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Citation: Chin. Phys. B, 2023, 32 (**7**): 078801. DOI: 10.1088/1674-1056/acb0bc
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Stability of connected and automated vehicles platoon considering communications failures

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(Received 10 October 2022; revised manuscript received 6 December 2022; accepted manuscript online 6 January 2023)

As a form of a future traffic system, a connected and automated vehicle (CAV) platoon is a typical nonlinear physical system. CAVs can communicate with each other and exchange information. However, communication failures can change the platoon system status. To characterize this change, a dynamic topology-based car-following model and its generalized form are proposed in this work. Then, a stability analysis method is explored. Finally, taking the dynamic cooperative intelligent driver model (DC-IDM) for example, a series of numerical simulations is conducted to analyze the platoon stability in different communication topology scenarios. The results show that the communication failures reduce the stability, but information from vehicles that are farther ahead and the use of a larger desired time headway can improve stability. Moreover, the critical ratio of communication failures required to ensure stability for different driving parameters is studied in this work.

Keywords: connected and automated vehicle, car-following model, communication failures, string stability

PACS: 88.85.–r, 89.40.–a **DOI:** 10.1088/1674-1056/acb0bc

1. Introduction

The road traffic system is a complex nonlinear physical system, and numerous researchers have focused on how to model vehicle following behavior. Connected and automated vehicles (CAVs) are widely considered to be the future of vehicle development.[1] As the highest level of intelligent vehicles defined by the Society of Automotive Engineers (SAE) International, they are capable of fully autonomously driving based on sensors and communication.[2] They have vehicle-vehicle and vehicle-road communication capabilities, which makes them different from ordinary automated vehicles (AVs). They can obtain information about vehicles farther ahead and therefore achieve closer following and rapidly respond as needed. These characteristics make it possible to significantly improve traffic conditions and reduce energy consumption.[3–8]

Ideal vehicle-to-vehicle (V2V) communication is the basis for ensuring the advantages of CAV platoons in all aspects. However, communication is generally established with dedicated short-range communication (DSRC).[9] Owing to the high mobility of vehicles, this type of connection has a high probability of packet loss or even complete interruption.[10–14] As a result, vehicle–vehicle communication may fail in environments such as tunnels or extreme weather. Malicious network attacks can also cause CAV communication failures. Any of these random circumstances can cause CAVs to lose their functionality.

Once the communication capabilities of one or more vehicles in a platoon are lost, the communication topology of the platoon changes. Most of studies have focused on a certain communication topology to model the CAV following state, but this setup is not easily applied to the communication failure scenario.[15–20] A new carfollowing model that can describe both the normal state of communication and the communication failure state is needed.[12] In particular, the model must have a clear physical meaning.

In addition, the influence of communication failures on stability should be analyzed in detail to identify the optimal CAV control parameters under different communication environments.[21] The results of such a study are needed to design a controller with communication robustness.

Therefore, the goal of this study is to develop a unified model that can describe the following state of each vehicle within a CAV platoon. Such a model can be applied to dynamic communication topologies, especially in a scenario of partial communication failures among the platoon vehicles. Based on this model, string stability analysis can be performed to quantify the influence of communication failures. The contributions of this study are as follows.

(i) We propose a general CAV model based on dynamic communication topologies. A revised intelligent driver model (IDM) can be built and used to describe the vehicle-following states of a platoon for both normal and failed communications. The weights of the information obtained from other vehicles are dynamically updated. The model is called the DC-IDM.

(ii) We analyze the changes in the communication topologies after communication failures in a platoon. The possi-

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ble types of communication topologies are explored, and their probabilities are analyzed.

(iii) The effects of different communication failure scenarios on the stability of a platoon are analyzed by using theoretical study and numerical experiments. The conditions for the stability of a platoon and the probabilities of critical communication failures are obtained.

The remainder of this paper is organized as follows. In Section 2 previous studies are summarized. In Section 3 a general description of the dynamic communication topology following model is provided and the DC-IDM is presented. In Section 4 a theoretical analysis of the stability of platoons with dynamic communications topologies is conducted. In Section 5, a numerical experiment is performed to analyze the stability variations in different scenarios. In Section 6 some conclusions are drawn from the present study.

2. Literature review

In the field of car following models, numerous models that simulate CAV designs have been developed. Typical models can be classified into two categories, *i.e.*, physical models and control models. First, in the physical models, researchers have transformed human-driven vehicle models into CAV models by adjusting their parameter values and adding new parameters that simulate data from multiple preceding vehicles.[22] For example, several improved models are based on the IDM and optimal velocity (OV) model.[23–29] Second, in the control models, such as various cooperative adaptive cruise control (CACC) models, they have been developed by using control theory.[10,30,31] Yu *et al.* comprehensively reviewed these models.[1] In this study, we use a physical model for analysis, as it is more generalizable. Based on these models, researchers have concluded that CAVs can effectively improve the efficiency and flow stability of traffic.

Considering the characteristics of CAV platoons, the communication topology, which describes the V2V connection between CAVs in a platoon, is a key element for modeling. Typical communication topologies include predecessor following (PF), leader predecessor following (LPF), and multi-predecessor following (MPF).[32] Researchers have conducted CAV-related studies of different communication topologies. For example, in Ref. [33], the PF topology degraded the performance of CAVs after a communications interruption. A different model was used to represent the vehicle-following state after degradation. Halder *et al.* proposed a control method for which the performance does not degrade when CAVs cannot communicate with preceding vehicles.[11] A general consensus among researchers about which communication topology should be used for CAVs is lacking. However, the inclusion of multiple preceding vehicles is generally assumed to effectively mitigate disturbances in a platoon. Dunn *et al.*[34] and Davis[35] concluded that communication with multiple preceding vehicles can effectively eliminate platoon perturbations, even with communication delays. Zheng *et al.* analyzed the influences of different communication topologies on platoon stability.[32]

Platoon stability research has focused on mixed platoons, including human-driven vehicles (HVs), AVs, and CAVs.[36–38] The analyses in such studies are almost always based on a certain communication topology. However, communication failures occurring in a platoon change the communication topology. Liu *et al.*[39] found that the communication failures in the MPF configuration cause more complex changes in the communication topology. Related studies based on changes in the communication topology have begun and received the attention of researchers.[40] Wang *et al.*[41] used model prediction control (MPC) to ensure the stability of CAVs subjected to communication topology changes. Zhai and Wu developed a self-delayed feedback controller that determines acceleration values based on the current and historical speed and headway of a vehicle, independent of the reception of information from the vehicle ahead.[42] Li *et al.*[43] proposed a distributed model predictive control (DMPC) method for multivehicle system control under changes in the communication topology. Sun *et al.*[21] determined how many vehicles are needed to establish communication connections based on the actual state of communications. Given the limitations of the communication distance among CAVs, Zhou *et al.*[7] studied the possible degradation of platoons and analyzed variations in the macroscopic traffic flow efficiency. Few studies on stability analysis considering communication failures have transformed the problem into a heterogeneous platoon;[44] in general, communication failures are assumed to lead the degradation to be controlled, and PF is used.

