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CO_2 emission control in new CM car-following model with feedback control of the optimal estimation of velocity difference under V2X environment*

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A new coupled map car-following model in this paper is proposed by considering the influence of the difference of the estimated optimal speed based on the coupled map (CM) car-following model under V2X environment. The stability of the new model is analyzed by applying the control theory, and the conditions are obtained for the stability of the traffic system. And the two scenes of vehicle stopping once and four times have been simulated. The simulation results show that the control term considered with optimal estimation of speed difference can effectively improve the stability of vehicle running and reduce CO_2 emissions in the CM car-following model.

Keywords: traffic flow, optimal velocity model, numerical simulation

PACS: 89.40.–a, 05.70.Fh **DOI:** 10.1088/1674-1056/ac1417

1. Introduction

With the rapid development of economy, the number of domestic vehicles is increasing year by year, which leads to more and more serious congestion in the traffic system. Traffic jams not only increase social costs, waste energy, but also aggravate environmental pollution.[1] The exhaust emission of urban traffic has become the biggest source of urban air pollution, which is more and more harmful to people's health and seriously affects the life of residents. Therefore, domestic and foreign scholars have done some researches in order to study the internal operation mechanism of transportation system. In 1961, Newell[2] presented a car-following model described by a differential equation of the first order. In 1995, Bando[3] built an optimized velocity model to simulate the phenomenon caused by traffic congestion on the actual road. After that, a few scholars[4–13] have proposed a series of improved models based on the modeling idea of optimal velocity model. Among these research results, coupled map (CM) car-following model plays an important role in studying traffic congestion control. It can not only reveal a variety of traffic phenomena, but also provide a concise algorithm for numerical simulation, which is suitable for describing complex traffic control problems. In 1999, Konishi *et al.*[4] studied the vehicle running control on single lane under open boundary conditions by using CM car-following model and setting the term of delayed feedback control, and proposed a scheme to curb traffic congestion. In 2004, Ge *et al.*[5] came up with an extended car following model by incorporating an intelligent transportation system in traffic. In 2006, Zhao and Gao[6] proposed a simpler and effective control method of traffic congestion. Their feedback control term is proportional to the relative speed between the front nearest neighbor vehicle and current vehicle, which substitutes a single feedback parameter for four parameters. Thus, the feedback gain was obtained by applying the stability theory and the strict mathematical analysis was carried out. It is found that traffic flux becomes bigger than before with the consideration of control term via numerical simulation, which has restrained traffic congestion control effectively. In 2007, Han *et al.*[7] came up with CM car-following model based on ITS application. In 2009, Shen *et al.*[8] put forward a control signal including the velocity differences of the two vehicles in front. Subsequently, Ge *et al.*[9,10] proposed a modified coupled map car-following model in which two successive vehicle headways in the optimal velocity function and velocity differences in front of the considering vehicle is incorporated. In 2015, Fang *et al.*[11] considered the velocity difference between two successive vehicles in the model. In 2016, Zheng *et al.*[12] put forward a new model by considering safe headway effect of the two preceding cars on the following one. In recent years, some scholars considered the effect of the electronic throttle dynamics. In 2020, Li *et al.*[13] considered the opening angle difference of electronic throttle and the delayed

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velocity difference.

With the development of 5G communication and intelligent transportation system, drivers can obtain a series of driving information to timely and effectively adjust the running state of vehicles under the V2X environment. With the application of V2X (vehicle to everything) technologies, including V2V (vehicle to vehicle), V2I (vehicle to infrastructure), V2N (vehicle to network), and V2P (vehicle to pedestrian), drivers can obtain massive traffic information and adjust their car-following behavior according to the information transmission via V2X technology. In 2013, Alsabaan *et al.*[14] explored the influence of V2V environment on vehicle energy consumption. In 2015, Li *et al.*[15] studied the influence of signal control on ecological driving of electric vehicles under V2X environment. In 2019, Peng *et al.*[16] put forward the delayed-feedback control method for car-following model with the combination of V2V communication. In 2021, Wang *et al.*[17] proposed a simulation framework based on the car-following model and the cellular automata under the V2X environment. Thus, the vehicles in the system can run collaboratively and traffic congestion was relieved under V2X environment. In the actual traffic environment, the effect of the optimal estimation of velocity difference is very important for vehicle operation. However, in the CM car-following model, the effect of the optimal estimation of velocity difference is rarely reported. In this paper, by considering the effect of the optimal estimation of velocity difference, we put forward a new congestion control model under V2X environment. Based on the modern control theory, we will carry out the stability analysis of control model and win the control method of the feedback gain parameters with cybernetics idea. Through numerical simulation with the aid of its own development software, we can realize to control the model validation, especially carbon dioxide emission control.

