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An Improved Cooperative Adaptive Cruise Control (CACC) Algorithm Considering Invalid Communication

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Abstract: For the Cooperative Adaptive Cruise Control (CACC) Algorithm, existing research studies mainly focus on how inter-vehicle communication can be used to develop CACC controller, the influence of the communication delays and lags of the actuators to the string stability. However, whether the string stability can be guaranteed when inter-vehicle communication is invalid partially has hardly been considered. This paper presents an improved CACC algorithm based on the sliding mode control theory and analyses the range of CACC controller parameters to maintain string stability. A dynamic model of vehicle spacing deviation in a platoon is then established, and the string stability conditions under improved CACC are analyzed. Unlike the traditional CACC algorithms, the proposed algorithm can ensure the functionality of the CACC system even if inter-vehicle communication is partially invalid. Finally, this paper establishes a platoon of five vehicles to simulate the improved CACC algorithm in MATLAB/Simulink, and the simulation results demonstrate that the improved CACC algorithm can maintain the string stability of a CACC platoon through adjusting the controller parameters and enlarging the spacing to prevent accidents. With guaranteed string stability, the proposed CACC algorithm can prevent oscillation of vehicle spacing and reduce chain collision accidents under real-world circumstances. This research proposes an improved CACC algorithm, which can guarantee the string stability when inter-vehicle communication is invalid.

Keywords: Cooperative adaptive cruise control (CACC), sliding mode control, chain collision accidents, vehicular ad hoc networks (VANETs)

1 Introduction

Recent improvements in sensing, communication, and computing technologies have led to the development of driver-assistance systems (DAS). Adaptive cruise control (ACC) system is the first commercial implementation of DAS[1]. ACC aims to relieve drivers from manually performing a repetitive and boring task, and to automatically maintain cruise driving while assisting them in reducing crashes. Extending the standard ACC functionality with wireless inter-vehicle communication enables driving at smaller inter-vehicle distances while maintains string stability[2]. Such extended functionality is called cooperative adaptive cruise control (CACC).

A vast amount of literature on CACC is available. NAUS, et al[3], worked on CACC setup aiming at ensuring the feasibility of real-world implementation. However, in their studies, all vehicles were assumed to communicate with their preceding vehicle only. Communication among multiple vehicles or between a vehicle and a designated platoon leading vehicle was not considered. GIRARD, et al[4], from the University of California Berkeley, established a fuzzy control algorithm and a collision warning model for CACC. Meanwhile, GERRIT, et al[5], from the Eindhoven University of Technology, established a CACC model based on the variable structure sliding control algorithm and analyzed the stability with frequency response. Several other researchers used longitudinal control algorithms to design CACC controllers for vehicle platoons[6–12] and intelligent vehicle highway system (IVHS)[14–15]. ZHANG, et al[13], applied vector Lyapunov function approach to longitudinal control of vehicles in a platoon, and the controller was established by sliding mode control method.

The design of controllers for the CACC system requires the specification of string stability. A precise definition of string stability was provided by CHU[17]. String stability refers to the capability in which any perturbation of the velocity or position of the leading vehicle will not result in amplified fluctuations to the following vehicle's velocity and position. XIAO, et al[21–25], considered the existence of delay factors in the sensors and actuators of communication systems. He analyzed the CACC string stability based on different information frameworks and then simulated the results.

A CACC algorithm considering invalid communication has not yet been developed according to the literature review. This is the reason why this paper focuses on

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designing an improved algorithm that ensures the functionality of the CACC system even if inter-vehicle communication is partially invalid. The improved algorithm is based on the sliding mode control algorithm and can adjust the CACC structure to ensure string stability. Therefore, the algorithm can prevent vehicle chain collisions even with communication system partially invalid. The feasibility of the algorithm has been verified based on MATLAB/Simulink.

The organization of this paper is described as follows. Section 2 focuses on designing the CACC hierarchical controller based on sliding control and obtains the string stable conditions. Section 3 improves the CACC hierarchical controller under the circumstance of communication being partially invalid and obtains the relevant string stability conditions. Section 4 then presents the simulation results of the MATLAB/Simulink model. Finally, section 5 summarizes the conclusions and proposes directions for further research.