Based on the analysis of previous studies, two problems remain to be solved, *i.e.*, car-following modeling cannot adapt to dynamic communication topologies, and platoon stability analysis under a communication failure is simplified into heterogeneous traffic flow analysis. The few studies that have addressed platoon communication topology change scenarios have mostly adopted a control point of view.[16]

Therefore, in this study, a unified dynamic communication topology-based car-following model is built, which can describe the following state of all vehicles after communication failures occur. Stability analysis is conducted based on the unified model to reveal the influence of communication failures on the platoon.

3. Model

The functionality of CAVs is based on V2V communication. Vehicle driving decisions are made by information about

which vehicles and how many vehicles are ahead. This information is supported by the communication topology of the platoon. In this section, a general car-following model based on dynamic communication topologies is established. The model is called the DC-IDM.

3.1. Communication topology

The different communication topologies within a platoon directly determine the information applicable to a vehicle for driving decisions. The topology form is generally limited by the communication protocol between vehicles, the wireless communication distance, and other conditions. Topologies include PF, LPF, and MPF as shown in Fig. 1.

As shown in Fig. 1, a CAV can at least obtain information about the vehicle immediately ahead of it by detecting the vehicle or by receiving information from the vehicle. However, the only way to obtain the driving status of vehicles farther ahead is through wireless communication. The vehicle information is a function of the current communication topology. For example, CAVs can obtain driving information from the lead vehicle of a platoon, as shown in Fig. 1(b). If the communication topology is shown in Fig. 1(c), the driving state of multiple vehicles ahead can be obtained. Once the communication capability of one vehicle in the platoon fails, the communication connection associated with it is lost, and the communication topology of the platoon changes. For example, in Fig. 1(c), when the communication of vehicle $n+1$ fails, the control mode degenerates from CACC to ACC. The communication topology of the platoon then changes into that shown in Fig. 1(d). In this case, vehicle $n+3$ will not receive the information from vehicle $n+1$, and $n+2$ will only sense the driving status of the vehicle ahead of it through its own detectors. However, vehicles $n+2$ and $n+3$ are not degraded. Notably, the influences of a communication failure under different topologies are different.

In previous studies, different communication topologies have been used to build their corresponding models and analyze the platoon stability. In these studies, a certain topology was assumed for the vehicles in the platoon. However, there is still no consensus about which topology CAVs should be adopted. The topology is dynamic and based on actual communication conditions, so different topology forms should be used to form platoons. Even if a single communication topology is assumed for a platoon, its form can be changed when communication fails (*e.g.* from Fig. 1(c) to Fig. 1(d)). Therefore, a CAV-following model must take the dynamic communication topologies into consideration.

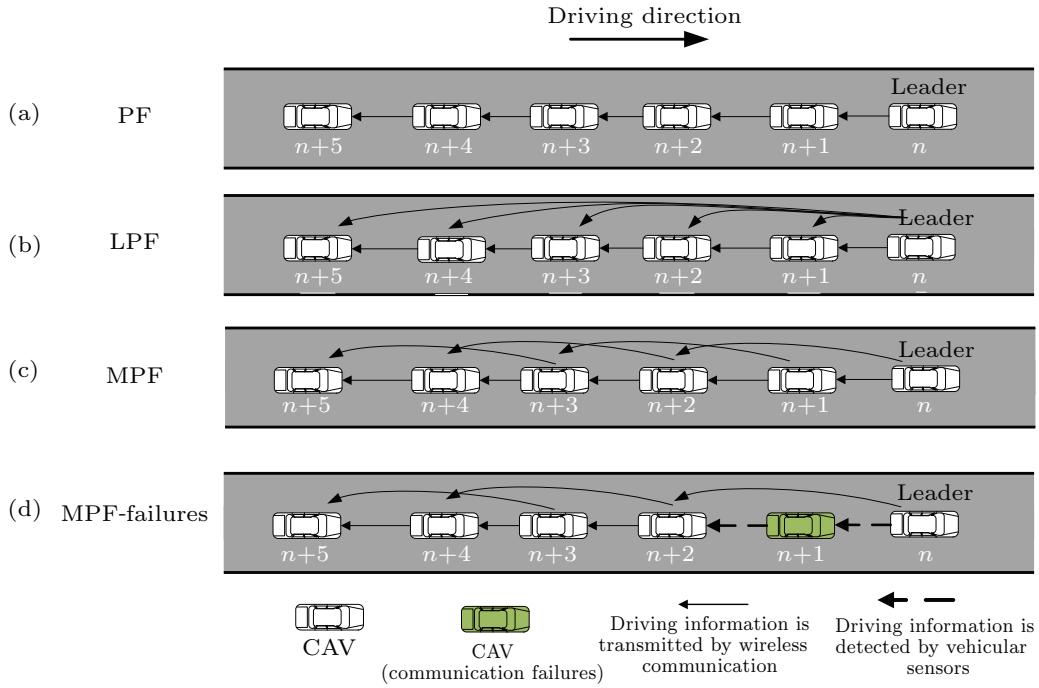


Fig. 1. Communication topologies in a platoon.

3.2. The dynamic communication topology-based car-following model

A car-following model is generally a continuous acceleration equation, the solution of which is determined by the speed and spacing of a vehicle relative to the vehicle ahead of it.[45–47] The generalized form is as follows:

$$\begin{aligned} \dot{x}_n(t) &= v_n(t), \\ \dot{v}_n(t) &= f_1\left(s_n(t-\tau), v_n(t-\tau), \Delta v_n(t-\tau)\right), \end{aligned} \tag{1}$$

where $\dot{v}_n(t)$ represents the acceleration of vehicle n at time t, $f_1(\cdot)$ is a nonlinear function, $s_n(t) = x_{n-1}(t) - x_n(t) - l$ repre-

sents the gap between vehicle n and $n-1$, $x_n(t)$ is the position of n at time t, l is the vehicle length, $v_n(t)$ is the speed of vehicle n, $\Delta v_n(t) = v_{n-1}(t) - v_n(t)$ is the difference in speed between vehicle n and $n-1$, and τ is the response delay of vehicle;[21,46] in general, to simplify the model, τ can be taken as 0, which means no delay in communication. This model is only applicable to the PF topology.

The CAVs can obtain information from multiple vehicles ahead, so the acceleration expression in Eq. (1) can be rewritten as

$$\dot{v}_n(t) = f_1\left(\sum_{m=1}^{M} \alpha_m s_{n-m+1}(t) v_n(t) \sum_{m=1}^{M} \beta_m \Delta v_n(t)\right), \quad (2)$$

where M is the number of vehicles ahead from which vehicle n can obtain information; α_m and β_m denote the weighting factors of the relative gap distance and the relative speed, respectively, that satisfy $\sum_{m=1}^{M} \alpha_m = \sum_{m=1}^{M} \beta_m = 1$. In this study, we assume that there is no communication delay. The vehicle information obtained from a closer vehicle is generally assumed to have a higher weight, so $\alpha_1 > \alpha_2 > \cdots \alpha_M$, $\beta_1 > \beta_2 > \cdots \beta_M$. To simplify the model, it is assumed that $\alpha_m = \beta_m = w_m$.[48]

The existing models assign a value to each weight. As shown in Fig. 1(c), vehicle $n+2$ obtains information from vehicle $n+1$ and vehicle n; Wang *et al.*[12] assumed that $w_1 = 0.8$ and $w_2 = 0.2$. When the communication of car $n+1$ fails, $n+2$ can only obtain the driving status of $n+1$ through detectors, and the information about vehicle n is lost (Fig. 1(d)). In this scenario, the weights should be updated to $w_1 = 1$ and $w_2 = 0$. A failure to update the weights in real time according to the changes in the communication topology leads to abnormal acceleration.

