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Study on the effects of driver's lane-changing aggressiveness on traffic stability from an extended two-lane lattice model

Zhipeng Li *, Run Zhang, Shangzhi Xu, Yeqing Qian

The Key Laboratory of Embedded System and Service Computing supported by Ministry of Education, Tongji University, Shanghai 201804, China

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A B S T R A C T

In this paper, the effects of driver's lane-changing aggressiveness on the stability of traffic flow of two-lane are studied by using a generalized lattice hydrodynamic model with consideration of lane-changing aggressiveness of each individual. The effect of lane-changing aggressiveness parameter on traffic stability is derived through employing linear stability analysis with finding that the driver's lane-changing aggressiveness has an important impact on the stability of the traffic flow in a two-lane system. To describe the phase transition, the mKdV equation near the critical point is derived by using the reductive perturbation method, with obtaining the dependence of the propagation kink solution for traffic jams on the lane-changing aggressiveness. It can be concluded from the phase diagram of stability criterion that the higher lane-changing aggressiveness leads to a more stable traffic flow. In addition, the stabilizing effect of the optimal current difference weakens gradually with the increasing of the lane-changing aggressiveness adjusting coefficient, even vanishes when the value of lane-changing aggressiveness adjusting coefficient is greater than a critical value. Theoretical conclusions are also confirmed by the numerical simulations.

1. Introduction

In recent years, the traffic flow problems have become one of the most concern issues in our daily life and have been widely studied by scientists with different background. Confronting the seriously traffic problems, the governments of the world have taken a variety of countermeasures with poor effects from these measures of traffic engineering [1,2]. At the same time, some scholars have been trying to understand the nature governing the traffic flow using theoretical approaches. The approach of mathematics would like to develop models of traffic incorporating only the most essential ingredients which describe the general features of real traffic fields, and there are three different conceptual frameworks for modeling traffic: microscopic model, mesoscopic model and macroscopic model, according to the details of the different descriptions of traffic flow.

Lattice hydrodynamic models proposed by Nagatani [3–4] are some of the well-known and favorable macro hydrodynamic models revealing the dynamic evolution of traffic congestion. The original version of the lattice models is that a driver adjusts vehicle velocity according to the preceding headway. Based on this, many extended versions of lattice hydrodynamic model of single-lane have been proposed to incorporating different traffic factors, such as different driving behaviors [5,6,10], cooperative driving [7–9,13] backward-looking effect [11,12], slope effect [14], density difference effect [15,27],

* Corresponding author.
E-mail address: lizhipeng@tongji.edu.cn (Z. Li).

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flow shift function [26], asymmetric effect [28], optimal current difference [29] etc. The theoretical analysis and simulations of these extended models of single-lane not only provide deep exploring into the properties of this kind of model but also help in better understanding the nature of the complex phenomena observed in real traffic fields.

However, the characteristics of the traffic flow has been mainly studied for lattice models of single-lane, and recently some researcher try to expand the original idea to the traffic flow modeling on two lanes. Although two-lane lattice models are evolved from single-lane models, there are some different characteristics in two-lane models. Under the circumstance of two-lane traffic, the lateral effects should also be taken into account to establish two-lane model apart from the effects in front. Nagatani [16–18] first extended his model to a two-lane highway and analyzed the stability of two-lane traffic flow with concluding that the critical point, the coexisting curve, and the neutral stability line decrease with increasing the rate of lane changing. After that, Wang et al. [19] considered the flow difference effect and proposed a modified lattice two-lane traffic flow model. Taking into account the optimal current difference, Peng [20–21] introduced a lattice hydrodynamic model and gave the conclusion that the new consideration has an important impact on the traffic jams. Also, Peng [22] proposed a two-lane driver anticipation effect (DAE) model focusing mainly on the stability analysis of two-lane traffic flow with the driver anticipation term. Moreover, Gupta and Redhu [23] incorporated the anticipation effect in sensing relative flux and presented a new lattice hydrodynamic model for two-lane traffic system.

In real two-lane traffic, lane-changing behaviors usually occur when the traffic density is different on two lanes. When a leading vehicle prevents its following ones from moving fast, the following vehicles attempt to overtake the leading vehicle by changing the lane. When the lane changing rules are satisfied, lane changing behavior occurs. Actually, the lane changing rules are different according to different driver psychological and traffic states. In 2003, Kurata et al. [24] presented three different lane changing rules for a vehicle running on the two-lane highway according to the velocity difference between the considered vehicle and its preceding one, its headway and the lateral distance between the considered vehicle and the preceding vehicle on the neighboring lane. Moreover, Zhang et al. [25] advised other lane changing rules of vehicle on the basis of its headway in comparison with the lateral distance on the neighboring lane. It is a common understanding that the vehicle headway (or density) and the lateral distance at the two neighboring sites on two lanes have important influence on the lane changing behaviors. The assumption that the lane-changing behaviors of each vehicle will occur only if the lateral distance is larger than its headway is unfound. The relationship between the headway and the lateral distance represents the lane-changing aggressiveness of each vehicle. A higher lane-changing aggressiveness driver needs a shorter lateral distance for a given headway. However, to our knowledge, the effects of lane-changing aggressiveness on the traffic stability for a two-lane system were ignored by the vast majority of existing studies. This motivates us to develop a two-lane lattice model to consider the factor of lane-changing aggressiveness and study its effect on the stability of traffic flow with two lanes.

In this paper, a new lattice model with the consideration of the driver's lane-changing aggressiveness for a two-lane system is presented. The smaller lane-changing aggressiveness is on behalf of a more cautious in conducting the behavior of lane-changing. The influence of lane-changing aggressiveness on stability of the two-lane traffic flow has been studied by the method of linear stability analysis. The method, developed from fluid dynamics, has been widely used in other research fields, for example, the research about a thin gas layer [30–32]. Meanwhile, the nonlinear analysis is also applied to the new model and the mKdV equation has been derived near the critical point by means of the perturbation method.

This paper is organized as follows: In the following section, the extended hydrodynamic lattice model for two-lane system is presented by taking into account the lane-changing aggressiveness. In Section 3, the stability condition of the new model is investigated in an analytical way. The lane-changing aggressiveness dependence of the kink solution for traffic jams is obtained from the method of nonlinear analysis in Section 4. To verify the validity of theoretical analysis, we will compare it with the result of our simulations in Section 5. Finally, Section 6 gives the conclusion.

2. Model

In 1998 Nagatani [3] advised two simplified versions of continuum models describing the traffic phenomena in traffic flow on a sing-lane freeway. One of them is expressed as

$$\partial_t \rho + \rho_0 \partial_x (\rho v) = 0 \tag{1}$$

$$\partial_t \rho v = a\rho_0 V(\rho(x+1)) - a\rho v \tag{2}$$

where ρ_0 is the average density, and a is the sensitivity of a driver; $\rho(x+1)$ is the local density at position $x+1$ at time t; $V(\rho(x+1))$ is the optimal velocity about $\rho(x+1)$. The idea is that the variation of traffic current ρv at position x depends on the current difference between optimal current $\rho_0 V(\rho(x+1))$ at position $x+1$ and actual current ρv at position x. The other simplified hydrodynamic model is the lattice version with dimensionless space x,

$$\partial_t \rho_j + \rho_0(\rho_j v_j - \rho_{j-1} v_{j-1}) = 0 \tag{3}$$

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

where j represents site j on the one-dimensional lattice and $\rho_j(t)$, $v_j(t)$ indicate the density and velocity on site j at time t. Eqs. (3) and (4) is actually the lattice version of model of Eqs. (1) and (2).