Compensation of Communication Delays in a Cooperative ACC System

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***Abstract*—Cooperative adaptive cruise control (CACC) employs intervehicle wireless communications to safely drive at short intervehicle distances, which improves road throughput. The underlying technical requirement to achieve this benefit is formulated by the notion of string stability, requiring the attenuation of the effects of disturbances in upstream direction. The wireless communication delay, however, significantly compromises string stability. In order to compensate for time delays and thus reduce the minimum string-stable time gap, a Smith predictor can be applied. For application of a Smith predictor, the time delay needs to be in a series connection with the plant to be controlled, which is realized by introducing a master-slave architecture for CACC. As a result, information exchange appears to become bidirectional, while the control scheme still follows the one-vehicle look-ahead strategy. Feasibility of both the master-slave CACC strategy and the Smith predictor is explicitly analyzed. With the proposed control scheme, the minimum string-stable time gap can be significantly decreased, even considering communication delay uncertainty. The results are validated using simulations with a platoon of CACC-equipped vehicles.**

***Index Terms*—Cooperative adaptive cruise control (CACC), Smith predictor, master-slave architecture, wireless communication delay, string stability.**

I. Introduction

THE number of road vehicles has significantly increased in the past decades, raising public awareness regarding limited road capacity. Meanwhile, many advanced driver assistance systems have been developed to meet an increasing societal demand to improve driving comfort and/or traffic safety. Adaptive cruise control (ACC) systems, for instance, relieve the driver's task by automatically keeping a desired intervehicle distance, which results in a vehicle platoon [1]. For a vehicle platoon, an important requirement is string stability, which is defined as attenuation of the effects of disturbances introduced by downstream vehicles, in upstream direction [2]. A string-stable vehicle platoon prevents amplifications of variations in velocities and intervehicle distances along the vehicle platoon, which will compromise road throughput, and potentially lead to traffic jams. In addition, a string-stable vehicle platoon can be beneficial for safety, and for fuel consumption, particularly for heavy-duty vehicles [3].

However, in ACC-equipped vehicle platoons, string-stable behavior is only obtained at large intervehicle distances, which does not improve road throughput [4], [5]. Therefore, to improve highway capacity, cooperative ACC (CACC) systems have been developed, in which wireless vehicle-to-vehicle (V2V) communications are employed [6], [7]. As a result, shorter intervehicle distances can be achieved while guaranteeing string stability. Highway capacity could be close to double with a 100% market penetration of CACC compared to only manually driven or only ACC controlled vehicles [8].

The main factors that affect string stability include vehicle dynamics [6], the intervehicle spacing policy [9], information flow topology [10], and the quality of intervehicle sensing and communication [11], [12]. In particular, communication delay, which inherently exists in V2V communications, can significantly compromise string stability [6], [11]. That is due to the fact that the CACC functionality relies to a large extent on the vehicle information transmitted by wireless communication, e.g., the position, velocity, actual and desired accelerations.

String stability analyses in various CACC strategies, which considered communication delays, have indicated the need of substantially restricting the delays in order to guarantee string stability [13]–[24]. However, the theoretical studies of string stability in many cases ignored the compromising effect of communication delays [25]–[32]. A string-stable CACC system can still be practically realized with certain communication delays when communication delay is not accounted in the process of controller design [33]–[35]. However, these studies selected a sufficiently large time gap as 0.6 s to 0.8 s, rather than considering the minimum intervehicle distance.

With a constant time gap spacing policy, which is the most common spacing policy to improve string stability [6], [36] and corresponds to human driver characteristics to some extent, there exists a minimum time gap to guarantee string stability [20], [37]. In order to take full advantage of CACC in view of road throughput, it is desired to adopt the minimum string-stable time gap.

The minimum string-stable time gap has been analyzed in many studies. [6] and [38] explicitly compared the minimum string-stable time gaps for ACC and CACC, using a Proportional Derivative (PD) controller with a one-vehicle look-ahead communication topology. In [36], two communication topologies were employed when designing optimal controllers, while the

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minimum time gap for a one-vehicle look-ahead topology is smaller than that for a two-vehicle look-ahead topology when communication delay is less than 0.1 s. With a multiple-vehicle look-head topology, [39] showed that increasing the number of predecessors can reduce the minimum string-stable time gap. However, this strategy may pose a high requirement on communication channels as the number of predecessors grows. Practical validations of string-stable CACC have been carried out with the minimum time gaps of 0.25 s and 0.7 s, given that the communication delay is 0.04 s and 0.15 s, respectively [23], [37]. [40] implemented a fractional-order-based controller algorithm to arrive at the time gap as 0.26 s with communication delay 0.08 s on a low-speed real platform.

To eliminate the effects of communication delays on the string-stable time gap, information-updating algorithms have been proposed in [41] and [42], in which an upper level information controller managed all vehicles in a platoon to update each vehicle's controller simultaneously with the delayed information. However, the performance of individual vehicles is sacrificed, and it is hardly possible to have all the vehicle controllers updated at exactly the same time in practice [41]. Moreover, a centralized controller is not suitable for a platoon due to the challenges of gathering the information of all vehicles in a platoon and solving a large-scale optimization problem [10]. Therefore, most CACC applications employ distributed controllers.

To further reduce the minimum string-stable time gap with distributed controllers, active compensation approaches for communication delay provide a promising option. Considering direct compensation for delays, Proportional Integral Derivative (PID), Model Predictive Control (MPC), and the Smith predictor are the most general approaches. However, PID, which can predict the future error with the derivative action, allows for easy analysis, rather than synthesis of string-stable behavior [43], [44]. Synthesis and analysis of string-stable behavior with MPC is difficult to perform because of the finite horizon used [13], [45], [46]. On the other hand, a Smith predictor allows for relatively straightforward synthesis and analysis of string-stable behavior. In addition, a Smith predictor is not computationally demanding (as opposed to MPC) [13], [44], [47], and can be applied as an add-on to existing CACC controllers [23], [48], [49].

The Smith predictor, proposed in [50], is known to handle large time delays very well in the sense of stability and performance [44], [51], [52]. The explicit knowledge of the delay and an accurate model of the plant are required to implement the Smith predictor. In CACC systems, the communication delay is available, since each message is stamped with Global Positioning System (GPS)-based time, of which the precision is better than 100 ns [22]. The vehicle model is also available based on the model identification from the experimental results [13], [37]. Thus, it is suitable to apply a Smith predictor on CACC. However, although there have been some studies to compensate for vehicle actuator delay to reduce the string-stable time gap [23], [48], [49], compensating for communication delay has not been developed. It is difficult to apply a Smith predictor on CACC systems, due to the fact that a Smith predictor can only be applied to compensate for time delays if the latter are in a series connection with the plant to be controlled. In most

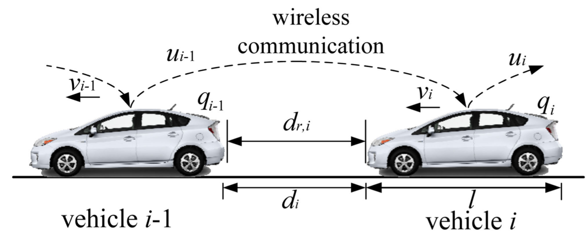


Fig. 1. CACC-equipped string of vehicles with the one-vehicle look-ahead topology.

CACC strategies, a vehicle receives information from other vehicles in the platoon, and generates the desired action by its local controller. Therefore, the communication delay is in the feedforward loop, in which case the Smith predictor is not applicable.

As a solution, in this paper, it is proposed to re-locate the controller, effectively putting the communication delay in series with the system to be controlled. Therefore, a master-slave control strategy is actually introduced to the CACC system. The novel master-slave CACC strategy proposed in this paper, employs a bidirectional communication topology and one-vehicle look-ahead strategy. This algorithm allows for the application of a Smith predictor on communication delays for the first time, which is the main contribution of this paper. Actually, with theoretical analysis, we realize an extremely small string-stable time gap by compensating for communication delay, which is demonstrated by simulations. It is also explicitly proved that individual vehicle stability can be guaranteed. Furthermore, it is only needed to slightly increase the theoretical minimum time gap to guarantee string stability in the presence of communication delay uncertainty.

The outline of this paper is as follows. The next section introduces a one-vehicle look-ahead CACC strategy. Section III presents a CACC system based on a master-slave strategy, in which the Smith predictor can be applied. In the fourth section, we analyze stability and string-stable performance of the proposed CACC structure. Simulation results are shown in Section V, upon which Section VI presents the robust performance with uncertain delays. The last section summarizes the main conclusions.

II. Modeling and Control of a CACC String

In this section, we focus on the modeling and control of CACC with a one-vehicle look-ahead strategy, which is practically feasible for CACC. As shown in Fig. 1, a homogeneous CACC string composed of n vehicles is assumed in this paper, where l_i, q_i, v_i and u_i are the length, position, velocity, and desired acceleration of vehicle i, respectively.

