ophiolite complex with age of Ordovician-Middle triassic should be divided into 7 parts: Early-Middle Ordovician ophiolite and chert, Middle-Late Ordovician argillaceous silty slate with intercalating of black slate, Middle Silurian-Middle Devonian molasse (?), Early Carboniferous-Early Permian ophiolite and radiolaria chert (or argillaceous chert), Late Carboniferous-Early Permian limestone including biological reef limestones, Late Permian-Early Triassic molasse and Triassic sandy slate. These data (especially the acritarchs) show that Ordovician ocean basin, Caledonian orogeny and Paleotethyan ocean basin once existed in the area, which have important significance for tectonic research of the studied area and even the north Qinghai-Tibetan Plateau.

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A new dynamics model for traffic flow

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Abstract As a study method of traffic flow, dynamics models were developed and applied in the last few decades. However, there exist some flaws in most existing models. In this note, a new dynamics model is proposed by using car-following theory and the usual connection method of micro-macro variables, which can overcome some ubiquitous problems in the existing models. Numerical results show that the new model can very well simulate traffic flow conditions, such as congestion, evacuation of congestion, stop-and-go phenomena and phantom jam.

Keywords: traffic flow, dynamics model, car-following model.

With the rapid development of transportation, traffic flow research has got more and more attention. In this field, the methods existing prevalently at present include car-following model, continuum model, gas-basedkinetics method, cellular automaton method, etc.[1,2].

The development of continuum models of traffic flow began from the LWR theory presented by Lighthill et al.[3] and Richards[4] independently. Considering a section of road, if there is no on-ramp and off-ramp, the number of vehicles in the section will satisfy conservation law and the variety rate of density will be equal to the difference of inflow and outflow. Assuming k denotes traffic density, u denotes space mean speed, it is obvious that

$$\frac{\partial k}{\partial t}+\frac{\partial (ku)}{\partial x}=0. \tag{1}$$

It is assumed by LWR theory that there is a relationship between u and k:

$$u=u_e(k), \tag{2}$$

which is called equilibrium speed-density relationship. In fig. 1, a typical equilibrium speed-density curve presented by Del Castillo et al.[5] is depicted.

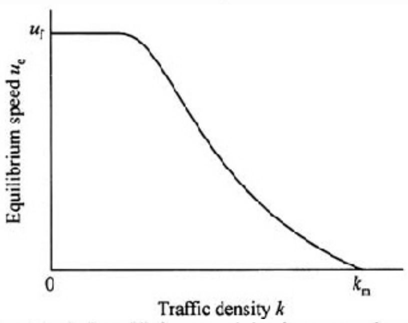

Fig. 1. A typical equilibrium speed-density curve, where u_f is free flow speed, k_m is jam density.

Since no fluctuations of speed around the equilibrium values are allowed in LWR theory, it is not able to describe the traffic conditions exactly under non-equilibrium conditions. In order to solve the problem, Payne[6] proposed a dynamics equation in addition to continuum equation (1)

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}=-\frac{\upsilon}{kT}\frac{\partial k}{\partial x}+\frac{u_e-u}{T}, \tag{3}$$

where T is the relaxation time and υ the anticipation index. In this model, fluctuations of speed around the equilibrium values are allowed, therefore, it is better than LWR theory in describing actual traffic conditions. And models composed of continuum equation and dynamics equation are called dynamics models for traffic flow.

Analyzing eqs. (1) and (3) by characteristics, there are two characteristic speeds $\lambda_1=u+\sqrt{\upsilon/T}$ and $\lambda_2=u-\sqrt{\upsilon/T}$, where λ_1 is greater than the macroscopic speed of traffic flow. As pointed out by Daganzo[7], it means that the future conditions of a traffic element are determined by what is happening behind it. Therefore, the fundamental feature of traffic flow that a vehicle is an anisotropic particle and drivers only respond to frontal stimuli is violated. For this reason, the model cannot describe the realistic conditions of traffic flow exactly, either. The example in Section 3 will be a good proof of it.

