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A macro traffic flow model accounting for real-time traffic state

Tie-Qiao Tang [a,b,*], Liang Chen [a], Yong-Hong Wu [b], Lou Caccetta [b]

[a] School of Transportation Science and Engineering, Beijing Key Laboratory for Cooperative Vehicle Infrastructure Systems and Safety Control, Beihang University, Beijing 100191, China

[b] Department of Mathematics and Statistics, Curtin University, WA 6845, Australia

HIGHLIGHTS

- A traffic flow model with real-time traffic state is proposed.
- The effects of real-time traffic state on uniform flow are explored.
- The effects of real-time traffic state on small perturbation are studied.

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ABSTRACT

In this paper, we propose a traffic flow model to study the effects of the real-time traffic state on traffic flow. The numerical results show that the proposed model can describe oscillation in traffic and stop-and-go traffic, where the speed–density relationship is qualitatively accordant with the empirical data of the Weizikeng segment of the Badaling freeway in Beijing, which means that the proposed model can qualitatively reproduce some complex traffic phenomena associated with real-time traffic state.

1. Introduction

To date, many traffic flow models have been proposed to study the traffic phenomena such as the time-spatial distribution of traffic flow and driving behavior from different perspectives [1,2]. Roughly speaking, the existing traffic flow models can be classified into micro models and macro models, where the macro models mainly study the macro phenomena of traffic flow (e.g., the time-spatial distribution of density) while the micro models mainly explore the micro properties of traffic flow (e.g., the driving behavior). The first macro traffic flow model was proposed independently by Lighthill and Whitham [3] and Richards [4], but this model cannot describe the non-equilibrium flow, thus researchers developed high-order models to study the non-equilibrium property of traffic flow [5–23]. As to the micro models, Pipes [24] developed the first car-following model, which was later extended by Helly [25], Kometani and Sasaki [26] and Gazis et al. [27]. Gipps [28] constructed the Gipps model based on the assumption that each driver sets limits to his/her desired braking and acceleration rates. Bando et al. [29] proposed the optimal velocity model. Helbing and Tilch [30] developed the generalized force model. Ahmed [31] used car-following model to study the lane-changing behavior. Nagatani [32] used car-following model to study the traffic

* Corresponding author at: School of Transportation Science and Engineering, Beijing Key Laboratory for Cooperative Vehicle Infrastructure Systems and Safety Control, Beihang University, Beijing 100191, China.
E-mail address: tieqiaotang@buaa.edu.cn (T.-Q. Tang).

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Table 1
Some variables.

Name	Physical meaning	Unit
x	Spatial variable	m
t	Time variable	s
ρ	Traffic density	veh/m
ρ_t	The partial derivative of the density with respect to t	
ρ_x	The partial derivative of the density with respect to x	
$v_e(\rho)$	Equilibrium speed without road condition	m/s
$(\rho v_e)_x$	The partial derivative of the flow ρv_e with respect to x	
v_f	The free flow speed	m/s
ρ_j	The jam density	veh/m
v	Speed	m/s
v_t	The partial derivative of the speed with respect to t	
v_x	The partial derivative of the speed with respect to x	
$(\rho v)_x$	The partial derivative of the flow ρv with respect to x	
τ	The driver's reaction time	s
c_0	The propagation speed of small perturbation without road condition	m/s
$v_{r,e}(\rho)$	The equilibrium speed with road condition	m/s
$c_{r,0}$	The propagation speed of small perturbation under road condition	m/s
a_r	The acceleration adjustment term resulted by road condition	m/s^2
v_r	The speed adjustment term resulted by road condition	m/s

wave. Jiang et al. [33] proposed the full velocity difference model. Toledo [34] used car-following model to explore the integrated driving behavior. Koutsopoulos and Farah [35] proposed a latent class model to explore the driving behavior. Wagner [36] studied the fluctuation of the driving behavior under car-following model. In addition, there exist other micro traffic flow models [37–60].

However, the above models cannot reproduce the effects of road condition on traffic flow since this factor is not considered. In fact, any road has its own specific condition (e.g., road quality) and the road condition has great impacts on traffic flow. To study the impacts, Treiber et al. [61] proposed the GKT (gas-kinematic-based traffic) model and studied the effects of varying street on traffic flow. Bellouquid and Delitala [62] proposed a traffic flow model with road conditions based on the model [63]. However, the models [61–63] assumed that the road condition is fixed, so they cannot be used to study the effects of varying road condition on traffic flow. To conquer this limitation, Tang et al. [64] proposed a traffic flow model with the varying road condition, but they assumed that the road condition is independent on the spatial and time variables. Jiang et al. [65] used experiments to explore the nature of car-following behavior and found that the oscillating phenomena of each vehicle speed are relevant to the traffic state, but they did not study the effects of the real-time road condition on the car-following behavior.

In this paper, we propose a traffic flow model to explore the effects of real-time traffic state on traffic flow. Comparing with the existing other studies, this paper has three contributions, i.e., the traffic state in our model is a real-time variable; our model can qualitatively describe the effects of real-time traffic state on traffic flow; the scatter velocity–density data calculated by the numerical tests are qualitatively consistent with the empirical data of the Weizikeng Segment of the Badaling freeway in Beijing [64].

2. Model

For convenience, we list all the variables in Table 1. The first macro traffic flow model was proposed independently by Lighthill and Whitham [3] and Richards [4], which is called the LWR model and can be expressed by

$$\rho_t + (\rho v_e(\rho))_x = 0 \tag{1}$$

where $v_e(\rho)$ satisfies the following conditions:

(1) the flow $\rho v_e(\rho)$ is a concave function of the density;
(2) $v_e(0) = v_f$, $v_e(\rho_j) = 0$.

It is known that Eq. (1) cannot be used to study the non-equilibrium property of traffic flow since the speed is determined by $v_e(\rho)$. To conquer this shortcoming, some high-order models were proposed, including the DG (density-gradient) models [5,6] and the SG (speed-gradient) models [7,8]. The first DG model is the Payne model that can be expressed as follows [5]:

$$\begin{cases} \rho_t + (\rho v)_x = 0 \\ v_t + v v_x = \dfrac{v_e - v}{\tau} - \dfrac{\upsilon}{\rho\tau}\rho_x, \end{cases} \tag{2}$$

where $\upsilon = v_e'(\rho)$ is the anticipation coefficient. Eq. (2) can describe the non-equilibrium property of traffic flow, but it will produce backwards movement under some specific condition [66]. To avoid the backwards movement, Jiang et al. [8]