A simplified vehicle model is often adopted for CACC design, obtained through the feedback linearization of a nonlinear vehicle model [53]. The resulting vehicle dynamics read

$$\begin{pmatrix} \dot{q}_i(t) \\ \dot{v}_i(t) \\ \dot{a}_i(t) \end{pmatrix} = \begin{pmatrix} v_i(t) \\ a_i(t) \\ -\frac{1}{\tau}a_i(t) + \frac{1}{\tau}u_i(t-\theta_\mathrm{a}) \end{pmatrix}, \tag{1}$$

where a_i is the actual acceleration of vehicle i, θ_a represents the vehicle actuator delay. The third equation in (1) represents the driveline dynamics, where τ is a time constant. Note that $u_i(t) = 0$ for $t < \theta_\mathrm{a}$. Here, no constraint is taken into account in view of the vehicle model, because for the operational domain of CACC, possible constraints (power, speed) do not play an important role, if any at all. Consequently, the transfer function $G(s)$ from the desired acceleration u_i to position q_i reads

$$G(s) = \frac{q_i(s)}{u_i(s)} = e^{-\theta_\mathrm{a} s}\frac{1}{s^2(\tau s+1)} \tag{2}$$

where $s \in \mathbb{C}$ is the Laplace variable, $u_i(s)$ and $q_i(s)$ denote the Laplace transform of $u_i(t)$ and $q_i(t)$, respectively. Note that, with a slight abuse of mathematical notation, $\cdot(s)$ denotes the Laplace transform of the corresponding time-domain variable $\cdot(t)$.

A constant time gap spacing policy is utilized, which is the most common spacing policy to improve string stability, see [6] and the references contained therein. Then the desired intervehicle distance $d_{\mathrm{r},i}$ between vehicle $i-1$ and i involves a standstill distance r_i and a velocity-dependent part:

$$d_{\mathrm{r},i}(t) = r_i + hv_i(t) \tag{3}$$

where h is the time gap, being identical for all vehicles in this homogeneous CACC string. The actual intervehicle distance d_i reads

$$d_i(t) = q_{i-1}(t) - q_i(t) - l_i. \tag{4}$$

To realize the vehicle-following objective, the intervehicle distance error e_i, defined as

$$e_i(t) = d_i(t) - d_{\mathrm{r},i}(t) \tag{5}$$

should asymptotically converge to zero, with the first vehicle driving at a constant velocity. To this end, the controller in [37] is adopted, where a pre-compensator with input ξ_i is introduced according to

$$\dot{u}_i(t) = -\frac{1}{h}u_i(t) + \frac{1}{h}\xi_i(t). \tag{6}$$

To stabilize the error dynamics, the control law for ξ_i is chosen as,

$$\xi_i(t) = u_{i-1,\mathrm{c}}(t) + k_\mathrm{p} e_i(t) + k_\mathrm{d}\dot{e}_i(t) \tag{7}$$

where k_p and k_d represent the controller parameters; $u_{i-1,\mathrm{c}}(t)$ is the received desired acceleration of the preceding vehicle, which suffers from the wireless communication delay θ_ff, reading

$$u_{i-1,\mathrm{c}}(t) = u_{i-1}(t-\theta_\mathrm{ff}). \tag{8}$$

Without loss of generality, we choose $r_i = l_i = 0$ when analyzing stability and string stability. Hence, the control structure can be depicted as in Fig. 2, where $H(s)$, $K(s)$ and $D_\mathrm{ff}(s)$ represent the Laplace transforms,

$$H(s) = hs + 1 \tag{9a}$$

$$K(s) = k_\mathrm{p} + k_\mathrm{d}s \tag{9b}$$

$$D_\mathrm{ff}(s) = e^{-\theta_\mathrm{ff}s}. \tag{9c}$$

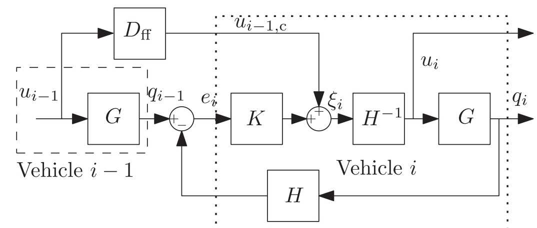


Fig. 2. Block scheme of the one-vehicle look-ahead CACC system.

Here, we introduce string stability of this one-vehicle look-ahead CACC system, adopting the so-called performance-oriented approach [6], [37], which is characterized by the amplification in upstream direction of the signal of interest. Therefore, the string stability transfer function $S(s)$ is defined as the relation between a relevant (scalar) signal of vehicle i and the corresponding signal of its preceding vehicle i-1. A CACC system of (homogeneous) interconnected vehicles is string stable if

$$\sup_\omega |S(j\omega)| \leq 1. \tag{10}$$

A string-stable platoon indicates energy dissipation along the string, which corresponds to the absence of overshoot in many cases. Considering for instance the desired acceleration, the transfer function $S_\mathrm{org}(s)$ from u_{i-1} to u_i reads

$$S_\mathrm{org}(s) = \frac{1}{H(s)}\cdot\frac{D_\mathrm{ff}(s) + G(s)K(s)}{1+G(s)K(s)} \tag{11}$$

for the original CACC scheme in Fig. 2. Note that the transfer function is the same for the velocity, acceleration, intervehicle distance and distance error in a homogeneous CACC string.

In the case of zero communication delay, (11) reduces to

$$S_\mathrm{org}(s) = \frac{1}{H(s)}\cdot\frac{1+G(s)K(s)}{1+G(s)K(s)} = \frac{1}{H(s)}. \tag{12}$$

Hence, (10) is fulfilled for any non-negative time gap, i.e., $h \geq 0$ s. However, as previously stated, a communication delay inherently exists in reality, which plays a significant role in view of string stability. With $\theta_\mathrm{ff} > 0$, a certain minimum time gap h_min is required to meet the string stability criterion (10), since a bigger time gap h results in smaller magnitudes of $\frac{1}{H(s)}$ and, hence, $S_\mathrm{org}(s)$ in (11).

III. Smith Predictor With Master-Slave CACC Strategy

The communication delay plays a key role in designing a string-stable time gap in the CACC system as presented in the previous section. To actively compensate for the delay with a Smith predictor, it is necessary to put the delay in series with the system to be controlled, while the communication delay D_ff is not in series with G (the vehicle to be controlled) in the original CACC scheme as shown in Fig. 2. To this end, a master-slave architecture for CACC systems is introduced in this section. Based on this control strategy, we apply a Smith predictor to compensate for wireless communication delay and analyze the resulting system with respect to string stability.

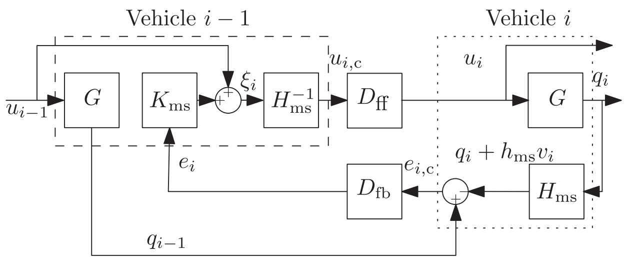


Fig. 3. CACC scheme with a master-slave control strategy.

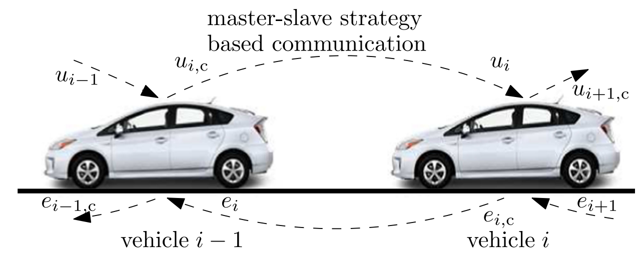


Fig. 4. Wireless communication topology and information flow in a master-slave CACC architecture.

A. CACC With Master-Slave Control Strategy

In this section, communication delay is put in series by rearranging the controller structure, as will be explained next. The proposed master-slave CACC strategy is shown in Fig. 3. Here, the preceding vehicle $i-1$ (in the dashed block) acts as a master, while the vehicle i serves as a slave (in the dotted block). This master-slave CACC strategy is derived from the original CACC scheme as shown in Fig. 2, with the preceding vehicle $i-1$ in the dashed block and the vehicle i in the dotted block. The modification from the original CACC scheme can be described as follows.