Based on Payne model, a few different dynamics models[8—12] are presented. However, these models do not solve the characteristic speed problem in Payne model. In this note, we will propose a new dynamics model from car-following theory, in which there does not exist characteristic speed greater than macroscopic speed of traffic flow. Therefore, it is suitable for describing realistic traffic conditions.

1 Review and improvement of car-following model

In the process of car-following, if no passing is permitted, the dynamics condition of the following car will be determined by the speed of the leading car, its own speed, the distance between the two cars, the road condition, capability of the car, driver's personalities and so on. However, due to complication of the problems and in order to describe the conditions, some factors are sometimes neglected. For example, we assume that different drivers have same personalities, the road condition is ideal and cars have equal capability. Under such assumptions, classical car-following equation is proposed as[13]:

$$\frac{\mathrm{d}v_{n+1}(t+\Delta t)}{\mathrm{d}t}=\lambda\Delta v, \tag{4}$$

where $\Delta v=v_n(t)-v_{n+1}(t)$, v_n and v_{n-1} are the speeds of leading car and following car respectively, Δt is the reaction time and λ the reaction coefficient. When the speeds of the leading car and following car are equal, the moving state of the following car will not be changed, whatever the distance of two cars is. It is obvious that this is not realistic.

Recently, Bando et al.[14] presented the optimal velocity model (OVM). They indicated that there are two types of theories for car-following regulation. The first type is based on the idea that each car must maintain the legal safe distance of the leading car, which depends on the relative speed of these two cars. This theory is called the classical car-following theory. The other idea is that each car has the legal speed, which depends on the following distance of the leading car. Based on the latter idea, they proposed the following form:

$$\frac{\mathrm{d}v_{n+1}(t)}{\mathrm{d}t}=\kappa[V(\Delta x)-v_{n+1}(t)], \tag{5}$$

where κ is the reaction sensitivity, $\Delta x=x_n(t)-x_{n+1}(t)$, x_n, x_{n+1} are the positions of the leading car and following car respectively, V is function of Δx, representing legal speed.

Basing on OVM theory, Helbing et al.[15] presented generalized force model(GFM). They think that when $\Delta v<0$, it is necessary to consider the acceleration caused by the relative speed of the leading car and the following car, the model is as follows:

$$\frac{dv_{n+1}(t)}{dt} = \kappa[V(\Delta x) - v_{n+1}(t)] + \lambda \Delta v H(-\Delta v), \quad (6)$$

where H is Heaviside function ($H(x) = 1$, where $x \geqslant 0$ and $H(x) = 0$, where $x < 0$).

According to our observation to car-following phenomena, we think that relative speed of the leading car and following car should be considered, whether $\Delta v < 0$ or $\Delta v > 0$, for changing the motion state of the following car. At the same time, the acceleration of the following car depends on the distance of the two cars, too. According to this idea, we present an improved car-following model

$$\frac{dv_{n+1}(t)}{dt} = \kappa[V(\Delta x) - v_{n+1}(t)] + \lambda \Delta v. \quad (7)$$

This model considers adequately the effects of both the distance and relative speed of leading car and following car on the acceleration of the following car, so it is more exact than previous models. In the next section, we will develop a new dynamics model from the improved car-following model equation (7).

