Cooperative Adaptive Cruise Control for a Platoon of Connected and Autonomous Vehicles
Considering Dynamic Information Flow Topology

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Abstract

Vehicle-to-vehicle communications can be unreliable as interference causes communication failures. Thereby, the information flow topology (IFT) for a platoon of Connected Autonomous Vehicles (CAVs) can vary dynamically. This limits existing Cooperative Adaptive Cruise Control (CACC) strategies as most of them assume a fixed IFT. To address this problem, we introduce a CACC scheme that considers a dynamic information flow topology (CACC-DIFT) for CAV platoons. An adaptive Proportional-Derivative (PD) controller under a two-predecessor-following IFT is proposed to attenuate the negative effects when communication failures occur. The parameters of PD controller are determined to ensure the string stability of the platoon. Furthermore, the proposed PD controller also factors the performance of individual vehicles. Hence, when communication failure occurs, the system will switch to a certain type of CACC instead of degenerating to adaptive cruise control, which improves the platoon control performance considerably. The effectiveness of the proposed CACC-DIFT is validated through numerical experiments based on NGSIM field data. Simulation results indicate that the proposed CACC-DIFT design outperforms CACC based on a predetermined information flow topology.

Keywords: Connected and autonomous vehicles, Cooperative adaptive cruise control, Communication failure, Dynamic information flow topology, String stability
INTRODUCTION

Platoon control aims to minimize the speed differences among vehicles in a group while maintaining a stable and safe headway between adjacent vehicles. It has significant potential to enhance traffic safety and highway capacity, and reduce fuel consumption. Existing studies show that autonomous vehicle (AV) platoons achieved through adaptive cruise control (ACC) can improve platoon safety and stability compared with platoons involving human drivers as AVs can execute platoon control strategies reliably and consistently. AV platoon performance can be further enhanced through cooperative adaptive cruise control (CACC) if all vehicles in the platoon are connected through vehicle-to-vehicle (V2V) communications that enables information exchange between vehicles. The communication capability in such connected autonomous vehicles also enables cooperative platoon control strategies to achieve system level objectives through coordination across all or some of the vehicles in the platoon.

The platoon control/CACC framework for CAVs typically consists of four components: (i) node dynamics, which describe the dynamics of each vehicle in the platoon, (ii) information flow topology (IFT), which describes the configuration of V2V communication links among vehicles, (iii) distributed controller, which uses information from other vehicles in the platoon to devise control strategies, and (iv) formation geometry, which describes the desired headway between vehicles. Many studies have modeled the four components of a CAV platoon realistically in different scenarios. Vehicle dynamics are generally modeled using second-order dynamics models or third-order models. Different controllers are designed to control the CAV platoon, including Proportional-Integral-Derivative (PID) controller, car-following model based controller, sliding mode controller, and model predictive controller using a constant distance (CD) policy or a constant time headway (CTH) policy with some predetermined IFT (such as predecessor-following leader, two predecessor-following, and global communication).

Although a CAV platoon has several advantages over an AV platoon, the effectiveness of platoon control depends on the number of communication failures. A communication failure may occur due to communication interference or information congestion, especially when the ambient traffic is congested. Information congestion is the reduced quality of service when a communication network node carries more data than it can handle, which in the context of V2V communications is modeled through the potential for failure of information propagation in a V2V communications-enabled traffic network. Communication interference typically refers to the disruption of a signal as it travels between a sender and a receiver. Thus, the evolving information flow topologies for a CAV platoon are critical to the performance of the platoon control, as they determine the amount of information being shared among individual vehicles through V2V communications.

Several studies have been investigating the effects of different IFTs on platoon control performance in terms of internal stability, convergence rate, etc. For example, Zheng et al. studied the influence of IFT for a homogeneous CAV platoon and introduced two methods to improve stability by carefully choosing the IFT. Zheng et al. analyzed the influence of IFT on internal stability and scalability of platoon, deriving internal stability margin and showing that a bidirectional-leader topology will improve scalability of platoon. Fax et al. demonstrated a separation principal which decomposed formation stability into two components: internal stability is achieved through information flow and controller of individual vehicle. Gong et al. illustrated analytically that the performance of platoon control in terms of string stability can
be significantly improved by using a global communication topology, that is, each vehicle has the capability to send information to and receive information from all other vehicles in the platoon. However, most studies in CACC design assume an idealized and fixed IFT. This assumption ignores the fact that the IFT can change dynamically due to communication failures \((13)(14)(18)\).

The probability of a communication failure is proportional to the number of activated V2V communications occurring within the vehicle’s communication range. Other factors, such as the dynamic CAV traffic flow density, also impact the number of ongoing communications within the communication range, and further impact communication failure. Hence, the IFT is less likely to be fixed in the real-world. Under this circumstance, a CACC based on a fixed IFT may execute an erroneous control action, which will diminish platoon performance related to mobility, stability and even safety. Moreover, string stability is also required under varying IFT condition, which is lack of analytical proof in most studies.

To attenuate the negative effects of IFT dynamics, this paper introduces a CACC that considers a dynamic IFT of a CAV platoon, labeled as CACC-DIFT. An adaptive Proportional-Derivative (PD) controller under a two predecessor-following topology is proposed to reduce the negative effects of communication failures. When a communication failure occurs, instead of directly degrading into ACC, the CAV platoon will be controlled by a CACC corresponding to the communication status of the vehicle to maintain the desired control performance. To determine the parameters of the PD controller, we would not merely consider individual vehicle stability (i.e. closed-loop stability for individual vehicle) and measurement noise mitigation, but also we would put great emphasis on ensuring the string stability of CAV platoon. The effectiveness of the proposed CACC-DIFT is validated through numerical simulation experiments based on NGSIM field data \((19)\). The study results indicate that the proposed design outperforms the CACC with a predetermined IFT.

The following parts of this paper are organized as follows. FORMULATION OF DYNAMIC IFT PROBLEM section briefly introduces the CACC based on the two predecessor-following topology and the degeneration that occurs due to the IFT dynamics. The proposed CACC-DIFT controller is formulated in DESIGN OF CACC-DIFT section. STRING STABILITY AND DETERMINATION OF PARAMETERS section discusses the parameters in CACC-DIFT by considering the string stability of the platoon and factoring the performance of individual vehicles. The proposed control design is validated using numerical experiments presented in NUMERICAL EXPERIMENTS section. Conclusions are provided in CONCLUDING COMMENTS section.

