Smith Predictor Compensating for Vehicle Actuator Delays in Cooperative ACC Systems

Haitao Xing, Jeroen Ploeg, and Henk Nijmeijer, *Fellow, IEEE*

***Abstract*—Cooperative adaptive cruise control (CACC) employs intervehicle wireless communications to realize short intervehicle distances and, hence, to improve road throughput. However, the vehicle actuator delay and communication delay have a significant effect on the (string) stability properties. Therefore, a Smith predictor has been applied to compensate for the vehicle actuator delay, while utilizing a proportional–derivative controller and a constant time gap spacing policy. The control actuation is conducted on a delay-free vehicle model to follow a preceding vehicle with a desired distance, such that the resulting scheme leads to individual vehicle stability independent of the vehicle actuator delay. Moreover, this approach allows for a smaller minimum string-stable time gap compared to without the compensator, thus taking full advantage of CACC. In addition, the Smith predictor has been adapted to take acceleration disturbances into account. The results are experimentally validated using a platoon of two passenger vehicles, illustrating the practical feasibility of this approach.**

***Index Terms*—Cooperative adaptive cruise control (CACC), Smith predictor, vehicle actuator delay, string stability, road throughput.**

I. Introduction

Adaptive Cruise Control (ACC) systems have penetrated into the market, relieving the driver's task by automatically keeping a desired intervehicle distance [1]. For a vehicle platoon, an important requirement is string stability, which is defined as attenuation of disturbances, e.g., velocity variations of downstream vehicles, in upstream direction, potentially leading to traffic jams [2]. In addition, safety challenges such as rear-end collisions can be efficiently prevented in a string stable platoon [3], [4]. Therefore, string stability is worthwhile considering in the design of a vehicle platoon. However, in ACC-equipped vehicle platoons, the string stable behavior is only obtained at large intervehicle distances, which do not improve road throughput [5], [6]. To improve highway capacity, Cooperative ACC (CACC) systems have been developed, in which wireless vehicle-to-vehicle communications are employed [7], [8]. As a result, shorter intervehicle distances can be achieved while guaranteeing string stability. Therefore, highway capacity could be close to double with a 100% market penetration of CACC compared to with only manually driven or only ACC controlled vehicles [9].

String stability is affected by vehicle dynamics [7], information flow topology and the quality of intervehicle sensing and communication [10]–[12], and the intervehicle spacing policy [13]. In particular, both communication delay and vehicle actuator delay, which inherently exist in CACC platoons [2], [6], can significantly compromise string stability. Various CACC strategies considering time delays have been developed, which indicate the need of substantially restricting the delays in order to guarantee string stability [2], [7], [14]–[16].

However, the non-rational property of time delay gives rise to difficulties in the controller design for CACC. Most CACC studies have only taken into account the effects of wireless communication delays while ignoring vehicle actuator delays [17]–[20], or even assumed a delay-free intervehicle communication [21]–[23]. In the studies where vehicle actuator or communication delays are ignored, a sufficiently large, rather than a minimum string-stable time gap is selected in the controller design, such that CACC platoons can be string stable with certain time delays in practice [24], [25]. On the other hand, realizing a smaller time gap is a main advantage of CACC. Thus, it is worth considering to compensate for time delays in the controller design process, in order to realize string stability with short time gaps.

In particular, the effect of vehicle actuator delay on string stability, which has been observed in [7], [26], needs more attention to arrive at a shorter intervehicle distance. In [27], the relation between minimum string-stable time gaps and vehicle actuator delays has been presented for a homogeneous CACC platoon. The results showed that the minimum string-stable time gap would at least double when the vehicle actuator delay increased from 0.1 s to 0.5 s, considering various possible values of communication delays from 0.01 s to 0.1 s.

Individual vehicle stability is another requirement for a CACC platoon. 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 [28]. Individual vehicle stability is affected by the vehicle dynamics, and particularly the vehicle actuator delay [29]–[31].

To deal with time delay, Proportional Integral Derivative (PID), Model Predictive Control (MPC), and the Smith

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predictor are the most common approaches. PID can predict the future error with the derivative action, which allows for easy analysis, rather than synthesis of string-stable behavior. In addition, PID is limited to compensate for small time delays from a stability point of view [32], [33]. MPC can also be used to avoid the effects of time delay. However, synthesis and analysis of string-stable behavior with MPC is difficult to obtain because of the finite horizon used [34]–[36]. On the other hand, a Smith predictor is known to handle large time delays very well in the sense of stability and performance, provided the model is sufficiently accurate [33], [37]. In addition, with a systematic controller-design process, a Smith predictor allows for relatively straightforward synthesis and analysis of string-stable behavior. Moreover, a Smith predictor is not computationally demanding (as opposed to MPC), and can be applied as an add-on to existing CACC controllers.

Active compensation approaches for time delays with a Smith predictor have not been developed in the scope of the CACC controller design. There are exceptions in the ACC controller design, which are closely related to CACC systems. In ACC, a Smith predictor has been applied to compensate for the vehicle actuator delay [38], while string stability was not significantly improved. In [39], a predictor-based design method was proposed in an ACC scheme, which is a modification of the Smith predictor [40]. The control law required the information of signal history over the period of time delay, which is computation costly. The resulting minimum string-stable time gap is the sum of the vehicle actuator delay, and some performance related coefficients according to complex theoretical analyses.

Since wireless communication is utilized, the control function in CACC differs from ACC. Thus, applying a Smith predictor for the vehicle actuator delay in CACC may be a promising method to decrease the minimum string-stable time gap, and thus improving road throughput. Note that a Smith predictor cannot be applied to communication delay in most CACC systems in the literature, since it can only compensate for time delays in a series connection with the plant to be controlled.

