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Impacts of moving bottlenecks on traffic flow

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HIGHLIGHTS

- A macro model with moving bottleneck is proposed.
- The impacts of moving bottleneck on uniform flow are studied.
- The effects of moving bottleneck on small perturbation are studied.

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ABSTRACT

Bottleneck (especially the moving bottleneck) widely exists in the urban traffic system. However, little effort has been made to study the impacts of the moving bottleneck on traffic flow (especially the evolution and propagation of traffic flow). In this article, we introduce the speed of a moving bottleneck into a traffic flow model, then propose an extended macro traffic flow with a moving bottleneck, and finally use the proposed model to study the effects of a moving bottleneck on the evolution and propagation of traffic flow under uniform flow and a small perturbation. The numerical results indicate that the moving bottleneck has prominent influences on the evolution of traffic flow under the two typical traffic situations and that the impacts are dependent on the initial density.

1. Introduction

To date, congestions, jams, accidents and other traffic problems have attracted researchers to propose many traffic flow models to study various complex traffic phenomena (including formation, evolution, propagation, etc.) [1–35]. Roughly speaking, the traffic flow models can be sorted into microscopic ones [3–17] and macroscopic ones [18–35]. The microscopic models explore the driving behavior while the macroscopic models study the formation, evolution, propagation (especially time-space distribution) of traffic flow by some macroscopic variables of traffic flow (e.g., density, speed and flow). However, the traffic flow models [3–35] did not consider bottleneck, so they cannot be applied to directly investigate the influences of bottleneck on traffic flow (including the evolution and propagation). In the real urban traffic system, bottleneck (e.g., bus station, accident, traffic light, on-ramp, etc.) widely exists and may have some significant impacts on traffic flow. For example, stop-and-go traffic and queue occur because of the above bottlenecks. To describe the complex traffic phenomena that are caused by bottleneck, researchers proposed many models accounting for bottleneck to explore the influences of bottleneck on traffic flow from different perspective. For example, Cassidy and Bertini [36] applied some observed data to explore the

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formation, propagation and dissipation of the queue caused by a bottleneck; Ishibashi and Fukui [37] proposed a model to explore the impacts of a bottleneck on the high-speed vehicle's motion behaviors; Ni and Leonard [38] developed a first-order model to explore the priority that each vehicle enters the merging bottleneck; Daganzo and Laval [39] used the kinematic wave theory to investigate the influences of a moving bottleneck on the evolution of traffic flow; Yamamoto el al. [40] developed a coupled-map optimal velocity model to study the influences of a bottleneck on the vehicle's driving behavior; Kerner [41] used some empirical data and the three phase traffic flow theory to explore the traffic flow features that are caused by bottleneck; Lattanzio et al. [42] used the differential equation theory to explore the impacts of a bottleneck on the evolution of traffic flow, and developed an coupled ODE-PDE (ordinary differential equation-partial differential equation) model accounting for a moving bottleneck; based on the work [42], Tang et al. [43,44] proposed an extended coupled ODE-PDE model to study the effects of some static bottlenecks on traffic flow under some typical traffic situations; Nagatani et al. [45,6,46] used some simulation models to explore the effects of some special bottlenecks (e.g., signal light, sudden braking, lane-changing, etc.) on each vehicle's driving behavior from the microscopic perspective.

However, most of the models [36–45,6,46] assumed that the bottleneck is static (i.e., it cannot move or propagate backward), so they cannot be used to study the effects of a moving bottleneck on the evolution of traffic flow. Based on the model [43,44], we in this paper propose an extended macro traffic flow model to simulate the impacts of a moving bottleneck on the evolution and propagation of traffic flow under two typical situations.

2. Model

The first macro traffic flow model was independently developed by Lighthill and Witham [18] and Richards [19], where the control equation can be formulated as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial\left(\rho v_{\mathrm{e}}(\rho)\right)}{\partial x}=0, \tag{1}$$

where ρ is the traffic density; $v_{\mathrm{e}}(\rho)$ is the equilibrium speed. Eq. (1) is later called as the LWR model. The classical LWR model can describe the formation, propagation and evolution of shock. However, the traffic speed Eq. (1) is determined by the equilibrium speed $v_{\mathrm{e}}(\rho)$, so the LWR model cannot be used to describe the non-equilibrium traffic flow. In many real traffic systems, the traffic speed deviates from the equilibrium speed. For example, the deviation will occur when lane-changing exists. In order to overcome the fatal shortcoming of the classical LWR model, researchers used an acceleration equation to substitute of the equilibrium speed, thus proposed many high-order models to study the complex phenomena that are caused by various non-equilibrium traffic flow [20–35]. Based on the features of the accelerations, the high-order models [20–35] can be sorted into density-gradient (DG) models and speed-gradient (SG) models. The first DG model was proposed by Payne [20], which was later called as the Payne model [20]:

$$\begin{cases} \dfrac{\partial \rho}{\partial t}+\dfrac{\partial(\rho v)}{\partial x}=0 \\ \dfrac{\partial v}{\partial t}+v\dfrac{\partial v}{\partial x}=\dfrac{v_{\mathrm{e}}(\rho)-v}{\tau}-\dfrac{\upsilon}{\rho\tau}\dfrac{\partial \rho}{\partial x}, \end{cases} \tag{2}$$

where τ is the reactive time; $\upsilon=-\frac{1}{2}v_{\mathrm{e}}'(\rho)$ is the sonic speed. Eq. (2) can conquer the shortcoming of the classical LWR model, but it produced the backward motion under some given specific conditions due to the density gradient in the acceleration of Eq. (2). To eliminate the backward motion, researchers used the speed gradient to substitute the density gradient, thus proposed the SG models, where one simplest SG model was proposed by Jiang et al. [21], i.e.,

$$\begin{cases} \dfrac{\partial \rho}{\partial t}+\dfrac{\partial(\rho v)}{\partial x}=0 \\ \dfrac{\partial v}{\partial t}+v\dfrac{\partial v}{\partial x}=\dfrac{v_{\mathrm{e}}(\rho)-v}{\tau}-c_0\dfrac{\partial v}{\partial x}, \end{cases} \tag{3}$$

where c_0 is the coefficient of speed gradient, which represents the speed that a small perturbation propagates backward. For simplicity, Jiang et al. [21] defined the parameter c_0 as a constant.

However, Eqs. (1)–(3) do not consider bottleneck (including the static and moving bottlenecks), so they cannot be used to describe the complex traffic flow caused by bottleneck (especially the impacts of bottleneck on traffic flow). In fact, bottleneck widely exists (especially during the rush hours). For example, a bottleneck occurs when an incident occurs, and the incident may have some great impacts on traffic flow. To describe various bottlenecks, researchers developed many traffic flow models to study the complex traffic phenomena caused by bottlenecks [36–41], but the models do not consider the impacts of the moving bottleneck on the propagation features of traffic flow, so they cannot describe the impacts of the moving bottleneck on the dynamic properties of traffic flow. In fact, many traffic behaviors (e.g., retrograde, lane-changing, overtaking, etc.) produce some moving bottlenecks that may have significant impacts on traffic flow. To describe the moving bottleneck in traffic flow model, Lattanzio et al. [42] proposed an ODE-PDE (ordinary differential equation-partial differential