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Impact of the Self-Interruption Probability Involving the Anticipation Optimal Velocity on Traffic Stability for Car-Following Theory Under V2X Environment

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ABSTRACT Traffic interruption is very easy to cause traffic congestion. For the problem of traffic interruption, a novel car-following model in this paper is presented to correct the effect of traffic self-interruption probability with the combination of the anticipation information communication under V2X environment. The stability condition concerning the self-interruption probability correction is acquired via linear analysis. The mKdV equation involving the self-interruption probability correction is deduced from nonlinear analysis. Moreover, numerical simulation demonstrates that the self-interruption probability correction can effectively relieve traffic jam, which agrees with analytical results.

INDEX TERMS Optimal velocity model, numerical simulation, self-interruption probability.

I. INTRODUCTION

There are many factors affecting traffic behaviors with the rapid growth of the number of vehicles, which may cause traffic congestions. With the rapid increase of traffic flux, traffic accidents randomly occur more frequently though they are very disgusting. To investigate the impact of traffic accidents, some scholars [1]–[5] have proposed several traffic models resulted from the traffic interruption. Moreover, a novel macroscopic continuum model [6] and a novel car-following model [7] have been presented by taking into account the traffic interruption probability of leading vehicle's velocity. Furthermore, a two-lane macroscopic continuum model [8] was developed to observe the traffic jams caused by the traffic interruption probability factor besides lane changing behaviors. Different from the interruption probability of leading car's speed in [6]–[8], Peng *et al.* [9] established a novel type of lattice model by considering the traffic interruption probability of traffic flux. Recently, based on the expansion of the Newell's car-following model [10], Bando *et al.* [11] proposed an optimal velocity (OV) model to adjust vehicle's acceleration. Subsequently, considerable car-following models [12]–[32] have been constructed by considering different traffic information on the basis of the OV model, which shows that OV model has a high advantage in analyzing traffic flow. However, previous car-following models did not consider the self-interruption probability involving the compensation algorithm of the anticipation optimal velocity. With the development of V2X(Vehicle to X) technology, traffic interruption information can be acquired by drivers. Therefore, the self-interruption probability involving the anticipation effect can be collected by applying V2X technology. In real traffic situation, to avoid traffic accidents, the drivers will adjust running speed by estimating their optimal speed when the traffic interruption occurs. Therefore, based on this consideration point of view, we in this paper propose a novel optimal velocity model with the consideration of the self-interruption probability of current vehicle's velocity on

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traffic stability involving the anticipation optimal velocity. Subsequently, the theoretic analyses and numerical simulations will be executed to explore the impact of traffic self-interruption probability with anticipation optimal velocity on traffic stability, which will demonstrate that it is necessary and meaningful to reveal the factors of traffic interruption in our consideration.

II. MODELING

The OV model proposed by Newell [10] was described as below:

$$\frac{dv_n(t)}{dt} = a[V(\Delta x_n(t)) - v_n(t)] \tag{1}$$

Here x_n(t), v_n(t) and a respectively indicate the position, velocity of car n at time t and the sensitivity of a driver; $\Delta x_n = x_{n+1} - x_n$ denotes the headway; $V(\Delta x_n(t))$ represents the optimal velocity function as

$$V(\Delta x_n(t)) = 0.5v_{\max} \tanh[\Delta x_n(t) - h_c] \tag{2}$$

where $v_{\max}$ and h_c respectively express the maximum velocity and the safe distance. When the self-interruption problem of current vehicle's velocity occurs, it will stimulate the driver's anticipation of optimal velocity. Consequently, a novel optimal velocity model is established with the self-interruption probability involving the anticipation optimal velocity as below:

$$\begin{aligned}\frac{dv_n(t)}{dt} = a[V(\Delta x_n(t)) - v_n(t)](1-p_n)\\ + aV(\Delta x_n(t+\vartheta\tau)p_n\end{aligned} \tag{3}$$

