Benefits of Communication for Enhancing Cooperative Behavior in a Vehicle Platooning Application

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Abstract: Collaborative driving, enabled by the integration of communication among automated vehicle systems, holds great potential to enhance transportation safety and efficiency. One prominent application in this area is Cooperative Adaptive Cruise Control (CACC), particularly in vehicle platooning, which has garnered significant research attention. However, communication disruptions—caused by issues such as signal obstruction, weak transmission, or equipment malfunctions—can compromise the stability of vehicle strings and increase the risk of collisions. To address this challenge, this study introduces a fallback mechanism for the CACC system. Specifically, when communication failures occur, the system transitions to the ACC_2 mode, leveraging onboard sensors to maintain operations. The effectiveness of this approach in preserving string stability is demonstrated through a series of comparative analyses and numerical simulations.

Keywords: Intelligent Driver Assistance, Communication Interruption, Time Headway, Car Platooning, String Stability.

1. INTRODUCTION

Cooperative car groups enhance the performance of automated cars Wu et al. (2025), Mohammadi et al. (2025), Viet Hung et al. (2024). In this case, cars can capitalize on the group's regulations to enhance travel quality and minimize costs. Adequate headway between vehicles must be maintained to avoid collisions. Within the group, cars can share sensor measurements, action predictions, and state information. These data can then be utilized to formulate control algorithms.

One commonly employed car group structure is the platoon, which comprises a leading car followed by a series of follower cars. The leader's role is to guide the platoon with a predetermined velocity, while each follower is tasked with maintaining a desired safety distance from the preceding car. Each car has the ability to transmit information regarding its velocity, position, commands, and more to the car trailing behind it, thus improving platoon performance Orosz (2019), Apostolakis et al. (2023), Cai et al. (2023), Luu et al. (2022a).

ACC-based platooning operates independently of inter-vehicle communication and does not require cooperative interactions between cars Luu et al. (2021a). Instead, these systems depend on onboard sensors, such as radar, to determine the relative speed and spacing between vehicles in the formation Luu et al. (2021b), Guo et al. (2017). In recent years, the research community has been focused on advancements of ACC, namely CACC system, which possess an added capability of receiving state information, usually acceleration, directly from the preceding car through wireless Vehicle-to-Vehicle (V2V) communication Dai et al. (2023), Luu et al. (2022b), Balador et al. (2022), Tiganasu et al. (2021). Cooperative car groups rely on V2V communication, enabling group members to establish continuous contact with their neighboring cars. This enables them to respond more rapidly to alterations in traffic conditions, in contrast to relying solely on onboard sensors.

Maintaining string stability is a critical aspect of safe and efficient platoon operations. To achieve string stability, disturbances originating at the front of the platoon must attenuate as they travel downstream, thereby preventing amplification of errors and reducing the risk of collisions within the vehicle group Swaroop and Hedrick (1996), Corli and Fan (2023), Feng et al. (2023). Because of the benefits gained from information exchange among CACC cars, maintaining the stability of the platoon can be easily ensured Darbha et al. (2018). There are also numerous studies conducted in this field Zhang et al. (2023), Naus et al. (2010). Currently, various communication modes are found in some studies: Dedicated short range communications in Alipour et al. (2017), LTE in Chen et al. (2016) and other communication modes in the Internet of cars are discussed in Feng et al. (2023). Communication delays and interruptions are common, often arising from factors such as channel obstructions, weak signal strength, or equipment malfunctions. Under such circumstances, the functionality of the CACC system is inevitably compromised due to missing control inputs or delayed transmissions. V2V communication can have a negative impact on the performance, and stability of a CACC platoon due to factors like time delay and data packet losses Godinho et al. (2023), Maxim et al. (2020), Chehardoli (2023), Tan et al. (2023). This highlights the necessity for communication devices in the CACC system to sustain a high signal transmission frequency and a minimal packet loss rate within a given time frame to uphold string stability.

In Ploeg et al. (2014), the authors applied a Kalman filter to estimate the acceleration of the lead vehicle during communication interruptions. Their experimental results indicated that increasing the time headway of a malfunctioning vehicle could help maintain string stability. Similarly, Gong et al. (2019) proposed a CACC scheme incorporating a dynamic information flow topology, which enables the system to adaptively select a suitable CACC strategy during packet losses, avoiding a direct fallback to the ACC algorithm. While these approaches effectively ensure string stability during communication interruptions, they impose constraints, such as the need to increase the time headway. In cases where a CACC platoon operates with a relatively small time headway, a sudden communication interruption might prevent timely system adjustments, thereby increasing the risk of collisions.