**FORMULATION OF DYNAMIC IFT PROBLEM**

As shown in Figure 1, this study considers a CAV platoon where information of each vehicle is intended to
be delivered to the two vehicles immediately following it through V2V communications (labeled as two predecessor-following IFT). Each $i$ is also able to detect the states of its immediate predecessor’s (vehicle $i - 1$) kinematic state (i.e. location $x_{i-1}$ and speed $\dot{x}_{i-1}$) through on-board sensors such as radar, Lidar and camera (see Figure 2). The acceleration rates of its two predecessors (i.e. $\ddot{x}_{i-1}$ and $\ddot{x}_{i-2}$) are obtained using V2V communications.

Due to communication interference, V2V communications between two arbitrary vehicles can fail (14). Then, the expected IFT (i.e. CACC1 in Figure 2(a)) may degenerate into the three scenarios shown in Figures 2(b)-2(d). Figures 2(b) and 2(c) show the cases when one communication link fails. In these cases, vehicle $i$ can detect the kinematic state of its immediate predecessor $i - 1$, and one predecessor vehicle’s acceleration rate through V2V communications. When both communication links fail (Figure 2(d)), the acceleration rates of its two predecessor vehicles will not be available to vehicle $i$. Then, the CACC will reduce to a traditional ACC to update the acceleration based on the relative spacing and speed between vehicles $i$ and its immediate predecessor $i - 1$.

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**FIGURE 2. The proposed CACC-DIFT**

Based on these four scenarios of vehicle $i$, this paper seeks to develop four sets of controllers which will be switched adaptively based on the dynamic IFTs.

**DESIGN OF CACC-DIFT**

This study assumes all CAVs in the platoon to be identical, forming a homogeneous vehicle string. The control schematic of vehicle $i$ in the platoon is described in Figure 3.

**FIGURE 3. Block diagram of control schematic**

In Figure 3, $U_i$ represents the control command, which consists of control feedback $U_{b,i}$ from the error $E_i$ and two extra feedforward terms $U_{f,i-1}$ and $U_{f,i-2}$ from the acceleration rates $\ddot{x}_{i-1}$ and $\ddot{x}_{i-2}$, respectively. $X_i$ is the position output of vehicle $i$, $X_{d,i}$ is the processed position output (considering spacing policy) of vehicle $i$, $X_{i-1}$ is the feedback position information from the immediate predecessor...
\( i - 1 \). \( K_i \) is the feedback controller which generates a control command to rectify the error. \( G_i \) represents the ideal longitudinal vehicle dynamics. \( H_i \) denotes the spacing policy (i.e., CD and CTH), and \( F_{1,i} \) and \( F_{2,i} \) are feedforward filters to process the acceleration information from the corresponding predecessor vehicles. \( \alpha \) and \( \beta \) are indicators for the success of V2V communications (\( \alpha \) and \( \beta \) are equal 1 to for a successful communication between specific vehicle and corresponding predecessors, and 0 otherwise). These terms will be explained in detail hereafter.

**Vehicle Dynamics**

We ignore the air drag, rolling resistance and actuator delay in the vehicle dynamics model for simplification. The idealized longitudinal vehicle dynamics can be represented using ordinary differential equations (ODE):

\[
\dot{x}_i(t) = v_i(t) \\
\dot{v}_i(t) = u_i(t)
\]

where \( x_i(t) \), \( v_i(t) \), \( u_i(t) \) are the absolute position, velocity and acceleration of vehicle \( i \) at time \( t \), respectively.

To analyze stability performance, the modeling and analysis are performed in the frequency domain. Hence, the idealized longitudinal vehicle dynamics in the Laplace domain can be described by using a transfer function:

\[
G_i(s) = \frac{X_i(s)}{U_i(s)} = \frac{1}{s^2}
\]

where the input \( U_i(s) \) denotes the acceleration of vehicle \( i \) and the output \( X_i(s) \) denotes the absolute position of vehicle \( i \) in the Laplace domain.

**Spacing Policy**

To guarantee a decent performance of damping traffic oscillation, a CTH policy is used to model the desired relative distance between adjacent vehicles as follows:

\[
d_i(t) = L + h_d \dot{x}_i(t)
\]

where \( d_i(t) \) is the desired relative distance between vehicle \( i \) and immediate predecessor \( i - 1 \), \( L \) is the constant standstill distance between the two vehicles, \( \dot{x}_i(t) \) is the velocity of vehicle \( i \) and \( h_d \) is the desired time headway.

According to Equation (4), the spacing error is:

\[
e_i(t) = x_{i-1}(t) - x_i(t) - d_i(t) = x_{i-1}(t) - x_i(t) - (L + h_d \dot{x}_i(t))
\]

In Laplace domain, the spacing error can be expressed equivalently as:

\[
E(s) = X_{i-1}(s) - H_i(s) X_i(s)
\]

where \( H_i(s) \) is the CTH spacing policy which is formulated as:

\[
H_i(s) = 1 + h_d s
\]

**Acceleration Feedforward Filter**

In CACC, the acceleration rate of the two predecessors can be obtained through V2V communications. The acceleration rate data is used generate a feedforward control signal \( U_{f,i-1}(s) \) though a feedforward filter \( F_i(s) \). To eliminate the spacing error between adjacent vehicles, the feedforward filter is designed based on a zero-error condition proposed in (9) to eliminate the steady-state spacing error, where the relationship
between tracking error $E_i(s)$ and feedforward acceleration $X_{i-1}(s) = s^2X_{i-1}(s)$ of the immediate predecessor $i - 1$ in Laplace domain is formulated as:

$$E_i(s) = \frac{1 - H_i(s)G_i(s)F_i(s)s^2}{1 + H_i(s)G_i(s)K_i(s)} X_{i-1}(s)$$

(8)