where p_n means the traffic interruption probability of current vehicle's velocity. For simplicity, the traffic interruption probability p_n is assumed as a constant, i.e.. $p_n = p$. ϑ is the response coefficient for driver's anticipation ability and the delay time $\tau = 1/a$. Moreover, by series expansion and ignoring higher order terms for $\Delta x_n(t+\vartheta\tau) = \Delta x_n(t) + \vartheta\tau\Delta v_n(t)$ and $V(\Delta x_n(t+\vartheta\tau)) = V(\Delta x_n(t)) + \vartheta\tau V'\Delta v_n(t)$, we deduce the following equation:

$$\begin{aligned}\frac{dv_n(t)}{dt} = a[V(\Delta x_n(t)) - v_n(t)]\\ + apv_n(t) + \vartheta pV'\Delta v_n(t)\end{aligned} \tag{4}$$

Here $V' = dV(\Delta x)/d\Delta x$. Henceforth, by discretizing Eq. (4), we get the difference form as below:

$$\begin{aligned}\Delta x_n(t+2\tau) = {} & \Delta x_n(t+\tau) + \tau[V(\Delta x_{n+1}(t))\\ & -V(\Delta x_n(t))] + p[\Delta x_n(t+\tau) - \Delta x_n(t)]\\ & +\tau p\vartheta V'[\Delta x_{n+1}(t+\tau) - \Delta x_{n+1}(t)\\ & -\Delta x_n(t+\tau) + \Delta x_n(t)]\end{aligned} \tag{5}$$

III. LINEAR STABILITY ANALYSIS

We chose the optimal velocity $V(b)$ corresponding to constant headway b for the uniform steady state. Hence, the position for the uniformly steady state can be displayed as below:

$$x_{n,0}(t) = hn + V(b), b = L/N \tag{6}$$

Here N and L show respectively the number of cars and the length of the road. Suppose a small deviation $y_n(t)$ for the uniform solution $x_{n,0}(t)$: $x_n(t) = x_{n,0}(t) + y_n(t)$. Then Eq. (5) can be rewritten for $y_n(t)$ with linearization as below:

$$\begin{aligned}\Delta y_n(t+2\tau) = {} & \Delta y_n(t+\tau) + \tau V'(b)[\Delta y_{n+1}(t)\\ & -\Delta y_n(t))] + p[\Delta y_n(t+\tau)) - \Delta y_n(t))]\\ & +\tau p\vartheta V'[\Delta y_{n+1}(t+\tau) - \Delta y_{n+1}(t)\\ & -\Delta y_n(t+\tau) + \Delta y_n(t)]\end{aligned} \tag{7}$$

where $V'(b) = dV(\Delta x)|_{\Delta x=b}$. By expanding $\Delta y_n(t) = A\exp(ikn + zt)$, we win

$$\begin{aligned}e^{2z\tau} - e^{z\tau} - \tau V'(e^{ik} - 1) - p(e^{z\tau} - 1)\\ - \tau p\vartheta V'(e^{ik} - 1)(e^{z\tau} - 1) = 0\end{aligned} \tag{8}$$

Making $z = z_1(ik) + z_2(ik)^2 + \cdots$ and neglecting the greater terms than two, we gains:

$$\begin{aligned}z_1 &= V'(b)/(1-p),\\ z_2 &= \frac{1}{2(1-p)}[V'(b) - 3\tau z_1^2\\ &\quad -p\tau z_1^2 + 2\tau\vartheta pV'(b)z_1]\end{aligned} \tag{9}$$