Firstly, the controller for vehicle i (slave) is re-located into the preceding vehicle $i-1$ (master), which is a fundamental characteristic of the master-slave strategy. Consequently, the desired acceleration of vehicle i is generated in the preceding vehicle $i-1$, which is defined as $u_{i,\mathrm{c}}$. As shown in Fig. 3, vehicle $i-1$ receives the intervehicle distance error from vehicle i, and then calculates u_i with the same scheme as in the original CACC system as shown in Fig. 2. Vehicle i receives desired acceleration u_i, which suffers from a feedforward communication delay θ_{ff}, yielding

$$u_i(t) = u_{i,\mathrm{c}}(t - \theta_{\mathrm{ff}}). \tag{13}$$

Secondly, due to the re-arrangement of the controller, the intervehicle distance error $e_{i,\mathrm{c}}$ needs to be transmitted to the preceding vehicle $i-1$ by the "feedback communication". Here, the desired intervehicle distance of vehicle i reads

$$d_{\mathrm{r},i,\mathrm{ms}}(t) = h_{\mathrm{ms}} v_i(t), \tag{14}$$

where h_{ms} represents the time gap in this master-slave CACC strategy. Therefore, the intervehicle distance error to be communicated $e_{i,\mathrm{c}}$ is

$$e_{i,\mathrm{c}}(t) = d_i(t) - d_{\mathrm{r},i,\mathrm{ms}}(t). \tag{15}$$

Note that a feedback communication delay θ_{fb} is induced, leading to that vehicle $i-1$ receives the distance error e_i according to

$$e_i(t) = e_{i,\mathrm{c}}(t - \theta_{\mathrm{fb}}). \tag{16}$$

In the master-slave strategy depicted in Fig. 3, $H(s)$, $K(s)$, $D_{\mathrm{ff}}(s)$ and $D_{\mathrm{fb}}(s)$ represent the Laplace transforms,

$$H_{\mathrm{ms}}(s) = h_{\mathrm{ms}} s + 1 \tag{17a}$$

$$K_{\mathrm{ms}}(s) = k_{\mathrm{ms,p}} + k_{\mathrm{ms,d}} s \tag{17b}$$

$$D_{\mathrm{ff}}(s) = e^{-\theta_{\mathrm{ff}} s} \tag{17c}$$

$$D_{\mathrm{fb}}(s) = e^{-\theta_{\mathrm{fb}} s}, \tag{17d}$$

where $k_{\mathrm{ms,p}}$ and $k_{\mathrm{ms,d}}$ are the controller parameters. The subscripts of θ_{ff} and θ_{fb} indicate the direction of information communication.

In view of feasibility, this master-slave CACC strategy can be realized in practice with the bidirectional communication as shown in Fig. 4. However, this master-slave strategy is still a one-vehicle look-ahead approach, since the controller of vehicle i only uses information of vehicle i and the preceding vehicle $i-1$. Note that the controller function of vehicle i is partly executed on vehicle $i-1$, which requires that vehicle $i-1$ should be reliable. In fact, in the common CACC structure (see Fig. 2), vehicle i also relies on vehicle $i-1$ in the sense that the desired acceleration of vehicle $i-1$ is used by vehicle i. Therefore, a master-slave CACC does not essentially increase intervehicle dependency. However, in case of so-called multi-brand platoons, there may be a problem, which is one drawback of this algorithm. The communication security requirement for both topologies is more or less the same. Since the preceding vehicle is required to perform specific computations, the master-slave CACC strategy is less flexible compared to simply communicating u_{i-1} in the original scheme. In addition, this algorithm does not allow for different controller implementations. However, the computation effort of the proposed scheme will not exceed that of the original scheme, since there is no optimization/iteration or any other computationally intensive operation involved.

In the master-slave CACC strategy, the string stability transfer function from u_{i-1} to u_i reads

$$S_{\mathrm{ms}} = \frac{1}{H_{\mathrm{ms}}} \cdot \frac{D_{\mathrm{ff}}(1 + D_{\mathrm{fb}} G K_{\mathrm{ms}})}{1 + D_{\mathrm{ff}} D_{\mathrm{fb}} G K_{\mathrm{ms}}}. \tag{18}$$

The Laplace variable s is omitted here for the sake of readability. Similar to the case of (11), the magnitude of S_{ms} decreases with an increasing time gap h_{ms}. Therefore, to fulfill the criterion (10), there exists a minimum string-stable time gap $h_{\mathrm{ms,min}}$, which depends on the communication delays. Here, the minimum string-stable time gap h_{min} for the original one-vehicle look-ahead CACC and $h_{\mathrm{ms,min}}$ for the master-slave CACC in Fig. 3 can be calculated with given values of the communication delay. To this end, we adopt the vehicle parameters identified in experiments [37], being: $\tau = 0.1$ and $\theta_{\mathrm{a}} = 0.2$ s. The controller

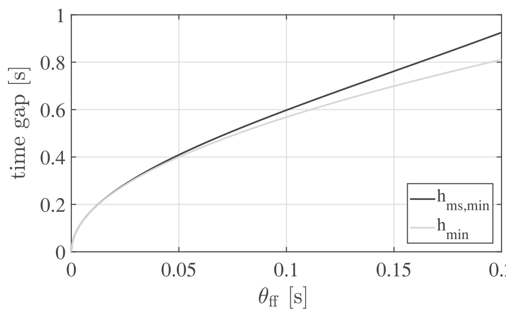


Fig. 5. Minimum string-stable time gaps $h_{\mathrm{ms,min}}(\theta_{\mathrm{ff}})$ and $h_{\mathrm{min}}(\theta_{\mathrm{ff}})$, with $\theta_{\mathrm{fb}} = \theta_{\mathrm{ff}}$.

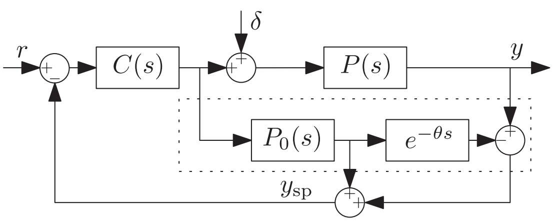


Fig. 6. Block diagram of a Smith predictor.

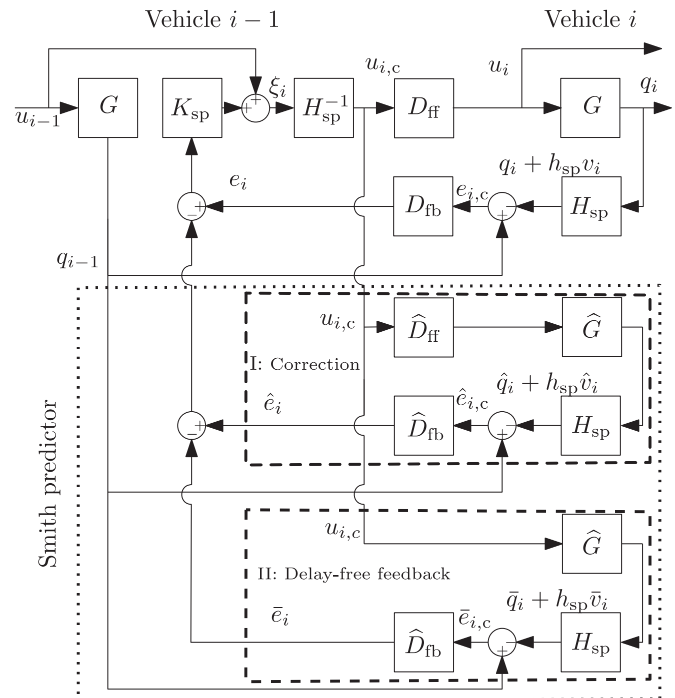


Fig. 7. Smith predictor compensating for feedforward communication delay in a master-slave CACC strategy.

parameters $k_{\mathrm{p}} = k_{\mathrm{ms,p}} = 0.2$ and $k_{\mathrm{d}} = k_{\mathrm{ms,d}} = 0.7$ according to [37] are used. Fig. 5 shows h_{min} (gray) and $h_{\mathrm{ms,min}}$ (black) as functions of the communication delay, for the original and for the master-slave CACC, respectively, where the feedback delay θ_{fb} is chosen equal to θ_{ff} for the sake of simplicity. Fig. 5 has been obtained by taking a fixed value for the communication delay and then searching for the smallest value of the time gap, such that $\sup_{\omega} |S(j\omega)| = 1$. From the figure, both $h_{\mathrm{ms,min}}$ and h_{min} increase with increasing communication delay. Apparently, introducing the master-slave architecture leads to a larger minimum string-stable time gap than that of the original scheme. However, the master-slave strategy allows for a Smith predictor approach. This appears to greatly reduce the minimum string-stable time gap, as will be shown in the next section.

B. Smith Predictor With Master-Slave Control Strategy

In this section, firstly, the Smith predictor is briefly introduced. Secondly, the application of the Smith predictor to the master-slave CACC strategy will be described.