Existing fallback or hybrid CACC strategies typically resort to increasing time headway during communication disruptions or adapting the control law based on vehicle dynamics and environmental conditions Bian et al. (2019), Abolfazli et al. (2021), Vegamoor et al. (2019). In Ploeg et al. (2014), the authors applied a Kalman filter to estimate the acceleration of the lead vehicle during communication interruptions. Their experimental results indicated that increasing the time headway of a malfunctioning vehicle could help maintain string stability. Gong et al. (2019) proposed a CACC scheme incorporating a dynamic information flow topology, which enables the system to adaptively select a suitable CACC strategy during packet losses, avoiding a direct fallback to the ACC algorithm. While these approaches effectively ensure string stability during communication interruptions, they impose constraints, such as the need to increase the time headway. These methods may lead to inefficiencies in traffic flow or a significant increase in the headway between vehicles, thereby reducing the platooning benefits such as fuel savings and reduced congestion. The novelty of our proposed approach lies in the introduction of an ACC_2 fallback mode for maintaining string stability and traffic flow in the event of communication disruptions, which does not require increasing the time headway between vehicles and without the need for real-time sensor recalibration.

The main contribution of this paper is the analysis of the string stability of the platoon for the CACC system, the traditional ACC_1 system, and the advanced ACC_2 system under different time headway values. In this context, the CACC system in a platoon utilizes communication with the directly preceding vehicle, whereas both the traditional ACC_1 system and the advanced ACC_2 system correspond to the loss-of-communication mode. In fact, communication interruptions frequently occur, the solution given to solve the problem of string stability is the CACC system can switch to the ACC_1 system or ACC_2 system without changing the time headway. The simulation results show that the proposed method offers considerable flexibility.

The study is structured as follows: In Section 2, we first consider the modeling of cars. Then cooperative control algorithms are presented in Section 3. In Section 4, vehicle platooning string stability analysis for the following car is presented. In Section 5, simulations study are implemented with performance analysis, and in Section 6, conclusions will close this study.

2. DYNAMIC MODELING

According to Newton's second law, the force equilibrium along the longitudinal axis of a vehicle can be expressed as follows:

$$m\ddot{p}(t) = F_v - T_R, \tag{1}$$

where, m is the weight of the car, p is the longitudinal position, F_v is the actuation force generated by the engine and drive-train,and the resistance forces include the resistance to the air, road friction, the resistance to gradients which are defined as:

$$T_R = \frac{1}{2}\rho_v C_v A_v v^2 + mgsin\vartheta + C_r mg\cos\vartheta, \tag{2}$$

where, g is the gravity constant, ϑ is the road slope, ρ_v is the air density, A_v is the windward area of the car, C_v is the air resistance coefficient, C_r is a modified resistance coefficient to take account of cornering resistances.

Substituting Eq.2 into Eq.1:

$$m\ddot{p}(t) = F_v - \frac{1}{2}\rho_v C_v A_v v^2 - mgsin\vartheta - C_r mg\cos\vartheta, \tag{3}$$

where, the time lag constant of the car is denoted as τ_v, with the assumption that $\tau_v \le \tau_0$, where τ_0 represents the upper bound of the time lag constant and is set to 0.5s. Consequently, the variation in the actual acceleration of the car may be expressed as follows:

$$\dddot{p} = \frac{1}{m\tau_v}(F_u - F_v). \tag{4}$$

Bring Eq.1 into Eq.4:

$$\dddot{p} = \frac{1}{m\tau_v}(F_u - m\ddot{p} - mgsin\vartheta - C_r mg\cos\vartheta - \frac{1}{2}\rho_v C_v A_v v^2). \tag{5}$$

The expected traction force applied to the car is represented by:

$$F_u = mu + mgsin\vartheta + C_r mg\cos\vartheta + \frac{1}{2}\rho_v C_v A_v v^2, \tag{6}$$

where, u_i represents the desired acceleration determined by the car's controller. By substituting Eq.6 into Eq.5, the following is obtained:

$$\begin{aligned} \dddot{p} &= \frac{1}{\tau_v}(u - \ddot{p}) \\ \tau_v \dot{a}_i + a_i &= u_i. \end{aligned} \tag{7}$$

The linear state-space representation of the car's dynamics may be expressed as follows:

$$\begin{aligned} \dot{x} &= A_v x + b_u u \\ y &= cx, \end{aligned} \tag{8}$$

In Eq.7:

$$A_v = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau_v} \end{bmatrix}; b_u = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\tau_v} \end{bmatrix}; c = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$x = [p \ \ v \ \ a]^T$$

3. COOPERATIVE CONTROL ALGORITHMS

We consider a platoon of homogeneous $N+1$ cars, consisting of a leader and N followers, indexed $i = 1,...,N$, traveling from left to right in a single lane (as shown in Fig.1).Each car in the platoon leverages V2V communication devices to acquire the expected acceleration and other pertinent data from the preceding car. Additionally, radar sensors are installed on each car to detect positional information.