To satisfy the zero-error condition, the numerator of the right side in Equation (8) should be zero. By combining Equation (3), we have:

$$F_i(s) = (H_i(s)G_i(s)s^2)^{-1} = \frac{1}{H_i(s)}$$

(9)

We apply the same kind of feedforward filter to the acceleration information from the second predecessor $X_{i-2}(s)$ as well. Hence, we can define the feedforward filters $F_{1,i}(s)$ for acceleration from the first predecessor and $F_{2,i}(s)$ for acceleration from the second predecessor as:

$$F_{1,i}(s) = F_{2,i}(s) = \frac{1}{H_i(s)} = \frac{1}{1 + h_d s}$$

(10)

Control Command

As illustrated in Figure 3, our control command consists of a feedback term and two feedforward terms:

$$U_i(s) = U_{b,i}(s) + U_{f,i-1}(s) + U_{f,i-2}(s)$$

(11)

Recall that the feedback term $U_{b,i}(s)$ uses spacing error to stabilize the closed-loop system while feedforward terms $U_{f,i-1}(s)$ and $U_{f,i-2}(s)$ use acceleration rate from predecessors to minimize the spacing error. Next, we determine the three terms in detail analytically.

The feedback term $U_{b,i}(s)$ and the corresponding PD feedback controller $K_i(s)$ are defined as (9):

$$U_{b,i}(s) = K_i(s)E_i(s)$$

(12)

$$K_i(s) = k_p + k_d s = \omega_{K,i}(\omega_{K,i} s + s)$$

(13)

where $E_i(s)$ is the spacing error in the Laplace domain. $\omega_{K,i}$ is the cut-off frequency\(^1\) of the PD controller. It has a strong impact on the string stability of the platoon as well as individual vehicle stability, and will be determined analytically in next section. $k_p = \omega_{K,i}^2$ is the proportional gain utilized to rectify the spacing error $E_i(s)$ while $k_d = \omega_{K,i}$ is the derivative gain for rectifying the speed tracking error $sE_i(s)$.

The first feedforward term $U_{f,i-1}(s)$ indicates that the acceleration rate information of immediate predecessor $i - 1$ is sent to vehicle $i$:

$$U_{f,i-1}(s) = \alpha F_{1,i}(s)s^2X_{i-1}(s)$$

(14)

The second feedforward term $U_{f,i-2}(s)$ indicates that the acceleration rate information of the second predecessor $i - 2$ is sent to vehicle $i$:

$$U_{f,i-2}(s) = \beta F_{2,i}(s)s^2X_{i-2}(s)$$

(15)

Note that according to the two predecessor-following IFT, the second vehicle in the platoon can only receive acceleration information from the leading vehicle, that is, the feedforward term of vehicle 1 only includes $U_{f,0}(s)$.

The overall control command is obtained by summing up Equations (12), (14) and (15). Through

\(^1\) Cut-off frequency is the crossover frequency where the frequency response a system will roll off below -3.01dB. For a PD controller, cut-off frequency equals the ratio of proportional gain to derivative gain. In a specific control system, controller will not have effect on the high-frequency component which lies beyond controller cut-off frequency.
inverse Laplace transformation, the expression for the control command can be formulated as:
\[
u_i(t) = \omega^2_{K,i}e_i(t) + \omega_{K,i}\dot{e}_i(t) + \alpha F_{1,i}(t)\ddot{x}_{i-1}(t) + \beta F_{2,i}(t)\ddot{x}_{i-2}(t)\]

(16)

**Controller switching process**

Since the switching process of controller parameters corresponding to IFT dynamics needs to implement in discrete time domain, the continuous control command in Equation (16) will be discretized with a sampling period of \( T \). At sampling time instance \( k \), the control command is determined by Equation (17) according to the specific communication scenario at that time instance:

\[
u_i(k) = K_{p,i}e(k) + K_{d,i}\dot{e}(k) + \alpha(k)u_{f,i-1}(k) + \beta(k)u_{f,i-2}(k)\]

(17)

where,

\[
e(k) = x_{i-1}(k-1) - x_i(k-1) - h_d V_i(k-1) - L
\]

\[
\dot{e}(k) = V_{i-1}(k-1) - V_i(k-1) - h_d u_i(k-1)
\]

\[
u_{f,i-1}(k) = \frac{1}{T + h_d}(h_d u_{f,i-1}(k-1) + Tu_{i-1}(k))
\]

\[
u_{f,i-2}(k) = \frac{1}{T + h_d}(h_d u_{f,i-2}(k-1) + Tu_{i-2}(k))
\]

(18)-(21)

The switching process can be described as: at each sampling instance \( k \), the electric control unit equipped on vehicle will check the communication status of the vehicle to determine which control strategy will be devised (i.e., the values of \( \alpha(k) \) and \( \beta(k) \) in control command) in this sampling period.

Recalling Figure 2, we can note that: \( \alpha(k) = 1 \) and \( \beta(k) = 1 \) indicates CACC1 strategy since both of the predecessors successfully transmit their acceleration information; \( \alpha(k) = 1 \) and \( \beta(k) = 0 \) indicates CACC2 strategy since only the immediate predecessor successfully transmits its acceleration information; \( \alpha(k) = 0 \) and \( \beta(k) = 1 \) indicates CACC3 strategy since only the second predecessor successfully transmits its acceleration information; \( \alpha(k) = 0 \) and \( \beta(k) = 0 \) indicates ACC strategy since both of the predecessors fail transmit their acceleration information. Thereby, based on different communication scenarios, the control input in Equation (17) can be more explicitly expressed as:

\[
u_i(k) = \begin{cases} 
K_{p,i}e(k) + K_{d,i}\dot{e}(k) + u_{f,i-1}(k) + u_{f,i-2}(k), & \text{CACC1} \\
K_{p,i}e(k) + K_{d,i}\dot{e}(k) + u_{f,i-1}(k), & \text{CACC2} \\
K_{p,i}e(k) + K_{d,i}\dot{e}(k) + u_{f,i-2}(k), & \text{CACC3} \\
K_{p,i}e(k) + K_{d,i}\dot{e}(k), & \text{ACC} 
\end{cases}
\]

(22)

**STRING STABILITY AND DETERMINATION OF PARAMETERS**

There are two parameters in the designed system that significantly impact the platoon performance: the time headway \( h_d \) and cut-off frequency \( \omega_{K,i} \). This section seeks to analyze the two parameters, establishing lower bounds and upper bounds to improve the performance of individual vehicles while guaranteeing the string stability of the platoon.