Accordingly, traffic flow falls into unstable state for $z_2 < 0$ and remains stable as $z_2 > 0$ by contrary. Correspondingly, the neutral stability condition is inferred as below:

$$\tau = \frac{(1-p)^2}{(3-p-2\vartheta p)V'(b)} \tag{10}$$

Consequently, the linear stable condition is derived naturally for the uniform traffic flow as below:

$$\tau < \frac{(1-p)^2}{(3-p-2\vartheta p)V'(b)} \tag{11}$$

Obviously, both the self-interruption probability p and the response coefficient ϑ play a considerable role on traffic stability. Spontaneously, the neutral stability lines can be described for different p and ϑ as shown in Fig. 1 (solid line). In view of Fig. 1(a), the stable region becomes gradually smaller with the self-interruption probability p increasing at $\vartheta = 0$ (no anticipation in optimal velocity), which shows that the self-interruption probability of current vehicle's velocity deteriorates the stability of traffic flow. However, the stable region expands wider and wider in the opposite direction with the increase of the response coefficient ϑ for the anticipation in optimal velocity when the self-interruption probability of current vehicle's velocity happens from Fig. 1(b). The result shows that we can eliminate the negative impact of self-interruption probability of current vehicle's velocity by providing a modified compensation method of anticipation in optimal velocity under V2X environment.

IV. NONLINEAR ANALYSIS

In this section, the nonlinear analysis is executed to achieve the mKdV equation. Firstly, the slow variables X and T are

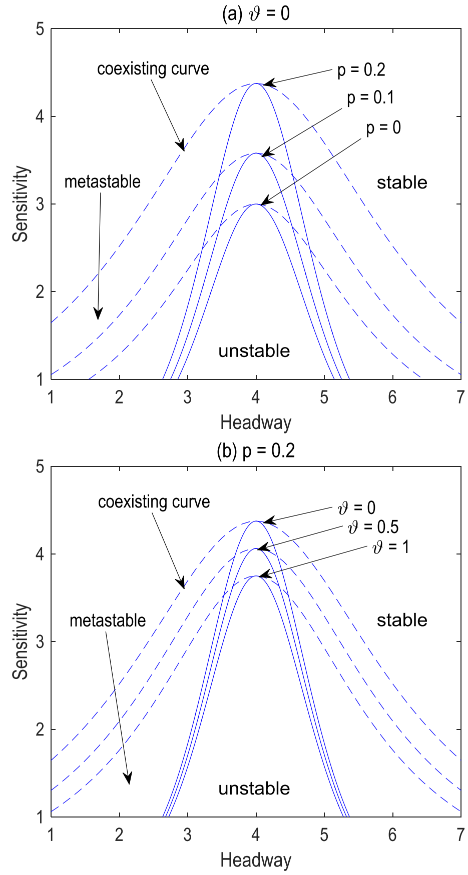

FIGURE 1. Phase diagram in parameter space (b; a).

assumed with space variable n and time variable t for a small positive scaling parameter ε as follows:

$$X = \varepsilon(n + bt) \text{ and } T = \varepsilon^3 t, \tag{12}$$

Here b is a constant. And the headway is adopted as below

$$\Delta x_n(t) = h_c + \varepsilon R(X, T) \tag{13}$$

Subsequently, by expanding Eq. (5) to the fifth order of ε, one gets:

$$\begin{aligned}&\varepsilon^2 m_1 \partial_X R + \varepsilon^3 m_2 \partial_X^2 R\\ &\quad + \varepsilon^4(\partial_T R + m_3 \partial_X^3 R + m_4 \partial_X R^3)\\ &\quad + \varepsilon^5(m_5 \partial_T \partial_X R + m_6 \partial_X^4 R + m_7 \partial_X^2 R^3) = 0\end{aligned} \tag{14}$$

$$m_1 = b - V'/(1-p) \tag{15a}$$

$$m_2 = \frac{(3-p)b^2\tau - V' - 2\tau\vartheta p V'}{2(1-p)} \tag{15b}$$

$$m_3 = \frac{(7-p)b^3\tau^2 - V' - 3\tau\vartheta p V' b(b\tau+1)}{6(1-p)} \tag{15c}$$

$$m_4 = -\frac{V'''}{6(1-p)}, m_5 = \frac{(3-p)b\tau - \tau\vartheta p V'}{1-p} \tag{15d}$$