For the followers, the reference distance is determined using the constant time headway strategy Hung et al. (2024), which is defined as follows:

$$d_{i,r} = r_0 + r_i v_i, \tag{9}$$

in which, r_0 is the desired spacing at standstill, r_i is the the time headway and v_i is the measured speed of car i.

The distance between the following car and the preceding car is determined using a radar sensor installed on the front bumper of each car and is formulated as follows:

$$d_i = p_{i-1} - p_i - L_v, \tag{10}$$

in which, p_{i-1}, p_i are the position of the rear bumper of the car i and $i-1$, L_v is the length of the car.

The deviation for the closed-loop system between the real distance and the reference distance is defined as:

$$e_i = p_{i-1} - p_i - L_v - d_{i,r}. \tag{11}$$

The primary control objective is to reduce the error and bring it as close to zero as possible.

In conjunction with Eq.7, the third-order derivative of e_i is expressed as follows:

$$\dddot{e}_i = \frac{-1}{\tau_v}\ddot{e}_i + \frac{1}{\tau_v}(u_{i-1} - u_i - r_i\dot{u}_i), \tag{12}$$

in which, u_{i-1} represents the expected acceleration of the preceding car.

To minimize the distance error e_i and bring it closer to zero, the expected acceleration of the current car must be adjusted to counteract the influence of the preceding car's acceleration. By combining this with Eq.12, it can be concluded that the distance error e_i should depend solely on its first-order and second-order derivatives.

$$u_{i-1} - u_i - r_i\dot{u}_i = k_1 e_i + k_2\dot{e}_i + k_3\ddot{e}_i. \tag{13}$$

The expected acceleration of the preceding car, u_{i-1}, can be acquired through V2V communication devices (as illustrated in the block diagram in Fig.2). Based on this, the control law for the CACC vehicle can be formulated as follows:

$$r_i\dot{u}_{i,CACC} + u_{i,CACC} = -(k_1 e_i + k_2\dot{e}_i + k_3\ddot{e}_i - u_{i-1,CACC}). \tag{14}$$

In practice, wireless channels are prone to packet loss due to interference and bandwidth limitations. When this occurs, the affected car cannot receive the expected acceleration data from the preceding car and must rely solely on its onboard sensors to acquire positional information. The system allows for a switch from CACC to ACC mode when there is no communication

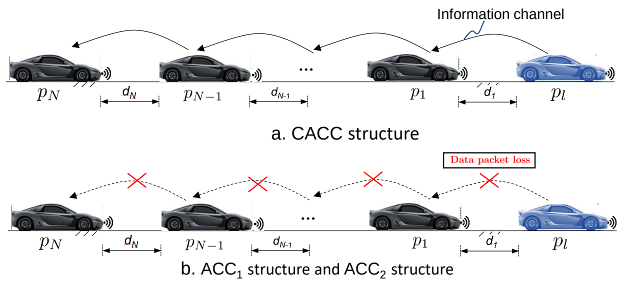

Fig. 1. Platoon control structure

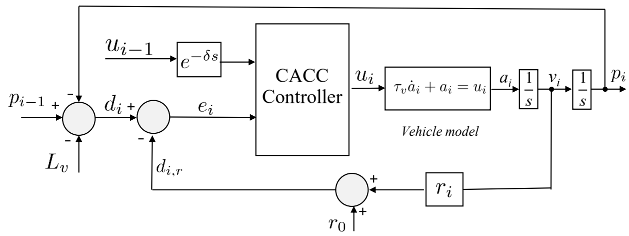

Fig. 2. CACC control structure

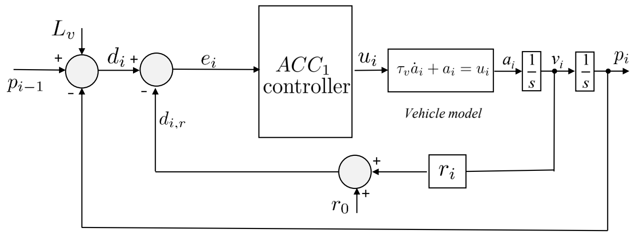

Fig. 3. ACC$_1$ control structure

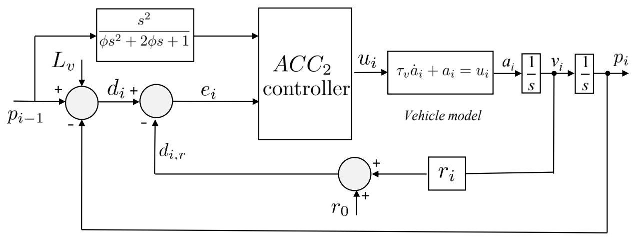

Fig. 4. ACC$_2$ control structure

available (see the block diagram of in Fig.3). The control law for the ACC$_1$ car can be derived as follows:

$$r_i\dot{u}_{i,ACC_1} + u_{i,ACC_1} = -(k_1 e_i + k_2\dot{e}_i + k_3\ddot{e}_i). \tag{15}$$

Wireless channels are vulnerable to packet drops caused by interference or bandwidth limitations. In such cases, the car must rely solely on its onboard sensors to detect the position of the preceding car. The actual acceleration of the preceding vehicle can then be estimated by calculating the second-order derivative of its position. However, when using sensors for position detection, fluctuations are common and may affect the accuracy of the measurements. Performing the second-order differentiation directly can lead to the value becoming infinity. To address this issue, it is necessary to add a secondary filter. However, it is important to note that the coefficient of the secondary filter should not be too large. A large coefficient can significantly impact the amplitude and phase of the acceleration. The substitution of ACC$_2$ as in Fig.4 can be expressed as follows:

$$r_i \dot{u}_{i,ACC_2} + u_{i,ACC_2} = -[k_1 e_i + k_2 \dot{e}_i + k_3 \ddot{e}_i - \frac{s^2 x_{i-1}}{(\phi s+1)^2}]. \quad (16)$$

4. VEHICLE PLATOONING STRING STABILITY ANALYSIS

String stability is a property that ensures deviations in distance, speed, or acceleration between vehicles upstream do not amplify as they propagate through the platoon. If these errors are amplified from one car to the next, it will result in increased control efforts for the rear cars. This can adversely affect driving comfort and may increase the risk of rear-end collisions.

The transfer function of the position between adjacent cars is defined as:

$$H_i(s) = \frac{p_i(s)}{p_{i-1}(s)}. \quad (17)$$

By definition, string stability can be analyzed and represented within the frequency domain.

$$\|H_i(j\omega)\|_\infty \leq 1 \Leftrightarrow \|p_{i-1}\|_\infty \geq \|p_i\|_\infty \geq \ldots \geq \|p_n\|_\infty \quad \text{for } i \geq 2. \quad (18)$$

After taking the Laplace transform Eq.14, the following is obtained:

$$r_i s u_{i,CACC}(s) + u_{i,CACC}(s) = -(k_1 + k_2 s + k_3 s^2) e_i(s) - u_{i-1,CACC}(s). \quad (19)$$

A simple calculation results:

$$u_{i,CACC}(s) = \frac{u_{i-1,CACC}(s)}{r_i s+1} - \frac{k_1 + k_2 s + k_3 s^2}{r_i s+1} e_i(s). \quad (20)$$

Bring Eq.7 into Eq.20:

$$[s^2(r_i s+1)(\tau_v s+1) - (k_1 + k_2 s + k_3 s^2)(r_i s+1)] p_i = [s^2(\tau_v s+1)e^{-\delta s} - (k_1 + k_2 s + k_3 s^2)] p_{i-1}, \quad (21)$$

where, δ is the value of the time delay. The transfer function for string stability in CACC systems is given by:

$$H_{i,CACC} = \frac{p_i(s)}{p_{i-1}(s)} = \frac{s^2(\tau_v s+1)e^{-\delta s} - (k_1 + k_2 s + k_3 s^2)}{(r_i s+1)[s^2(\tau_v s+1) - (k_1 + k_2 s + k_3 s^2)]}. \quad (22)$$

Applying a similar procedure as for the ACC_1 system, the transfer function for string stability can be derived as follows:

$$H_{i,ACC_1} = \frac{p_i(s)}{p_{i-1}(s)} = \frac{-(k_1 + k_2 s + k_3 s^2)}{(r_i s+1)[s^2(\tau_v s+1) - (k_1 + k_2 s + k_3 s^2)]}. \quad (23)$$

For the ACC system, during a communication interruption, the affected car is unable to receive the expected acceleration of the preceding car. Instead, it must rely solely on its onboard sensor to gather positional data of the preceding car. Applying the Laplace transform to Eq.16, we obtain:

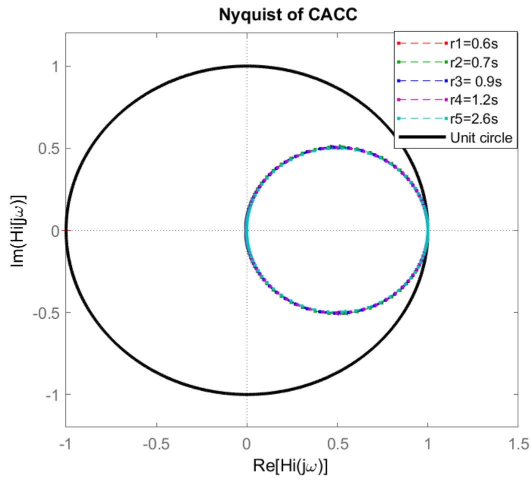

Fig. 5. String stability plots based on CACC system

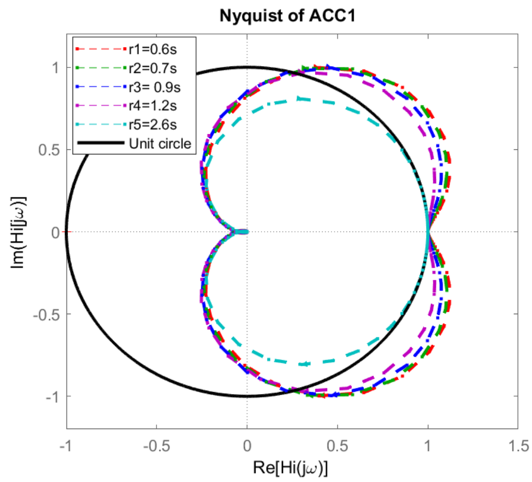

Fig. 6. String stability plots based on ACC_1 system

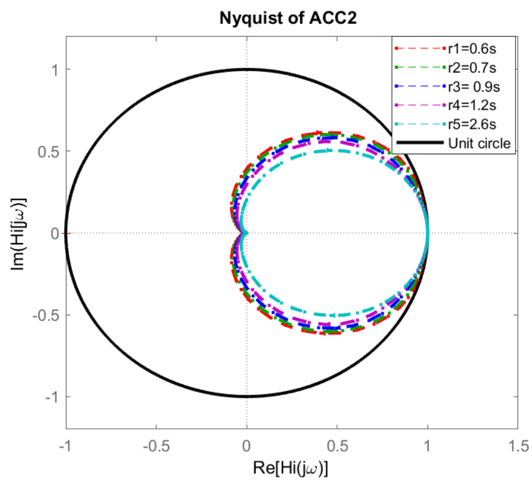

Fig. 7. String stability plots based on ACC_2 system

$$u_{i,ACC_2}(s) = \frac{p_{i-1}s^2}{(\phi s+1)^2(r_i s+1)} - \frac{k_1+k_2 s+k_3 s^2}{r_i s+1} e_i(s). \quad (24)$$

Bring Eq.7 into Eq.24:

$$s^2(r_i s+1)(\tau_v s+1)p_i(s) = \frac{s^2}{(\phi s+1)^2} p_{i-1}(s) - (k_1+k_2 s+k_3 s^2)[p_{i-1}(s) - p_i(s)(r_i s+1)]. \quad (25)$$

In the Laplace domain, this can be expressed as:

$$H_{i,ACC_2} = \frac{p_i(s)}{p_{i-1}(s)} = \frac{k_1+k_2 s+k_3 s^2 - \frac{s^2}{(\phi s+1)^2}}{(r_i s+1)[(k_1+k_2 s+k_3 s^2) - s^2(\tau_v s+1)]}. \quad (26)$$

The stability analysis of the string was performed based on the model parameters and others parameters: $\tau_v = 0.1s$, $\phi = 0.001s, \delta = 0.005s$, $k_1 = -0.3$, $k_2 = -0.8$, $k_3 = 0$, $r_i = [0.6, 0.7, 0.9, 1.2, 2.6]s$.

Figs.5, 6, 7 illustrate the Nyquist diagram of the CACC cars, ACC_1 cars, ACC_2 cars, considering the different time headways mentioned above and based on Eq.22, Eq.23, Eq.26. The Nyquist diagram provides insight into the stability and performance characteristics of the platoon for varying time heads.

The Nyquist diagrams of the transfer functions in Eq.22, Eq.23, and Eq.26 were plotted as r_i was incrementally increased from zero until stability was achieved. These diagrams are displayed within a unit circle centered at the origin, effectively demonstrating the system's stability and robustness.