2 CACC Controller

As in many other longitudinal vehicle control applications, the CACC hierarchical controller in this paper also consists of an upper control layer and a lower execution layer, as shown in Fig. 1. The upper control layer calculates the value of the desired acceleration using all the relevant information obtained by the CACC module, and then transfers the information to the lower execution layer. The lower execution layer achieves the desired acceleration by the actuators, which are controlled by the relevant control module. This process is the core of the CACC controller.

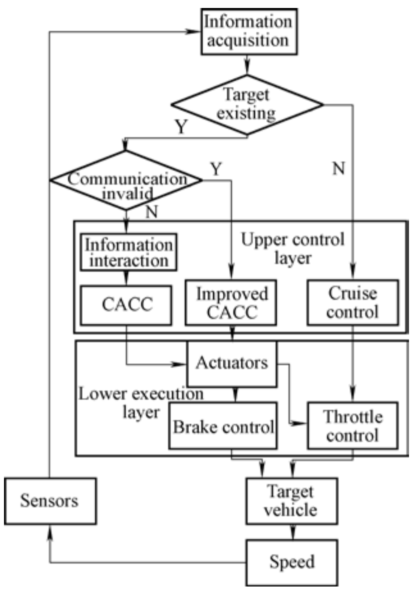

Fig. 1. Structure of CACC

2.1 CACC algorithm based on sliding control

In the CACC platoon, vehicles communicate with each other to exchange information, thus facilitating fleet cooperative control. The latest Wi-Fi is based on the IEEE802.11g communication protocol and utilizes 2.4 GHz band, transmission speed of up to 54 Mb/s, and maximum transmission distance of 6.5 km. Such communication technology is suitable for vehicle communications owing to its high stability.

The leading vehicle of the platoon controlled by the CACC controller runs along certain orbits, followed by the other vehicles. The platoon structure is shown in Fig. 2.

Fig. 2. CACC platoon

In Fig. 2, the CACC platoon obtains the acceleration information by the communication system according to the CACC algorithm with Wi-Fi. Hence, the CACC controller Y can sum the spacing error and calculate the relative speed of the following vehicles, which tends to approach zero:

$$Y \equiv \delta_i(t)+\dot{\xi}_i(t) := \dot{\xi}_i(t)+\xi_i(t)-hv_i(t)-D_{\min}, \quad (1)$$

where $\delta_i(t)$ is the deviation between the real spacing and the desired spacing; $\xi_i(t)$ represents the real spacing (real following distance) between vehicle i and vehicle $i-1$; $\dot{\xi}_i(t)$ is the derivative of $\xi_i(t)$, i.e., the relative speed; $D_{\min}$ denotes the minimum distance of the two successive following vehicles when the platoon of vehicles stands still; h denotes the constant time headway (CTH) of the vehicle $i-1$; and $v_i(t)$ denotes the velocity of the vehicle i.

All the above can be represented as follows:

$$\delta_i(t)=\xi_i(t)-hv_i(t)-D_{\min}, \quad (2)$$

$$\xi_i(t)=x_{i-1}(t)-x_i(t)-l, \quad (3)$$

$$\dot{\xi}_i(t)=v_{i-1}(t)-v_i(t),. \quad (4)$$

where l is the vehicle length. Using the sliding control method, we can obtain $Y\to 0$ (i.e., $\delta_i(t)+\dot{\xi}(t)\to 0$), when $\dot{Y}=-\lambda Y$ ($\lambda>0$) the equation is true, and λ is the control parameter.

Taking the time delay of the actuators and sensors into consideration, the CACC controller $U_i(t)$ is represented as follows:

$$U_i(t)=\frac{1}{H}\left\{\dot{\xi}_i(t)+\dot{v}_{i-1}(t)+\lambda\left[\delta_i(t)+\dot{\xi}_i(t)\right]\right\}. \quad (5)$$

Delay time exists in the data transmission process in actual communication systems; hence it must be taken into account when calculating the expected acceleration algorithm. The time compensation is represented by Δ, which means that the expression of the control law $U_i(t)$

is replaced with $U_i(t-\Delta)$:

$$U_i(t-\Delta)=\frac{1}{H}\{\dot{\xi}_i(t-\Delta)+\dot{v}_{i-1}(t-\Delta)+\lambda\left[\delta_i(t-\Delta)+\dot{\xi}_i(t-\Delta)\right]\}. \tag{6}$$

where $H=h+1$ and $\dot{Y}+\lambda Y=0$ is established.