$$m_6 = \frac{(15-p)b^4\tau^3 - V' - 2\tau\vartheta p V' b(2b^2\tau^2 + 3b\tau + 2)}{24(1-p)} \tag{15e}$$

$$m_7 = -\frac{V'''}{12(1-p)} \tag{15f}$$

where $V' = dV(\Delta x)/d\Delta x|_{\Delta x = h_c}$, $V''' = d^3V(\Delta x)/d\Delta x^3 |_{\Delta x = h_c}$. Near the critical point (a_c, h_c), make $a_c/a = 1 + \varepsilon^2$ and $b = V'/(1-p)$. Then we can eliminate the second- and third-order terms of ε in Eq. (15a) to obtain:

$$\begin{aligned}&\varepsilon^4[\partial_T R - g_1 V' \partial_X^3 R + g_2 \partial_X R^3]\\ &\qquad + \varepsilon^5[g_3 \partial_X^2 R - g_4 \partial_X^4 R + g_5 \partial_X^2 R^3] = 0\end{aligned} \tag{16}$$

where

$$g_1 = -\frac{(7-p)b^3\tau_c^2 - V' - 3\tau_c\vartheta p V' b(b\tau_c+1)}{6(1-p)} \tag{17a}$$

$$g_2 = -\frac{V'''}{6(1-p)}; g_3 = \frac{V' + 2\tau_c\vartheta p V' b}{2(1-p)} \tag{17b}$$

$$\begin{aligned}g_4 = &\frac{(15-p)b^4\tau_c^3 - V'}{24(1-p)}\\ &- \frac{2\tau_c\vartheta p V' b(2b^2\tau_c^2 + 3b\tau_c + 2)}{24(1-p)}\\ &- \frac{[(3-p)b\tau_c - \tau_c\vartheta p V']}{6(1-p)^2}\\ &\frac{[(7-p)b^3\tau_c^2 - V' - 3\tau_c\vartheta p V' b(b\tau_c+1)]}{6(1-p)^2}\end{aligned} \tag{17c}$$

$$g_5 = \frac{2[(3-p)b\tau_c - \tau_c\vartheta p V']V''' - V'''}{12(1-p)} \tag{17d}$$

Furthermore, a transformation for Eq.(16) is chosen as follows:

$$T' = g_1 V' T, R = \sqrt{\frac{g_1}{g_2}} R' \tag{18}$$

As a result, the mKdV equation can be derived with correction terms $O(\varepsilon)$ as below:

$$\partial_T R' - \partial_X^3 R' + \partial_X R'^3 + \varepsilon M[R'] = 0 \tag{19}$$

Here

$$M[R'] = \sqrt{\frac{1}{g_1}} \left[g_3\ \partial_X^2 R' + \frac{g_1 g_4}{g_2} \partial_X^2 R'^3 + g_4 \partial_X^4 R'\right] \tag{20}$$

By ignoring the term $O(\varepsilon)$, the kink-antikink soliton solution is educed for the standard mKdV equation as below:

$$R_0'(X, T') = \sqrt{c} \tanh \sqrt{c/2}(X - cT') \tag{21}$$

where c means the propagation velocity of wave. To determine the propagation velocity, solvability conditions need to be satisfied as below:

$$(R_0', M[R_0']) = \int_{-\infty}^{+\infty} dX R_0'(X, T') M[R_0'(X, T')] = 0 \tag{22}$$

where $M[R_0'] = M[R']$. By integrating Eq. (20), the solution of propagation velocity is obtained:

$$c = \frac{5g_2 g_3}{2g_2 g_4 - 3g_1 g_5} \tag{23}$$

Thereby, the kink-antikink soliton solution is obtained for the mKdV equation as below:

$$R(X, T) = \sqrt{\frac{g_1 c}{g_2}\left(\frac{a_c}{a} - 1\right)} \times \tanh \sqrt{c/2}(X - c g_1 T) \tag{24}$$