**Performance of Individual Vehicle**

The proposed control strategy seeks to improve the performance of individual vehicle related to the following two criteria:
1) **Guarantee stability of individual vehicle.** The movement of each individual vehicle is stable if the states of certain vehicle would converge to its equilibrium point asymptotically after effect by outside disturbances.

To ensure the stability of individual vehicle, the roots of characteristic equation (i.e., the poles of sensitivity function $S_i(s)$ and complementary sensitivity function $T_i(s)$) are required to be checked. As Figure 3 shows, the sensitivity function $S_i(s)$ is defined as the relationship between spacing error $E_i(s)$ and the position of immediate predecessor $X_{i-1}(s)$. The complementary sensitivity function $T_i(s)$ is defined as the relationship between the processed position output $X_{d,i}(s)$ and the position of immediate predecessor $X_{i-1}$.

$$S_i(s) = \frac{E_i(s)}{X_{i-1}(s)} = \frac{1}{1 + H_i(s)G_i(s)K_i(s)}$$

$$T_i(s) = \frac{X_{d,i}(s)}{X_{i-1}(s)} = \frac{H_i(s)G_i(s)K_i(s)}{1 + H_i(s)G_i(s)K_i(s)}$$

(23)

(24)

To guarantee the stability of a closed-loop system, the roots of characteristic equation (the denominator of $S_i(s)$ and $T_i(s)$ in Equations (23) and (24)) must lie in the left half complex plane (LHP), in which the solutions of corresponding ODEs will decay and converge to specific steady-state value as time approaching infinity. Thereby, the responses of vehicles will converge to specific equilibrium points asymptotically. According to Equations (3), (7), and (13), the characteristic equation can be derived as:

$$1 + H_i(s)G_i(s)K_i(s) = \frac{(1 + h_d\omega_{K,i})s^2 + (h_d\omega_{K,i}^2 + \omega_{K,i})s + \omega_{K,i}^2}{s^2}$$

and the root $\eta_i$ for each vehicle $i$ is:

$$\eta_i = -\frac{\omega_{K,i}}{2} \left(1 \pm \frac{\sqrt{A}}{1 + h_d\omega_{K,i}}\right)$$

$$A = (h_d\omega_{K,i})^2 - 2h_d\omega_{K,i} - 3$$

Then, we could discuss more about the value of $A$. If $0 < h_d\omega_{K,i} < 3$, then $A = (h_d\omega_{K,i})^2 - 2h_d\omega_{K,i} - 3 < 0$, consequently the roots will have imaginary part and negative real part, which lies within LHP. If $h_d\omega_{K,i} \geq 3$, we have $\sqrt{A} < 1 + h_d\omega_{K,i}$, which means $1 \pm \sqrt{A}/(1 + h_d\omega_{K,i}) > 0$. Thus, both roots will still stay inside LHP as well, ensuring the closed-loop stability. Hence, the real parts of both roots will be negative when $h_d\omega_{K,i} > 0$, and correspondingly, the stability of individual vehicle is guaranteed.

2) **Measurement noise mitigation.** Measurement noise is usually a high-frequency noise generated from onboard sensors that produces inaccurate trajectory information, leading to undesirable control commands. Hence, the mitigation of measurement noise effect is essential to improve control performance in terms of stability for individual vehicles in the platoon.

For any following vehicle $i$ in the platoon, the measurement noise is mainly generated from the movement states detection of its immediate predecessor $i-1$. The measured position $X_{i-1}(s)$ of immediate predecessor $i-1$ consists of true value of position $\tilde{X}_{i-1}(s)$ and measurement noise $N_{i-1}(s)$:

$$X_{i-1}(s) = \tilde{X}_{i-1}(s) + N_{i-1}(s)$$

From Figure 3, the complementary sensitivity functions $T_i(s)$ can be used
to describe the relationship between the processed position output \( X_{d,i}(s) \) of vehicle \( i \) and measurement noise \( N_{i-1}(s) \) included in position of immediate predecessor \( i - 1 \).

\[
T_i(s) = \frac{X_{d,i}(s)}{N_{i-1}(s)} = \frac{H_i(s)G_i(s)K_i(s)}{1 + H_i(s)G_i(s)K_i(s)} \quad (28)
\]

The magnitude of complementary sensitivity function \( T_i(s) \) at a high-frequency represents the effect of measurement noise mitigation (a larger value of \( T_i(s) \) indicates reduced mitigation of measurement noise). The key aspect of mitigating high-frequency measurement noise of \( X_{i-1}(s) \) is to decrease the value of \( T_i(s) \) in high-frequency band. Substituting \( G_i(s), H_i(s) \) and \( K_i(s) \) from Equations (3), (7) and (13) into Equations (28), we have:

\[
\lim_{s \to \infty} T_i(s) = \lim_{s \to \infty} \frac{h_d \omega_{K,i} s^2 + (h_d \omega_{K,i}^2 + \omega_{K,i})s + \omega_{K,i}^2}{(1 + h_d \omega_{K,i})s^2 + (h_d \omega_{K,i}^2 + \omega_{K,i})s + \omega_{K,i}^2} = \frac{h_d \omega_{K,i}}{1 + h_d \omega_{K,i}} \quad (29)
\]

The value of \( \lim_{s \to \infty} T_i(s) \) can be interpreted as the noise mitigation factor and it will increase as \( h_d \omega_{K,i} \) becomes larger. By setting an upper bound for \( h_d \omega_{K,i} \) as: \( h_d \omega_{K,i} \leq W_{\text{max}} \), the upper bounds of \( \lim_{s \to \infty} T_i(s) \) can be determined as: \( \lim_{s \to \infty} T_i(s) \leq \frac{h_d \omega_{K,i}}{1 + h_d \omega_{K,i}} \leq \frac{W_{\text{max}}}{1 + W_{\text{max}}} \), which indicates that the high-frequency measurement noise is attenuated by at least \( \frac{W_{\text{max}}}{1 + W_{\text{max}}} \).