2.2 String stability of the CACC platoon

According to Ref. [21], based on the vehicle longitudinal dynamics model, vehicle i has a delay of Δ seconds to respond to the actuators, and suffers a lag of τ seconds to respond to the commanding signal. Combining the equations of the controller, the longitudinal dynamics equation of the following vehicle i is as follows:

$$\tau\dot{a}_i(t)+a_i(t)=\frac{1}{H}\{\dot{\xi}_i(t-\Delta)+\dot{v}_{i-1}(t-\Delta)+\lambda\left[\delta_i(t-\Delta)+\dot{\xi}_i(t-\Delta)\right]\}. \tag{7}$$

Similarly, the longitudinal dynamics equation of the following vehicle $i-1$ is as the following:

$$\tau\dot{a}_{i-1}(t)+a_{i-1}(t)=\frac{1}{H}\{\dot{\xi}_{i-1}(t-\Delta)+\dot{v}_{i-2}(t-\Delta)+\lambda\left[\delta_{i-1}(t-\Delta)+\dot{\xi}_{i-1}(t-\Delta)\right]\}. \tag{8}$$

The above two equations show the acceleration and spacing error, and the distance between vehicle i and vehicle $i-1$. After subtracting Eq. (8) from Eq. (7), the following Eq. (9) is obtained through a differential and a Laplace transform:

$$H(s)=\frac{\delta_i(s)}{\delta_{i-1}(s)}=\frac{\left[s^2+(1+\lambda)s+\lambda\right]\exp(-\Delta s)}{H\tau s^3+Hs^2+(1+H\lambda)s\exp(-\Delta s)+\lambda\exp(-\Delta s)}. \tag{9}$$

Eq. (9) is the spacing error dynamic model for a platoon controlled by CACC in the frequency domain. In order to maintain stability, which means keeping $|H(\mathrm{j}\omega)|<1$, the following two conditions should be satisfied.

Condition 1: According to $|H(\mathrm{j}\omega)|<1$, the controller parameter λ takes any value in the following range:

$$\lambda\in\left(0,\frac{h^2+2h-2(h+1)(\Delta+\tau)}{2(h+1)^2(\Delta+\tau)-2(h+1)\Delta\tau}\right). \tag{10}$$

Condition 2: Because the controller parameter $\lambda>0$, fixed time spacing should be described as follows:

$$h>2\frac{h+1}{h+2}(\Delta+\tau), \tag{11}$$

where Δ is the delay time of communication and τ is the delay time of the actuators.

When the two conditions are satisfied, $|H(\mathrm{j}\omega)|<1$ can be founded for any $\omega\,(\omega>0)$, and the platoon controlled by CACC can maintain string stability.

3 Improved CACC Algorithm in Case of Communication Being Partially Invalid

In this section, we demonstrate that the traditional CACC algorithm cannot ensure string stability under consideration of the communication being partially invalid, and the CACC algorithm how to be improved to meet the requirements of string stability.

3.1 Improved control algorithm for vehicle *i*

In case of invalid communication for vehicle i, the following vehicle i cannot obtain the acceleration information of the preceding vehicle $i-1$, making the traditional CACC algorithm dysfunctional. Therefore, the algorithm should be improved in cases such that the communication between vehicle i and vehicle $i-1$ is not available, but vehicle $i-1$ can communicate with vehicle $i+1$, as shown in Fig. 3.

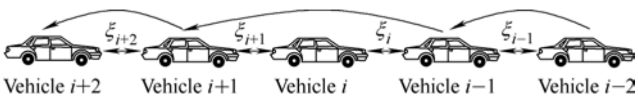

Fig. 3. CACC platoon in cases of invalid communication (vehicle i cannot communicate with vehicle $i-1$)

In Fig. 3, according to string stability, the communication of vehicle i is invalid, making it unable to obtain the acceleration information of the preceding vehicle.

The aim of the controller design is to make the spacing error at a minimum, hence it is important to maintain the ideal distance. The equation is as follows:

$$Y_i\equiv\delta_i(t):=\xi_i(t)-h_iv_i(t)-D_{\min}. \tag{12}$$

Using the sliding control method, we can obtain $Y_i\to 0$ (i.e., $\delta_i(t)+\dot{\xi}_i(t)\to 0$), when $\dot{Y}_i=-\lambda_iY_i$ ($\lambda_i>0$) the equation is true, and λ_i is the control parameter.