And this paper is mainly divided into the following parts: In Section 2, a new CM car-following model is presented. In Section 3, we get stability analysis of the new CM car-following model, and the value of the parameter k is also derived. In Section 4, we introduce the CO_2 emission estimation model. In Section 5, numerical simulation results will be carried out. Finally, conclusions are drawn in Section 6.

2. New CM car-following model

Figure 1 shows a schematic of the car-following model. Based on the CM car-following model, we propose a new CM car-following model with the consideration of the influence of the optimal estimation of velocity difference (called for OEVD-CM car-following model) under V2X environment as follows:

$$\begin{cases} v_i(n+1) = \alpha_i[v_i^{\rm op}(y_i(n)) - v_i(n)]T + v_i(n) + u_i(n), \\ y_i(n+1) = v_{i-1}(n)T - v_i(n)T + y_i(n), \end{cases} \tag{1}$$

where $v_i(n)$ and $y_i(n)$ denote the i-th vehicle speed and headway at time step n, respectively. T means the sampling time and α_i shows the i-th vehicle driver's sensitivity. There is deviation between the actual optimal speed and the estimated optimal speed, which affects the running state of following vehicles. We put forward $u_i(n)$ by considering the impact of this information transmission on the driver under V2X environment $u_i(n)$ and $v_i^{\rm op}(y_i(n))$ correspond to the control term and the optimal speed function, respectively.

$$u_i(n) = k[v_i^{\rm op}(\eta_i) - v_i^{\rm op}(y_i(n))], \tag{2}$$

$$v_i^{\rm op}(y_i(n)) = \frac{v_i^{\max}}{2}\left[1 + \overline{H_{\rm sat}}\left(2\frac{y_i(n)-\eta_i}{\zeta_i}\right)\right]. \tag{3}$$

Here $v_i^{\max}$ is the maximum speed, η_i is the neutral headway distance, ζ_i is the parameter, k is the feedback gain of traffic control system. $\overline{H_{\rm sat}}(\cdot)$ is described as

$$\overline{H_{\rm sat}}(p) = \begin{cases} 1, & (p > 1), \\ p, & (-1 \le p \le 1), \\ -1, & (p < -1). \end{cases} \tag{4}$$

To ensure that the team can stay in formation for a long time and avoid the collisions and backward motions, all the vehicles adopt the full-braking action

if $y_i(n) < y_i^{\min}$, then, $x_i(n+1) = x_i(n)v_i(n+1) = 0$.

The action implies that the vehicle stops suddenly when headway distance is less than the safety distance $y_i^{\min}$

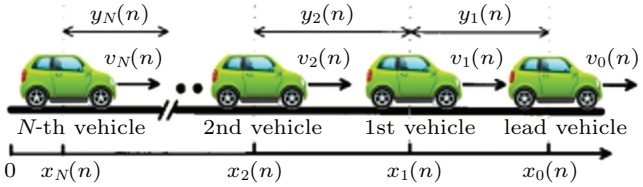


Fig. 1. The schematic diagram of the car-following model.

3. Stability analysis

In this section, the steady state of the system is assumed as

$$[v_i^*, d_i^*]^{\rm T} = \left[v_0, \frac{v_0}{r_i} - \frac{\zeta_i}{2} + \eta_i\right]^{\rm T}. \tag{5}$$