**String Stability Analysis**

The string stability transfer function is defined as a measure of the signal amplification upstream a platoon. In this paper, the head-to-tail string stability will be analyzed to ensure that the oscillations in the upstream traffic will be damped when they reach the tail of the CAV platoon. To improve readability, \( X_i(s), G_i(s), K_i(s), H_i(s), F_{1,i}(s) \) and \( F_{2,i}(s) \) are simplified to \( X_i, G_i, K_i, H_i, F_{1,i} \) and \( F_{2,i} \). The head-to-tail string stability transfer function is represented as:

\[
SS_{X,i} = \frac{X_i}{X_0} \quad (30)
\]

To ensure the head-to-tail string stability condition, as illustrated in (8) and (9), we restrict the \( H_{\infty} \) norm of string stability transfer function to be no greater than one:

\[
\|SS_{X,i}(j\omega)\|_{\infty} = \left\| \frac{X_i(j\omega)}{X_0(j\omega)} \right\|_{\infty} \leq 1 \quad (31)
\]

in which \( s = j\omega, j = \sqrt{-1} \), and \( \|SS_{X,i}(j\omega)\|_{\infty} \) indicates the maximum magnitude of the frequency response of string stability transfer function.

Note that the string stability condition described in Equation (31) can be satisfied if \( |SS_{X,i}(j\omega)| \leq 1 \). Specifically, because \( \|SS_{X,i}(j\omega)\|_{\infty} \) indicates the peak value of the frequency response of \( SS_{X,i}(j\omega) \) while \( |SS_{X,i}(j\omega)| \) represents all the values of the frequency response of \( SS_{X,i}(j\omega) \), the controller parameter settings that can guarantee \( |SS_{X,i}(j\omega)| \leq 1 \) will also guarantee that \( \|SS_{X,i}(j\omega)\|_{\infty} \leq 1 \), satisfying the string stability condition.
According to Equations (3), (6), (8), (9), (12), (14) and (15), the absolute position of all vehicles in the platoon can be described as:

\[ \bar{X}_n = M \bar{X}_{n-1} \]  \hspace{1cm} (32)

where \( \bar{X}_n = (X_1, X_2, \ldots, X_N)^T \), \( \bar{X}_{n-1} = (X_0, X_1, \ldots, X_{N-1})^T \).

\[ M = \begin{pmatrix}
\varphi_{11} & 0 & \cdots & 0 & 0 \\
\varphi_{21} & \varphi_{22} & \cdots & 0 & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
0 & 0 & \cdots & \varphi_{n-1,1} & 0 \\
0 & 0 & \cdots & \varphi_{n-1,2} & \varphi_{n,1}
\end{pmatrix} \]

\[ \varphi_{i,1} = \alpha \Lambda_{f,i-1} + \Lambda_{b,i-1} \]  \hspace{1cm} (33)

\[ \varphi_{i,2} = \beta \Lambda_{f,i-2} \]  \hspace{1cm} (34)

Also, the position of vehicle \( i \) (\( i > 1 \)) can be described as:

\[ X_i = \beta \Lambda_{f,i-2} X_{i-2} + (\alpha \Lambda_{f,i-1} + \Lambda_{b,i-1}) X_{i-1} \]  \hspace{1cm} (35)

where \( \Lambda_{f,i-2} = \frac{G_{iF_{2,i}} s^2}{1 + G_{iK_i} H_i} \) is the transfer function between position of the second predecessor \( i - 2 \) and vehicle \( i \) with feedforward term \( U_{f,i-2}(s) \); \( \Lambda_{f,i-1} = \frac{G_{iF_{1,i}} s^2}{1 + G_{iK_i} H_i} \), represents the transfer function between immediate predecessor \( i - 1 \) and vehicle \( i \) with feedforward term \( U_{f,i-1}(s) \); \( \Lambda_{b,i-1} = \frac{G_{iK_i}}{1 + G_{iK_i} H_i} \), represents the transfer function between the position of immediate predecessor \( i - 1 \) and vehicle \( i \) with the feedback term \( U_{b,i}(s) \).

Based on the four possible communication scenarios described in Figure 2, we will analyze the corresponding feasible region for the time headway \( h_d \) and cut-off frequency \( \omega_{K,i} \) to guarantee string stability of the platoon.

1) CACC1 Case: When \( \alpha = 1 \) and \( \beta = 1 \), the head-to-tail string stability transfer function in Equation (35) becomes:

\[ SS_{X,i} = \Lambda_{f,i-2} \frac{X_{i-2}}{X_0} + (\Lambda_{f,i-1} + \Lambda_{b,i-1}) \frac{X_{i-1}}{X_0} \]  \hspace{1cm} (36)

Note that to analyze string stability based on this Equation (36) is complex as it is a high order transfer function. To address this problem, we only consider the worst-case scenario in Equation (36) where the value of both \( X_{i-2}/X_0 \) and \( X_{i-1}/X_0 \) are equal to 1 (both are head-to-tail marginally string stable\(^2\)). This enables us to find a more conservative, stable region of the two parameters to ensure string stability. When \( X_{i-2}/X_0 = X_{i-1}/X_0 = 1 \), Equation (36) becomes:

\[ SS_{X,i} = \frac{G_{iK_i} + G_{i} (F_{1,i} + F_{2,i}) s^2}{1 + G_{iK_i} H_i} \]  \hspace{1cm} (37)

From Equations (10) and (37), the string stability transfer function becomes:

\(^2\) Marginally string stable means the traffic oscillation is neither amplified nor damped when it propagates in traffic flow. Here, the marginally string stable between vehicle \( i \) and vehicle 0 indicates the position output of vehicle \( i \) equals to the position output of the leading vehicle 0, i.e. \( X_i/X_0 = 1 \).
\[ SS_{X,i} = \frac{2 + G_iK_iH_i}{H_i(1 + G_iK_iH_i)} \]  