The CACC controller $U_i(t)$ is shown as the following:

$$U_i(t)=\dot{v}_i(t)=\frac{1}{h_i}\left[\dot{\xi}_i(t)+\lambda_i\right]. \tag{13}$$

$\dot{Y}_i+\lambda_iY_i=0$ is established, indicating that the controller $U_i(t)$ can make the spacing error approaching to zero.

Taking the time delays of the actuators and sensors into consideration, when the communication of vehicle i is invalid, the CACC controller $U_i(t)$ is as follows:

$$U_i(t)=u_i(t-\Delta)=\frac{1}{h_i}\left[\dot{\xi}_i(t-\Delta)+\lambda_i\delta_i(t-\Delta)\right]. \tag{14}$$

Based on the vehicle longitudinal dynamics model, the following equation is obtained:

$$U_i(t) = \tau \dot{a}_i(t) + a_i(t), , \quad (15)$$

where $a_i(t)$ is the acceleration of the vehicle i; The lag time of the actuators is denoted by $\tau(s)$. Combining this with the equation of the controller, the longitudinal dynamics equations of the following vehicle i and its preceding vehicle $i-1$ are shown as follows:

$$\tau \dot{a}_i(t) + a_i(t) = \frac{1}{h}\left\{\dot{\xi}_i(t-\Delta) + \lambda\left[\xi_i(t-\Delta) - hv_i(t-\Delta) - D_{\min}\right]\right\}, \quad (16)$$

$$\tau \dot{a}_{i-1}(t) + a_{i-1}(t) = \frac{1}{h}\left\{\dot{\xi}_{i-1}(t-\Delta) + \lambda\left[\xi_{i-1}(t-\Delta) - hv_{i-1}(t-\Delta) - D_{\min}\right]\right\}. \quad (17)$$

After subtracting Eq. (17) from Eq. (16) to obtain a differential and a Laplace transform, the following is concluded:

$$H(s) = \frac{\delta_i(s)}{\delta_{i-1}(s)} = \frac{\left[s+\lambda_i\right]\exp(-\Delta s)}{h_i\tau s^3 + h_i s^2 + (1+h_i\lambda_i)s\exp(-\Delta s) + \lambda_i\exp(-\Delta s)}. \quad (18)$$

To maintain communication stability, when the communication of vehicle i is invalid, $\left|H(\mathrm{j}\omega)\right| < 1$ must be satisfied; hence the range of the controller parameter λ is as follows:

$$\lambda_i \leqslant \frac{h_i - 2(\Delta+\tau)}{2\left[h_i(\Delta+\tau) - \Delta\tau\right]}. \quad (19)$$

In addition, because the controller parameter meets $\lambda > 0$, the fixed time spacing should be satisfied as follows:

$$h_i > 2(\Delta+\tau). \quad (20)$$

The controller parameter λ should be adjusted as above to ensure the communication stability and keep vehicle i in the platoon.

3.2 Improved control algorithm for vehicle $i+1$

In case of invalid communication for vehicle i, the following vehicle $i+1$ cannot obtain the acceleration information of the preceding vehicle i. Vehicle $i+1$ will communicate with vehicle $i-1$, and vehicle $i+1$ will obtain the acceleration information of vehicle $i-1$. The controller $U_{i+1}(t)$ is shown as follows:

$$U_{i+1}(t) = \frac{1}{H}\{\dot{\xi}_{i+1}(t-\Delta) + \dot{v}_{i-1}(t-\Delta) + \lambda\left[\delta_{i+1}(t-\Delta) + \dot{\xi}_{i+1}(t-\Delta)\right], \quad (21)$$

then,

$$\xi_{i+1}(t) = x_{i-1}(t) - x_{i+1}(t) - 2l, \quad (22)$$

$$\dot{\xi}_{i+1}(t) = v_{i-1}(t) - v_{i+1}(t), \quad (23)$$

where $\delta_i(t)$ is the deviation between the real spacing and the desired spacing:

$$\delta_{i+1}(t) = \xi_{i+1}(t) - h_{i+1}v_{i+1}(t) - h_i v_i(t) - 2D_{\min}. \quad (24)$$