Therefore, we gain the general kink-antikink soliton solution of the headway as below:

$$\Delta x_j(t) = h_c + \sqrt{\frac{g_1 c}{g_2}(\frac{\tau}{\tau_c} - 1)} \tanh \sqrt{\frac{c}{2}(\frac{\tau}{\tau_c} - 1)} \times \left[j + (1 - g_1 c V'(\frac{\tau}{\tau_c} - 1))t \right] \quad (25)$$

The amplitude A of the kink–antikink soliton solution can be written as below:

$$A = \sqrt{\frac{g_1 c}{g_2}(\frac{\tau}{\tau_c} - 1)} \quad (26)$$

So we can draw the coexisting curves according to $\Delta x = h_c \pm A$ as shown in Fig. 1 (dashed curves), which shows that the phase space is divided into three regions involving stable, metastable and unstable domains. It can be seen from Fig. 1(b) that the coexisting line and the neutral stability lines are increasing with the increase of the self-interruption probability of current vehicle's velocity at $\vartheta = 0$ (no anticipation in optimal velocity), which indicates that the traffic self-interruption probability of current vehicle's velocity deteriorates the traffic stability. However, the coexisting lines and the neutral stability lines fall down with the increase of anticipation coefficient ϑ in optimal velocity under the same self-interruption probability p, which implies that the anticipation coefficient ϑ in optimal velocity can improves the traffic stability to offset the negative impact of the self-interruption probability of current vehicle's velocity.

V. NUMERICAL SIMULATION

Periodic boundary conditions are adopted for numerical simulation. The parameters are chosen: $h_c = 4\text{m}$, $v_{\max} = 2\text{m/s}$, $a = 2.96\text{s}^{-1}$, the total cars $N = 100$. And the initial disturbance is considered as follows:

$$\begin{cases} \Delta x_n(0) = \Delta x_n(1) = 4, n \neq N/2, n = N/2 + 1 \\ \Delta x_n(0) = \Delta x_n(1) = 4 - 0.1, n \neq N/2 \\ \Delta x_n(0) = \Delta x_n(1) = 4 + 0.1, n = N/2 + 1 \end{cases} \quad (27)$$

Fig. 2 respectively delivers the headway evolution after 10^4 time steps for different self-interruption probability p at $\vartheta = 0$. Fig. 3 respectively shows the headway profiles corresponding to Fig. 2 at $t = 10,300$. In view of Fig. 2 and Fig. 3, the kink–antikink soliton solution occurs and traffic waves propagate backward under a small perturbation since the stability condition Eq. (11) is broken. Unfortunately, with the increase of the self-interruption probability under no consideration of anticipation effect in optimal velocity, the traffic fluctuation becomes greater from Fig. 2 and Fig. 3. That is to say, the self-interruption probability of current vehicle's velocity is a negative factor affecting traffic stability.

To overcome the defect of the self-interruption probability factor, we propose a new correction method by introducing the anticipation effect in optimal velocity. Fig. 4 respectively expresses the headway evolution after 10^4 time steps for different anticipation coefficient ϑ when the self-interruption probability $p = 0.3$. Fig. 5 respectively represents the headway profiles corresponding to Fig. 4 at $t = 10,300$. Brightly seen in Fig. 4 and Fig. 5, it's worth celebrating that a positive effect was found by considering the anticipation effect in optimal velocity under the self-interruption occur-