2 Dynamics modeling and analysis

Car-following theories describe traffic flow conditions from microscopic views, but it does not obstruct that we link it to continuum conditions from macroscopic views. In fact, microscopic description is always an embodiment of macroscopic description, the difference between continuum and discretization lies in the different scale of observation. Just as in ref. [8], we assume that the dynamic properties of a car $n+1$ at location x_{n+1} represent the average traffic condition at $[x-\Delta, x+\Delta]$, and are determined by the average traffic condition in the region $[x, x+2\Delta]$. By transferring the microscopic variables to the macroscopic ones[16], we have

$$v_{n+1}(t) \to u(x,t), \quad v_n(t) \to u(x+\Delta, t), \quad V(\Delta x) \to u_e(k) \quad (8a)$$

and

$$\kappa \to 1/T, \quad \lambda \to 1/\tau, \quad (8b)$$

where T is relaxation time, τ is the time needed for backward propagated disturbance passing distance Δ. Applying this analysis to eq. (7), we have

$$\frac{du(x,t)}{dt} = \frac{u_e(k) - u(x,t)}{T} + \frac{u(x+\Delta, t) - u(x,t)}{\tau}. \quad (9)$$

Expanding the right-hand side of eq. (9) with respect to $u(x,t)$, and neglecting higher-order terms, we have

$$\frac{du}{dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \frac{u_e - u}{T} + \frac{\Delta}{\tau}\frac{\partial u}{\partial x}. \quad (10)$$

Analyzing eqs. (1) and (10) by characteristics, we have two characteristic speeds:

$$\lambda_1 = u, \quad \lambda_2 = u - c_0, \quad (11)$$

where $c_0 = \Delta / \tau \geqslant 0$ is the disturbance propagation speed. We can see that in this new model there does not exist the characteristic speed greater than macroscopic speed of traffic flow. It is suitable for realistic traffic flow conditions.

Next we will analyze that if there exists the negative travel speed problem presented by Daganzo[7] using the new model. The initial condition of traffic flow presented by Daganzo is as follows:

$$u = 0, \quad k = k_m H(x); \quad \forall x \leqslant A, \quad t = 0 (A > 0), \quad (12a)$$

$$u = 0; \quad x = A, \quad t > 0, \quad (12b)$$

where $H(x)$ is also Heaviside function, k_m is jam density. Under the initial condition, it is obvious that the correct solution to this problem should be the initial condition itself, so we will have $du/dt = 0$. According to Payne model, substituting it into eq. (3), we have

$$u(x,t) = u_e - \frac{v}{k}\frac{\partial k}{\partial x}.$$

Since $u(x,t) \geqslant 0$, it requires

$$\frac{\partial k}{\partial x} \leqslant \frac{k u_e}{v}, \quad (13)$$

i.e. a finite density gradient. Any density gradient greater than $k u_e / v$ will lead to negative speed $u(x,t)$, i.e. cars go backward. From initial condition (12), at the discontinuous location, we can assume $\partial k / \partial x \to \infty$, which does not satisfy inequality (13). Therefore, applying Payne model will anticipate that cars go backward, and it is not realistic.

Now we use the new model to analyze this problem. Substituting $du/dt = 0$ into eq. (10), from the initial condition, the speed gradient $\partial u / \partial x = 0$, so we will have $u(x,t) = u_e$. Because $u_e \geqslant 0$, $u \geqslant 0$ is always satisfied, i.e. the model will not anticipate that cars go backward.

3 Numerical results

Applying finite difference method to discretizing the model equations, we have the difference equations as (14a)—(14c). For the discretization of continuum equation, the difference format suitable for physical sense of traffic flow[12,17] is applied:

$$k_i^{j+1} = k_i^j + \frac{\Delta t}{\Delta x} k_i^j (u_i^j - u_{i+1}^j) + \frac{\Delta t}{\Delta x} u_i^j (k_{i-1}^j - k_i^j). \quad (14a)$$

And for the dynamics equation, one-order upwind scheme is applied:

(i) when the traffic is heavy, $u_i^j < c_0$,

$$u_i^{j+1} = u_i^j + \frac{\Delta t}{\Delta x}(c_0 - u_i^j)(u_{i+1}^j - u_i^j) + \frac{\Delta t}{T}(u_e - u_i^j); \quad (14b)$$