Substituting for \( G_i, \ H_i \) and \( K_i \) from Equations (3), (7) and (13), respectively, into the string stability condition (31), the inequality yields:

\[
\frac{(2 + h_d \omega_{K,i})s^2 + \omega_{K,i}(h_d \omega_{K,i} + 1)s + \omega_{K,i}^2}{(1 + h_d s)(1 + h_d \omega_{K,i})s^2 + \omega_{K,i}(h_d \omega_{K,i} + 1)s + \omega_{K,i}^2} \leq 1
\]  

which can be modified to:

\[
\frac{(2 + h_d \omega_{K,i})s^2 + \omega_{K,i}(h_d \omega_{K,i} + 1)s + \omega_{K,i}^2}{(1 + h_d \omega_{K,i})s^2 + \omega_{K,i}(h_d \omega_{K,i} + 1)s + \omega_{K,i}^2} \leq |1 + h_d s|
\]  

Substituting \( s = j\omega \) into the inequality above, the inequality can be transformed into:

\[
\frac{\omega^2}{(\omega_{K,i}^2 - (h_d \omega_{K,i} + 1)\omega^2)^2 + \omega^2 \omega_{K,i}^2(h_d \omega_{K,i} + 1)^2} \leq h_d^2
\]  

Since \((\omega_{K,i}^2 - (h_d \omega_{K,i} + 1)\omega^2)^2 > 0\), by using inequality scaling method, \((\omega_{K,i}^2 - (h_d \omega_{K,i} + 1)\omega^2)^2\) can be eliminate from the denominator of the left-hand side to produce a more conservative inequality. Thereby, the inequality (41) can be reduced to:

\[
\frac{1}{\omega_{K,i}^2(h_d \omega_{K,i} + 1)^2} \leq h_d^2
\]  

which can directly be solved via the quadratic inequality \((h_d \omega_{K,i})^2 + h_d \omega_{K,i} - 1 \geq 0\).

Hence, the string stability region of time headway and controller cut-off frequency is:

\[ h_d \omega_{K,i} \geq (-1 + \sqrt{5})/2 \]  

2) CACC2 Case: When \( \alpha = 1 \) and \( \beta = 0 \), the head-to-tail string stability transfer function in Equation (35) is represented as:

\[ SS_{X,i} = \frac{X_i}{X_0} = (\Lambda_{f,i-1} + \Lambda_{b,i-1})\frac{X_{i-1}}{X_0} \]  

As we require the head-to-tail transfer function to be string stable, the worst-case scenario is \( X_{i-1}/X_0 = 1 \), indicating marginal string stability. Hence, by setting \( X_{i-1}/X_0 = 1 \), we can obtain a more conservative string stability transfer function:

\[ SS_{X,i} = \frac{G_iK_i + G_iF_{i-1}F_{i-1}s^2}{1 + G_iK_iH_i} \]  

Using Equation (10), the string stability transfer function can be reduced to:

\[ SS_{X,i} = \frac{G_iK_i + \frac{1}{H_i}}{1 + G_iK_iH_i} = \frac{1}{H_i} = \frac{1}{1 + h_d s} \]

When the time headway satisfies: \( h_d > 0 \), correspondingly, \( SS_{X,i} < 1 \), and the string stability
condition in Equation (31) can be guaranteed.\(^3\)

3) CACC3 Case: When \(\alpha = 0\) and \(\beta = 1\), the head-to-tail string stability transfer function in Equation (35) is represented as:

\[
SS_{X,i} = \frac{X_i}{X_0} = \frac{X_{i-2}}{X_0} + \frac{X_{i-1}}{X_0} \Lambda_{b,i-1}
\]

By using the same relaxation approach (marginal head-to-tail string stability) as in CACC2, we can set both \(X_{i-1}/X_0\) and \(X_{i-2}/X_0\) equal to one, yielding the same string stability transfer function as the CACC2 scenario:

\[
SS_{X,i} = \frac{G_iK_i + G_iF_{z,i}s^2}{1 + G_iK_iH_i} \] (48)

Thus, we obtain the same string stability condition in Equation (31) as the second scenario: \(h_d > 0\).

4) ACC Case: Using a similar method, when \(\alpha = 0\) and \(\beta = 0\), the head-to-tail string stability transfer function in Equation (35) will degrade to:

\[
SS_{X,i} = \frac{X_i}{X_0} = \frac{X_{i-1}}{X_0} \Lambda_{b,i-1} = \frac{G_iK_i}{1 + G_iK_iH_i} \]

Consequently, by substituting \(s = j\omega\) into Equation (49), and according to the string stability condition in Equation (31), Equation (49) becomes:

\[
\frac{\omega_{K,i}^2(\omega^2 + \omega_{K,i}^2)}{(\omega_{K,i}^2 - (1 + h_d\omega_{K,i})\omega^2)^2 + \omega_{K,i}^2(1 + h_d\omega_{K,i})^2} \leq 1
\] (50)

Then we can multiply the denominator in the left-hand side to the right-hand side and simply the inequality in Equation (50) into:

\[
\frac{\omega_{K,i}^2(2 - h_d^2\omega_{K,i}^2)}{(1 + h_d\omega_{K,i})^2} \leq \omega^2
\] (51)

Since \(\min \omega^2 = 0\), this inequality can be solved by:

\[
\frac{\omega_{K,i}^2(2 - h_d^2\omega_{K,i}^2)}{(1 + h_d\omega_{K,i})^2} \leq 0
\] (52)

Hence, the string stability region of time headway and controller cut-off frequency is:

\[
h_d\omega_{K,i} \geq \sqrt{2}
\] (53)

Remark 1: Based on the above analysis, the decision-making process can be summed up as: (i) positive \(h_d\omega_{K,i}\) to ensure individual vehicle stability; (ii) \(h_d\omega_{K,i}\) has specific upper-bound \(W_{\max}\) for mitigating

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\(^3\) For first-order type transfer function: \(q(j\omega) = \frac{1}{1 + j\sigma\omega}\); since \(|q(j\omega)| = \frac{1}{\sqrt{1 + \sigma^2\omega^2}}\) and phase angle \(\angle q(j\omega) = -\arctan (\sigma\omega)\), the magnitude of \(q(j\omega)\) will always be lesser than or equal to one. However, when \(\sigma < 0\), the phase angle of \(q(j\omega)\) is positive, which indicates that the system corresponding to the first-order transfer function is not practically deployable. Hence, \(\sigma \geq 0\) is essential and necessary to guarantee string stability.
noise effects; and (iii) string stability condition: 
\[ h_d \omega_{K,i} \geq \frac{-1+\sqrt{5}}{2} \] 
for CACC1, \( h_d > 0 \) for CACC2 and CACC3, \( h_d \omega_{K,i} \geq \sqrt{2} \) for ACC scenario.