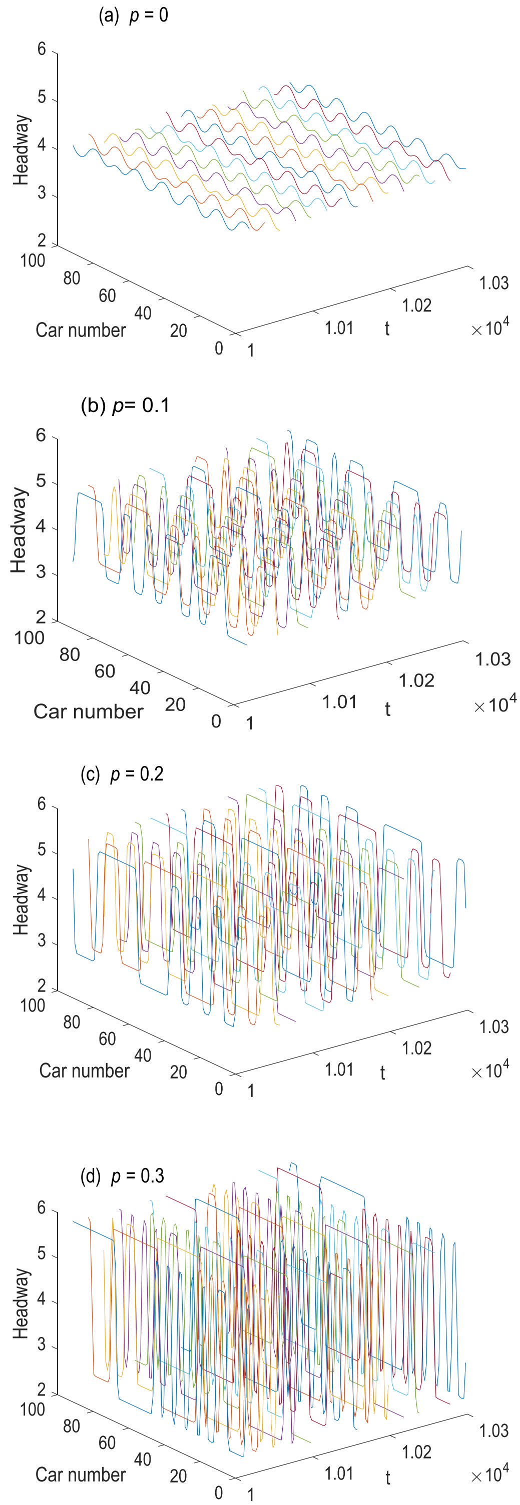

FIGURE 2. **The spatiotemporal evolution of headway for different self-interruption probability of current vehicle's velocity without the anticipation effect.**