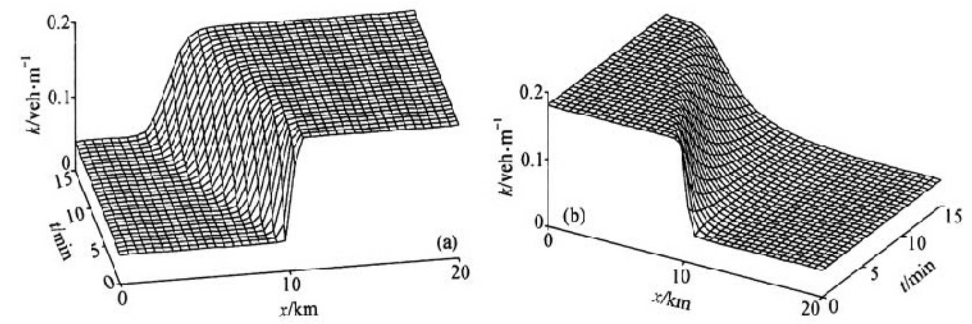

Fig. 2. The spatiotemporal evolution of density under different Riemann initial conditions. (a) For condition (i); (b) for condition (ii).

(ii) when the traffic is light, $u_i^j \geqslant c_0$,

$$u_i^{j+1} = u_i^j + \frac{\Delta t}{\Delta x}(c_0 - u_i^j)(u_i^j - u_{i-1}^j) + \frac{\Delta t}{T}(u_e - u_i^j). \tag{14c}$$

Next we will carry on numerical tests under two Riemann initial conditions to investigate traffic flow under congestion condition and when congestion getting evacuated, i.e. to evaluate whether the new model and its discretization can solve traffic flow conditions such as traffic shock and rarefaction wave well.

$$\text{(i)}\ k_u^1 = 0.04,\ k_d^1 = 0.18;$$

$$\text{(ii)}\ k_u^2 = 0.18,\ k_d^2 = 0.04, \tag{15a}$$

where k_u, k_d are densities of upstream and downstream respectively, subscripts 1, 2 denote two initial conditions. Initial speed conditions are

$$u_u^{1,2} = u_e(k_u^{1,2}),\ u_d^{1,2} = u_e(k_d^{1,2}). \tag{15b}$$

Free boundary condition are used, i.e. $\partial k / \partial x$ and $\partial u / \partial x$ are equal to zero on the boundary. The equilibrium speed-density relationship presented by Del Castillo et al.[5] is applied:

$$u_e = u_f\left[1 - \exp\left(1 - \exp\left(\frac{c_m}{u_f}\left(\frac{k_m}{k} - 1\right)\right)\right)\right], \tag{16}$$

where c_m is disturbance propagation speed under jam density. The tested road is 20 km, divided into 100 meshes equally, time step interval is determined by requirement of numerical stability. According to field measurement and parameter calibration in China1) and overseas[5], parameter value u_f = 30 m/s, k_m = 0.2 veh/m, T = 7 s, c_m = c_0 = 6 m/s. The results are shown in fig. 2.

From fig. 2, we can see that the new model provides qualitatively correct predictions under both Riemann initial conditions. For condition (i), traffic shock wave propagates backward. For condition (ii), there exists traffic rarefaction wave. These results are consistent with the traffic flow properties given in ref. [18]. Linear stability analysis and further numerical tests show that the new model can also describe traffic flow conditions such as stop-and-go wave, local breakdown effect quite well.

4 Conclusion

In these last few decades, with the rapid development of transportation, more and more attention has been paid on traffic flow research. In order to solve existing traffic problems, researchers put forward many kinds of traffic flow theory. Dynamics method is an important one in the field. However, there are this or that problem for this theory. This note first proposes an improved car-following model, which considers various behavior of the following car adequately, synthesizes the virtues of the existing theory. Then a new dynamics model of traffic flow is derived. This new model overcomes the ubiquitous characteristic speed problem in existing dynamics models. Physically, it is more suitable for realistic traffic. Numerical tests show that the model is able to simulate various traffic flow conditions quite satisfactorily.

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