Around the steady state, the controlled system (1) can be described by

$$\begin{bmatrix} \delta v_i(n+1) \\ \delta y_i(n+1) \end{bmatrix} = \begin{bmatrix} 1-\alpha_i T & \alpha_i r_i T - k r_i \\ -T & 1 \end{bmatrix} \begin{pmatrix} \delta v_i(n) \\ \delta y_i(n) \end{pmatrix} + \begin{bmatrix} 0 \\ T \end{bmatrix} \delta v_{i-1}(n), \tag{6a}$$

$$\delta v_i(n) = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} \delta v_i(n) \\ \delta y_i(n) \end{pmatrix}, \tag{6b}$$

where $\delta v_i(n) = v_i(n) - v_i^*$ and $\delta y_i(n) = y_i(n) - y_i^*$. After z-transformation, the transfer function is obtained as

$$\overline{G_i}(z) = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} z-1+\alpha_i T & k r_i - \alpha_i r_i T \\ T & z-1 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ T \end{bmatrix}, \tag{7}$$

where $\overline{p_i}(z) = z^2 + \overline{a_i}z + b_i$, $\overline{a_i} = \alpha_i T - 2$, $\overline{b_i} = 1 - \alpha_i T + \alpha_i r_i T^2 - k r_i T$.

The lemma of stable operation of traffic system is given below.

Lemma 1 According to the system control theory, k satisfies the following equations and at the same time, formula (1) is in a stable state;

(i) $\overline{p_i}(z)$ is stable;

(ii) $\max\limits_{|z|=1} \left|\overline{G_i}(z)\right| < 1$ $(i = 1, 2, \ldots, N)$.

According to Lemma 1, the boundary stability theorem of traffic system (1) is given.

Theorem 1 When the feedback gain k meets the following five conditions, the traffic system (1) is in a stable state.

If $\alpha_i T < 1$, then, the feedback gain k is set as

$$\max\left\{\frac{\alpha_i^2 r_i T^2 - \alpha_i^2 T + 2\alpha_i r_i T}{\alpha_i r_i T + 2r_i}, \alpha_i T - \frac{\alpha_i}{r_i}\right\} < k < \alpha_i T. \quad (8)$$

If $1 < \alpha_i T < 2$, then, the feedback gain k is set as

$$\frac{\alpha_i r_i T^2 - \alpha T + 1}{r_i T_i} < k < \alpha_i T. \quad (9)$$

If $2 < \alpha_i T < 3$, then, the feedback gain k is set as

$$\frac{\alpha_i r_i T^2 - \alpha T + 1}{r_i T_i} < k < \frac{\alpha_i r_i T^2 - 2\alpha_i T + 4}{r_i T_i}. \quad (10)$$

If $\alpha_i T > 3$, $\alpha_i r_i T^2 - 2r_i T < 0$, then the feedback gain k is set as

$$\alpha_i T - \frac{\alpha_i}{r_i} < k < \frac{\alpha_i r_i T^2 - 2\alpha_i T + 4}{r_i T_i}. \quad (11)$$

According to the above conditions, congestion control of traffic system (1) is realized by setting feedback gain k

4. CO_2 emission estimation model

Road and traffic flow conditions will affect a car's CO_2 emission.[18] According to different road conditions, vehicles will produce different CO_2 emissions. Even if road conditions are good, traffic status has a great impact on a car's CO_2 emission, and traffic congestion will produce more CO_2. Oguchi[19] presented a formula to estimate vehicle CO_2 emissions as follows:

$$E = K_c(\beta_1 T + \beta_2 L + \beta_3 Acc), \quad (12)$$

$$Acc = \sum_k \delta_k (v_k^2 - v_{k-1}^2). \quad (13)$$

Here E is the total CO_2 emission (in unit kg), K_c is the emission coefficient between gasoline consumed and CO_2 emission, β_i $(i = 1, 2, 3)$ is the distance coefficients. δ_k is Heaviside function

$$\delta_k = \begin{cases} 1, & v_k > v_{k-1}, \\ 0, & v_k \le v_{k-1}. \end{cases} \quad (14)$$

This model is very suitable for our study to calculate a vehicle's CO_2 emission theoretically.

5. Simulation results

In order to verify that the theoretical derivation is correct, the new model is simulated numerically under open boundary conditions, and the initial value of parameters is set as $\eta_i = 25.0$ m, $\zeta_i = 23.3$ m, $v^{\max} = 33.6$ m/s, $v_0 = 20$ m/s, $T = 0.1$ s, $\alpha_i = 2.0\ \mathrm{s}^{-1}$, $y_i^{\min} = 7.02$ m, $r_i = v^{\max}/\zeta_i \approx 1.44\ \mathrm{s}^{-1}$, $\beta_1 = 0.3$, $\beta_2 = 0.028$, $\beta_3 = 0.056$.

