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Lattice hydrodynamic modeling of traffic flow with consideration of historical current integration effect

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HIGHLIGHTS

- A new lattice hydrodynamic model considering historical current integration is built.
- Linear analysis reveals the stability condition of the new model.
- Nonlinear analysis uncovers the density wave in the unstable region.
- The historical current integration effect can enhance traffic stability efficiently.

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ABSTRACT

A new traffic lattice hydrodynamic model with consideration of historical current integration effect is proposed in this paper and the influence of current integration effect on traffic flow is studied through linear and nonlinear analyses. The linear stability condition obtained by linear analysis reveals that the traffic stability can be enhanced by considering the impact of historical current integration effect. Also the nonlinear analysis shows that the traffic density wave in the unstable region near the critical point can be described by the kink–antikink solution of the mKdV equation. Finally, numerical simulation is carried out to verify the analytical results and it is proved that the historical current integration effect can improve the stability of traffic flow importantly.

1. Introduction

In recent years, due to the rapid increase of automobile on roads, traffic jam problem has attracted considerable attention of scholars from the point of traffic efficiency, traffic safety and energy consumption. Lots of traffic models [1–17] have been proposed to explain the mechanism of traffic phenomena caused by various traffic factors. Among these models, one category is the micro car-following models [1–11]. A famous and widely extended car-following model is the optimal velocity car-following model proposed by Bando et al. [1]. And the further studies in the car-following modeling is by considering the traffic information like vehicle's velocity [2–5], vehicle's headway [6–8], driver's individual behavior [9,10], traffic jerk [11] and so on. The other category is the macro traffic models [12–15] and the main idea of the macro traffic modeling is that the road traffic flow is regarded as compressible fluid and the traffic feature is revealed by studying the relation among traffic parameters of traffic flow, mean speed and traffic density. Also the linkage between the micro car-following modeling and the macro traffic modeling is researched by some researches [16,17].

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In 1998, in view of the car-following theory, Nagatani [18] developed the first lattice hydrodynamic model for single lane highway and derived the mKdV equation to describe the evolution properties of traffic density wave. Later, many extended lattice hydrodynamic models have been constructed by taking various traffic factors into account. In these models, some were proposed by considering the multi-lattices effect [19–21], the flux difference effect [22–25], the density difference effect [26], the road condition [27], driver's individual behaviors (e.g. driver's physical delay [28], driver's memory effect [29] and driver's forecast effect [30–32]), and the others were relating to uncover the traffic mechanism of two-lane traffic system [33–39].

Actually, the driving process is a continuous process and the adjustment of vehicle's movement is not only depending on the vehicle's current state, but also on the vehicle's historical state. In 2015, Redhu et al. [40] developed a delayed-feedback control method in a lattice hydrodynamic model by considering the historical current information at a previous time and it is proved that the traffic stability can be enhanced when the historical current information is considered. Recently, Zhang et al. [41] studied the self-stabilization effect of lattice's historical flow in a new lattice hydrodynamic model by taking the flow difference of a lattice's current flow and its historical flow into account and the stabilization effect of lattice's historical flow is obvious. Also in 2015, on the basis of the continuity of the driving process, Cao et al. [42] developed a car-following model by considering driver's continuous memory effect in sensing headway and studied the impact of traffic information in a continuous historical time interval on traffic stability. And it is found out that the continuous historical traffic information is very significant in stabilizing traffic flow in micro traffic modeling. On the other hand, comparing to the micro traffic modeling which focuses on the vehicle's individual behavior, the macro traffic modeling treat the road traffic as a whole and it is more appropriate to describe the real traffic phenomena and more helpful for traffic control. But to the authors' knowledge, the traffic properties influenced by the continuous historical traffic information has not been researched from the macro traffic modeling so far. So the main work of this paper is to construct a new macro traffic lattice hydrodynamic model by considering the historical current integration effect in a continuous time interval and analyze the influence of continuous historical current information on traffic stability.

The rest of this paper is organized as follows. The new model is developed in Section 2. Sections 3 and 4 provide the linear and nonlinear analyses of the new model. Numerical simulation is carried out in Section 5, and finally, a conclusion is given in Section 6.

2. The new model

The first lattice hydrodynamic model proposed by Nagatani [18] is given by:

$$\partial_t \rho_j + \rho_0 \left(\rho_j v_j - \rho_{j-1} v_{j-1}\right) = 0, \tag{1}$$

$$\partial_t(\rho_j v_j) = a\rho_0 V(\rho_{j+1}) - a\rho_j v_j, \tag{2}$$

where ρ_0 is the average traffic density, ρ_j and v_j respectively denote the traffic density and velocity of lattice j at time t, a is the driver's sensitivity, V represents the optimal velocity and a widely adopted expression of V is:

$$V(\rho_j) = \frac{v_{\max}}{2}\left[\tanh(\frac{1}{\rho_j} - \frac{1}{\rho_c}) + \tanh(\frac{1}{\rho_c})\right], \tag{3}$$

where $v_{\max} = 2$ m/s is the maximal velocity, and $\rho_c = 0.25$ veh/m is the safety critical traffic density which denotes the number of vehicle per every meter.

In order to suppress traffic congestion, Li et al. [22] proposed a new lattice hydrodynamic model by taking the relative current into account and the governing equation of Li's model is:

$$\partial_t \rho_j + \rho_0 \left(\rho_j v_j - \rho_{j-1} v_{j-1}\right) = 0, \tag{4}$$

$$\partial_t(\rho_j v_j) = a\rho_0 V(\rho_{j+1}) - a\rho_j v_j + p\left(\rho_{j+1} v_{j+1} - \rho_j v_j\right), \tag{5}$$

where $\rho_{j+1} v_{j+1} - \rho_j v_j$ is the relative current between lattices $j+1$ and j and p is the response coefficient to the relative current.

Recently, Redhu et al. [40] constructed a delayed-feedback control strategy in lattice hydrodynamic modeling as below:

$$\partial_t \rho_j + \rho_0 \left(\rho_j v_j - \rho_{j-1} v_{j-1}\right) = 0, \tag{6}$$

$$\partial_t(\rho_j v_j) = a\rho_0 V(\rho_{j+1}) - a\rho_j v_j + aq\left(\rho_{j+1}(t) v_{j+1}(t) - \rho_{j+1}(t-\tau) v_{j+1}(t-\tau)\right), \tag{7}$$

where τ denotes the delay time and q is the delayed-feedback gain. It is shown that the delayed-feedback control method can stabilize traffic flow efficiently.