The plot demonstrates that the Nyquist diagrams for the CACC system, corresponding to all r_i values, remain entirely within the unit circle. This analysis confirms that the CACC fleet reliably ensures string stability regardless of the selected time headway settings. Additionally, the diagram shows that as r_i increases, the Nyquist diagram decreases more rapidly. This indicates that larger time headways between vehicles in a string facilitate maintaining stability, thereby enhancing the overall stability of the platoon.

Fig.6 illustrates the Nyquist diagram of the ACC_1 system under various time headway settings. The figure shows that the Nyquist diagram corresponding to the same r_i as the CACC system lies outside the unit circle, indicating system instability due to the maximum magnitude exceeding 1. This implies that if a communication interruption occurs within the CACC string and no corrective action is taken, the string will become unstable. Additionally, it can be observed that the ACC_1 system achieves stability when r_i is set to $2.5s$.

Fig.7 displays the Nyquist diagram of the ACC_2 system under different time headways. From the figure, it is evident that the Nyquist diagram of the ACC_2 system for every time headway is located within the unit circle. This signifies that in the event of a sudden communication interruption, transitioning from the CACC system to the ACC_2 system can maintain string stability without requiring changes to the original time headway r_i. The string can continue to operate seamlessly under the ACC_2 system, ensuring smooth and uninterrupted functionality.

5. SIMULATIONS STUDY

To evaluate the performance of the proposed systems (CACC, ACC_1, and ACC_2), simulations were conducted in MATLAB/Simulink with the considered parameters: $L_v = 5m$, $r_0 = 2m$, $r_i = 0.75s$. The cars are lined up with respect to the initial position and velocity of each car as follows: $p_i(m) = [35; 28; 21; 7; 0]$ at $t = 0$, and $v_i = 0(m/s)$, meaning that at the time of departure the distance between each car is r_0. The scenario involved a group of identical vehicles forming a homogeneous platoon, and their behavior was observed when travelling on a highway. The following assumptions are considered in this case study:

- no speed limits are considered in this scenario.
- the platoon does not change lanes.
- no obstacles are present on the platoon's lane, and no other factors exist that might cause the platoon to split.
- the driver of the lead car in the platoon is using the onboard CC system to control its speed.
- the followers autonomously respond to the leader's accelerations or decelerations.

The velocity reference v_{ref} used in this simulation study is derived from the Highway Fuel Economy Test (HWFET), a driving cycle designed to evaluate the fuel efficiency and emission levels of passenger vehicle engines. The driving cycles are illustrated in Fig.8.

5.1 CACC simulation results

The signals obtained through simulation for the car platoon with followers containing CACC controllers are depicted in the following figures:

- Fig.9 illustrates the velocities of the followers along with the leader, with zoomed-in views in specific area.
- Fig.10 shows the inter-car distances between cars during their movement.
- Fig.11 shows the distance errors, which are the differences between the inter-vehicle distances d_i and the distance reference $d_{i,r}$.

The simulation results show that the last five cars in the platoon successfully track the speed of the lead car by the end of the simulation. In Fig.10, the distance waveforms closely follow the velocity profile set as a reference for the leader. The standstill distance is assumed to be $2m$. As the car's velocity increases, the distance between it and its predecessor correspondingly increases. This proportional relationship also holds true when the velocity decreases.

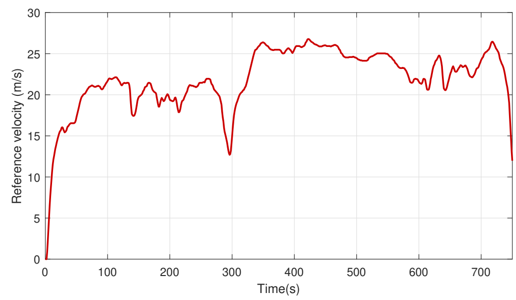

Fig. 8. Highway Fuel Economy Test (velocity reference)