To make a car-following model adapt to change in its communication topology, we first model the communication topology of a platoon. The topology is represented as a directed graph $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$, where $\boldsymbol{V}$ is the set of nodes, and E is the set of edges. We define each vehicle in the platoon as a node, $\boldsymbol{V} = 1, 2, \ldots, n$. $\boldsymbol{E} \subseteq \boldsymbol{V} \times \boldsymbol{V} = \{e_{1,1}, e_{2,1}, \ldots, e_{i,j}\}$ represents the edge where all communication connections are established in the platoon, with i and j being in $\boldsymbol{V}$. An edge $e_{i,j} = 1$ means that vehicle i can receive information from j; otherwise, $e_{i,j} = 0$. The adjacent matrix of graph $\boldsymbol{G}$ can be expressed as $\boldsymbol{A}(\boldsymbol{G})$ given below:

$$\boldsymbol{A}(\boldsymbol{G}) = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ c_{2,1} & 0 & \cdots & 0 & 0 \\ c_{3,1} & & \ddots & & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ c_{n,1} & c_{n,2} & \cdots & c_{n,n-1} & 0 \end{bmatrix} = \begin{bmatrix} \boldsymbol{c}_1 \\ \vdots \\ \boldsymbol{c}_n \end{bmatrix}, \quad (3)$$

where $c_{i,j} = e_{i,j}$.

Taking Fig. 1(c) for example, the communication topology can be represented by the following matrix:

$$\boldsymbol{A}_{\mathrm{c}}(\boldsymbol{G}) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}. \quad (4)$$

When the communication of vehicle $n+1$ fails, the matrix changes into

$$\boldsymbol{A}_{\mathrm{d}}(\boldsymbol{G}) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}. \quad (5)$$

We need a method of updating the weights assigned to the obtained information according to changes in the communication topology. The method must satisfy two properties, *i.e.*,[39] (i) the farther ahead the vehicle sending a message is, the smaller the weight assigned to the message is. (ii) When a vehicle cannot send information, its message weight is 0. The weight of the remaining vehicle information is increased, but the more distant the vehicle is, the smaller the weight increase is.

A power function can satisfy the above requirements, such as Eq. (6), where μ is a constant greater than 1. If vehicle n has received the information sent by M vehicles ahead, then $\boldsymbol{c}_n = [0, \ldots, c_{n,n-M}, \ldots, c_{n,n-1}, 0, \ldots, 0]$, where $c_{n,n-M} = c_{n,n-1} = 1$. We define $w_{n,n-m}$ as the weight to which vehicle n assigns the information from the m-th vehicle ahead. Then, $w_{n,n-m}$ can be expressed as Eq. (7).

$$y = \mu^{-m+1}. \quad (6)$$

$$w_{n,n-m} = \frac{c_{n,n-m} \cdot \mu^{-m+1}}{\sum_{m=1}^{M} c_{n,n-m} \cdot \mu^{-m+1}}. \quad (7)$$

For a platoon of 8 vehicles with $M = 5$, the communication topology of the 7th vehicle can be written as the vector $\boldsymbol{c}_7 = [0,\ 1,\ 1,\ 1,\ 1,\ 1,\ 0,\ 0]$. When $\mu = 2$, we can obtain the weight coefficients as indicated in Eq. (8). Equation (7) shows that the coefficients satisfy property 1: $w_{n,n-1} > w_{n,n-2} > \cdots > w_{n,n-M}$, and $\sum_{m=1}^{M} w_{n,n-m} = 1$. If the communication of the 5th vehicle fails, the communication topology vector changes into $\boldsymbol{a}_7 = [0,\ 1,\ 1,\ 0,\ 1,\ 1,\ 0,\ 0]$. New weight coefficients can be calculated from Eq. (9). The $w_{n,n-3}$ becomes 0, and $w_{n,n-2}$ increases more than $w_{n,n-5}$. Property 2 is also satisfied. A larger value of μ means that the information from the closer vehicles has a higher weight.

$$w_{n,n-1} = 0.52, \quad w_{n,n-2} = 0.26, \quad w_{n,n-3} = 0.13,$$

$$w_{n,n-4}=0.06,\quad w_{n,n-5}=0.03, \tag{8}$$
$$w_{n,n-1}=0.59,\quad w_{n,n-2}=0.30,\quad w_{n,n-3}=0,$$
$$w_{n,n-4}=0.07,\quad w_{n,n-5}=0.04. \tag{9}$$

Therefore, the generalized form of the dynamic communication topology-based car-following model can be expressed as

$$\begin{aligned}\dot{v}_n(t) &= f_1\Bigg(\sum_{m=1}^{M} w_{n,n-m}s_{n-m+1}(t), v_n(t),\\ &\qquad \sum_{m=1}^{M} w_{n,n-m}\Delta v_{n-m+1}(t)\Bigg),\\ w_{n,n-m} &= f_2(c_{n,n-m},\mu),\\ c_{n,n-m} &= \begin{cases}1, & \text{if } n-m \text{ can communicat with } n;\\ 0, & \text{if } n-m \text{ cannot communicat with } n.\end{cases}\end{aligned} \tag{10}$$

Here, $f_2(\cdot)$ is a function of $c_{n,n-m}$ and μ.

3.3. Communication topology

In this subsection, a dynamic communication topology model is proposed for simulation analysis. We modify the intelligent driver model (IDM) proposed in Ref. [29]. The IDM is chosen for three reasons. First, the IDM assumes that each vehicle has its desired time headway, which is consistent with the driving characteristics of AVs. Second, the acceleration equation of the IDM is continuously differentiable with respect to all three variables, which is necessary for stability analysis. Third, the IDM has been applied to many CAV studies.

The IDM is expressed as follows:

$$\begin{cases} a_n(t)=a_{\max}\left[1-\left(\dfrac{v_n(t)}{v_0}\right)^4-\left(\dfrac{s^*(v_n(t),\Delta v_n(t))}{s_n(t)}\right)^2\right],\\ s^*(v_n(t),\Delta v_n(t))=s_0+t_{\mathrm{d}}v_n(t)-\dfrac{v_n(t)\Delta v_n(t)}{2\sqrt{a_{\max}d}}, \end{cases} \tag{11}$$

where s^* is the desired distance between vehicles, s is the actual distance between vehicles, t_{d} is the desired time headway, $a_{\max}$ is the maximum acceleration, and d is the comfortable deceleration. In the model, when the actual distance between vehicles is large, the vehicle gradually reduces the distance with a smooth acceleration. When the vehicle is driving too fast or is too close to the vehicle in front of it, the vehicle slows down until it reaches the required spacing. All these features can be better adapted to the driving characteristics of AVs, so the model is widely used in AV-related research.[5,12,21,23,25] After communication failures occur, the control model degenerates to ACC, and the IDM is a good option.