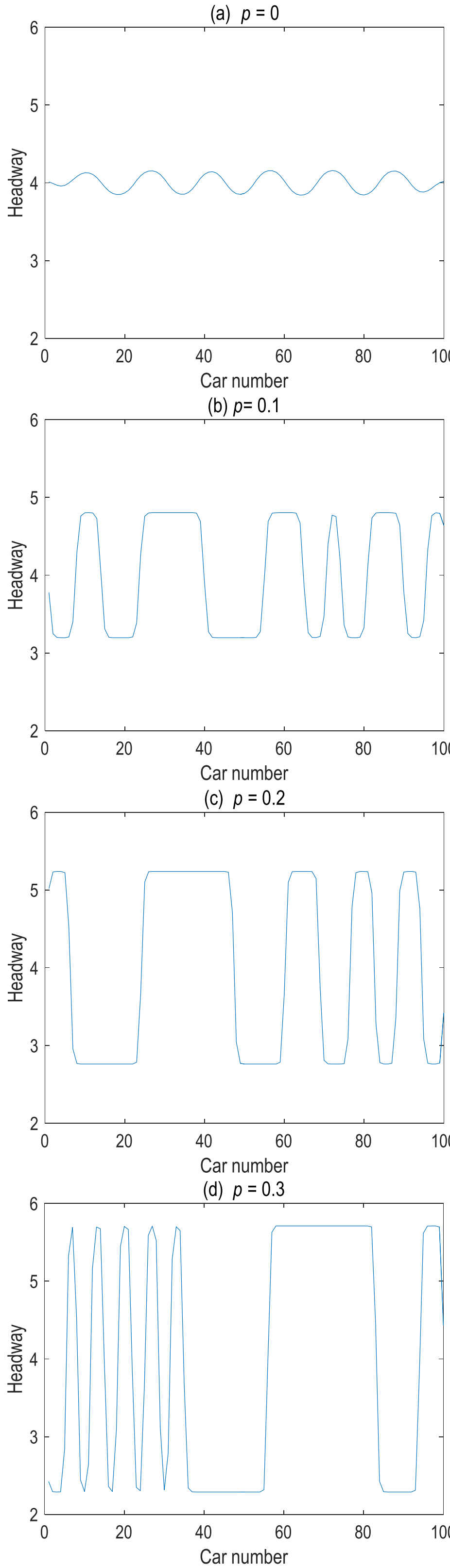

FIGURE 3. **Profile of headway at time step 10300 corresponding to Fig. 2.**

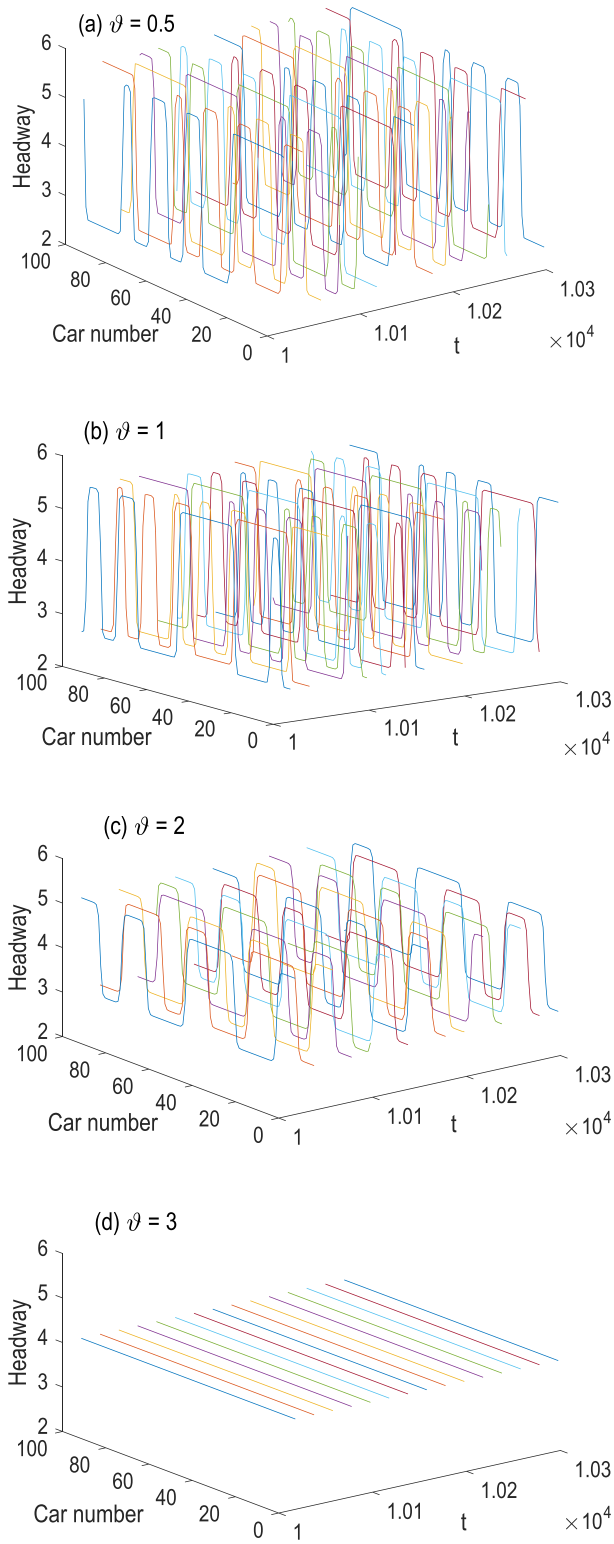

FIGURE 4. **The spatiotemporal evolution of headway for different anticipation coefficient ϑ at $p = 0.3$.**

ring. On the basis of Fig. 4 and Fig. 5, what's more interesting, the headway fluctuation shrinks gradually with the anticipation coefficient ϑ increasing else if the self-interruption probability destroys the stability of the traffic flow. Finally, according to Fig. 5(d), traffic flow entirely enters into the stable state when $\vartheta = 3$ at $p = 0.3$ because of the stability condition Eq. (11) being satisfied. It is conclusion