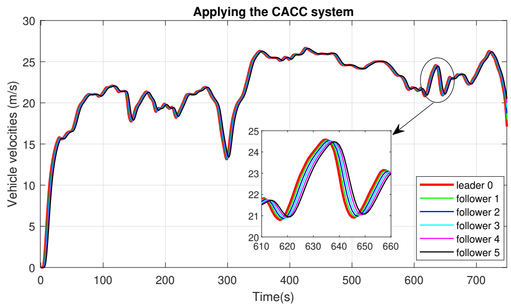

Fig. 9. The velocities of CACC cars in the platoon

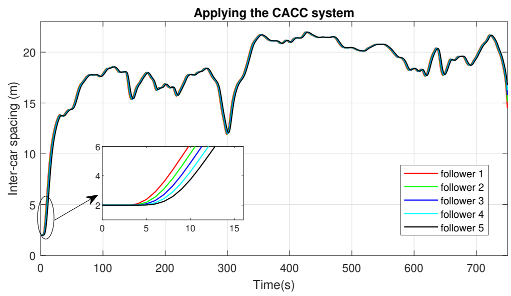

Fig. 10. The inter-car distances of CACC cars in the platoon

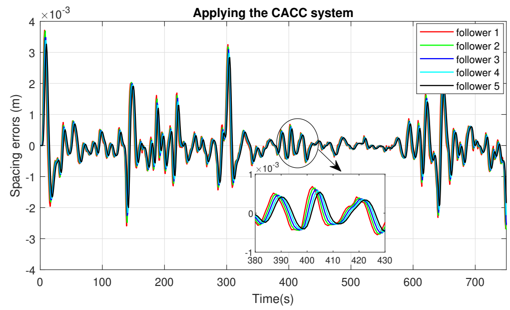

Fig. 11. The spacing errors of CACC cars in the platoon

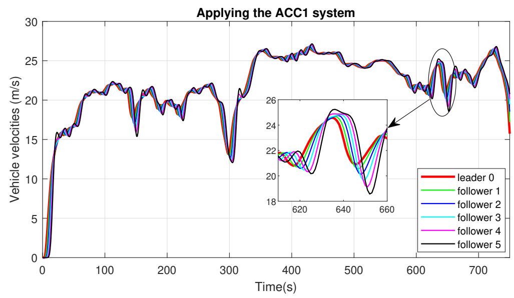

Fig. 12. The velocities of ACC_1 cars in the platoon

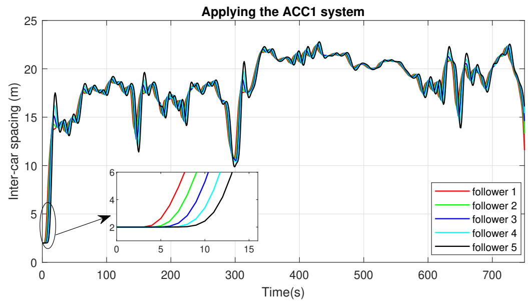

Fig. 13. The inter-car distances of ACC_1 cars in the platoon

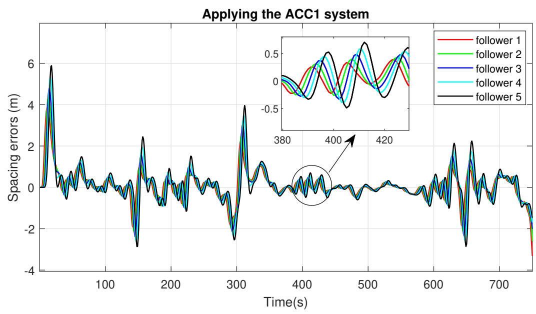

Fig. 14. The spacing errors of ACC_1 cars in the platoon

Fig.11 shows that the maximum distance error in CACC mode is approximately $0.008m$, and this value decreases over time. As the number of vehicles in the platoon increases, the spacing deviations gradually converge to zero. This demonstrates that the CACC system reliably maintains stability throughout the travel process, effectively preventing collisions or similar issues.

5.2 ACC_1 simulation results

In the case of the ACC_1 platoon implemented for the followers, the signals obtained after simulation can be observed as follows:

- Fig.12 The car speeds with zooms in a specific area are depicted in Fig. 9, showing that they closely follow the speed profile introduced as a reference for the leader.
- Fig.13 illustrates the inter-vehicle distances during the movement of the cars, the distance waveforms closely follow the velocity profile set as a reference for the leader, as can be seen in the simulation results.
- The spacing errors with zooms in a specific area obtained in this simulation case are depicted in Fig.14.

In the case of the wireless channels are susceptible to packet drops caused by interference and/or bandwidth limitations, the faulty car may not receive the expected acceleration of the preceding car. Instead, it can rely solely on the onboard sensor to obtain position information. From the spacing errors with zooms in a specific area we can find that the string is unstable, it indicates that the spacing errors between cars will progressively amplify, eventually resulting in car collision and other accidents.

5.3 ACC_2 simulation results

In the case of the platoon implemented with ACC_2 controllers for followers, the signals obtained after simulation are illustrated as follows:

- The velocities of the cars are shown in Fig.15, where it can be observed that they closely track the velocity profile set as a reference for the leader..
- Fig.16 contains the distances between cars during their movement.
- The distance errors obtained in this simulation case may be observed in Fig.17.