To improve both string stability and individual vehicle stability characteristics, this paper applies a Smith predictor to compensate for the vehicle actuator delay in CACC systems. The underlying objective here is to decrease the minimum allowable time gap, thus increasing road throughput. Furthermore, the Smith predictor-based controller allows for larger ranges of gains to guarantee individual vehicle stability. In addition, the Smith predictor has been modified to be robust to the acceleration disturbance. Finally, the practical feasibility of the Smith predictor-based controller is shown through experimental evaluation in a platoon of two passenger vehicles.

The outline of this paper is as follows. The next section presents the model of a CACC control vehicle string. Section III presents the Smith predictor applied to the CACC system. In the fourth section, the experimental results are shown. The last section summarizes the main conclusions.

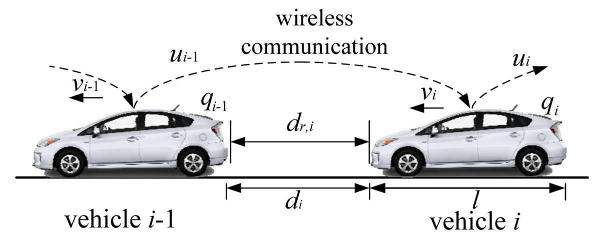


Fig. 1. CACC-equipped vehicle string.

II. CACC String

A homogeneous CACC string, as shown in Fig. 1, is considered, where q_i, v_i and u_i are the position, velocity, and desired acceleration of vehicle i, respectively; l is the vehicle length; $d_{r,i}$ and d_i represent the desired and actual distance between vehicle i and its preceding vehicle $i-1$, respectively.

With feedback linearization, a simplified vehicle model is generally derived from the nonlinear vehicle dynamics for CACC controller design [41]. The resulting vehicle dynamics read

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

where a_i is the actual acceleration of vehicle i; θ_a and τ are the vehicle actuator delay and time constant representing the longitudinal vehicle response, respectively. This model adequately describes the longitudinal vehicle dynamics in view of CACC systems [26], [42]–[44]. Note that time delays cannot be compensated for with feedback linearization. The Laplace transfer function from the desired acceleration u_i to the position q_i reads

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

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. Here,

$$D_a(s) = e^{-\theta_a s} \tag{3a}$$

$$G(s) = \frac{1}{s^2(\tau s+1)} \tag{3b}$$

represent the vehicle actuator delay $D_a(s)$ and delay-free vehicle dynamics $G(s)$, respectively. We assume that the vehicle is operated in the region of feasible accelerations/decelerations.

In CACC platoons, the wireless intervehicle link is generally employed for feedforward purposes. In our case, the feedforward input is the desired acceleration u_{i-1} of the preceding vehicle. Considering communication delay θ_c, the received feedforward input of vehicle i is

$$u_{i-1,c}(t) = u_{i-1}(t-\theta_c). \tag{4}$$

Note that packet loss is neglected in the theoretical analysis. In [12], event-triggered control strategies were proposed to guarantee desired stability and performance criteria in the presence of packet losses.

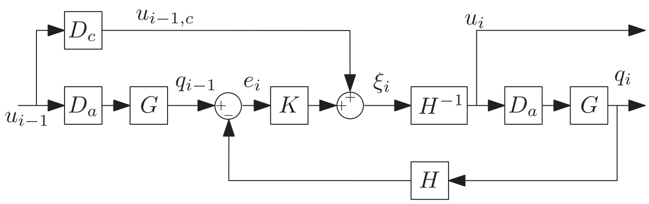


Fig. 2. Block scheme of the CACC system.

A constant time gap spacing policy is utilized, which is the most common spacing policy to improve string stability, see [7] and the references contained therein. According to this spacing policy, the desired intervehicle distance reads

$$d_{r,i}(t) = r + hv_i(t) \tag{5}$$

where h and r represent the time gap and the standstill distance, respectively, which are identical for all vehicles in the string due to the homogeneity assumption. The actual intervehicle distance d_i reads

$$d_i(t) = q_{i-1}(t) - q_i(t) - l. \tag{6}$$

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

$$e_i(t) = d_i(t) - d_{r,i}(t) \tag{7}$$

should asymptotically converge to zero. To this end, a PD controller is most widely adopted, especially in experimental applications [2], [6]. In addition, it is assumed that there is no initial error in this CACC platoon, i.e., $e_i(t_0) = 0$. Here the algorithm in [2] is adopted, where a new input ξ_i is introduced, which is related to the desired acceleration u_i as follows:

$$\dot{u}_i(t) = -\frac{1}{h}u_i(t) + \frac{1}{h}\xi_i(t). \tag{8}$$

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

$$\xi_i(t) = u_{i-1}(t-\theta_c) + k_p e_i(t) + k_d \dot{e}_i(t) \tag{9}$$

where k_p and k_d represent the proportional and derivative gains, respectively. Without loss of generality, we choose $r = l = 0$ when analysing individual vehicle stability and string stability. Thus, the control structure can be depicted as in Fig. 2, where $H(s)$, $D_c(s)$ and $K(s)$ represent the Laplace transforms,

$$H(s) = hs + 1 \tag{10a}$$

$$D_c(s) = e^{-\theta_c s} \tag{10b}$$

$$K(s) = k_p + k_d s, \tag{10c}$$

respectively.

III. Smith Predictor for Vehicle Actuator Delay

By applying a Smith predictor, we aim to eliminate the actuator delay $D_a(s)$ in the feedback loop in Fig. 2. In this way, individual vehicle stability will become independent of the vehicle actuator delay and string stability can be guaranteed with a smaller time gap.