The classic IDM only considers information about the nearest preceding vehicle. The revised IDM shown in Eq. (12), which is called the DC-IDM, is based on the ability of a CAV to obtain information from multiple vehicles and dynamic communication topologies. The model can make driving decisions based on the actual communication topology at time t.The information obtained from multiple preceding vehicles is weighted according to the communication topology. If $M=1$, then the model degenerates to the classic IDM. If the communication topology does not change, the model is a CIDM[12] or an MAC-IDM.[21]

$$\begin{cases} a_n(t)=a_{\max}\left[1-\left(\dfrac{v_n(t)}{v_0}\right)^4-\left(\dfrac{s^*(v_n(t),\Delta v_n(t))}{\sum_{m=1}^{M} w_{n,n-m}s_{n-m+1}(t)}\right)^2\right],\\ s^*(v_n(t),\Delta v_n(t))=s_0+t_{\mathrm{d}}v_n(t)-\dfrac{v_n(t)\sum_{m=1}^{M} w_{n,n-m}\Delta v_{n-m+1}(t)}{2\sqrt{a_{\max}d}},\\ w_{n,n-m}=f_2(a_{n,n-m},\mu). \end{cases} \tag{12}$$

4. Stability analysis

4.1. Definition of platoon stability

If a platoon is stable, when a vehicle in the platoon, which is in equilibrium, causes a disturbance, the response of the vehicles to the rear of the disturbance is not constantly amplified. Each vehicle maintains the same spacing s_{e} and speed $v_{\mathrm{e}}=V(s_{\mathrm{e}})$ without acceleration or deceleration, which is defined as the equilibrium state. The model can be expressed as $f(s_{\mathrm{e}}v_{\mathrm{e}})=0$ when it is in the equilibrium state.

If a platoon experiences a slight disturbance at time t, $\tilde{s}_n(t)=s_n(t)-s_{\mathrm{e}}$ represents the distance deviation, and $\tilde{v}_n(t)=v_n(t)-v_{\mathrm{e}}$ represents the speed deviation from the equilibrium state. The acceleration equation in Eq. (13) is a first-order Taylor expansion. Because $\Delta v_n(t)=v_{n-1}(t)-v_n(t)=\tilde{v}_{n-1}(t)-\tilde{v}_n(t)=\dot{\tilde{s}}_n(t)$, equation (13) can be rewritten as follows:

$$\begin{aligned}\tilde{v}_n(t) &= f(s_{\mathrm{e}},v_{\mathrm{e}},0)+\frac{\partial f}{\partial s}\Big|_{\mathrm{e}}(s_n(t)-s_{\mathrm{e}})\\ &\quad+\frac{\partial f}{\partial v}\Big|_{\mathrm{e}}(v_n(t)-v_{\mathrm{e}})+\frac{\partial f}{\partial \Delta v}\Big|_{\mathrm{e}}(\Delta v_n(t)-0),\end{aligned} \tag{13}$$
$$\dot{\tilde{v}} = f_n^s\tilde{s}_n+f_n^v\tilde{v}_n+f_n^{\Delta v}\dot{\tilde{s}}_n, \tag{14}$$

where f_n^s, f_n^v, and $f_n^{\Delta v}$ are the Taylor expansion coefficients.[49] In equilibrium, $f_n^s=f_{n-1}^s$, $f_n^v=f_{n-1}^v$, and $f_n^{\Delta v}=f_{n-1}^{\Delta v}$. Because $\ddot{s}_n(t)=\dot{v}_{n-1}(t)-\dot{v}_n(t)$, and hence $\ddot{\tilde{s}}_n(t)=\dot{\tilde{v}}_{n-1}(t)-\dot{\tilde{v}}_n(t)$. Substitution of Eq. (14) into this equation yields

$$\begin{aligned}\ddot{\tilde{s}}_n &= f_{n-1}^s\tilde{s}_{n-1}+f_{n-1}^v\tilde{v}_{n-1}+f_{n-1}^{\Delta v}\dot{\tilde{s}}_{n-1}\\ &\quad-(f_{n-1}^s\tilde{s}_n+f_{n-1}^v\tilde{v}_n+f_{n-1}^{\Delta v}\dot{\tilde{s}}_n)\\ &= f_n^s(\tilde{s}_{n-1}-\tilde{s}_n)+f_n^v(\tilde{v}_{n-1}-\tilde{v}_n)+f_n^v(\dot{\tilde{s}}_{n-1}-\dot{\tilde{s}}_n).\end{aligned} \tag{15}$$

The frequency domain approach is a simple and effective method of analyzing the platoon stability that has been widely used in previous studies.[37,38,50–53] Let $\tilde{s}_n(t)=U\mathrm{e}^{\mathrm{i}n\theta+\lambda t}$, and $\tilde{v}_n(t)=Y\mathrm{e}^{\mathrm{i}n\theta+\lambda t}$, where U and Y are complex constants (independent of n and t) that represent the magnitude of the perturbation, θ is a discrete wavenumber in a range of $0<\theta\le\pi$, and λ is the growth rate in terms of the wavenumber θ, which determines whether the traffic flow is stable when a perturbation occurs. Because $\tilde{v}_n-\tilde{v}_{n-1}=-\dot{\tilde{s}}_n$, equation (16) can be obtained to be

$$U=\frac{Y(\mathrm{e}^{-\mathrm{i}\theta}-1)}{\lambda}. \tag{16}$$

Substituting $\tilde{s}_n(t)$, $\tilde{v}_n(t)$, and Eq. (16) into Eq. (15) yields the following equation:

$$\lambda^2 - \lambda(f_n^v - f_n^{\Delta v}(1-\mathrm{e}^{-\mathrm{i}\theta})) + f_n^s(1-\mathrm{e}^{-\mathrm{i}\theta}) = 0. \quad (17)$$

According to the root formula, λ_+ and λ_- are a pair of complex solutions of Eq. (17). If the real part of λ_+ is less than or equal to zero at any θ, the platoon may be stable, and for the opposite condition, it may be unstable.[21,28] The geometry of λ_+ at $\theta = 0$ determines the stability type. λ_+ is expanded into$\lambda_+ = \lambda_1 \mathrm{i}\theta + \lambda_2(\mathrm{i}\theta)^2 + \cdots$ around $\theta \to 0$ where λ_1 and λ_2 are real coefficients. The $\mathrm{e}^{-\mathrm{i}\theta}$ is expanded into $\mathrm{e}^{-\mathrm{i}\theta} = 1 - \mathrm{i}\theta + (\mathrm{i}\theta)^2/2 + \cdots$. Substitution of he two expanded equations into Eq. (17) yields

$$\begin{aligned}&({\lambda_2}^2 - \lambda_2 f_n^{\Delta v})\theta^4 + \left(-2\lambda_1\lambda_2 + \frac{\lambda_1 f_n^{\Delta v}}{2} - \lambda_2 f_n^{\Delta v}\right)\mathrm{i}\theta^3 \\ &+ \left(-{\lambda_1}^2 - \lambda_1 f_n^{\Delta v} + \lambda_2 f_n^v + \frac{f_n^s}{2}\right)\theta^2 \\ &+ (-\lambda_1 f_n^v + f_n^s)\,\mathrm{i}\theta = 0. \end{aligned} \quad (18)$$

Here, λ_1 and λ_2 can be found to be

$$\begin{aligned}\lambda_1 &= \frac{f_n^s}{f_n^v}, \\ \lambda_2 &= \left(\frac{f_n^s}{f_n^v}\right)^2 \frac{1}{f_n^v} + \frac{f_n^{\Delta v} f_n^s}{{f_n^v}^2} - \frac{f_n^s}{2f_n^v}. \end{aligned} \quad (19)$$