Each figure includes zoomed-in views of specific areas, which facilitate a detailed analysis of the results. In the ACC_2 case, The decreasing spacing errors along the platoon indicate the

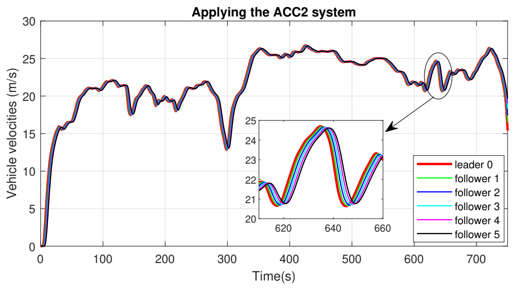

Fig. 15. The velocities of ACC_2 cars in the platoon

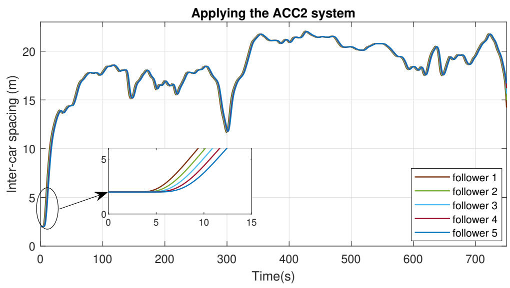

Fig. 16. The inter-car distances of ACC_2 cars in the platoon

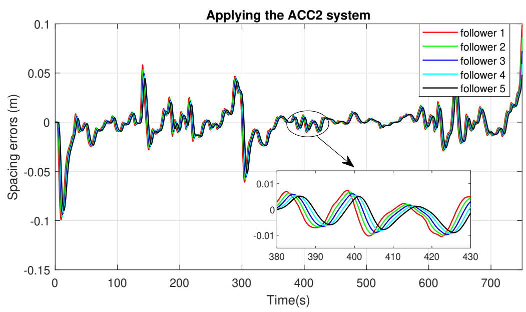

Fig. 17. The spacing errors of ACC_2 cars in the platoon

string stability of a platoon when a sudden communication interruption occurs.

5.4 Comparative Analysis

To evaluate the effectiveness of the three control algorithms CACC, ACC_1, and ACC_2 the maximum spacing errors for each algorithm without considering the departure zone are presented in TABLE II. The five follower cars are labeled as 1, 2, 3, 4, and 5, respectively.

	CACC	ACC_2	ACC_1
0-1	0.003251	0.06094	2.255
1-2	0.003177	0.05835	2.617
2-3	0.003093	0.05593	3.06
3-4	0.002975	0.05382	3.449
4-5	0.002834	0.05196	3.957

From TABLE II, it can be observed that the CACC platoon demonstrates the best control performance, with the maximum spacing error being only $0.003251m$. Additionally, the spacing errors between vehicles progressively decrease along the platoon, ensuring string stability. In contrast, when communication is interrupted, the maximum spacing error in the ACC_1 platoon can reach as high as $3.957m$. In such scenarios, the spacing errors amplify progressively, making it impossible to ensure the stability of the platoon string. If the system switches to the ACC_2 platoon during a communication breakdown, the initial spacing error between vehicles may increase, but it gradually diminishes, allowing the string to maintain stability. The maximum spacing error in this case is $0.1339m$, which is comparable to that of the CACC system. However, one of the main challenges in implementing the ACC_2 fallback mode lies in proposing a filter to accurately estimate vehicle dynamics, especially the derivatives of vehicle position (velocity and acceleration), in the presence of sensor noise, while designing an efficient switching mechanism to avoid introducing delays, which can further degrade performance during communication loss.

6. CONCLUSIONS

In this paper, the CACC control law is developed based on the time headway strategy, with the goal of maintaining zero distance error as the primary control target. In cases of communication interruptions, the ACC_2 system is proposed as an alternative solution. Numerical simulations demonstrate that the CACC system effectively maintains string stability and minimizes distance errors. However, during communication disruptions, the string may become unstable, potentially resulting in rear-end collisions. By transitioning to the ACC_2 system during such interruptions, string stability can still be preserved without the need to adjust the time headway, as the control mechanism closely resembles that of the CACC system.

In reality, vehicle platooning occurs in more complex and dynamic environments. To address these limitations, future research will focus on testing the ACC_2 fallback strategy in more diverse scenarios, these include: external disturbances, heterogeneous vehicle platoons, overtaking and lane-changing maneuvers.

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AUTHORS' CONTRIBUTIONS

D. L. Luu: conceptualization, methodology, data curation, writing – review & editing. **C. Lupu**: formal analysis, software, validation. **N. S. Dong**: reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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