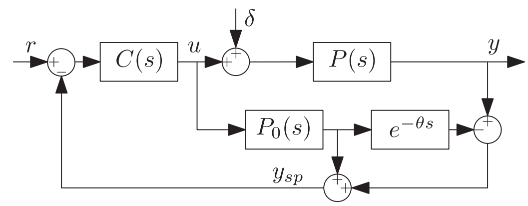


Fig. 3. Block diagram of a Smith predictor.

We first introduce the Smith predictor in Section III-A, following the application of the Smith predictor on CACC in Section III-B. Then, in Section III-C and Section III-D, we analyse individual vehicle stability and string stability of the Smith predictor-based CACC, respectively. The virtual delay-free vehicle model as used in the Smith Predictor results in a virtual delay-free distance. However, this delay-free distance does not correspond to the actual distance, which influences the steady-state behavior of the controlled system. This is further discussed in Section III-E. The effect of packet loss is shown with simulations in Section III-F. In Section III-G, the Smith predictor is modified to be robust to exogenous acceleration disturbances.

A. Smith Predictor Introduction

The Smith predictor, proposed in [45], is the most common time delay compensating controller. Numerous generalizations and modifications of the Smith predictor have been presented, see [46] and the references therein. The Smith predictor structure is shown in Fig. 3. The controlled plant is $P(s)$, which is estimated by a delay-free part $P_0(s)$ and time delay $e^{-\theta s}$. r, y and δ represent the reference, plant output and disturbance, respectively. The original complimentary sensitivity, which is the transfer function $T(s)$ from r to y, reads

$$T(s) = \frac{C(s)P_0(s)e^{-\theta s}}{1 + C(s)P_0(s)e^{-\theta s}}. \tag{11}$$

In the Smith predictor-based scheme, the plant output y is adapted to y_{sp}, by adding feedback loops from the controller output u through a process $P_0(s)e^{-\theta s}$, and a delay-free process $P_0(s)$. In the ideal situation of perfect modelling ($P(s) = P_0(s)e^{-\theta s}$), the Smith predictor-based complimentary transfer function reads

$$T_{sp}(s) = \frac{C(s)P_0(s)}{1 + C(s)P_0(s)}e^{-\theta s}. \tag{12}$$

In view of stability analyses, the main advantage of the Smith predictor control method is that, the time delay is eliminated from the characteristic equation of the closed-loop system. Note that a Smith predictor cannot be directly applied to compensate for communication delay in current CACC scheme as shown in Fig. 2, since communication delay is not in a series connection with the plant to be controlled.

B. Smith Predictor-Based CACC

According to the Smith predictor strategy, two feedback loops are added to the scheme in Fig. 2, resulting in the Smith

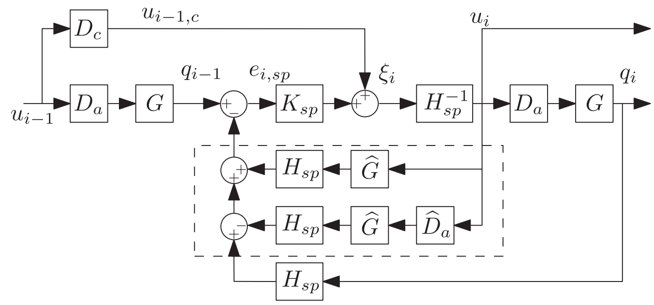


Fig. 4. Control block of a Smith predictor-based CACC vehicle string.

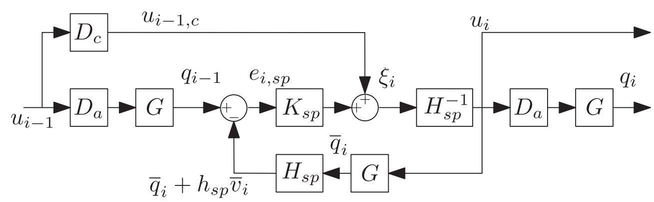


Fig. 5. Simplified control block of a Smith predictor-based CACC vehicle string, with accurate vehicle dynamics.

predictor-based block in Fig. 4. $\hat{G}(s)$ and $\hat{D}_a(s)$ represent the estimated delay-free vehicle dynamics and actuator delay, respectively. The Smith predictor is indicated by the dashed box. Here, the time gap and PD controller can be chosen differently from the original ones. Thus, H_{sp} and K_{sp} are introduced, with the Smith predictor-based time gap h_{sp}, and PD controller gains $k_{sp,p}$ and $k_{sp,d}$, according to

$$H_{sp}(s) = h_{sp}s + 1 \tag{13}$$

$$K_{sp}(s) = k_{sp,p} + k_{sp,d}s. \tag{14}$$

The inner and outer loops in the Smith predictor are with and without delay, respectively; the feedback loop with the real plant will be eliminated by the outer loop in the Smith predictor, providing that $G(s)$ and $D(s)$ are exactly known, i.e., $\hat{G}(s) = G(s)$ and $\hat{D}_a(s) = D(s)$. Thus, the delay-free inner loop is the only feedback loop, leading to the simplified control scheme as shown in Fig. 5. According to our experiment for vehicle dynamics identification [2], [44], vehicle actuator delay $\theta_a = 0.2$ s and the time constant $\tau = 0.1$ appears to be invariant. Thus, θ_a and τ are considered to be exactly known in this paper, and we focus on analysis of the simplified control scheme. Acceleration disturbances due to the road friction and slope, and weather/wind will be considered in Section III-G. Note that it is possible to estimate slowly time-varying delays in a Smith predictor-based scheme [47].