Thus, the platoon is string stable if $\lambda_2 \le 0$. Because $f_s > 0$, $f_v < 0$, the stability condition is

$$\frac{1}{2}{f_n^v}^2 - f_n^{\Delta v} f_n^v - f_n^s \ge 0. \quad (20)$$

4.2. Stability of dynamic communication topology-based car-following model

When the communication topology of a platoon is not changed, the proposed dynamic communication topology-based car-following model degenerates into the CIDM described in Ref. [12]. Then, equation (14) can be rewritten as Eq. (21), the corresponding Eq. (15) can be written as Eq. (22), and equation (17) can be written as Eq. (23).

$$\begin{aligned}\dot{\tilde{v}}_n(t) &= f_n^s \sum_{m=1}^{M} w_{n,n-m}\tilde{s}_{n-m+1} \\ &\quad + f_v\tilde{v}_i + f_{\Delta v}\sum_{m=1}^{M} w_{n,n-m}\dot{\tilde{s}}_{n-m+1}, \end{aligned} \quad (21)$$

$$\begin{aligned}\ddot{\tilde{s}}_n &= f_{n-1}^s \sum_{m=1}^{M} w_{n-1,n-m-1}\tilde{s}_{n-m} \\ &\quad + f_{n-1}^v\tilde{v}_{n-1} + f_{n-1}^{\Delta v}\sum_{m=1}^{M} w_{n-1,n-m-1}\dot{\tilde{s}}_{n-m} \\ &\quad - \left(f_n^s \sum_{m=1}^{M} w_{n,n-m}\tilde{s}_{n-m+1}\right. \\ &\quad \left. + f_n^v\tilde{v}_n + f_n^{\Delta v}\sum_{m=1}^{M} w_{n,n-m}\dot{\tilde{s}}_{n-m+1}\right) \\ &= f_n^s \sum_{m=1}^{M} w_{n,n-m}(\tilde{s}_{n-m} - \tilde{s}_{n-m+1}) + f_n^v(\tilde{v}_{n-1} - \tilde{v}_n) \\ &\quad + f_n^{\Delta v}\sum_{m=1}^{M} w_{n-1,n-m-1}(\dot{\tilde{s}}_{n-m} - \dot{\tilde{s}}_{n-m+1}), \end{aligned} \quad (22)$$

$$\begin{aligned}&\lambda^2 - \lambda\left(f_n^v - f_n^{\Delta v}\left(1-\mathrm{e}^{-\mathrm{i}\theta}\right)\sum_{m=1}^{M} w_{n,n-m}\mathrm{e}^{(1-m)\mathrm{i}\theta}\right) \\ &+ f_n^s(1-\mathrm{e}^{-\mathrm{i}\theta})\sum_{m=1}^{M} w_{n,n-m}\mathrm{e}^{(1-m)\mathrm{i}\theta} = 0. \end{aligned} \quad (23)$$

The solution to Eq. (23) can be found to be

$$\begin{aligned}\lambda_2 &= \left(\frac{f_n^s}{f_n^v}\right)^2 \frac{1}{f_n^v} + \frac{f_n^{\Delta v} f_n^s}{{f_n^v}^2} - \frac{f_n^s}{2f_n^v} \\ &\quad - f_n^s \sum_{m=1}^{M} w_{n,n-m}(1-m). \end{aligned} \quad (24)$$

Therefore, the stability condition for an unchanged topology is represented by inequality (25). The stability of a platoon is related to the weights of the information obtained about the vehicles ahead.

$$\frac{1}{2}{f_n^v}^2 - f_n^{\Delta v} f_n^v - f_n^s - \sum_{m=1}^{M} w_{n,n-m}(1-m) > 0. \quad (25)$$

4.3. Probabilistic model of communication topology in a platoon

When the communication of some vehicles in a platoon fails, the weights assigned to the information obtained by the rear vehicles according to Eq. (7) change, which changes the stability of the platoon. However, different types and numbers of failures bring different changes to the weights. Therefore, modeling the failure probabilities of different communication topology forms is important.

Table 1. Probabilities of different communication topologies for $M = 3$.

Scenarios	n	$n-1$	$n-2$	$n-3$	Probability	Category
1	√	×	√	√	$(1-p)^3 p$	*A*
2	√	√	×	√	$(1-p)^3 p$	*B*
3	√	√	√	×	$(1-p)^3 p$	*C*
4	√	×	×	√	$(1-p)^2 p^2$	*B*
5	√	×	√	×	$(1-p)^2 p^2$	*C*
6	√	√	×	×	$(1-p)^2 p^2$	*D*
7	√	×	×	×	$(1-p)p^3$	*D*
8	√	√	√	√	$(1-p)^4$	*A*
9	×	√/×	√/×	√/×	p	*D*

Note: "×" refers to failed communications, and "√" represents normal communications. In scenario 9, vehicle n cannot receive or send messages. Then, whether the vehicle communication in front of vehicle n fails does not affect the driving status of vehicle n because it can only rely on the state of vehicle $n-1$ measured by its detector to make driving decisions. In this work, we assume that no difference exists between the information obtained by self-detection and the information received directly and that communication delay occurs.

We start with an infinitely long platoon in which each vehicle can obtain driving information from M vehicles ahead, and the probability of a communication failure for each vehicle is p. Then, when $M = 3$, the communication topology form of vehicle j will be one of 9 cases, each with the probability shown in Table 1. These 9 cases can be divided into 4 categories, each of which represents the information that is essentially available to vehicle n. For example, in category A, vehicle n can obtain the information about all 3 vehicles ahead of it, and in category C, vehicle n cannot obtain the information about only vehicle $n-3$.

According to Table 1, scenarios 1–3 indicate that the communication of only one vehicle in front of vehicle n fails, which results in C_M^1 categories of communication topologies. Scenarios 4–6 indicate two vehicle communication failures, so $C_M^2 - (C_M^1 - 1)$ categories of new topologies appear because $C_M^1 - 1$ categories are duplicates. Similarly, we can obtain the new categories for each additional vehicle communication failure. All communication failures of a front vehicle belong to the same category as the communication failures of vehicle j itself. The communications of all vehicles are normal, and only one failure can be considered to be in the same category. Thus, for the scenario in which a vehicle can obtain information about M preceding vehicles, several categories of topologies may arise as follows:

$$\begin{aligned} &C_M^1 + \left(C_M^2 - \left(C_M^1 - 1\right)\right) + \cdots \\ &+ \left(C_M^{M-1} - \left(C_M^{M-2} - \left(\cdots\left(C_M^1 - 1\right)\right)\right)\right). \end{aligned} \tag{26}$$

The probability expressions for each category are shown in Table 2.

Table 2. Probabilities for each category of communication topology.