Based on the vehicle longitudinal dynamics model, $U_i(t) = \tau\dot{a}_i(t) + a_i(t)$, the lag time of the actuators is denoted by *τ(s)*. Combining this with the equation of the controller, the longitudinal dynamics equations of the following vehicle $i+1$ and its preceding vehicle $i-1$ are shown as follows:

$$\tau\dot{a}_{i+1}(t) + a_{i+1}(t) = \frac{1}{H}\{\dot{\xi}_{i+1}(t-\Delta) + \dot{v}_{i-1}(t-\Delta) + \lambda\left[\delta_{i+1}(t-\Delta) + \dot{\xi}_{i+1}(t-\Delta)\right]\}. \quad (25)$$

Similarly, the longitudinal dynamics equation of the following vehicle $i-1$ is shown as below:

$$\tau\dot{a}_{i-1}(t) + a_{i-1}(t) = \frac{1}{H}\{\dot{\xi}_{i-1}(t-\Delta) + \dot{v}_{i-2}(t-\Delta) + \lambda\left[\delta_{i-1}(t-\Delta) + \dot{\xi}_{i-1}(t-\Delta)\right]\}. \quad (26)$$

After subtracting Eq. (26) from Eq. (25) to obtain a differential and a Laplace transform, the following equation is obtained:

$$H(s) = \frac{\delta_{i+1}(s)}{\delta_{i-1}(s)} = \frac{\left[s^2 + (2+\lambda)s + \lambda\right]\exp(-\Delta s)}{H\tau s^3 + Hs^2 + (2+H\lambda)s\exp(-\Delta s) + 2\lambda\exp(-\Delta s)}. \quad (27)$$

To maintain communication stability when communication of the vehicle i is invalid, $\left|H(\mathrm{j}\omega)\right| < 1$ must be satisfied; hence the range of controller parameter λ is as follows:

$$\lambda_{i+1} \in \left(0, \frac{{h_{i+1}}^2 + 4h_{i+1} - 2(h_{i+1}+1)(\Delta+\tau)}{2(2h_{i+1}+1)^2(\Delta+\tau) - 2(2h_{i+1}+1)\Delta\tau}\right). \quad (28)$$

Additionally, because the controller parameter meets $\lambda > 0$, the fixed time spacing should be satisfied as

$$h_{i+1} > 2\frac{h_{i+1}+1}{h_{i+1}+4}(\Delta+\tau) . \tag{29}$$

The controller parameters should be adjusted as above to ensure communication stability and keep the vehicle i in the platoon.

In conclusion, the sliding controller parameters should be satisfied as follows:

$$\begin{cases} \lambda \in \left(0, \dfrac{h^2+2h-2(h+1)(\Delta+\tau)}{2(h+1)^2(\Delta+\tau)-2(h+1)\Delta\tau}\right), \text{valid}, \\ \lambda_i \leqslant \dfrac{h_i-2(\Delta+\tau)}{2\left[h_i(\Delta+\tau)-\Delta\tau\right]}, \text{invalid}, \\ \lambda_{i+1} \in \left(0, \dfrac{h_{i+1}{}^2+4h_{i+1}-2(h_{i+1}+1)(\Delta+\tau)}{2(2h_{i+1}+1)^2(\Delta+\tau)-2(2h_{i+1}+1)\Delta\tau}\right), \text{invalid}. \end{cases} \tag{30}$$

The fixed time spacing should be satisfied as follows:

$$\begin{cases} h > 2\dfrac{h+1}{h+2}(\Delta+\tau), \\ h_i > 2(\Delta+\tau), \\ h_{i+1} > 2\dfrac{h_{i+1}+1}{h_{i+1}+4}(\Delta+\tau). \end{cases} \tag{31}$$

In case of invalid communication for vehicle i, the traditional CACC algorithm should be adjusted, and the algorithm for vehicle i and vehicle $i+1$ should be improved with the other maintaining invariants. The controller parameters should be adjusted to maintain communication stability when the communication of vehicle i is invalid and ensure that vehicle i is kept in the platoon. Chain collisions arising from invalid communication can be avoided.