The Smith predictor structure is shown in Fig. 6. The controlled plant is denoted by $P(s)$, which is assumed to consist of a delay-free part $P_0(s)$ and a time delay $e^{-\theta s}$. x, y and δ represent the reference, the plant output, and the disturbance, respectively. In case of without a Smith predictor, the complimentary sensitivity transfer function $T(s)$ from x to y reads

$$T(s) = \frac{C(s)P_0(s)e^{-\theta s}}{1 + C(s)P_0(s)e^{-\theta s}}. \tag{19}$$

In the Smith predictor-based scheme, the plant output y is adapted to y_{sp}, by adding two feedback loops (in the dotted block) from the controller output u through a process $P_0(s)e^{-\theta s}$, and a delay-free process $P_0(s)$. The essence of a Smith predictor is that a delay-free plant output is estimated, which is then used for feedback control. The difference between the delayed estimated output and the actual plant output is used for correcting the model mismatch. In the ideal situation of perfect modeling ($P(s) = P_0(s)e^{-\theta s}$), the Smith predictor-based complimentary sensitivity reads

$$T_{\mathrm{sp}}(s) = \frac{C(s)P_0(s)}{1 + C(s)P_0(s)} e^{-\theta s}. \tag{20}$$

In view of stability analysis, the main advantage of the Smith predictor approach is that the time delay is eliminated from the feedback loop.

According to the Smith predictor approach, two feedback loops are added to the scheme in Fig. 3, resulting in the Smith predictor-based CACC structure in Fig. 7. The Smith predictor is shown in a dashed block, which is a part of the controller located at vehicle $i-1$. Note that the Smith predictor is applied to the error in this specific case, instead of the plant output as shown in the general scheme in Fig. 6. However, it does not change the principle of the Smith predictor. H_{sp} and K_{sp} are introduced in this Smith predictor-based CACC system according to

$$H_{\mathrm{sp}}(s) = h_{\mathrm{sp}} s + 1 \tag{21a}$$

$$K_{\mathrm{sp}}(s) = k_{\mathrm{sp,p}} + k_{\mathrm{sp,d}} s \tag{21b}$$

with the Smith predictor-based time gap h_{sp}, and controller parameters $k_{\mathrm{sp,p}}$ and $k_{\mathrm{sp,d}}$.

The two added feedback loops are introduced as follows. The input of the Smith predictor is $u_{i,\mathrm{c}}$, which is generated in vehicle $i-1$. One loop in Block I is an estimated plant with feedforward

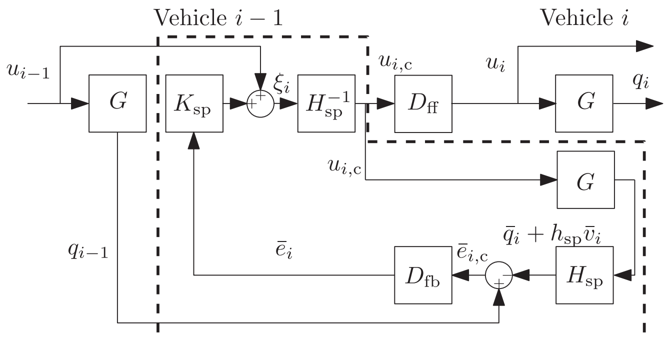


Fig. 8. Smith predictor-based control scheme in a master-slave CACC, when the values of vehicle parameters and communication delay are exactly known.

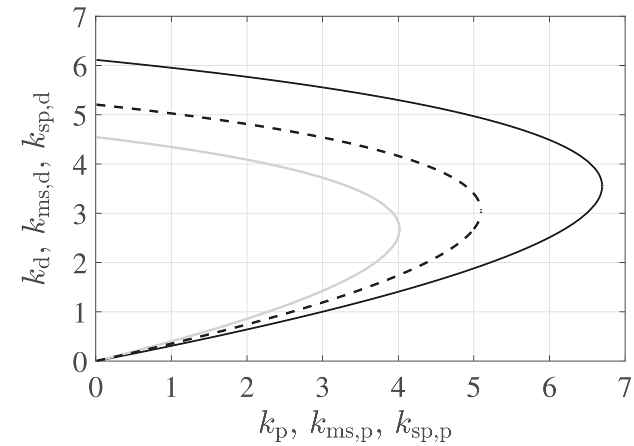


Fig. 9. Ranges of controller gains to guarantee individual vehicle stability: $\{k_{\rm p}, k_{\rm d}\}$, $\{k_{\rm ms,p}, k_{\rm ms,d}\}$, and $\{k_{\rm sp,p}, k_{\rm sp,d}\}$ in the area bounded by the solid dark curve, the solid gray curve, and the dashed dark curve, respectively. Here $\tau = 0.1$, $\theta_a = 0.2$ s, and $\theta_{\rm ff} = \theta_{\rm fb} = 0.04$ s, and the 3rd-order Padé approximation of the time delay is used.

communication delay, as $P_0(s)e^{-\theta s}$ in Fig. 6. $\hat{q}_i$, $\hat{v}_i$, $\hat{e}_i$ and $\hat{e}_{i,c}$ are the estimated position, velocity, intervehicle distance error and communicated error, respectively. The other loop in Block II is free of the feedforward communication delay, as $P_0(s)$ in Fig. 6. $\bar{q}_i$, $\bar{v}_i$, and $\bar{e}_i$ represent the corresponding predicted states given that $\widehat{D}_{\rm ff}$ is eliminated. The output of the Smith predictor is the difference of $\hat{e}_{i,\rm c}$ and $\bar{e}_{i,\rm c}$. $\widehat{G}$, $\widehat{D}_{\rm ff}$ and $\widehat{D}_{\rm fb}$ represent the estimated vehicle dynamics, feedforward delay and feedback delay, respectively.

In the case that G, $D_{\rm ff}$ and $D_{\rm fb}$ are exactly known, i.e., $\widehat{G} = G$, $\widehat{D}_{\rm ff} = D_{\rm ff}$ and $\widehat{D}_{\rm fb} = D_{\rm fb}$, $\hat{e}_{i,\rm c} = e_{i,\rm c}$, Block I in Fig. 7 will compensate for the response of the real vehicle, leaving only Block II in the control loop as shown in Fig. 8. Consequently, the string stability transfer function from u_{i-1} to u_i reads

$$S_{\rm sp} = \frac{1}{H_{\rm sp}} \cdot \frac{D_{\rm ff} + D_{\rm ff} D_{\rm fb} G K_{\rm sp}}{1 + D_{\rm fb} G K_{\rm sp}} = \frac{D_{\rm ff}}{H_{\rm sp}}. \tag{22}$$

The string stability criterion (10) is then fulfilled with any time gap $h_{\rm sp} \geq 0$, i.e., the minimum string-stable time gap $h_{\rm sp,min}$ is zero. Note that a large feedforward communication delay may compromise safety, although string stability is guaranteed. According to our experiment for vehicle dynamics identification [36], [37], vehicle actuator delay $\theta_{\rm a} = 0.2$ s and the time constant $\tau = 0.1$ appears to be invariant. The vehicle dynamics are considered to be exactly known in this paper.

In this section, a Smith predictor has been applied to compensate for communication delay on the proposed master-slave CACC system in view of string stability. The performance of this master-slave CACC will be further analyzed in the next section. In particular, the actual intervehicle distance is concerned in Section IV-B due to the difference between the predicted position $\bar{q}_i$ and the actual position $q_i(t)$.

IV. Performance of Master-Slave CACC With Smith Predictor

In this section, we analyze the performance of the master-slave CACC, in which a Smith predictor is applied to compensate for the feedforward communication delay.

A. Individual Vehicle Stability

Individual vehicle stability states that every vehicle in the string should track any bounded acceleration and velocity profile of the preceding vehicle with a bounded spacing and velocity error [54]. We assume there is no model uncertainty here. Stability analysis of the Smith predictor-based CACC with model uncertainties is beyond the scope of this paper.