The initial state of the team is adopted as follows:

$$x_i(0) = \sum_{j=i+1}^{N} y_j^*, \quad y_j(0) = y_j^*, \quad (15)$$

$$v_i(0) = v_i^*, \quad i = 1, 2, \ldots, N. \quad (16)$$

Simulation scenarios are set firstly: we assume that the first running vehicle stopped at 100 s for duration of 3 s to observe the state evolution of the entire fleet. According to the stability condition of the traffic system, the feedback gain range is determined by parameters for the OEVD-CM car-following model. From Theorem 1, we get the value range of the feedback gain being $0.0737 < k < 0.2$. Therefore, we adopt $k = 0.115$ in the following simulation.

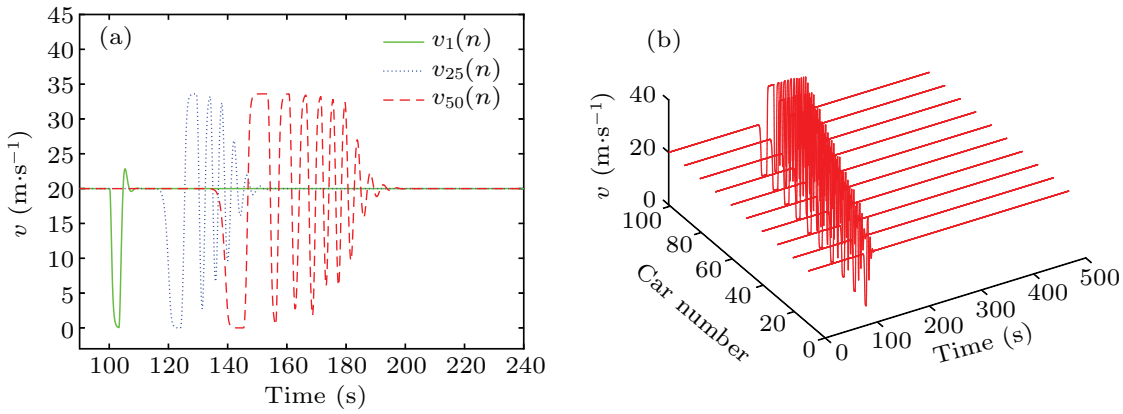


Fig. 2. The velocity distribution for CM car-following model as the leading vehicle stops suddenly for only time.

Firstly, the leading-vehicle stops suddenly for only time and the three vehicles are observed for the first, the 25-th, and the 50-th vehicles. Figures 2 and 3 show the temporal velocity behavior viewed from two and three dimensions, respectively. By comparison, it is clearly seen that the fluctuation of the speed of the OEVD-CM model is significantly reduced and the traffic flow runs more smoothly due to the addition of new feedback control.

Furthermore, figure 4 shows the space–time plot when the leading vehicle stops suddenly for only time. By comparison, it can be clearly seen that the oscillation amplitude is relatively flat between the head car and the following car head space due to the addition of feedback control term for the OEVD-CM car-following model, which implies the stability of the traffic system becomes better.

Moreover, the CO_2 emissions are viewed over time from two and three dimensions in Figs. 5 and 6, which implies that the OEVD-CM model is lower CO_2 emissions due to the addition of new feedback control.

Secondly, we observe the leading vehicle stopping suddenly for four times. Figures 7 and 8 respectively present the temporal velocity from two and three dimensions for the two vehicles including the first and the 100-th vehicles. By comparison, the fluctuation of the speed of the OEVD-CM model becomes smaller, which shows that the traffic flow runs more smoothly because of new feedback control term.