4 Simulation Results

In the initial situation, the leading vehicle stands still, v_0=0 m/s and a_0=0 m/s^2. After continuous acceleration, the speed of the leading vehicle reaches v_f=40 m/s at time t=20 s. Its speed then remains constant. The other four vehicles' initial state is the same as that of the head vehicle, and they are as following.The initial spacing between any two vehicles is 5 m. The parameters of CACC are shown in Table 1.

Table 1. Parameters of the traditional CACC

Parameter	Value
Constant time headway (CTH) h/s	0.8
Time compensation of communication systems Δ/s	0.2
Lag time of the actuators τ/s	0.2
Sliding control parameter λ/s	0.3

4.1 Results of traditional CACC in case of communication being partially invalid

In this case, we assume that the communication of the third vehicle is invalid at t=10 s. The result of the traditional CACC platoon is shown as Figs. 4–6.

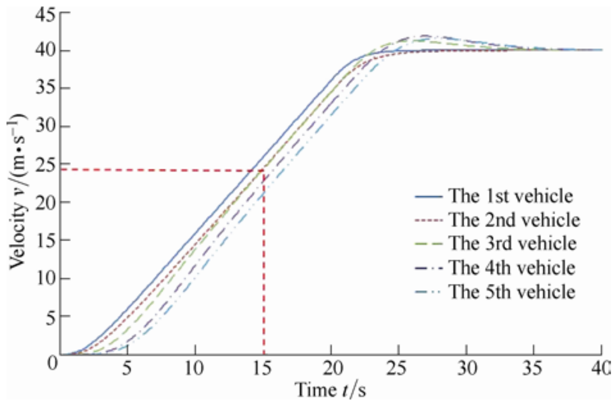

Fig. 4. Velocity curve of the traditional CACC platoon

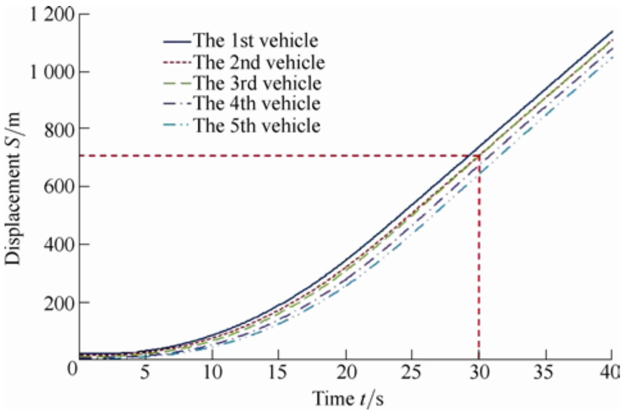

Fig. 5. Displacement curve of the traditional CACC platoon

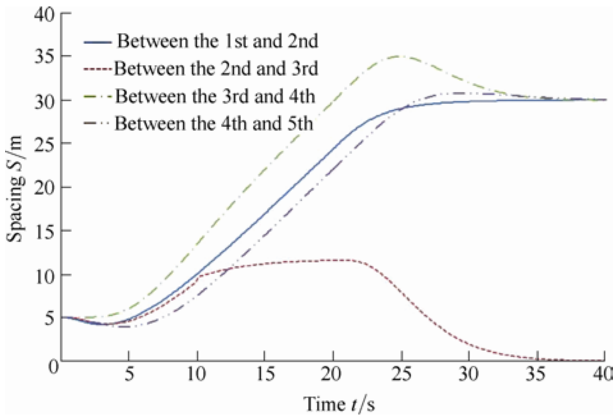

Fig. 6. Spacing curve of the traditional CACC platoon

As shown in the above figures, at t=15 s, the speed of the third vehicle is higher than that of the second vehicle; and the conditions of string stability are not satisfied. At t=30 s, the displacement of the third vehicle is more than that of the second vehicle, and the collision accident occurred. In addition, the spacing between the second and third vehicles tends to reach zero. String stability cannot be maintained, and chain collisions happen under actual circumstances.

4.2 Results of the improved CACC in case of communication being partially invalid

In order to solve the problem of the communication of the third vehicle being invalid, the CACC controller of the third vehicle is improved, and the parameters are adjusted according to Eq. (30) and Eq. (31) to meet the requirements of string stability as shown in Table 2.