Individual vehicle stability can be analyzed with the characteristic polynomial of the relevant string stability transfer functions. According to (11), (18), and (22), the characteristic polynomials read

$$F := 1 + GK \tag{23a}$$

$$F_{\rm ms} := 1 + D_{\rm ff} D_{\rm fb} G K_{\rm ms} \tag{23b}$$

$$F_{\rm sp} := 1 + D_{\rm fb} G K_{\rm sp} \tag{23c}$$

for the original, the master-slave, and the Smith predictor-based CACC systems, respectively, with no occurrence of pole-zero cancellation. The vehicle parameters of the previous section ($\tau = 0.1$, $\theta_{\rm a} = 0.2$ s) are used. In our experimental setting, the update frequency of the wireless link is 25 Hz, which leads to a maximum communication delay of 0.04 s in the experimental setting [36], assuming that there is no significant delay in the transmitter and/or receiver. Individual vehicle stability conditions can be derived with the Routh-Hurwitz criterion by replacing the time delay by a 3rd-order Padé approximation, which is sufficient for the frequency range of interest for the vehicle and CACC [20]. Then, the allowable ranges for the controller gains $\{k_{\rm p}, k_{\rm d}\}$, $\{k_{\rm ms,p}, k_{\rm ms,d}\}$ and $\{k_{\rm sp,p}, k_{\rm sp,d}\}$, to achieve individual vehicle stability for the original, the master-slave, and the Smith predictor-based CACC systems, respectively, can be numerically found. The results are shown in Fig. 9. $\{k_{\rm p}, k_{\rm d}\}$, $\{k_{\rm ms,p}, k_{\rm ms,d}\}$ and $\{k_{\rm sp,p}, k_{\rm sp,d}\}$ should be within the area bounded by the solid dark curve, solid gray curve, and dashed dark curve, respectively. Here, the maximum stability ranges of the proportional gains are $0 < k_{\mathrm{p}} < 6.69$, $0 < k_{\mathrm{ms,p}} < 4.01$, $0 < k_{\mathrm{sp,p}} < 5.09$; The actual stability range depends on the value of the differential gain, as can be seen in the figure. It is reasonable that increasing communication delay increases the total value of time delay in the characteristic polynomials, which leads to a smaller range of the proportional and differential gains in view of individual vehicle stability.

B. Effect of Tracking Latency

In this section, we assume that communication delay is exactly known. According to the CACC scheme as shown in Fig. 8, the predicted position $\bar{q}_i$ reads

$$\bar{q}_i(t) := q_i(t + \theta_{\mathrm{ff}}). \tag{24}$$

Similarly, the predicted velocity $\bar{v}_i$ yields

$$\bar{v}_i(t) := v_i(t + \theta_{\mathrm{ff}}). \tag{25}$$

The objective of the controller is to regulate $\bar{e}_{i,\mathrm{c}}$ to zero, which implies the delayed error $\bar{e}_i$ also approaches zero, see Fig. 8. $\bar{e}_{i,\mathrm{c}}$ reads,

$$\bar{e}_{i,\mathrm{c}}(t) = q_{i-1}(t) - \bar{q}_i(t) - h_{\mathrm{sp}}\bar{v}_i(t), \tag{26}$$

which indicates that the controller aims to control a virtual distance $\bar{d}_i = q_{i-1}(t) - \bar{q}_i(t)$, rather than the actual distance $d_i(t) = q_{i-1}(t) - q_i(t)$, to a desired value. Given the fact that $\bar{q}_i(t) > q_i(t)$ for a forward driving platoon, it follows that $\bar{d}_i(t) < d_i(t)$. Hence, the actual distances $d_i(t)$ will converge to a value that is larger than the desired distance. This difference is referred to as "tracking latency" Δq_i, defined as

$$\Delta q_i(t) := d_i(t) - \bar{d}_i(t) = \bar{q}_i(t) - q_i(t), \tag{27}$$

which is the additional distance due to the Smith predictor scheme. This tracking latency will be investigated in the remainder of this section.

Firstly, a stationary condition is considered, and vehicle i drives at a constant velocity v_i^*. Here, $\cdot^*(t)$ denotes the corresponding variable $\cdot(t)$ in this stationary condition. Consequently, (24) and (25) can be re-written as

$$\bar{q}_i^*(t) = q_i^*(t + \theta_{\mathrm{ff}}) = q_i^*(t) + \theta_{\mathrm{ff}} v_i^* \tag{28a}$$

$$\bar{v}_i^*(t) = v_i^*(t + \theta_{\mathrm{ff}}) = v_i^*. \tag{28b}$$

Substituting (28) into (26), leads to

$$q_{i-1}^*(t) - q_i^*(t) - h_{\mathrm{sp}} v_i^* - \theta_{\mathrm{ff}} v_i^* = 0, \tag{29}$$

i.e., $q_{i-1}^*(t) - q_i^*(t) = h_{\mathrm{sp}} v_i^* + \theta_{\mathrm{ff}} v_i^*$. Therefore, the actual stationary intervehicle distance d_i^* reads

$$\begin{aligned} d_i^*(t) &= q_{i-1}^*(t) - q_i^*(t) \\ &= (h_{\mathrm{sp}} + \theta_{\mathrm{ff}}) v_i^* \end{aligned} \tag{30}$$

Consequently, the actual time gap $h_{\mathrm{sp,a}}^*$ in this Smith predictor-based CACC system is

$$h_{\mathrm{sp,a}}^* = h_{\mathrm{sp}} + \theta_{\mathrm{ff}}, \tag{31}$$

which corresponds to the earlier conclusion that the actual stationary distance is larger than the desired value.

Now we can compare the minimum string-stable time gaps for the original and Smith predictor-based CACC systems. When the minimum string-stable time gap $h_{\mathrm{sp}} = h_{\mathrm{sp,min}} = 0$ is selected for the Smith predictor-based CACC system, the minimum actual time gap reads $h_{\mathrm{sp,min,a}}^* = \theta_{\mathrm{ff}}$. Considering the upper bound of the communication delay $\theta_{\mathrm{ff}} = 0.04$ s as mentioned before, $h_{\mathrm{sp,min,a}}^* = 0.04$ s is much smaller than minimum time gap $h_{\mathrm{min}} \approx 0.35$ s in the original CACC scheme as shown in Fig. 5. In other words, despite the fact that the tracking latency introduces an additional intervehicle distance, the minimum string-stable distance $h_{\mathrm{sp,min,a}}^* v_i^*$ is still significantly smaller than that in the original CACC system. In a highway scenario, for example, with a stationary velocity $v_i^* = 120$ km/h $= 33.33$ m/s, the stationary distance thus reduces from $0.35 \times 33.33 = 11.66$ m to $0.04 \times 33.3 = 1.33$ m.

Having analyzed the tracking latency in the stationary situation, we now consider the transient behavior, i.e., $a_i \neq 0$. The predicted velocity and position read

$$\bar{v}_i(t) = v_i(t + \theta_{\mathrm{ff}}) = v_i(t) + \int_t^{t+\theta_{\mathrm{ff}}} a_i(\gamma)\,\mathrm{d}\gamma \tag{32a}$$

$$\begin{aligned} \bar{q}_i(t) &= q_i(t + \theta_{\mathrm{ff}}) \\ &= q_i(t) + \int_t^{t+\theta_{\mathrm{ff}}} v_i(\lambda)\,\mathrm{d}\lambda \\ &= q_i(t) + \int_t^{t+\theta_{\mathrm{ff}}} \left(v_i(t) + \int_t^{\lambda} a_i(\gamma)\,\mathrm{d}\gamma \right) \mathrm{d}\lambda \\ &= q_i(t) + \theta_{\mathrm{ff}} v_i(t) + \int_t^{t+\theta_{\mathrm{ff}}} \int_t^{\lambda} a_i(\gamma)\,\mathrm{d}\gamma\,\mathrm{d}\lambda. \end{aligned} \tag{32b}$$

Substituting (32) into (26) leads to

$$\begin{aligned} \bar{e}_{i,\mathrm{c}}(t) = q_{i-1}(t) - q_i(t) - \theta_{\mathrm{ff}} v_i(t) - \int_t^{t+\theta_{\mathrm{ff}}} \int_t^{\lambda} a_i(\gamma)\,\mathrm{d}\gamma\,\mathrm{d}\lambda \\ - h_{\mathrm{sp}} \left(v_i(t) + \int_t^{t+\theta_{\mathrm{ff}}} a_i(\gamma)\,\mathrm{d}\gamma \right). \end{aligned} \tag{33}$$

Focusing on the effect of the Smith predictor, the distance error is assumed to be zero. Thus, the actual intervehicle distance $d_i(t)$ reads

$$\begin{aligned} d_i(t) &= q_{i-1}(t) - q_i(t) \\ &= (h_{\mathrm{sp}} + \theta_{\mathrm{ff}}) v_i(t) + h_{\mathrm{sp}} \int_t^{t+\theta_{\mathrm{ff}}} a_i(\gamma)\,\mathrm{d}\gamma \\ &\quad + \int_t^{t+\theta_{\mathrm{ff}}} \int_t^{\lambda} a_i(\gamma)\,\mathrm{d}\gamma\,\mathrm{d}\lambda. \end{aligned} \tag{34}$$

It follows that the largest possible intervehicle distance in the Smith predictor-based CACC scheme occurs when a_i equals its maximum positive value. Considering a constant acceleration $a_i(t) = a_i'$, (34) leads to

$$d_i(t) = (h_{\mathrm{sp}} + \theta_{\mathrm{ff}}) v_i(t) + a_i' h_{\mathrm{sp}} \theta_{\mathrm{ff}} + \frac{1}{2} a_i' \theta_{\mathrm{ff}}^2. \tag{35}$$

With the minimum string-stable time gap $h_{\mathrm{sp}} = h_{\mathrm{sp,min}} = 0$, $a_i' = 4$ m/s^2 and $\theta_{\mathrm{ff}} = 0.04$ s, $d_i(t) = \theta_{\mathrm{ff}} v_i(t) + 0.0032$. Compared to (30), the increase of d_i between the stationary and

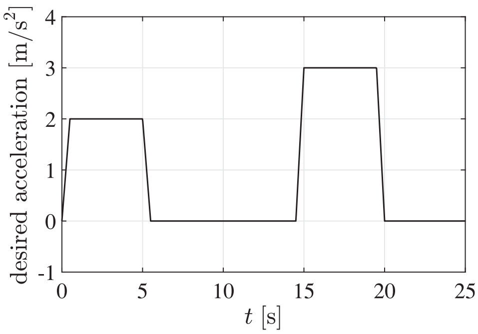


Fig. 10. Desired acceleration of the leading vehicle in a CACC platoon.

transient situations is 0.0032 m, which can be neglected with respect to the nominal distance, being in the order of meters.