Category	Probability
1	$(1-p)^M p + (1-p)^{M+1}$
2	$(1-p)^M p + (1-p)^{M-1} p^2$
…	$(1-p)^M p + (1-p)^{M-1} p^2$
C_M^1	$(1-p)^M p + (1-p)^{M-1} p^2$
$C_M^1 + 1$	$(1-p)^{M-1} p^2 + (1-p)^{M-2} p^3$
…	$(1-p)^{M-1} p^2 + (1-p)^{M-2} p^3$
$C_M^1 + C_M^2 - (C_M^1 - 1)$	$(1-p)^{M-1} p^2 + (1-p)^{M-2} p^3$
…	…
$C_M^1 + (C_M^2 - (C_M^1 - 1) + \cdots + (C_M^{M-1} - (C_M^{M-2} - (\cdots (C_M^1 - 1))))$	$(1-p)^2 p^{M-1} + (1-p) p^M + p$

4.4. Stability analysis after a communication failure

Reference [54] presented the stability conditions for platoons containing different types of vehicles, such as cars and trucks. The results have been widely used for heterogeneous traffic flow stability analysis.[50,51,55] In this study, when some vehicles lose their communication functionalities in a platoon, the CAVs change their communication topologies. Vehicles that make driving decisions based on different types of information can be considered to be in different vehicle categories. The percentage of vehicles in each category can be calculated from Table 2. Their stabilities can be obtained according to Eq. (25) and given in inequality (27), by considering a dynamic communication topology. When $M = 1$, the stability condition degenerates to the results presented in Ref. [54].

$$\sum_n \left[\frac{1}{2} f_n^{v^2} - f_n^{\Delta v} f_n^v - f_n^s - \sum_{m=1}^{M} w_{n,n-m}(1-m)\right] \left(\prod_{l \neq n} f_l^s\right)^2 \geq 0. \tag{27}$$

To consider the possibility of a communication failure, the vehicles in a platoon are divided into K categories based on their communication topologies. The inequality (27) can be rewritten as follows:

$$\sum_{k=1}^{K} \frac{N P_k [\frac{1}{2} f_k^{v^2} - f_k^{\Delta v} f_k^v - f_k^s - W_k]}{f_k^{s^2}} \geq 0, \tag{28}$$

where P_k and w_k are the probability of occurrence of the k-th category of communication topology and the weighting factor, respectively. The weighting factor is expressed as follows:

$$W_k = \sum_{m=1}^{M} w_{n,n-m}(1-m), \tag{29}$$

which is associated with Eq. (7). We can easily find that the stability condition is related to the proportion of different types of topologies and the weighting factor of each type of topology, but unrelated to the location of the vehicle with failed communication.

Taking $M = 3$, $\mu = 2$, and $p = 0.2$ for example, we can obtain $P_1 = 08^3 \times 02 + 08^4 = 051$, $W_1 = \frac{1}{1.75} \times (1-1) + \frac{0.5}{1.75} \times (1-2) + \frac{0.25}{1.75} \times (1-3) = -057$.

5. Simulation

In this section, a series of simulations is performed to analyze the stability of a platoon based on the DC-IDM. The Taylor expansion coefficients f_n^s, f_n^v, and $f_n^{\Delta v}$ of the DC-IDM are expressed as

$$\begin{aligned} f_n^s &= \frac{2a_{\max}}{s_e}\left(\frac{s_0 + t_d v_e}{s_e}\right)^2; \\ f_n^v &= -2a_{\max}\left(\frac{2}{v_0}\left(\frac{v_e}{v_0}\right)^3 + \frac{t_d(s_0 + t_d v_e)}{(s_e)^2}\right); \\ f_n^{\Delta v} &= \sqrt{\frac{a_{\max}}{d}}\frac{v_e}{s_e}\left(\frac{s_0 + t_d v_e}{s_e}\right). \end{aligned} \tag{30}$$

These coefficients are the functions of the vehicle speed and spacing at equilibrium. In this state, all vehicles run at speed v_e and have a stable spacing s_e. The relationship between v_e and s_e is given by

$$s_e = \frac{s_0 + t_d v_e}{\sqrt{1 - (v_e/v_0)^4}}. \tag{31}$$

Table 3. Parameters of DC-IDM.

Parameters	Values
$a_{\max}$	2 m/s^2
d	2 m/s^2
v_0	33.3 m/s
s_0	2 m
$t_{\rm d}$	0.9 s, 1.1 s, 1.3 s 1.5 s
μ	1–4
M	2–6

We assume that an infinitely long platoon drives at equilibrium. We simulate the stability at each speed. A communication failure occurs randomly in the platoon. Once the communication failure occurs, the communication is not recovered. The communication failure rate is p, and its value range is 0–1. The parameters of the model are shown in Table 3.

5.1. Platoon stability for normal communication

Our proposed dynamic communication topology model adds two parameters to the classic IDM model, *i.e.*, the parameter M and the parameter μ. We analyze the influences of these two parameters on the stability in a scenario in which CAV communications are normal.

The left-hand part of inequality (25) is the stability discriminant value. Values greater than 0 are for stable status, and values less than 0 are unstable status. The simulation results for different values of M are shown in Fig. 2. At any value of the time headway, the larger the value of M is, the more stable the latoon is over a wider speed range, which means that the more information the CAV obtains about the vehicle driving ahead, the more stable the platoon becomes. However, CAVs can only obtain information from a few preceding vehicles due to the limited communication distance. The parameter setting of the desired time headway has a significant influence on the stability.

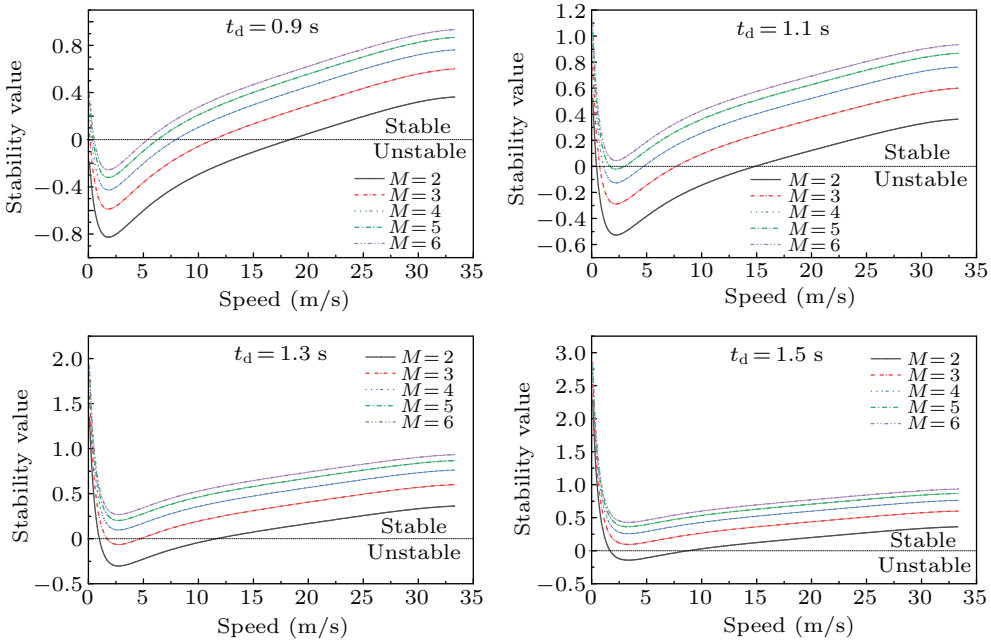


Fig. 2. Influence of parameter M on stability ($\mu = 2$).

If the expected headway of a CAV is larger, less information is needed to keep the platoon stable. For example, when the desired time headway is 1.1 s, the vehicle needs to obtain information from at least 6 vehicles in front of it for the platoon to keep stable at any speed. For a 1.3-s headway, information is needed from at least 4 vehicles. At 1.5 s, less information is needed, and 3 vehicles are sufficient. This means that setting a more highly desired time headway for CAVs can save communication resources and keep the platoon stable.