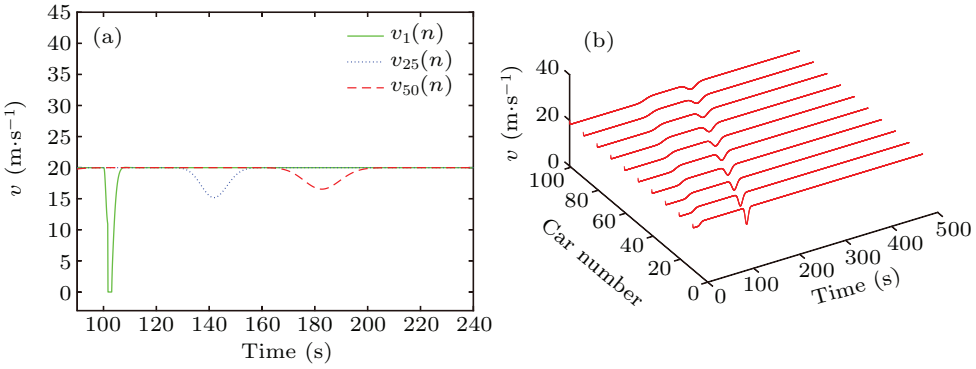


Fig. 3. The velocity distribution for OEVD-CM car-following model as the leading vehicle stops suddenly for only time.

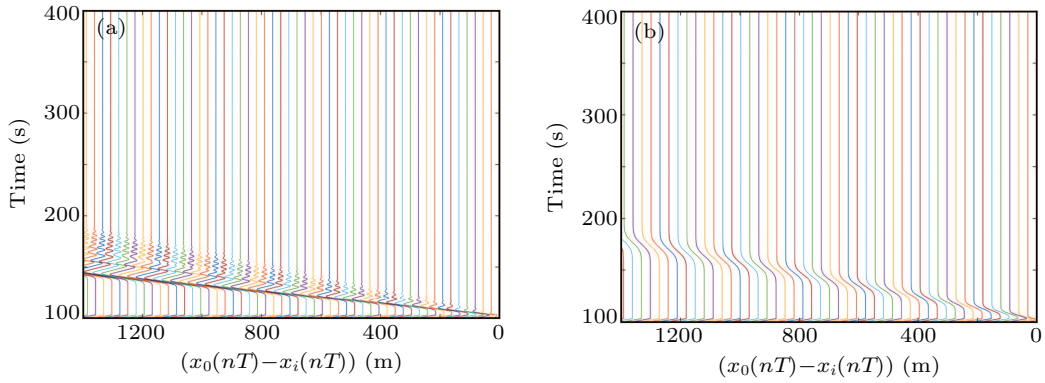


Fig. 4. Space–time diagram for CM car-following model and OEVD-CM car-following model as the leading vehicle stops suddenly for only time.

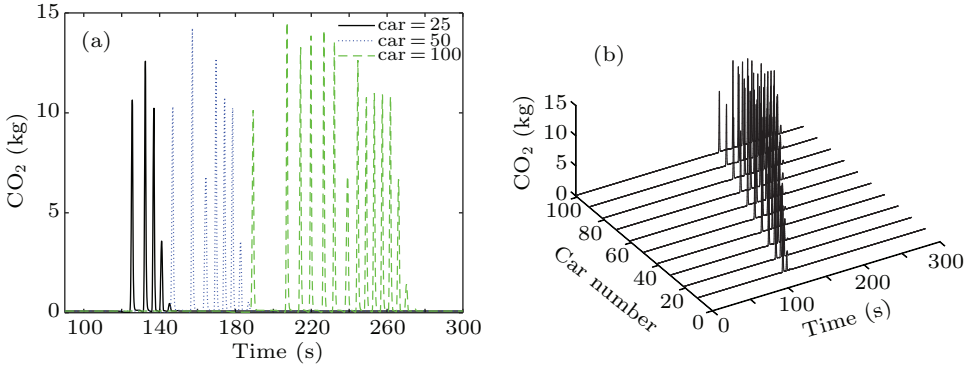


Fig. 5. CO_2 emission for CM car-following model as the leading vehicle stops suddenly for only time.

