yang et al. showed that considering the difference of the steady-state flux and the current flux can increase the stability of lattice model [40]. The effects of curve road on the lattice model were studied by Zhou et al. [41], Kaur et al. [42] and Jin et al. [43]. Ge et al. discussed the effect of the difference of the optimal fluxes of forward-looking sites [44]. Zhang studied the self stabilization of the history traffic flux on traffic flow of lattice model [45]. Xue et al. investigated the feedback control of driver's reaction time [46]. Zhang et al. focused on the effect of the difference between the current and anticipative densities [47]. Redhu et al. incorporated the traffic jerk into the lattice model [48].

To describe the complex traffic phenomena more accurately, single-lane traffic model is extended to the two-lane traffic model [49]. On account of the density difference effect, Gupta studied an improved two-lane lattice model [50]. Sharma discussed the impact of optimal current difference [51] in a two-lane lattice model. Li et al. presented a two-lane lattice model by changing the condition switching lane [52]. Wang et al. studied a two-lane lattice model with consideration of on-ramp [53].

To reduce the energy consumption caused by the vehicle's acceleration and deceleration, many drivers always prefer to drive as smoothly as possible. Sometimes, even if the proceeding vehicle's traffic condition allows the following vehicle's driver to make acceleration, the driver may not immediately accelerate to avoid the deceleration at the next moment. Thus, besides the forward vehicles' traffic situation, the traffic flow is also affected by the driver's desire of driving smoothly, i.e., there exists a driving behavior govern by the driver's desire that a driver may try to adjust the current actual traffic situation to the optimal steady state. Due to this point, it is necessary and important to incorporate the factor of driver's desire of driving smoothly into the traffic model.

This paper aims to present an improved lattice hydrodynamic model considering the factor of driver's desire of driving smoothly. The paper is organized as follows. In Section 2, the formulation of an improved lattice model is presented. And then by using the linear analysis method, the analytical stability condition is derived in Section 3. And then the nonlinear analysis method is used to obtain the modified KdV equation in Section 4. The characteristic of traffic jams near the critical point is described by the kink–antikink density wave of modified KdV equation. Section 5 will present the numerical simulation of improved lattice model discussed herein considering the effect of driver's desire of driving smoothly. The final section concludes this study.

2. The improved lattice hydrodynamic model

To describe the traffic flow on a highway, in 1998, by simplifying the continuum model, Nagatani firstly presented a simplified lattice hydrodynamic model [31]

$$\begin{cases} \partial_t \rho_j + \rho_0(\rho_j v_j - \rho_{j-1} v_{j-1}) = 0, \\ \partial_t(\rho_j v_j) = a\left[\rho_0 V(\rho_{j+1}) - \rho_j v_j\right], \end{cases} \tag{1}$$

where ρ_0 and a represent respectively the average density on the whole road and driver's sensitivity coefficient, j denotes the site j on the single lane, v_j and ρ_j respectively denote the velocity and density at site j. The idea of Nagatani's model is that when a car is moving at site j, its speed is adjusted according to the proceeding velocity at site $j+1$, and then the traffic current ρv at site j has a tendency to approach the product of average density and optimal velocity at site $j+1$. $V(\rho_j)$ is the optimal velocity function related to the density. The optimal velocity function is chosen to be [32]

$$V(\rho) = \frac{v_{\max}}{2}[\tanh(\frac{2}{\rho_0} - \frac{\rho}{\rho_0^2} - \frac{1}{\rho_c}) + \tanh(\frac{1}{\rho_c})], \tag{2}$$

where $v_{\max}$ is the maximum speed, and ρ_c is the safety-critical traffic density.

Many drivers always like to drive as smoothly as possible to avoid sudden acceleration or deceleration so that it can reduce the energy consumption, and then try to adjust our vehicle speed to the optimal steady smooth state during driving. Due to this, following traditional Nagatani's model, an improved lattice hydrodynamic model considering the factor of driver's desire of driving smoothly is developed

$$\begin{cases} \partial_t \rho_j + \rho_0(\rho_j v_j - \rho_{j-1} v_{j-1}) = 0, \\ \partial_t(\rho_j v_j) = a\left[\rho_0 V(\rho_{j+1}) - \rho_j v_j\right] + \lambda\rho_0\left[V(\rho_0) - V(\rho_j)\right], \end{cases} \tag{3}$$

where the parameter λ is the response coefficient to driver's desire of driving smoothly, and $\lambda\rho_0\left[V(\rho_0) - V(\rho_j)\right]$ denotes the effect of driver's desire of driving smoothly on traffic flow. Since the traffic flow has no acceleration or deceleration in the steady state, then the idea of the term $\lambda\rho_0\left[V(\rho_0) - V(\rho_j)\right]$ is that a driver estimates the difference between current