Then, taking $t_{\rm d} = 1.1$ s and $M = 4$, we analyze the effect of the parameter μ on the stability (Fig. 3). A larger value of μ indicates that a vehicle with a greater communication distance sends a lower weight of information. The results demonstrate that a smaller value of μ leads to more stability for the same amount of information from the forward vehicles. For example, the instability speed range is 0.5 m/s–10.8 m/s when $\mu = 3$. Accordingly, the stability speed ranges are 0 m/s–0.5 m/s and 0 m/s–above 10.8 m/s. When $\mu = 2$, the instability speed range is only 1 m/s–4.8 m/s, and the remainder of the speed range keeps the platoon stable. The smaller the value of μ is, the more stable the platoon is. We can conclude that the platoon will be more stable when the information sent from vehicles farther ahead of it has a higher weight. When the weight values of the messages sent by each vehicle reach the same value ($\mu = 1$), the platoon will be stable at any speed.

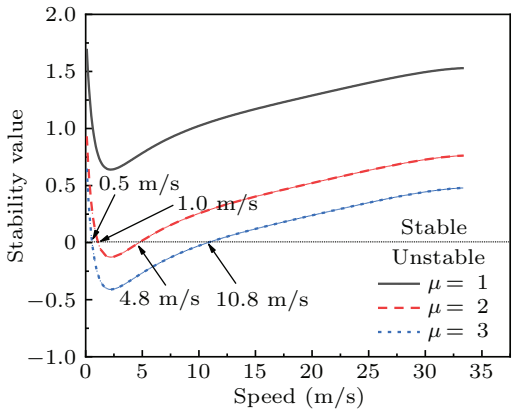


Fig. 3. Stability curves for different values of μ ($t_d = 1.1$ s, $M = 4$).

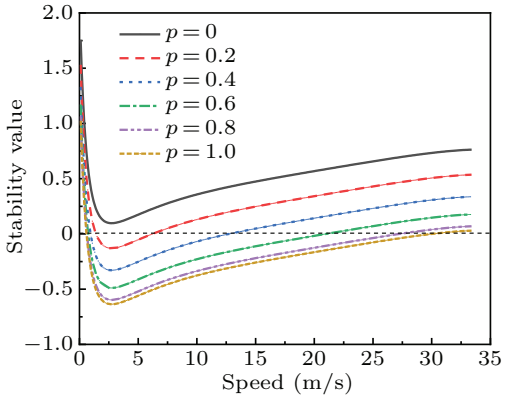


Fig. 4. Stability curves for different communication failure rates ($t_d = 1.3$ s, $M = 4$, $\mu = 2$).

5.2. Platoon stability after communication failures

Our model is characterized by its ability to describe the topological changes in the platoon when the communication of CAVs fails. In this subsection, we discuss the stability of a platoon after some of the CAVs lose their communication ability. The left part of inequality (28) describes the platoon stability discriminant value in the case of a communication failure.

First, we analyze the effect of the probability of a communication failure on the stability of the platoon. The results are shown in Fig. 4, indicating that the stability decreases continuously as the probability of a communication failure increases. The platoon is stable when no communication failures occur. Once a failure probability is reached, the platoon is unstable in a particular speed range. When all vehicles in the platoon lose their communication ability, they degrade into IDM-based follow-vehicles, which are unstable over a wide range of speeds.

To extend the above discussion, we analyze the influences of the probability of CAV communication failures on the stability of the platoon for different communication topologies. As shown in Fig. 5, the platoon is not stable in a particular speed range for $M = 3$ regardless of the presence of communication failures. When $M = 4$, the minimum failure rate is 8%, which allows the platoon to remain stable at any speed. We define this rate as the critical CAV communication failure rate for platoon stability, below which the platoon is stable. Similarly, we find a critical rate of 15% for $M = 5$ and 19% for $M = 6$. In summary, when a CAV has access to more information about the vehicles ahead of it, the platoon is more likely to remain stable, even under a communication failure.

Additionally, when the speed of a platoon is higher or lower than the speed corresponding to a critical failure rate and if more vehicles lose communications, the platoon can remain stable even if the failure rate exceeds the critical rate. These speed ranges are recommended for the platoon.

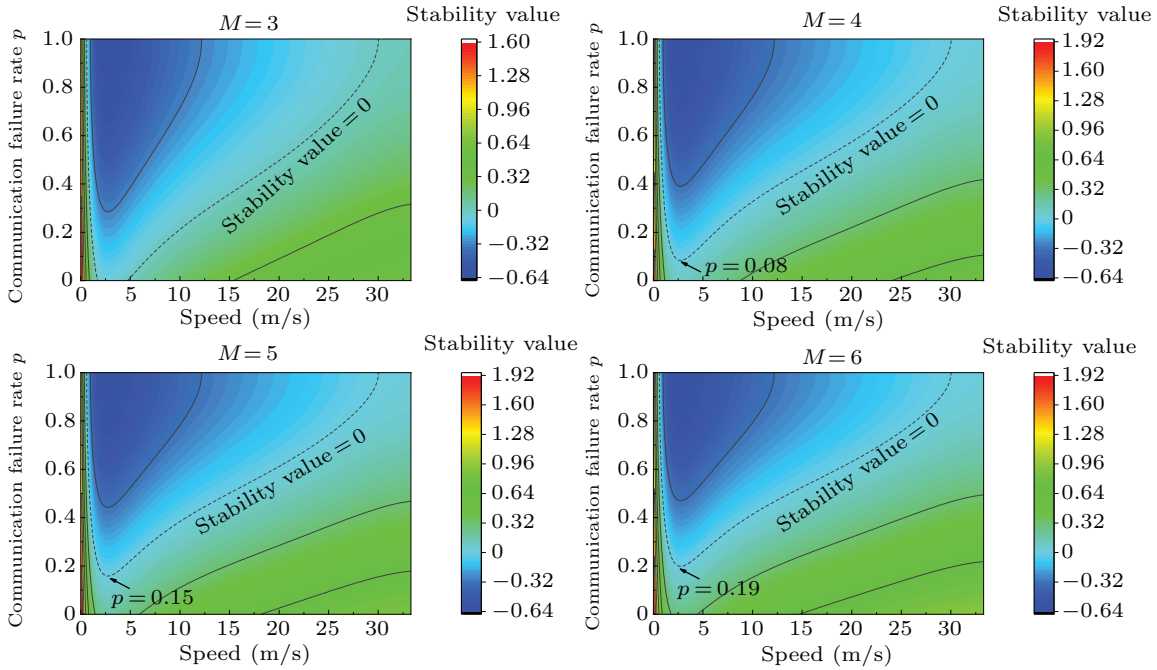


Fig. 5. Analytical results of stability for different communication failure rates ($t_d = 1.3$ s, $\mu = 2$).