In Fig. 5, the desired acceleration u_i is the input for vehicle i, whereas output is the actual vehicle position q_i. Note that the delay-free vehicle model is utilized in the control scheme in Fig. 5, while the actual vehicle information is used in the original CACC block scheme as shown in Fig. 2. Therefore, the predicted position $\bar{q}_i$ and the predicted velocity $\bar{v}_i$ represent the corresponding variables after the period of the vehicle actuator delay, which are according to

$$\bar{q}_i(t) := q_i(t + \theta_a) \tag{15}$$

$$\bar{v}_i(t) := v_i(t + \theta_a). \tag{16}$$

Here, the (virtual) intervehicle distance $d_{i,sp}$ can be interpreted as:

$$d_{i,sp}(t) := q_{i-1}(t) - \bar{q}_i(t) \tag{17}$$

and the desired distance as $d_{r,i,sp}$:

$$d_{r,i,sp}(t) := h_{sp}\bar{v}_i(t). \tag{18}$$

The tracking error $e_{i,sp}$ follows as

$$\begin{aligned} e_{i,sp}(t) &= d_{i,sp}(t) - d_{r,i,sp}(t) \\ &= [q_{i-1}(t) - \bar{q}_i(t)] - h_{sp}\bar{v}_i(t). \end{aligned} \tag{19}$$

The actual (real) intervehicle distance $d_i(t)$ is given in (6). Subtracting both sides of (6) and (17), $d_{i,sp}(t)$ relates to d_i as follows:

$$d_i(t) - d_{i,sp}(t) = \bar{q}_i(t) - q_i(t). \tag{20}$$

Hence, $d_i > d_{i,sp}$ (assuming the vehicles drive in forward direction). Since the virtual distance $d_{i,sp}$ is regulated to the desired distance $d_{r,i,sp}$ in the steady state, it follows that the actual steady-state distance d_i will be bigger than $d_{r,i,sp}$. This difference is referred to as the *tracking latency*, being inherent to the application of the Smith predictor in this setting. We will discuss the effect of the tracking latency in Section III-E.

C. Individual Vehicle Stability

Individual vehicle stability requires that the system should arrive at a stationary condition, when the preceding vehicle is driving with a constant speed. Employing the Smith predictor allows for individual vehicle stability to be independent of the vehicle actuator delay.

In the original control structure shown in Fig. 2, the transfer function $F(s)$ from the desired acceleration u_{i-1} of vehicle $i-1$ to the distance error e_i of vehicle i reads

$$F(s) = \frac{e_i(s)}{u_{i-1}(s)} = \frac{D_a(s)G(s)(1 - D_c(s))}{1 + D_a(s)G(s)K(s)}. \tag{21}$$

Then individual vehicle stability is determined by the denominator of (21). Note that communication delay θ_c occurring in the feedforward loop does not influence individual vehicle stability in the presented CACC structure.

Individual vehicle stability conditions can be derived with the Routh-Hurwitz criterion by replacing the time delay by a 4th-order Padé approximation, which is sufficient for the frequency range of interest for the vehicle and CACC [27]. Adopting the vehicle parameters identified in experiments [2], being: $\tau = 0.1$ and $\theta_a = 0.2$ s, with a specific proportional controller gain $k_p = 0.5$ as an example, individual vehicle stability requires

$$0.152 < k_d < 6.04. \tag{22}$$

Then, the allowable ranges for the PD controller gains k_p and k_d to keep individual vehicle stability can be numerically found, as

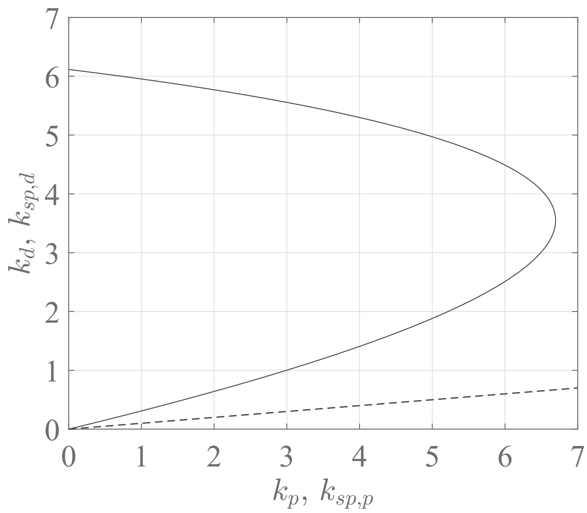


Fig. 6. Ranges of PD controller gains to guarantee individual vehicle stability: k_p and k_d in the area bounded by the solid curve, for the system with the 4th-order Padé approximation of the time delay; $k_{sp,p}$ and $k_{sp,d}$ above the dashed line with the slope of τ. Here, $\tau = 0.1$ and $\theta_a = 0.2$.

shown in Fig. 6, in which k_p and k_d should be within the area bounded by the solid curve. Note that the stable range of the proportional gain is $0 < k_p < 6.69$.

When applying the Smith predictor assuming an accurate vehicle model (see Fig. 5), the transfer function $F_{sp}(s)$ from the desired acceleration u_{i-1} to the control error $e_{i,sp}$ reads

$$F_{sp}(s) = \frac{e_{i,sp}(s)}{u_{i-1}(s)} = \frac{G(s)(D_a(s) - D_c(s))}{1 + G(s)K_{sp}(s)}. \tag{23}$$

Apparently, the vehicle actuator delay is eliminated from the characteristic equation. Hence, this delay does not influence individual vehicle stability, which is the first benefit of applying the Smith predictor. Applying the Routh-Hurwitz criterion to (23), it follows that the individual vehicle is stable for

$$k_{sp,p} > 0 \quad \text{and} \quad k_{sp,d} > \tau k_{sp,p} \tag{24}$$

With the same parameters, which result in the stability condition (22) for the original system, the individual vehicle stability requirement with the Smith predictor reads

$$k_{sp,d} > 0.05. \tag{25}$$

In the Smith predictor-based scheme, the range of $k_{sp,p}$ and $k_{sp,d}$ to keep individual vehicle stability is shown in Fig. 6, which is the area above the dashed line with the slope of $\tau = 0.1$. Hence, applying the Smith predictor results in less strict requirements in view of individual vehicle stability, in the sense that the allowable range for PD controller gains is larger.