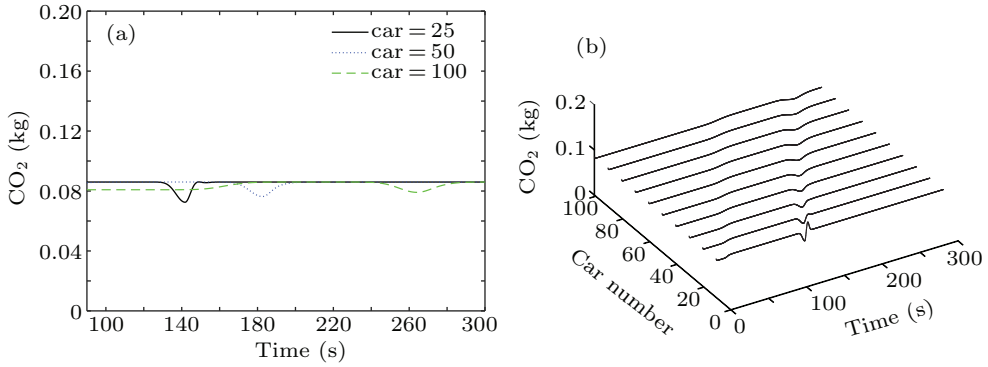


Fig. 6. CO_2 emission for OEVD-CM car-following model as the leading vehicle stops suddenly for only time.

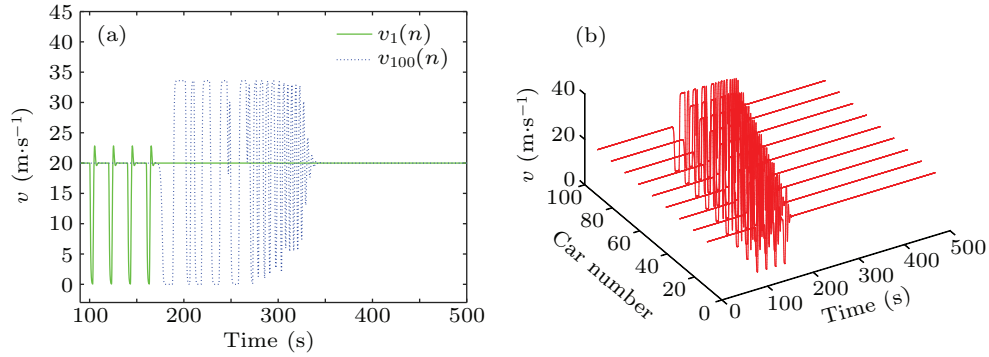


Fig. 7. The velocity distribution for CM car-following model as the leading vehicle stops suddenly for four times.

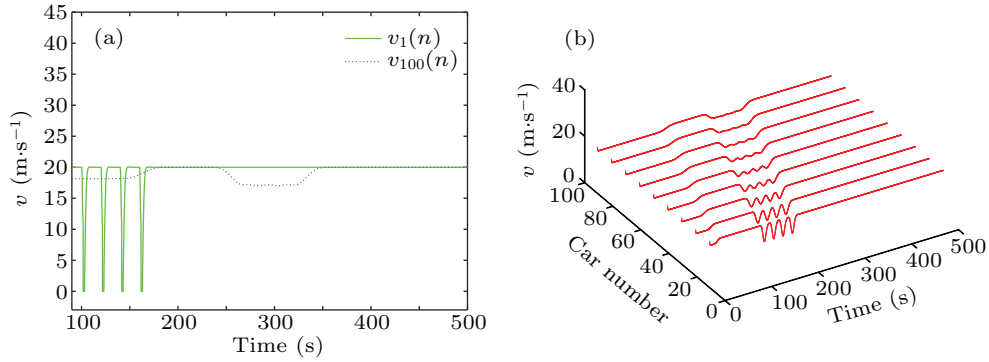


Fig. 8. The velocity distribution for OEVD-CM car-following model as the leading vehicle stops suddenly for four times.

Figure 9 indicates the space–time plot under the leading vehicle stopping suddenly for four times. From Fig. 9, It tells us that the oscillation amplitude of the headway space is relatively flat since the new feedback control term is considered, which indicates that the traffic stability becomes better with new feedback control.