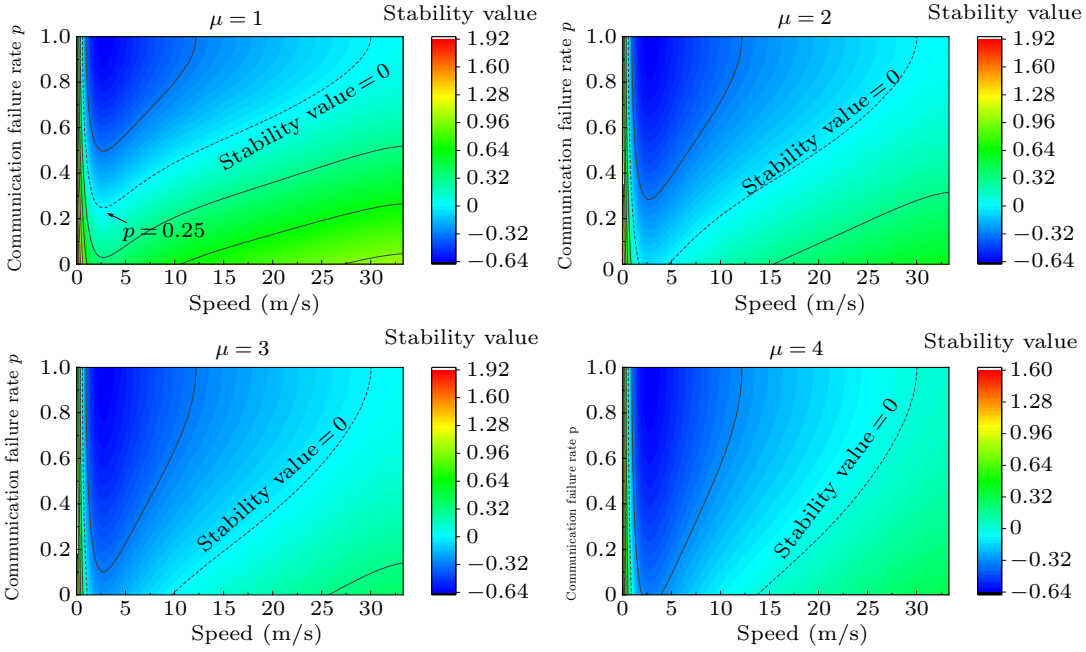


Fig. 6. Analytical results of stability for different μ values ($t_d = 1.3$ s, $M = 3$).

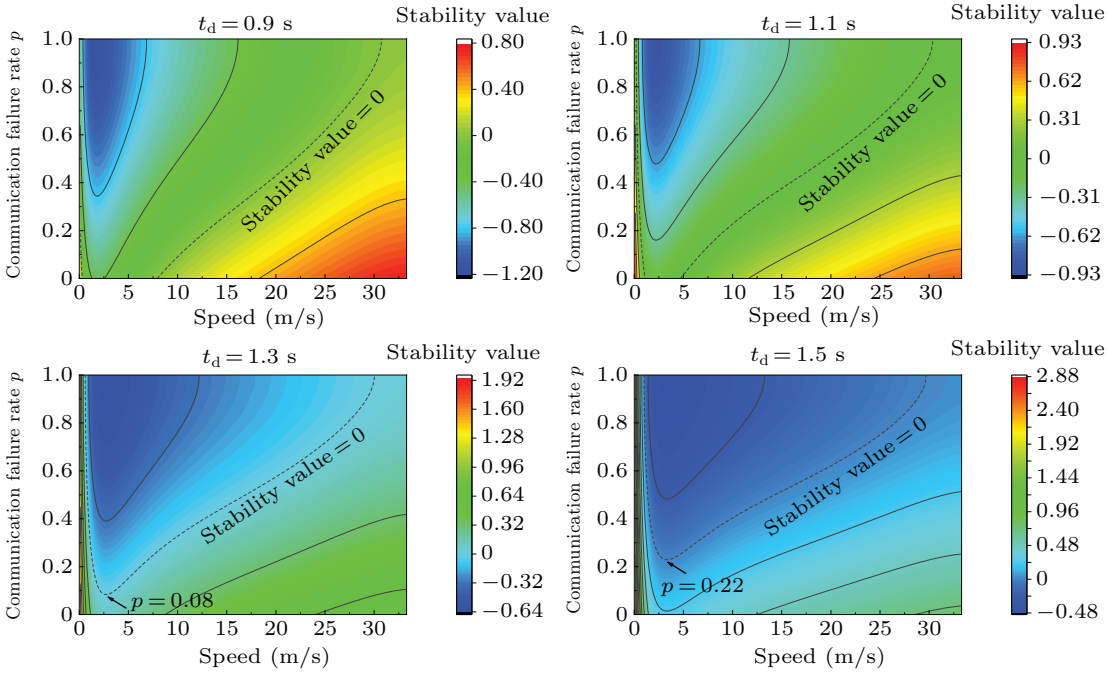


Fig. 7. Analytical results of stability for different communication failure rates ($M = 4$, $\mu = 2$).

Based on the DC-IDM, the value of μ can affect the distribution of the information weights. Assume that $t_d = 1.3$ s and $M = 3$. We analyze the influence of μ on the critical failure rate, and the simulation results are shown in Fig. 6, indicating that when $\mu = 1$, the critical communication failure rate is 25%. When $\mu = 2$, there is no critical communication failure rate because even if the vehicle does not have a communication failure, it will not keep stable in the speed range of 1.8 m/s–4.7 m/s. When μ further increases to 3 and 4, the speed range expands to 1.1 m/s–9.7 m/s and 1.0 m/s–13.6 m/s, respectively. The results indicate that if there occurs a communication failure, a smaller μ is a good choice for maintaining string stability.

Furthermore, taking $\mu = 2$ and $M = 4$ for example, we analyze the effects of different desired headways on the platoon stability in a communication failure scenario. Figure 7 shows that at $t_d = 0.9$ s and $t_d = 1.1$ s, the platoon is not stable in some speed ranges even it there occur no communication failures. When t_d increases to 1.3 s, the platoon remains stable if the communication failure rate is less than 8%, and the critical failure rate increases to 22% when t_d increases to 1.5 s. The combined results show that the longer the desired time

headway is, the larger the critical failure rate is.

6. Conclusions

In this work, the possible effects of CAV communication failures on the platoon stability are analyzed. A car-following model with considering the dynamic communication topologies of CAVs is developed, and a general expression of the model is presented. The model can dynamically adjust the weights of the obtained information based on the actual communication topology after a communication failure has occurred. The IDM model is modified to adapt to dynamic communications.

The communication topologies that emerge after a communication failure are modeled and analyzed with probabilities for each communication topology form. Finally, based on the DC-IDM, the stability of the platoon is analyzed theoretically. The stability conditions for a communication failure are obtained. The numerically experimental results are shown below.

(i) As the communication failure rate increases, the platoon becomes unstable.

(ii) The critical failure rates for different CAV parameter settings are obtained. For example, when CAVs can obtain the information about 4 vehicles driving and the desired time headway is 1.3 s, the critical failure rate is 8%.

(iii) The critical failure rate is improved when CAVs receive information from more preceding vehicles or a larger desired time headway is used.

The results in this study indicate that when CAVs are set with reasonable driving parameters, the stability of a platoon can be ensured even if some of the vehicles lose their communication ability. However, setting a larger desired time headway means less road capacity, and receiving more vehicle information means that more communication resources are needed. Balancing the traffic flow efficiency, communication resources, and platoon stability by optimizing the CAV parameters is the next subject in our research.

Acknowledgements

Project supported by the National Key Research and Development Project of China (Grant No. 2018YFE0204300), the Beijing Municipal Science & Technology Commission (Grant No. Z211100004221008), and the National Natural Science Foundation of China (Grant No. U1964206).

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