D. String Stability

The influence of the Smith predictor on string stability can be analysed as follows. In the frequently applied performance-oriented approach, string stability is characterized by the amplification in the upstream direction of the signal of interest [2], [7]. Denote the string stability transfer function as $S(s)$, which describes the relation between a relevant (scalar) signal of vehicle i and the corresponding signal of the preceding vehicle $i-1$. Then the system of interconnected vehicles is string stable if and only if

$$|S(j\omega)| \leq 1 \tag{26}$$

with the frequency $\omega \in \mathbb{R}^+$. The string stability transfer functions for the original control structure in Fig. 2 and the Smith predictor-based scheme in Fig. 5, denoted as S_o and S_{sp}, respectively, read

$$S_o = \frac{1}{H}\frac{D_c + D_a GK}{1 + D_a GK} \tag{27}$$

$$S_{sp} = \frac{1}{H_{sp}}\frac{D_c + D_a GK_{sp}}{1 + GK_{sp}}. \tag{28}$$

The minimum time gaps for the original scheme (27) and the Smith predictor-based scheme (28), which are denoted as $h_{\min}(k_p, k_d)$ and $h_{sp,\min}(k_{sp,p}, k_{sp,d})$, respectively, can be numerically calculated [27]. In our experimental setting, the wireless communication update frequency is 25 Hz, and the maximum communication delay $\theta_c = 0.04$ s is taken into account [44]. The vehicle parameters are $\tau = 0.1$, $\theta_a = 0.2$ s [2]. Considering individual vehicle stability and the speed of response [2], [7], the ranges of PD controller gains are set as: $k_p,\ k_{sp,p} \in [0.2, 0.5]$ and $k_d,\ k_{sp,d} \in [0.5, 0.8]$ for both the original and Smith predictor-based CACC schemes, respectively, in view of string stability analyses.

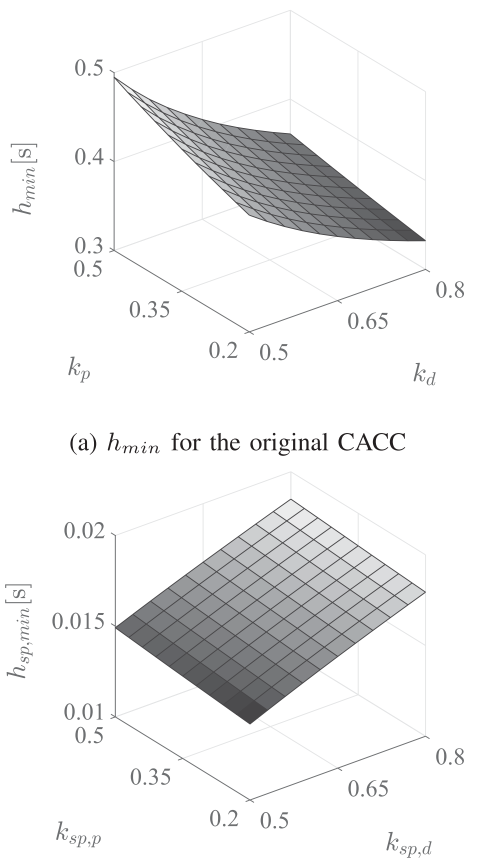
The minimum string-stable time gaps as a function of the controller gains are presented without and with the Smith predictor in Fig. 7(a) and (b), respectively. In Fig. 7(a), the minimum string-stable time gap $h_{\min}$ increases with increasing k_p and decreasing k_d, while Fig. 7(b) indicates that $h_{sp,\min}$ increases with increasing $k_{sp,p}$ and $k_{sp,d}$. $h_{\min}$ is bigger than 0.3 s. However, $h_{sp,\min}$ can be chosen as small as 0.02 s while still yielding string stability. Note that, as mentioned before, the actual intervehicle distance is not only determined by the minimum time gap $h_{sp,\min}$, but also by the tracking latency, as further detailed in the next section.

E. Effect of Tracking Latency

The tracking latency corresponds to the difference between the virtual intervehicle distance $d_{i,sp}$ and the actual distance d_i (see (20)). Since, however, the actual distance determines the road throughput and safety, it is necessary to analyse the actual distance instead of the virtual distance when applying the Smith predictor. Assume to this end that a stationary condition has been achieved, and the error $e_{i,sp}$ in (19) converges to zero. Thus,

$$d^*_{i,sp}(t) = d^*_{r,i,sp}(t) = h_{sp}\bar{v}^*_i(t). \tag{29}$$

Note that $\cdot^*(t)$ denotes the corresponding variable $\cdot(t)$ in the stationary condition. Substituting (20) into (29), the actual



(a) h_{min} for the original CACC

(b) $h_{sp,min}$ for the Smith predictor-based CACC

Fig. 7. The minimum string-stable time gaps.

intervehicle distance reads

$$d_i^*(t) = h_{sp}\bar{v}_i^*(t) + \bar{q}_i^*(t) - q_i^*(t). \tag{30}$$

Denoting the constant velocity as v_i^* in the CACC string at this stationary situation, it follows that the predicted velocity $\bar{v}_i^*$ and position $\bar{q}_i^*$ read

$$\bar{v}_i^*(t) = v_i^*(t+\theta_a) = v_i^* \tag{31}$$

$$\bar{q}_i^*(t) = q_i^*(t+\theta_a) = q_i^*(t) + \theta_a v_i^* \tag{32}$$

respectively. Substituting (31) and (32) into (30), results in the actual intervehicle distance:

$$d_i^*(t) = (h_{sp} + \theta_a)v_i^*(t) \tag{33}$$

which depends on the Smith predictor-based time gap h_{sp} and the vehicle actuator delay θ_a.