**NUMERICAL EXPERIMENTS**

**Numerical Experiment Design**

This study presents two numerical experiments to verify the performance of proposed CACC-DIFT platoon control strategy. The first experiment seeks to verify the effectiveness of the proposed CACC-DIFT design in a dynamic IFT environment and compares the performance of CACC-DIFT with a CACC based on fixed IFT (CACC-FIFT) which includes the CACC and ACC schemes developed in (9). The CACC-FIFT will degrade to ACC if the V2V communications fail because CACC-FIFT is designed for specific fixed IFT that is assumed to characterize the platoon control. The second experiment provides a sensitivity analysis to illustrate the impact exerted on the system performance by different setup of control parameters.

Consider a 10-CAV platoon with one leading vehicle \((i = 0)\) and 9 following vehicles. In all experiments, the movement of the leading vehicle is predetermined according to NGSIM field data. It contains 240-second of vehicle trajectories data collected on eastbound I-80 at Emeryville, San Francisco Bay Area, California, which involves location, speed and acceleration of each vehicle. This study considers the trajectory of leading vehicle as the source of the traffic oscillation in a CAV platoon. The vehicle trajectory from NGSIM data is directly inputted as the leading vehicle trajectory of a CAV platoon. More than 50 leading vehicle trajectories are tested in this study. Since the observations show that different input of leading vehicle trajectories yield out similar performance regarding traffic oscillation attenuation, we mainly introduce one leading vehicle trajectory with the most significant oscillating characteristic in this paper to analyze the performance of proposed CACC-DIFT.

More specifically, in CACC-DIFT, the first following vehicle \((i = 1)\) can receive information only from one proceeding vehicle \((i = 0)\); Hence, the controller of the first following vehicle will switch between CACC2 and ACC if the IFT changes. For the other following vehicles \((i = 2, ..., 9)\), their controllers can switch among the four controllers (i.e. CACC1, CACC2, CACC3 and ACC). To measure the IFT dynamics, a statistical model in (13), which is a function of distance, is used to describe the success rate of a packet delivery between two vehicles.

In addition, since measurement noise generated from onboard sensors and vehicle movements cannot be neglected in CACC/ACC implementation, we include measurement noise into measured position and speed of predecessors. The position measurement noise and speed measurement noise are both white, zero-mean Gaussian noise. As illustrated in (20), the standard deviation (SD) of speed measurement noise is: \( \sigma_v = 0.1 \text{m/s} \); and according to (21), the SD of position measurement noise can be calculated as: \( \sigma_x = \frac{T\sigma_v}{\sqrt{2}} = 0.1 \times \frac{0.1}{\sqrt{2}} = 0.007 \text{m} \), which significantly smaller than the SD of speed measurement noise.

In the experiment of performance verification, the desired time headways in all controllers are set to 1 second to prevent traffic oscillation generated by controller switching. Otherwise, the four controllers will have the different equilibrium states, which will lead the additional traffic oscillation during the switching.
of equilibrium states. The parameters of each controller are listed in Table 1. The initial state of the platoon is $v_i(0) = 25m/s$ for all $i$; the spacing between adjacent vehicles is $x_{i-1}(0) - x_i(0) = h_d v_i(0) + L_i = 30m$, where $L_i$ is the length of vehicle $i$ and it is set to 5m for all vehicles. In the following experiments, the sampling time interval is: $T = 0.1s$.

**TABLE 1. Control parameters in the experiment of performance verification**

| Controller | $w_k$ | $h_d$ | $\alpha$ | $\beta$ |
|------------|-------|-------|-----------|---------|
| CACC1      | 0.8   | 1     | 1         | 1       |
| CACC2      | 0.9   | 1     | 1         | 0       |
| CACC3      | 0.9   | 0     | 1         | 0       |
| ACC        | 1.45  | 0     | 0         | 0       |

**TABLE 2. Control parameters in the sensitivity analysis of controller cut-off frequency**

| Scenario | $h_d$ | $w_k$ | $\alpha$ | $\beta$ | $h_d$ | $w_k$ | $\alpha$ | $\beta$ |
|----------|-------|-------|-----------|---------|-------|-------|-----------|---------|
| 1        | 1     | 0.88  | 1         | 1       | 1.04  | 1.04  | 1         | 1       |
| 2        | 0     | 0.99  | 0         | 1       | 1.17  | 1.17  | 0         | 1       |
| 3        | 0.88  | 0.99  | 1.35      | 0.89    | 1.35  | 1.35  | 0.89      | 0.89    |
| 4        | 1.595 | 0     | 2.175     | 0       | 2.175 | 0     | 2.175     | 0       |

As mentioned in previous section, the values of time headway $h_d$ and controller cut-off frequency $\omega_{K,i}$ have significant impact on the performance of platoon control, therefore, sensitivity analysis of these two controller parameters is provided according to the bounds we set up in Remark 1. By setting the $h_d$ as 1 second, we first test the impact of controller cut-off frequency $\omega_{K,i}$ by comparing three set of parameters as scenario 1 to 3 in Table 2, which sequentially increases the $\omega_{K,i}$ of the four controllers at the same time. Then, the influence of time headway $h_d$ is also be analyzed. The $h_d$ is set as 1.1, 1.3 and 1.5 seconds in Scenario 4, 5 and 6, respectively. All remaining parameters are set as in Table 1.

**Experiment Results**

This section first compares the performance of CACC-DIFT with the performance of CACC-FIFT. Specifically, the experiments exam the stability of the CAV platoon controlled by two strategies in the context of time-varying IFT. Figures 4(a)-4(f) show the results of the spacing error, speed tracking error, and the speed of each vehicles in the platoon under two control strategies, respectively.