Table 2. Adjusted parameters of CACC

Parameter	Value
Constant time headway (CTH) h_3/s	1
Time compensation of communication systems Δ_3/s	0.2
Lag time of the actuators τ_3/s	0.2
Sliding control parameter λ_3/s	0.1

The simulation result of the improved CACC platoon is shown as Figs. 7–9. As shown in Figs. 7–9, the third vehicle's communication turns invalid at t=10 s, and the control algorithm switches at the same time to the improved CACC. As a result, the spacing between the third vehicle and the second vehicle was enlarged to prevent accidents. The displacement of the third vehicle is always less than that of the second vehicle, and there is no impact to the other vehicles' spacing. Chain collisions are therefore prevented.

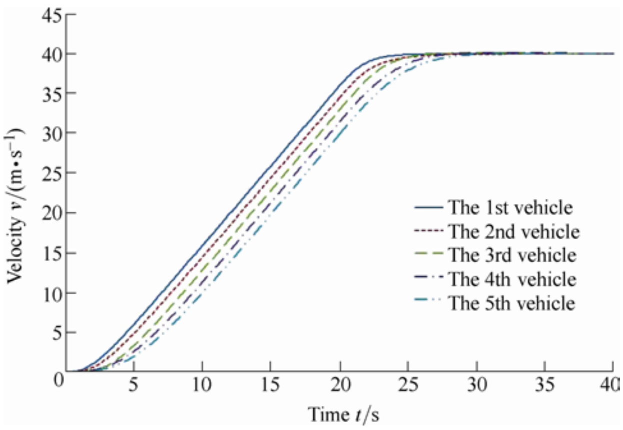

Fig. 7. Velocity curve of the improved CACC platoon

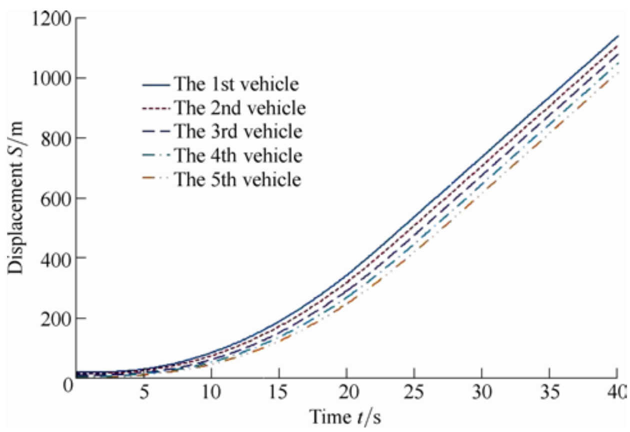

Fig. 8. Displacement curve of the improved CACC platoon

5 Conclusions

(1) This paper presents the improved CACC algorithm based on the sliding mode control algorithm. It establishes a dynamic model of vehicle spacing deviation in a platoon and analyzes the vehicle stability conditions under improved CACC.

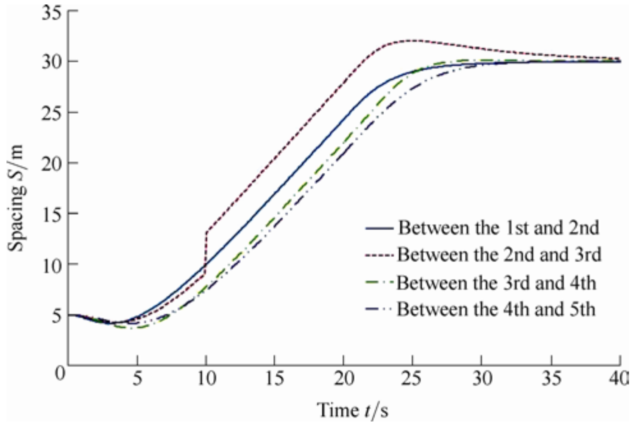

Fig. 9. Spacing curve of the improved CACC platoon

(2) The CACC algorithm is verified through an automatic platoon model involving five vehicles.

(3) The paper analyzes the improved CACC algorithm and the adjusted controller parameters to maintain string stability under the condition of communication being partially invalid.

(4) The feasibility of the algorithm has been demonstrated through model simulation. The improved CACC algorithm achieves vehicle-following effects and effectively maintains string stability.

(5) It covers the shortages of the traditional CACC algorithm by avoiding oscillation of vehicle spacing and chain collision accidents caused by partially invalid communication.

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