Now, we can derive the condition that a Smith predictor-based controller can improve the CACC string stability property. From (33), it follows that if the relation between Smith predictor-based minimum string-stable time gap $h_{sp,\min}$ and original minimum string-stable time gap $h_{\min}$ follows

$$(h_{sp,\min} + \theta_a) < h_{\min}, \tag{34}$$

the intervehicle distance in CACC systems can be decreased by applying the Smith predictor. With selected time gap $h > h_{\min}$ and $h_{sp} > h_{sp,\min}$, the improvement of the string-stable intervehicle distance is

$$d^*_{\text{improved}}(t) = (h - h_{sp} - \theta_a)v_i^*(t). \tag{35}$$

Choosing $h = 0.3$ s and $h_{sp,\min} = 0.05$ s to meet the string stability requirement according to Fig. 7, the improvement of intervehicle distance $d^*_{\text{improved}}(t) = 0.05\, v_i(t)$, given $\theta_a = 0.2$ s. Considering a highway scenario (velocity is 120 km/h, i.e., 33.3 m/s), the intervehicle distance can be decreased from 10 m to 8.33 m by $d^*_{\text{improved}} = 1.67$ m.

Until now the tracking latency and actual intervehicle distance have been analysed in the stationary situation. Next, let us consider the transient behavior, i.e., $a_i \neq 0$. We check the difference of the tracking latency between the steady-state and transient situations, and compare it with the improvement (35).

In the transient situation, the velocity $\bar{v}_i(t)$ and position $\bar{q}_i(t)$ of virtual delay-free vehicle model read

$$\bar{v}_i(t) = v_i(t+\theta_a) = v_i(t) + \int_t^{t+\theta_a} a_i(\gamma)\,\mathrm{d}\gamma \tag{36}$$

$$\begin{aligned}\bar{q}_i(t) &= q_i(t+\theta_a)\\ &= q_i(t) + \int_t^{t+\theta_a} v_i(\lambda)\,\mathrm{d}\lambda\\ &= q_i(t) + \int_t^{t+\theta_a}\left(v_i(t) + \int_t^{\lambda} a_i(\gamma)\,\mathrm{d}\gamma\right)\mathrm{d}\lambda\\ &= q_i(t) + \theta_a v_i(t) + \int_t^{t+\theta_a}\int_t^{\lambda} a_i(\gamma)\,\mathrm{d}\gamma\,\mathrm{d}\lambda\end{aligned} \tag{37}$$

respectively. Assuming the spacing error is zero, the actual intervehicle distance reads

$$d_i(t) = h_{sp}\bar{v}_i(t) + \bar{q}_i(t) - q_i(t). \tag{38}$$

Substituting (36) and (37) into (38), the actual intervehicle distance d_i with non-constant velocity reads

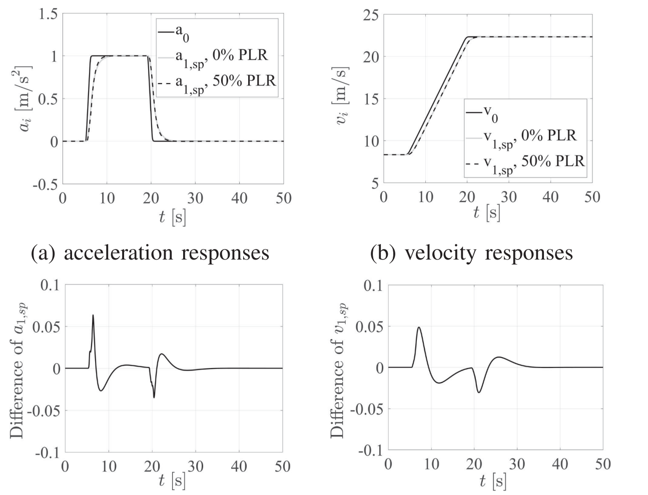
$$\begin{aligned}d_i(t) &= (h_{sp} + \theta_a)v_i(t)\\ &\quad + h_{sp}\int_t^{t+\theta_a} a_i(\gamma)\,\mathrm{d}\gamma + \int_t^{t+\theta_a}\int_t^{\lambda} a_i(\gamma)\,\mathrm{d}\gamma\,\mathrm{d}\lambda.\end{aligned} \tag{39}$$

It follows that the largest possible intervehicle distance in the Smith predictor-based CACC scheme occurs when a_i equals its maximum positive value. Assuming $a_i = 2\,\text{m/s}^2$, $h_{sp} = 0.05$ s, and $\theta_a = 0.2$ s, (39) becomes

$$d_i(t) = (h_{sp} + \theta_a)v_i(t) + 0.06. \tag{40}$$

Comparing (33) and (40), it follows that the increase of d_i between the situations from constant to non-constant velocities is 0.06 m. Thus, the intervehicle distance with Smith predicor-based scheme is still smaller than in the original scheme in the transient case, if the velocity $v_i(t) > 1.2$ m/s, i.e., $d^*_{\text{improved}}(t) > 0.06$ m. In a highway scenario (velocity is 33.3 m/s as assumed before), the intervehicle distance can be decreased from 10 m to 8.39 m by $d^*_{\text{improved}} = 1.61$ m/s.