Similarly to analyzing the largest possible intervehicle distance, we can consider the situation with respect to the shortest intervehicle distance for the sake of preventing collisions, which happens with the maximum deceleration. Taking $a_i' = -10$ m/s^2 for example, (34) becomes

$$d_i(t) = \theta_{\text{ff}} v_i(t) - 0.008 \tag{36}$$

with the minimum string-stable time gap $h_{\text{sp}} = h_{\text{sp,min}} = 0$. Therefore, there will no safety risk even if an emergency brake occurs.

In summary, applying a Smith predictor to compensate for the feedforward communication delay in a master-slave CACC system can significantly decrease the minimum string-stable intervehicle distance, even considering the tracking latency.

V. Simulation Results

To validate the theoretical results, simulations are conducted with the original controller and the Smith predictor-based controller for a CACC string with four vehicles. Based on ISO standard 15622 for intelligent transport systems [55], the desired acceleration for the leading vehicle is set as a trapezoidal acceleration profile, as shown in Fig. 10. Note that in CACC platoons, driving comfort depends on the driving behavior of the preceding vehicle. If the preceding vehicle's behavior is uncomfortable with a more aggressive acceleration profile, then the follower vehicle's behavior may also be uncomfortable, but to a lesser extent. In that respect, string-stable behavior in essence improves comfort. Here, all vehicles in this CACC string start from $v_i(0) = 0$ m/s at the desired distance, and equal to the standstill distance $r = 2.5$ m. The PD controller gains are set the same for both cases: $k_{\text{p}} = k_{\text{sp,p}} = 0.2$ and $k_{\text{d}} = k_{\text{sp,d}} = 0.7$ as in [37]. The communication delay θ_{ff} and θ_{fb} are assumed to be known, being equal to 0.04 s in this section.

Fig. 11 shows the time responses of four vehicles with $h = 0.3$ s, which is smaller than the minimum string-stable time gap as shown in Fig. 5. Consequently, the CACC-equipped vehicles are string unstable, i.e., the magnitudes of the acceleration and other signals in upstream direction are amplified. In Fig. 11(c), d_i increases from 2.5 m at $v_i(0) = 0$ m/s to 10 m at $v_i = 25$ m/s, which corresponds to the desired intervehicle distance in (3).

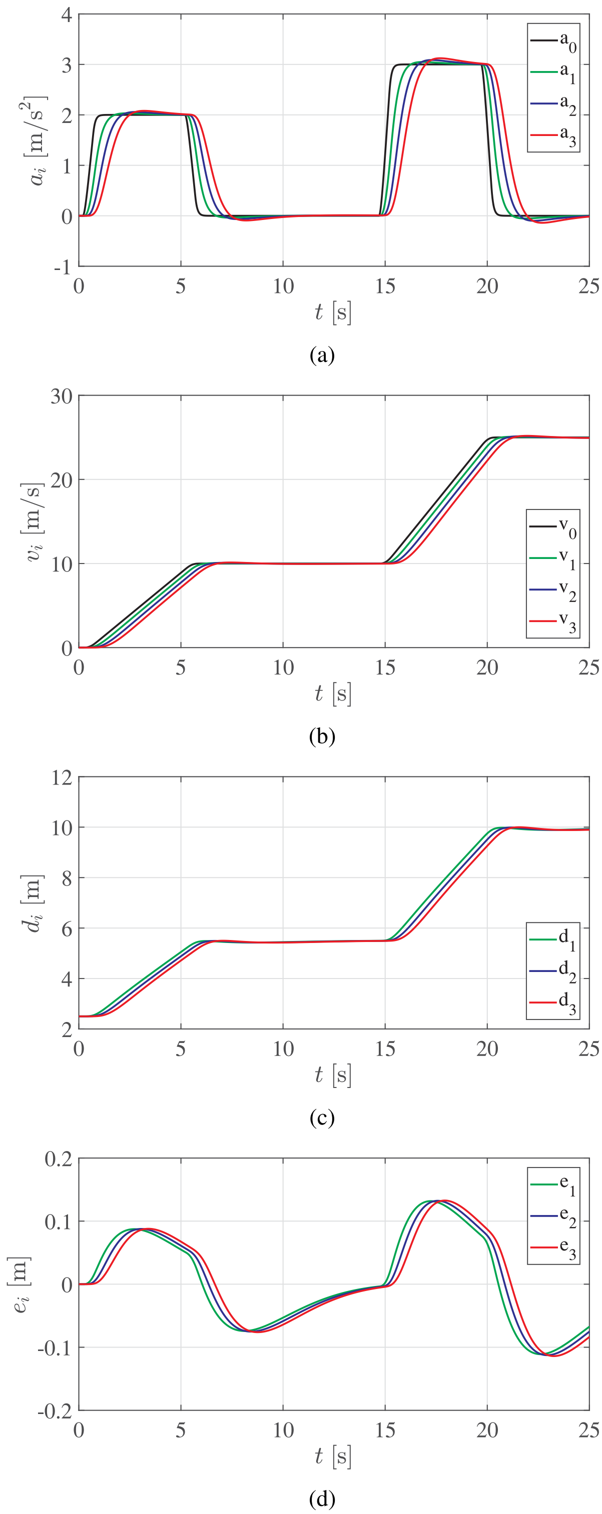


Fig. 11. Time responses with the original CACC controller. $\theta_{\text{ff}} = \theta_{\text{fb}} = 0.04$ s and $h = 0.3$ s.

Having compensated for feedforward communication delay, the time responses with $h_{\text{sp}} = 0.05$ s are presented in Fig. 12. The responses of vehicle 1 and 2 are omitted in Fig. 12 for reasons of readability. In fact, $h_{\text{sp}} = 0$ s can be chosen to guarantee string stability according to (22), while $h_{\text{sp}} = 0.05$ s is

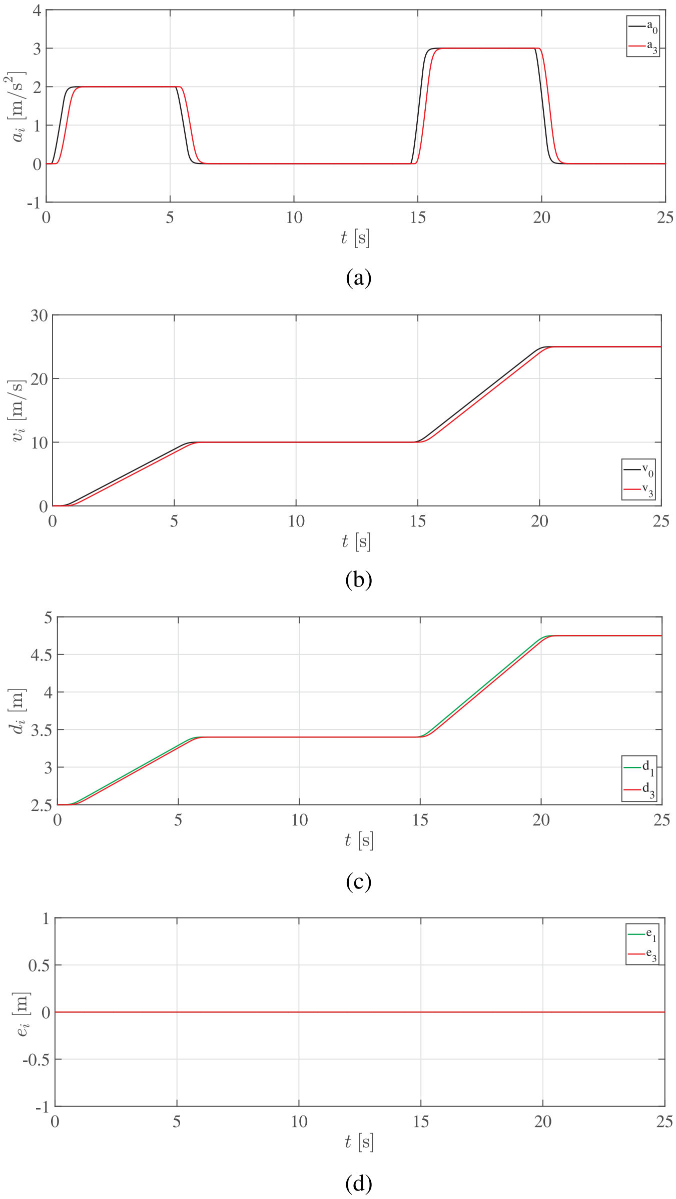


Fig. 12. Time responses with the Smith predictor-based CACC controller. $\theta_{\text{ff}} = \theta_{\text{fb}} = 0.04$ s and $h_{\text{sp}} = 0.05$ s.

