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Theoretical analysis of the density wave in a new continuum model and numerical simulation

Lai Ling-Ling [a], Cheng Rong-Jun [b], Li Zhi-Peng [c], Ge Hong-Xia [d,*]

[a] Faculty of Science, Ningbo University, Ningbo 315211, China
[b] Ningbo Institute of Technology, Zhejiang University, Ningbo 315100, China
[c] College of Electronics and Information Engineering, Tongji University, Shanghai, 200092, China
[d] Faculty of Maritime and Transportation, Ningbo University, Ningbo 315211, China

HIGHLIGHTS

- A new continuum model is proposed based on the AD-CF model.
- The stability condition and the KdV equation are obtained.
- The numerical simulation is carried out to the new system.

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ABSTRACT

Considered the effect of traffic anticipation in the real world, a new anticipation driving car following model (AD-CF) was proposed by Zheng et al. Based on AD-CF model, adopted an asymptotic approximation between the headway and density, a new continuum model is presented in this paper. The neutral stability condition is obtained by applying the linear stability theory. Additionally, the Korteweg–de Vries (KdV) equation is derived via nonlinear analysis to describe the propagating behavior of traffic density wave near the neutral stability line. The numerical simulation and the analytical results show that the new continuum model is capable of explaining some particular traffic phenomena.
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1. Introduction

Traffic jams have attracted much attention and various traffic flow models [1–6], including car-following models, gas kinetic models, cellular automaton models and macroscopic continuum models have been proposed to study complex traffic phenomena. Continuum traffic flow models, which fasten on the collective behavior of traffic, have played an important role in describing nonlinear complexity.

The study of continuum traffic flow models began with the first continuum model proposed independently by Lighthill and Whitham [7,8], and Richards [9] (the LWR model, for short). The LWR model is known as a simple continuum model, in which the relationships among the three aggregate variables (ρ, q, v) are modeled. The authors exploit the conservation laws in the following form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial q}{\partial x} = s(x, t). \tag{1}$$

* Corresponding author.
E-mail addresses: pandd1112@163.com (L.-L. Lai), gehongxia@nbu.edu.cn (H.-X. Ge).

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As we know, Eq. (1) is not a self-consistent model, it should be supplemented by the fundamental equation of traffic flow

$$q = \rho v,$$

and a relationship between the mean velocity and the traffic density under the condition of equilibrium

$$v = v_e(\rho),$$

where $v = v_e(\rho)$ is the equilibrium velocity, x and t represent space and time, respectively. Using the simple continuum model can describe the most basic traffic flow phenomena, such as the traffic congestion formation and the dissipation in a dense traffic. However, the model cannot describe non-equilibrium traffic flow dynamics, such as the stop-and-go traffic and the forward propagation of disturbances in a heavy traffic.

In order to solve these questions, in 1971, Payne [10] introduced a high-order continuum traffic flow model including a dynamic equation from the car-following theory:

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = -\frac{\mu}{\rho T}\frac{\partial \rho}{\partial x} + \frac{v_e - v}{T}, \tag{2}$$

where T is the relaxation time, and $\mu = -0.5\partial v_e/\partial \rho$ is the anticipation coefficient. The first term on the right-hand side of Eq. (2) is called the anticipation term, and the second term represents a relaxation to equilibrium state.

Payne's model improved the LWR model by incorporating the momentum equation and taking the acceleration and inertial effects into account, thus the model is suitable for the description of non-equilibrium situations. However, as pointed out by Daganzo [11], one of characteristic speeds in the Payne model is faster than the speed of the leading vehicle, which leads to a gas-like behavior. In general, the vehicle behind forces the vehicle ahead to speed up and the diffusion causes the wrong-way travel. To overcome this difficulty, Aw and Rascle [12], Jiang et al. [5] and Zhang [13] proposed a few other high-order continuum models.

Recently, Zheng et al. [14] developed a new car following model (AD-CF, for short) taking the anticipation driving behavior in real traffic into account. In this paper, we develop a new macroscopic continuum model by applying the usual connection method of macro–micro variables into AD-CF model.

The organization of the paper is as follows. In Section 2, we develop a new continuum model based on the improved car-following model. The stability analysis of the new model is discussed in Section 3. The KdV equation is derived through nonlinear analysis and the soliton solution is given in Section 4. In Section 5, we present the numerical scheme of the model and analyze the local cluster effect. Finally, the conclusion is given.

2. The new continuum model

In 1995, Bando et al. [15] put forward a car-following model by introducing an optimal velocity (OV) function. Later, Helbing and Tilch [16] developed the generalized force (GF) model in order to overcome its deficiency. In 2001, Jiang et al. [17] proposed the full velocity difference (FVD) model. Considering ITS application, Ge et al. [18] presented a two-velocity difference (TVD) model in 2008. Considering the driver always adjust his/her vehicle based on the dynamic estimation information in real traffic system, Zheng et al. [7] developed a new anticipation driving car-following (AD-CF) model, whose dynamic equation is

$$\frac{\mathrm{d}v_n(t)}{\mathrm{d}t} = a\{V[\Delta x_n(t) + k\Delta v_n(t)] - v_n(t)\} + \lambda\Delta v_n(t), \tag{3}$$

where k is the forecast time, $k\Delta v_n(t)$ represents the estimation space headway in the next moment. Eq. (3) shows that the acceleration of the nth vehicle at time t is determined not only by the velocity $v_n(t)$ and velocity difference $\Delta v_n(t)$, but also by the estimation of space headway $k\Delta v_n(t)$.

Making the Taylor expansion of the variables $V[\Delta x_n(t) + k\Delta v_n(t)]$ and neglecting the nonlinear terms, we rewrite Eq. (3) as follows:

$$\frac{\mathrm{d}v_n(t)}{\mathrm{d}t} = a[V(\Delta x_n(t)) - v_n(t)] + [akV'(\Delta x_n(t)) + \lambda]\Delta v_n(t). \tag{4}$$

Then we transfer the microscopic variables to the macroscopic ones as follows:

$$v_n(t) \to v(x, t), \qquad v_{n+1}(t) \to v(x + \Delta, t), \qquad V(\Delta x) \to V_e(\rho(x, t)), \qquad a \to 1/T, \qquad \lambda \to 1/\tau,$$

where T is the relaxation time and τ represents the propagating time of a distance Δ. Substituting the macro various in the car-following model Eq. (4), we get

$$\frac{\mathrm{d}v(x, t)}{\mathrm{d}t} = \frac{V_e(\rho(x, t)) - v(x, t)}{T} + \left(\frac{kV_e'(\rho)}{T} + \frac{1}{\tau}\right)[v(x + \Delta, t) - v(x, t)]. \tag{5}$$

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