Let us now consider the situation where a_i has a minimum value (maximum deceleration, $a_i = -5\,\text{m/s}^2$ for example). This



(a) acceleration responses (b) velocity responses

(c) difference of $a_{1,sp}$ (d) difference of $v_{1,sp}$

Fig. 8. Simulation results of the proposed system: in (a) and (b), the responses of the first vehicle, the follower in case of 0% PLR and 50% PLR are represented with solid black lines, solid gray lines and dashed black lines, respectively; the response differences of follower vehicle with 50% and 0% PLR are shown in (c) and (d).

situation is relevant in view of safety. (39) becomes

$$d_i(t) = (h_{sp} + \theta_a)v_i(t) - 0.15. \tag{41}$$

Thus, d_i with non-constant velocities is decreased by 0.15 m compared to that with a constant velocity, which is less than the velocity-dependent distance $(h_{sp} + \theta_a)v_i(t)$, if $v_i(t) >$ 0.6 m/s, i.e., $(h_{sp} + \theta_a)v_i(t) > 0.15$ m. Here, $\theta_a = 0.2$ s and $h_{sp} = 0.05$ s. Consequently, there will no safety risk even if an emergency brake occurs in this Smith predictor-based CACC platoon. Still considering that velocity is 33.3 m/s in a highway, the intervehicle distance can be decreased from 10 m to 8.18 m by $d^*_{\text{improved}} = 1.82$ m/s.

F. Packet Loss

With a wireless communication update frequency of 25 Hz, there is little effect of packet loss on string stability in the original CACC system [48]. To check whether the main result from [48] also holds for the system with Smith predictor, simulation results of the proposed CACC system are shown in Fig. 8, to compare the responses of the follower vehicle with and without packet loss. Packet loss is realized in a stochastic way, that one packet is dropped according to a loss probability with uniform distribution. Loss of a packet is independent from that of other packets. The loss probability is referred to as a packet loss rate (PLR). The PD controller gains are set as $k_{sp,p} = 0.2$ and $k_{sp,d} = 0.7$ as in [2]. The communication delay is chosen as 0.04 s, and the time gap is designed to be 1 s. Fig. 8 shows the follower vehicle responses to the same leading vehicle with a PLR of 0% and 50%, respectively. The differences of acceleration and velocity responses of the follower are very small. It can, therefore, be concluded that even a large PLR will not significantly affect the performance of the proposed CACC system.

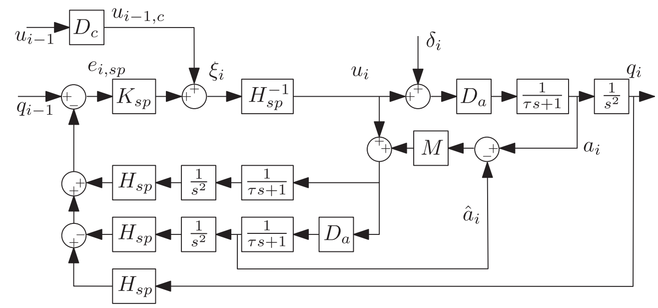


Fig. 9. Control block of a modified Smith predictor-based CACC vehicle string, considering acceleration disturbances.

G. Modification of the Smith Predictor

This section presents a modification of the Smith predictor-based CACC system, to deal with acceleration disturbances due to the rolling friction, drag force and road slope. We will use the approximated acceleration in the Smith predictor and the measured acceleration to estimate the disturbances. Then the estimated disturbances will be added to the vehicle model in the Smith predictor, such that the vehicle model in the Smith predictor can performance the same as the actual vehicle.

Considering the disturbance δ_i in the CACC scheme in Fig. 9, the measured actual acceleration a_i reads

$$a_i(s) = \frac{e^{-\theta_a s}}{\tau s + 1}[u_i(s) + \delta_i(s)]. \tag{42}$$

The acceleration in the outer loop in the Smith predictor is $\hat{a}_i$

$$\hat{a}_i(s) = \frac{e^{-\theta_a s}}{\tau s + 1}u_i(s). \tag{43}$$

Here, a correction function $M(s)$ is added to compensate for the disturbance δ_i. Then, the Laplace transfer function $F_\delta(s)$ from δ_i to the control error $e_{i,sp}$ reads

$$F_\delta(s) = \frac{e_{i,sp}(s)}{\delta_i(s)} = \frac{G(s)D_a(s)H_{sp}(s)}{1 + G(s)K_{sp}(s)} \cdot \frac{\frac{M(s)}{\tau s+1} - 1}{1 + \frac{D_a(s)M(s)}{\tau s+1}}. \tag{44}$$

Inspired by [49] and [50],

$$M(s) = \frac{1}{1 + \frac{1}{\tau s+1}\frac{1}{\theta_a s+1} - \frac{1}{\tau s+1}e^{-\theta_a s}} \tag{45}$$

is chosen in order to guarantee stability of (44), and to realize that the system has zero steady-state error. Note that it is possible to choose a different $M(s)$ to arrive at the same conclusion. It can be easily proven that with (45), (44) is stable, given that individual vehicle stability is guaranteed. Here, the third term $\frac{e^{-\theta_a s}}{\tau s+1}$ in the denominator of (45) is actually the transfer function from u_i to $\hat{a}_i$, and the second term is a first-order approximation of $\frac{e^{-\theta_a s}}{\tau s+1}$, which can decrease the effect of the possible non-constant disturbance. Furthermore, $\lim_{s\to 0} F_\delta = 0$ with (45), which proves that there will no steady-state error with a constant disturbance.