selected here to keep the simulation responses readable. It can be observed that the acceleration and the velocity smoothly respond to those of the preceding vehicles in Fig. 12(a) and 12(b), respectively. Fig. 12(d) indicates that the intervehicle distance error is zero. Fig. 12(c) shows that the intervehicle distance is 4.75 m at 25 m/s, which corresponds to (30), while the actual time gap $h_{\text{sp,a}}$ is 0.09 s.

With the same communication setting, previous publications of the authors also considered the minimum string-stable time gap [23], [36]. In [23], a Smith predictor was applied to compensate for the vehicle actuator delay. [36] proposed an $\mathcal{H}_\infty$ controller synthesis approach for string stability, which was applied to CACC controller design for one- and two-vehicle look-ahead communication topologies. The comparison with

TABLE I
COMPARISON OF THE MINIMUM STRING-STABLE TIME GAPS

	Control scheme	Time gap
This paper	Compensation for communication delay (Fig. 7)	0.09 s
This paper	Original scheme (Fig. 2)	0.35 s
[23]	Compensation for the vehicle actuator delay	0.25 s
[36]	$\mathcal{H}_\infty$ with one-vehicle look-ahead topology	0.30 s
[36]	$\mathcal{H}_\infty$ with two-vehicle look-ahead topology	0.45 s

different control schemes is presented in Table I, which indicates that by compensating for the communication delay with a Smith predictor in the proposed master-slave strategy, a much smaller string-stable intervehicle time gap can be realized.

VI. Robust String Stability Considering Uncertain Communication Delays

In practice, the vehicle dynamics and the wireless communication delay may suffer from uncertainty. With the help of a lower level controller to realize the desired acceleration, the accurate vehicle model can be accurately identified for the proposed scheme. On the other side, GPS-based time precision is not always optimal. Thus, in this section, the communication delay is considered uncertain with an upper bound. As already mentioned, the maximum communication delay is $\theta_{\text{ff,max}} = \theta_{\text{fb,max}} = 0.04$ s in the experimental setting [36]. In this section, we analyze the effect of communication delay uncertainty on string stability in the proposed control structure, and determine the suitable value of communication delays that should be chosen in the Smith predictor for a small minimum string-stable time gap. Here, we assume that the vehicle parameters in this homogeneous CACC system are accurately known.

With the variable communication delays θ_{ff} and θ_{fb}, and estimated communication delays $\hat{\theta}_{\text{ff}}$ and $\hat{\theta}_{\text{fb}}$, the string stability transfer function from u_{i-1} to u_i for the CACC structure in Fig. 7 reads

$$S_{\text{sp,u}} = \frac{1}{H_{\text{sp}}} \cdot \frac{D_{\text{ff}}(1 + D_{\text{fb}} G K_{\text{sp}})}{1 + (\widehat{D}_{\text{fb}} + D_{\text{ff}} D_{\text{fb}} - \widehat{D}_{\text{ff}} \widehat{D}_{\text{fb}}) G K_{\text{sp}}}, \quad (37)$$

while (22) holds for the plant with exactly known communication delay. Here, $\widehat{D}_{\text{ff}} = e^{-\hat{\theta}_{\text{ff}} s}$ and $\widehat{D}_{\text{fb}} = e^{-\hat{\theta}_{\text{fb}} s}$. $\hat{\theta}_{\text{ff}}$ and $\hat{\theta}_{\text{fb}}$ are constant values in the proposed Smith predictor-based scheme, and thus $\hat{\theta}_{\text{ff}}$ and $\hat{\theta}_{\text{fb}}$ should be selected such that the minimum string-stable time gap can be as small as possible.

Considering $\theta_{\text{ff}}, \theta_{\text{fb}} \in (0, 0.04]$ s, Fig. 13 shows the minimum string-stable time gap $h_{\text{sp,min}}$ as a function of the variable communication delay according to (37), given a selected set of $\hat{\theta}_{\text{ff}}$ and $\hat{\theta}_{\text{fb}}$. Fig. 13 clearly suggests that choosing the Smith predictor delays $\hat{\theta}_{\text{ff}}$ and $\hat{\theta}_{\text{fb}}$ equal to the maximum possible value of the real delays, overall leads to a very low minimum string-stable time gap. In fact, if $\hat{\theta}_{\text{ff}}$ and $\hat{\theta}_{\text{fb}}$ are chosen smaller than $\theta_{\text{ff,max}}$ and $\theta_{\text{fb,max}}$, the remaining part of delays can still significantly compromise string stability. With $\hat{\theta}_{\text{ff}} = \theta_{\text{ff,max}} = 0.04$ s, the resulting minimum string-stable time gap is $h_{\text{sp,min}} = 0.022$ s according to Fig. 13(a).

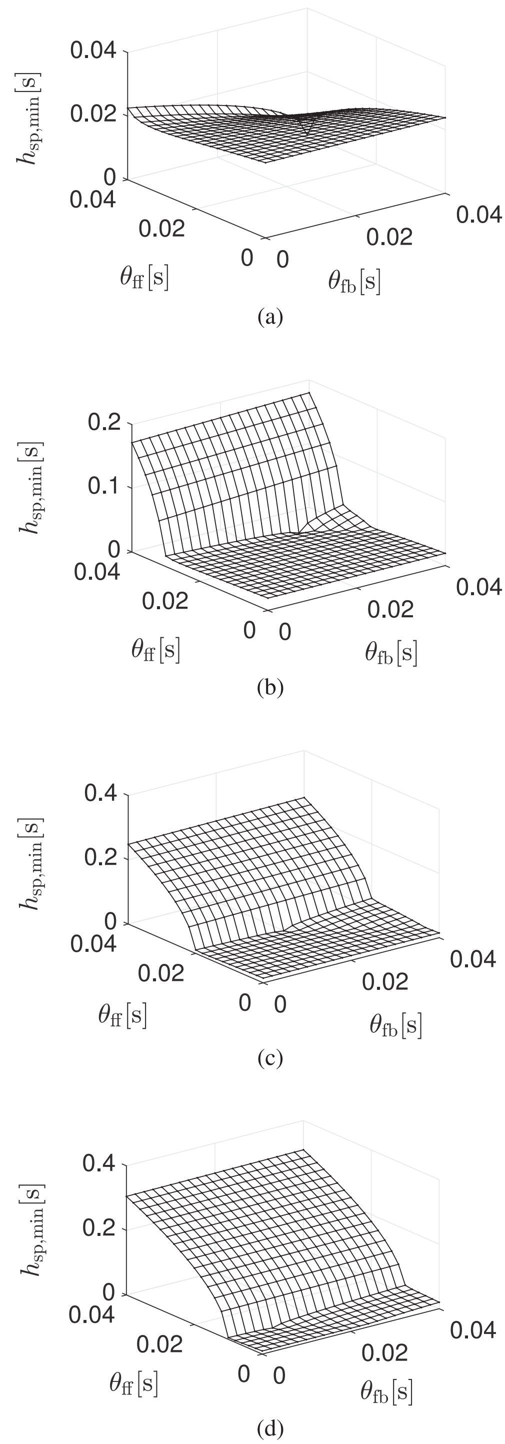


Fig. 13. $h_{\mathrm{sp,min}}$ as a function of θ_{ff} and θ_{fb}, given different selected $\hat{\theta}_{\mathrm{ff}}$ and $\hat{\theta}_{\mathrm{fb}}$. (a) $\hat{\theta}_{\mathrm{ff}} = \hat{\theta}_{\mathrm{fb}} = 0.04$ s. (b) $\hat{\theta}_{\mathrm{ff}} = \hat{\theta}_{\mathrm{fb}} = 0.03$ s. (c) $\hat{\theta}_{\mathrm{ff}} = \hat{\theta}_{\mathrm{fb}} = 0.02$ s. (d) $\hat{\theta}_{\mathrm{ff}} = \hat{\theta}_{\mathrm{fb}} = 0.01$ s.

