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An extended lattice hydrodynamic model considering the driver's sensory memory and delayed-feedback control

Yinyin Chang, Zhiting He, Rongjun Cheng [*]

Faculty of Maritime and Transportation, Ningbo University, Ningbo 315211, China
Jiangsu Province Collaborative Innovation Center for Modern Urban Traffic Technologies, Nanjing 210096, China
National Traffic Management Engineering and Technology Research Centre Ningbo University Sub-centre, Ningbo 315211, China

HIGHLIGHTS

- An extended lattice hydrodynamic model considering driver's sensory memory and delayed-feedback control is proposed.
- Applying the control theory, the new model's linear stability is obtained.
- The energy consumption for this new model are studied.

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ABSTRACT

In this paper, an extended lattice hydrodynamic model with consideration of the driver's sensory memory and delayed-feedback control is proposed. The control signal about the density difference of the vehicles ahead is taken into account. The control method is used to analyze the stability of the extended model, and the stability condition for the model is derived. Energy consumption is also taken into account in the extended model, which reflects the fuel consumption and emissions of each vehicle. The numerical simulations are explored to illustrate and clarify the results of theoretical analysis. The simulation results show that the driver's sensory memory can enhance the stability of traffic flow and reduce the energy consumption, while density difference weakens the stability of traffic flow and increases the energy consumption. Numerical results are consistent with the corresponding theoretical analysis.

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1. Introduction

In recent years, the problem of urban traffic is becoming more and more serious. Traffic congestion not only pollutes the air, but also brings inconvenience to people's life. Traffic flow is a topical issue in modern society, so it is highly concerned by many experts and scholars. Therefore, different types of traffic flow models have been proposed to solve various complex traffic phenomena, such as the car-following models [1–25], the cellular automation models [26–28], the macro models [29–55] and the gas-kinetic models [56–59].

In all of the models, the car-following model is the most common model, which mainly studies the dynamic behavior of individual vehicle and regards each individual vehicle as a particle. In 1995, Bando et al. [7] put forward the optimal velocity (for short, OV) car-following model, which has successfully revealed the dynamic evolution of traffic jam in a simple way. In 2006, Zhao and Gao [8] proposed a coupled-map (CM) car-following model and proved that the model can suppress the

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[*] Corresponding author at: Faculty of Maritime and Transportation, Ningbo University, Ningbo 315211, China.
E-mail address: chengrongjun@nbu.edu.cn (R. Cheng).

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traffic congestion. In 2014, a dynamic collaboration model with feedback signals was presented by Li [10]. Jin [14] proposed an extended car-following model which took the driver's memory and jerk into consideration, and stability criterion of traffic flow was obtained by linear stability theory. Yu [15,16] separately studied the car-following models with the consideration of the relative velocity difference and velocity fluctuation. Then, Ou [17] analyzed the effect of inter-vehicle communication in two-lane car-following model. A new car-following model for autonomous vehicles flow with mean expected velocity field was proposed by Zhu [18].

These models mentioned above are microscopic models that mainly study the relationship between vehicles. However, the traffic flow in the macroscopic models cannot be described. In 1998, Nagatani [30] proposed the original lattice hydrodynamic model, in which the traffic system is regarded as a continuous fluid formed by vehicles. The extended models accounting for multiple optimal velocity functions and driver's memory were carried out by Cheng [32,33]. In addition, Zhai [34] proposed an extended model which took the optimal velocity change with memory into consideration. The lattice hydrodynamic models [35–55] with different factors were studied by a great number of experts. Nevertheless, there are few studies of the lattice hydrodynamic model with delayed-feedback control. In 2015, a lattice hydrodynamic model with the flux change in adjacent time was introduced by Redhu [35]. Considering a decentralized delayed-feedback control, Ge [36] found an extended lattice hydrodynamic model by a simple control method. Qin [44] extended a new lattice hydrodynamic model to study the effect of flux change rate with delayed-feedback signal. Tian [51] and Sharma [59] studied the lattice hydrodynamic model including density difference and the timid and aggressive driving behavior. Lately, a new model with the consideration of electric bicycle's lane-changing and retrograde behaviors was presented by Tang [60].

In the actual traffic, the driver's sensory memory not only depends on the driver's characteristics, but also relates to the driving condition of the previous vehicles. But until now, the driver's sensory memory and density difference of the previous two vehicles were seldom studied. The study for the two mentioned factors will have a significant impact on traffic flow. Hence, we want to investigate it in traffic flow with the delayed-feedback control theory. Energy consumption is also taken into account, and the kinetic energy theorem is used to describe the change of energy consumption of automobiles in two adjacent times.

This paper is organized as follows. In Section 2, an improved lattice hydrodynamic model is proposed. The linear stability condition is obtained by delayed-feedback control theory in Section 3. In Section 4, numerical simulations are carried out to illustrate the impact of driver's sensory memory and density difference. Conclusions are drawn in Section 5.

2. An improved lattice hydrodynamic model

In order to describe the complex mechanism of traffic flow, Nagatani [30] put forward a simple lattice hydrodynamic model as follows:

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

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

where $a = \frac{1}{\tau}$ represents the driver's sensitivity, ρ and v denote the local density and average velocity respectively at site j, ρ_0 is the local average density and δ indicates the average space headway that is the inverse of ρ_0 ($\rho_0 = \frac{1}{\delta}$), $\rho(x+\delta)$ is the local density at the position of $x+\delta$, and $V(\rho)$ is the optimal velocity function which is determined by the density.

To facilitate the calculation below, the equation is modified by Nagatani with a discrete way as follows:

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

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

where the road is divided into N lattice sites and j denotes the site of the road, ρ_j and v_j severally indicate the local density and the local average velocity of lattice j at time t.

Considering the effect of driver's sensory memory, an extended lattice hydrodynamic model is presented as:

$$\partial_t \rho_{j+1} + \rho_0(q_{j+1} - q_j) = 0 \tag{5}$$

$$\partial_t(q_j) = a\rho_0[pV(\rho_{j+1})(t) + (1-p)V(\rho_{j+1})(t-\alpha\tau)] - aq_j \tag{6}$$

where q is the product of ρ and v, $0 \le p \le 1$ means the anticipation coefficient of the driver's sensory memory in traffic flow. α represents the intensity of influence characteristics and τ is the delay time.

The new optimal velocity function of lattice hydrodynamic model is proposed by Nagatani, and it is similar to that of Bando's car-following model. It can be expressed as follows:

$$V(\rho) = \frac{v_{\max}}{2}[\tanh(\frac{1}{\rho} - \frac{1}{\rho_c}) + \tanh(\frac{1}{\rho_c})] \tag{7}$$

where $v_{\max}$ and ρ_c mean the maximum speed and the critical safety density respectively. We assume the expect density and the flux of the traffic flow are ρ^* and q^*, therefore the uniform flow in steady state is:

$$[\rho_n, q_n]^T = [\rho_n^*, q_n^*]^T \tag{8}$$

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