Figures 4(a) and 4(b) show that spacing error between two adjacent vehicles in the CAV platoon decays upstream the platoon under two control strategies, and the performance of CACC-DIFT is more decent than the performance of CACC-FIFT. For example, under CACC-DIFT strategy, the maximum spacing error of the second following vehicle ($i = 2$) and the last following vehicle are 1.05m and 0.72m, comparing with 1.21m and 0.89m under CACC-FIFT strategy. Similar results can be observed by comparing Figures 4(c) and 4(d): the speed tracking error under CACC-DIFT strategy is more efficiently minimized compared with speed tracking error under CACC-FIFT strategy. Meanwhile, due to the noise mitigation requirement in the process of controller design, the measurement noise doesn’t generate any significant impact to the spacing...
error, speed tracking error, and the vehicle speed presented in Figures 4(a), 4(c) and 4(e), respectively.

(a). Spacing error of CACC-DIFT

(b). Spacing error of CACC-FIFT

(c). Speed tracking error of CACC-DIFT

(d). Speed tracking error of CACC-FIFT

(e). Speed of CACC-DIFT

(f). Speed of CACC-FIFT

FIGURE 4. Performance of the CACC-DIFT and CACC-FIFT

(a). Standard deviation of spacing error

(b). Standard deviation of speed tracking error

FIGURE 5. Comparison of CACC-DIFT and CACC-FIFT
FIGURE 6. Standard deviation of speed fluctuations

Figures 5(a) and 5(b) compares the SD of spacing error and speed tracking error under CACC-DIFT strategy and CACC-FIFT strategy. Figures 5(a) shows that the SD of spacing error decreases sequentially in the platoon for both CACC-DIFT and CACC-FIFT. However, CACC-DIFT outperforms CACC-FIFT in that the spacing error of CACC-DIFT decreases more appreciably upstream the platoon compared with the spacing error of CACC-FIFT. For instance, the SD of spacing error for the last following vehicle under CACC-DIFT is 0.170 m, while the SD is 0.319 m for CACC-FIFT. Similar trends and characteristics can be found on the comparison of SD of speed tracking error in the Figure 5(b): the SD of speed tracking error under CACC-DIFT strategy decreases more efficiently than CACC-FIFT strategy upstream the platoon.

Additionally, to further investigate the performance benefits under the CACC-DIFT, the performance of the two controller strategies is compared when traffic oscillates (e.g., stop-and-go or slow-and-fast traffic). The SDs of the vehicle speed under CACC-DIFT strategy and CACC-FIFT strategy are shown in Figure 6. Under CACC-DIFT strategy, it’s obvious that the SD of vehicle speed decreases appreciably upstream the platoon, indicating the fluctuations of speed are effectively attenuated when they approach to the tail of the platoon, which implies that traffic oscillations are significantly damped. However, CACC-FIFT cannot effectively attenuate the speed fluctuations due to the dynamic nature of IFT, where CACC will degenerate to ACC if V2V communications fail. Consistent results are also observed by comparing Figure 4(e) and 4(f), which show that the speed profile of each following vehicle under CACC-DIFT strategy is milder compared with CACC-FIFT strategy. Based on these results, we can conclude that the performance of CAV platoon controlled by proposed CACC-DIFT is more satisfactory and robust than the performance of CACC-FIFT in a realistic V2V communication environment.

This section then provides a sensitivity analysis to elaborate the influence of control parameters. The sensitivity analysis of the cut-off frequency $\omega_{K,d}$ is conducted by comparing the spacing error and vehicle acceleration in Scenario 1, 2 and 3, which are shown in Figure 7 (a), (c), (e) and (b), (d), (f), respectively. Figure 7 (a), (c) and (e) demonstrate that the spacing error will decrease as the value of $\omega_{K,d}$ increases. For example, the maximum spacing error of the last following vehicle in Scenario 1, 2 and 3 are 0.69 m, 0.63 m and 0.56 m, respectively. However, Figure 7 (b), (d) and (f) show that with the increasing of $\omega_{K,d}$, the high-frequency noise in vehicle acceleration will be enlarged as it reaches to the tail of the platoon, which is indeed undesirable for vehicle operation since the choppy acceleration profile is potentially hazardous to powertrain system. In Figure 8, similar results and trends can also be observed in the sensitivity analysis of time headway $h_d$: by increasing times headway $h_d$, spacing error will decrease, indicating better string stability performance, while the noise in vehicle acceleration will be amplified upstream the platoon,
triggering worse operating condition to vehicles.

The phenomenon above can be clarified by the different characteristics in string stability condition and measurement noise mitigation. Considering the string stability performance, from string stability transfer functions in Equation (39), (46), and (49), we can notice that increasing time headway $h_d$ or controller cut-off frequency $\omega_{K,i}$ will decrease the value of string stability transfer function, improving the damping effect of traffic oscillation. However, for the noise mitigation effect, the complementary sensitivity function in Equation (29) indicates that as the value of $h_d\omega_{K,i}$ becomes larger (by increasing either $h_d$ or $\omega_{K,i}$), the noise mitigation factor will increase, degrading the noise mitigation performance. Hence, increasing time headway or controller cut-off frequency will jeopardize the control performance regarding noise mitigation. Thereby, to guarantee a decent platoon control performance, careful selections of time headway $h_d$ and controller cut-off frequency $\omega_{K,i}$ are essential for future real-world application.

![FIGURE 7. Sensitivity analysis of cut-off frequency $\omega_{K,i}$](image)
CONCLUDING COMMENTS
This study introduces the CACC-DIFT design for CAV platoon by factoring the time-varying nature of the information flow topology arising from V2V communication failures in the future traffic flow with high-density CAV. The CACC-DIFT design is developed for the two-predecessor-following IFT. Four switchable PD controllers are provided to control the CAV platoon under possible IFTs by considering the stability performance of individual vehicles and string stability of CAV platoon. Insights from numerical experiments indicate that comparing with the commonly-proposed CACC-FIFT design, the proposed CACC-DIFT strategy can minimize both spacing error and speed tracking error, and damp traffic oscillation more efficaciously. Thereby, CACC-DIFT can guarantee decent string stability performance and outperforms CACC-FIFT considerably.
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