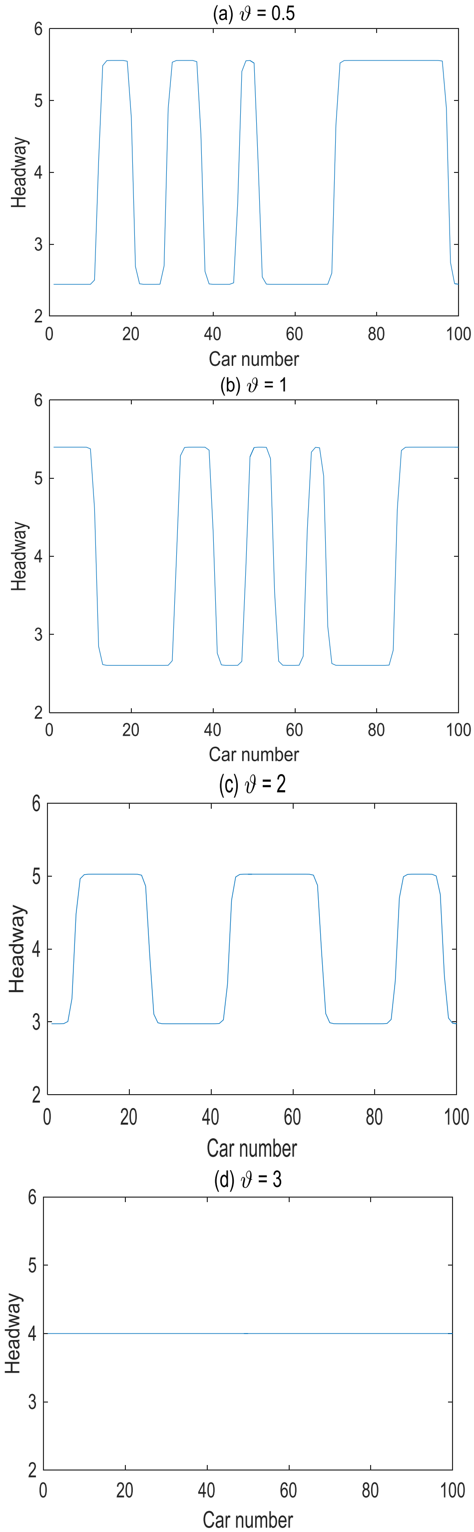

FIGURE 5. **Profile of headway at time step 10300 corresponding to Fig. 4.**

that the anticipation effect in optimal velocity can eliminate the negative impact resulted from the self-interruption probability of current vehicle's velocity. It is adequately certificated that the traffic stability is efficiently enhanced by considering the anticipation effect in optimal velocity when the self-interruption probability of current vehicle's velocity happens.

VI. CONCLUSION

A novel car-following model is constructed by considering the anticipation effect in optimal velocity to overcome the negative effect resulted from the self-interruption probability of current vehicle's velocity under V2X environment. The linear stable condition and the mKdV equation have been deduced via linear stability analysis and nonlinear analysis. Numerical simulation affirms that the self-interruption probability of current vehicle's velocity is easy to destroy the traffic stability. But the negative impact of traffic self-interruption can be effectively eliminated by the correction algorithm of the anticipation effect in optimal velocity in our new model. Therefore, although traffic self-interruption is one of the important factors causing traffic congestion, we can make up for the adverse effects caused by traffic self-interruption through certain compensation methods under V2X environment.

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