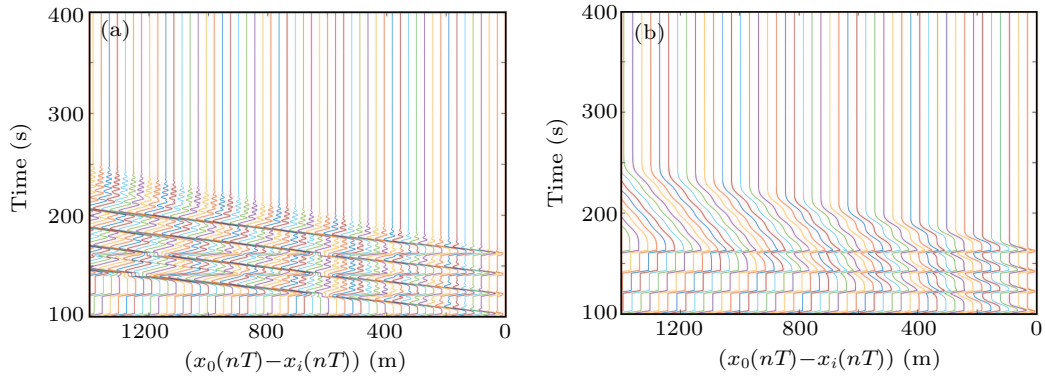


Fig. 9. Space–time diagram for CM car-following model and OEVD-CM car-following model as the leading vehicle stops suddenly for four times.

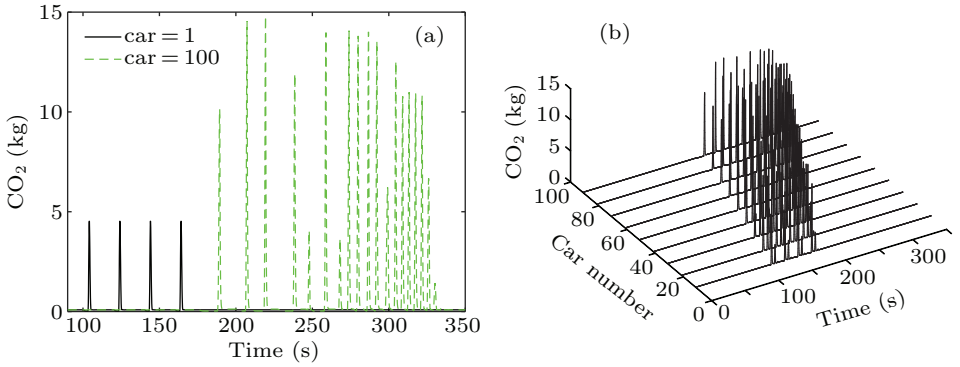


Fig. 10. CO_2 emission for CM car-following model as the leading vehicle stops suddenly for four times.

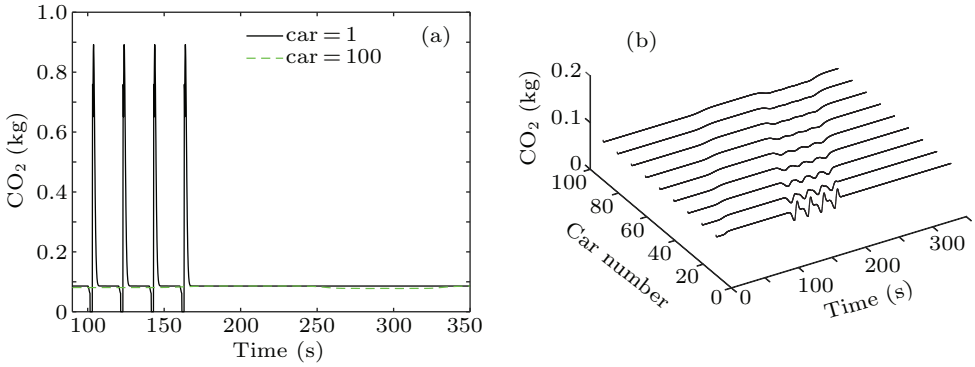


Fig. 11. CO_2 emission for OEVD-CM car-following model as the leading vehicle stops suddenly for four times.

Figures 10 and 11 represent the CO_2 emissions over time from two and three dimensions, respectively. Obviously, the lower CO_2 emission is observed by considering the new feedback control from Figs. 10 and 11.

6. Conclusion

Based on the CM car-following model, a new coupled map car-following model is proposed by considering the influence of the estimated optimal speed difference on the traffic flow under the V2X environment. At the same time, on the basis of the OEVD-CM car-following model with new feedback control, the stability condition of the traffic system is analyzed by applying the system control theory, and the critical conditions to maintain stability are obtained for the traffic system. The results from stable condition and CO_2 emissions mean that the OEVD-CM car-following model can make the traffic system more cooperative, more anti-interference, and less environmental pollution.

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