Having analyzed robust string stability regarding communication delay uncertainty, individual vehicle stability can be checked with the Nyquist stability criterion. Considering the closed-loop transfer function (37), the equivalent open-loop transfer function L with a negative unity feedback loop can be solved from $\frac{L}{1+L} = S_{\mathrm{sp,u}}$. Thus,

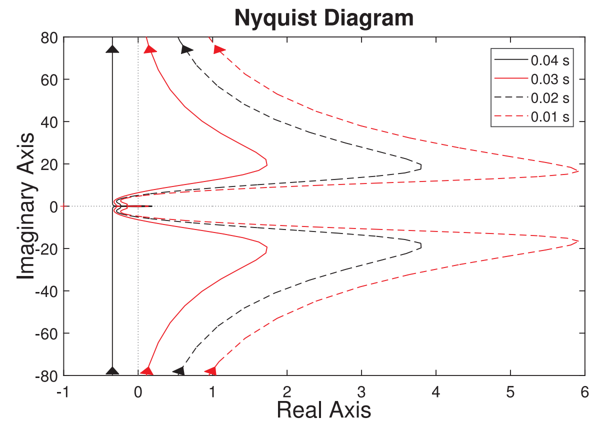


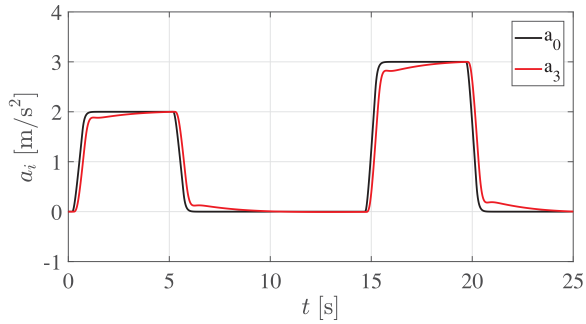
Fig. 14. Nyquist plots of the loop system function with uncertain communication delay, with selecting $\hat{\theta}_{\mathrm{ff}} = \hat{\theta}_{\mathrm{fb}} = 0.04$ s in the Smith predictor. The actual delays are 0.04 s, 0.03 s, 0.02 s and 0.01 s for the black, red, black dashed, and red dashed plots, respectively.

$$L = \frac{S_{\mathrm{sp,u}}}{1 - S_{\mathrm{sp,u}}} = \frac{D_{\mathrm{ff}}(1 + D_{\mathrm{fb}} G K_{\mathrm{sp}})}{H_{\mathrm{sp}}[1 + (\widehat{D}_{\mathrm{fb}} + D_{\mathrm{ff}} D_{\mathrm{fb}} - \widehat{D}_{\mathrm{ff}} \widehat{D}_{\mathrm{fb}}) G K_{\mathrm{sp}}] - D_{\mathrm{ff}}(1 + D_{\mathrm{fb}} G K_{\mathrm{sp}})}. \tag{38}$$

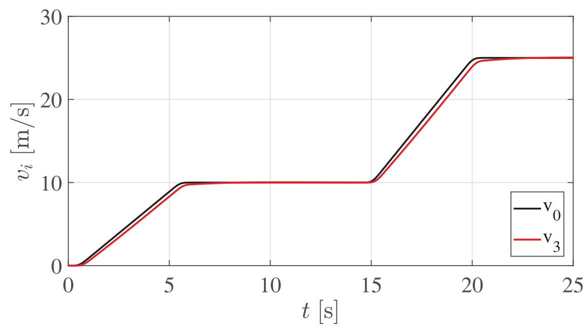
With $\hat{\theta}_{\mathrm{ff}} = \theta_{\mathrm{ff,max}} = 0.04$ s, $h_{\mathrm{sp}} = 0.05$ s and G and K_{sp} as mentioned in the previous sections, there is no right-half-plane pole for the equivalent open-loop transfer function L with the uncertain delays. Considering $\theta_{\mathrm{ff}} = \theta_{\mathrm{fb}} \in \{0.01, 0.02, 0.03, 0.04\}$ s, Fig. 14 shows that the Nyquist plots of L do not encircle (clock-wise) the point -1. Therefore, the closed-loop system is stable in the presence of communication delay uncertainty. No that there is sufficient stability margin for this system with possible actual communication delays.

As a summary, in the presence of communication delay uncertainty, the minimum string-stable time gap will only be slightly increased by selecting the maximum delay in the Smith predictor. Also, uncertain communication delay will not significantly influence individual vehicle stability in the proposed scheme. Note that other studies taking uncertain communication delay into account also choose the upper bound in the process of controller design [16], [17], [36], since the requirements of both string stability and individual stability are stricter with larger communication delay.

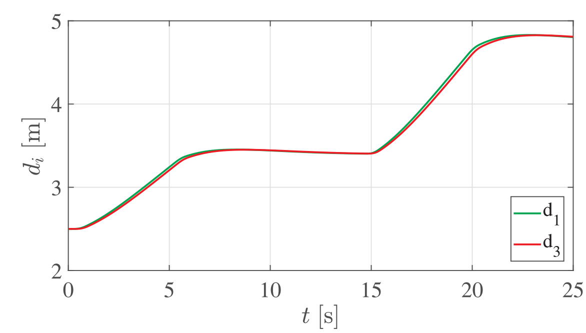
Simulations with respect to uncertain wireless communication delay are conducted here to validate the theoretical results. In the time-domain simulations, the desired acceleration for the leading vehicle is set as in Fig. 10. Parameters are the same as in Fig. 12, except for the actual communication delays, which are set to $\theta_{\mathrm{ff}} = \theta_{\mathrm{fb}} = 0.01$ s. $\hat{\theta}_{\mathrm{ff}} = \hat{\theta}_{\mathrm{fb}} = 0.04$ s are chosen in the Smith predictor, according to the results from Fig. 13. The time responses of vehicles 0 and 3 are shown in Fig. 15. In Fig. 15(a) and 15(b), the acceleration and the velocity of the last vehicle



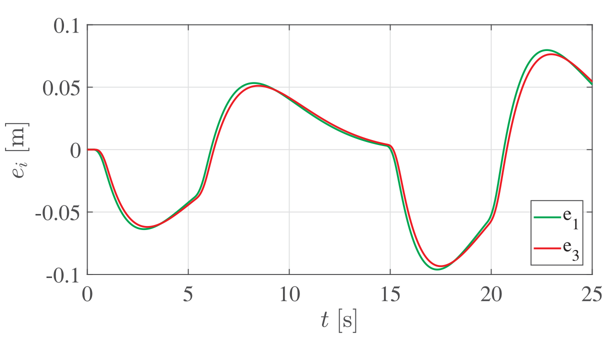
(a)



(b)



(c)



(d)

Fig. 15. Time responses with the Smith predictor-based CACC controller. $\theta_{\text{ff}} = \theta_{\text{fb}} = 0.01$ s, $\hat{\theta}_{\text{ff}} = \hat{\theta}_{\text{fb}} = 0.04$ s, and $h_{\text{sp}} = 0.05$ s.

reach those of the leading vehicle slower than in Fig. 12(a) and 12(b), respectively, which is due to the fact that the estimated communication delays in the Smith predictor are larger than the actual delays. The intervehicle distances in Fig. 15(c) show a slight overshoot compared to the desired intervehicle distance in (30) due to the effect of tracking latency. However, the signals in Fig. 15 attenuate in downstream direction, which indicates that the CACC platoon is string stable.

VII. Conclusion

In this paper, a Smith predictor was employed to compensate for communication delay in a homogeneous CACC system, in order to take more advantage of CACC in view of the road throughput. A master-slave control strategy is applied, based on re-arranging the communication delays, such that they are in series with the controlled plant, which allows for the application of a Smith predictor. Consequently, an extremely small minimum string-stable time gap was realized, even considering tracking latency which is due to fact that the actual intervehicle distance is larger than the predicted intervehicle distance. Even under communication delay uncertainty, the proposed control strategy performs adequately, in terms of yielding a small string-stable time gap. This can be realized by choosing the delays in the Smith predictor according to the maximum possible communication delay. The minimum string-stable time gap can retain very small while being robust to uncertain communication delays, by selecting maximum time delays in the Smith predictor. Individual vehicle stability can also be guaranteed in presence of uncertain delays. Simulations of CACC-equipped vehicles with the proposed strategy has been conducted, resulting in a string-stable platoon with a time gap less than 0.10 s with and without communication delay uncertainty, which validates the theoretical results.

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