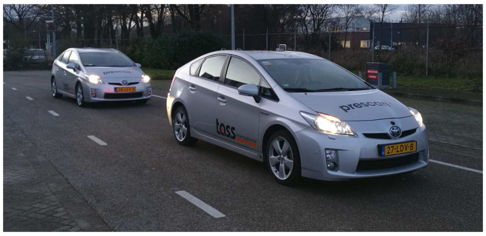


Fig. 10. Experimental vehicle platoon, consisting of two CACC-equipped passenger vehicles.

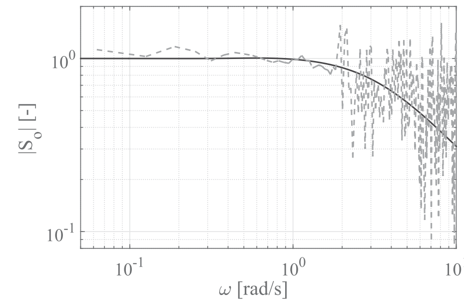
IV. Experimental Validation

The controllers with and without the modified Smith predictor have been implemented in a platoon of two passenger vehicles, equipped with a prototype CACC system as shown in Fig. 10. The selected test vehicle Toyota Prius III Executive has a modular setup and ex-factory ACC. The long-range radar determines the relative position, and the electronic stability program sensor cluster measures the acceleration. A real-time computer platform is added to execute the CACC control functionality. The communication device operates according to the ITS-G5 standard, based on IEEE 802.11p [51], allowing for communication of the vehicle motion and controller information between the CACC vehicles with an update rate of 25 Hz [44]; see [2] for more details. Information from GPS sensors is employed to associate the wireless communicated information with the corresponding radar measurement. After association, the GPS position included in the communicated information is not used anymore. The desired acceleration u_{i-1} of the preceding vehicle $i-1$ is the only information utilized to realize the vehicle following target. This section presents experimental frequency and time responses, which validate the theoretical results regarding the Smith predictor.

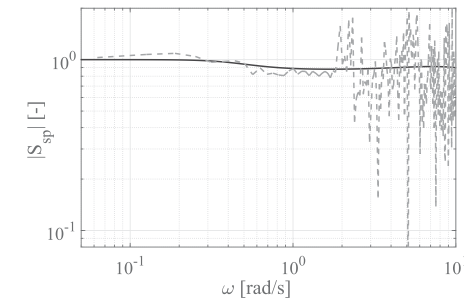
A. Frequency Response Experiments

For the sake of reproducibility of the experiments, the leading vehicle is programmed to track a predefined velocity trajectory which has been designed as a random-phase multisine excitation input [52]. This signal needs to excite the frequency range of interest for the assessment of string stability. Here, we choose the frequency values $\{0.01, 0.02, 0.03, ..., 0.3\}$ Hz with weighted amplitudes as in [14]. Then, the leading vehicle controller in [44] is employed to realize the desired velocity. The same velocity controller was applied to the time response experiments. The PD controller gains are set the same for both cases: $k_p = k_{sp,p} = 0.2$ and $k_d = k_{sp,d} = 0.7$ as in [2].

Fig. 11 shows the similarity between the theoretical (black) and experimental (gray) frequency response magnitudes of the string stability transfer function S_o and S_{sp}, despite the noise level due to estimation inaccuracy. Since we consider the worst case of communication delay $\theta_c = 0.04$ s, in Fig. 11(a), the theoretical magnitude only slightly exceeds 1 at around $\omega = 0.7$ rad/s in the original CACC scheme with $h = 0.3$ s. In practice, $\theta_c = 0.04$ s happens sometimes, and $\theta_c \approx 0.02$ s is the nominal value of the communication delay, which due to the fact that the update rate of wireless communication is 25 Hz.



(a) $h = 0.3$ s in the original scheme



(b) $h_{sp} = 0.05$ s in the Smith predictor-based scheme

Fig. 11. Frequency response magnitudes: estimated and theoretical magnitudes are represented with dashed gray and solid black lines, respectively.

In Fig. 11(b), it appears that string stability is guaranteed with the Smith predictor-based controller and $h_{sp} = 0.05$ s. Therefore, the actual time gap has been reduced from $h = 0.3$ s in the original CACC scheme to $h_{sp} + \theta_a = 0.25$ s in the Smith predictor-based scheme, i.e., by more than 15%. Note that the magnitudes are very close to 1 since we pursue the minimum string-stable time gap. The estimated magnitudes of both cases degrade for $\omega > 2$ rad/s, due to the fact that the text signal has no power in this frequency region.

B. Time Response Experiments

The time responses are also conducted with two vehicles, where the first vehicle is velocity controlled, subject to a trapezoidal acceleration profile. The time gaps $h = 0.3$ s and $h_{sp} = 0.05$ s are chosen for the original and Smith predictor-based CACC schemes, respectively. The standstill intervehicle distance is chosen as $r = 2.5$ m, and the vehicle actuator delay is around $\theta_a = 0.2$ s. Fig. 12 shows the time responses with the original (upper row) and Smith predictor-based (lower row) CACC schemes. The acceleration and velocity responses clearly show that the follower vehicle responds quite fast to its leader. The comparison of the intervehicle distances in Fig. 12(c) and (g) indicates that applying the proposed Smith predictor-based CACC controller reduces the minimum string-stable intervehicle distance from around 5.8 m to 5.3 m at the velocity of 11.1 m/s, with the decrease of 0.5 m, which experimentally validate (5), (33), and (35). Intervehicle distance errors as shown in Fig. 12(d) and (h) for the original and the Smith predictor-based CACC, show that the vehicle-following objective is realized. Comparing experiment results of the desired acceleration u_i

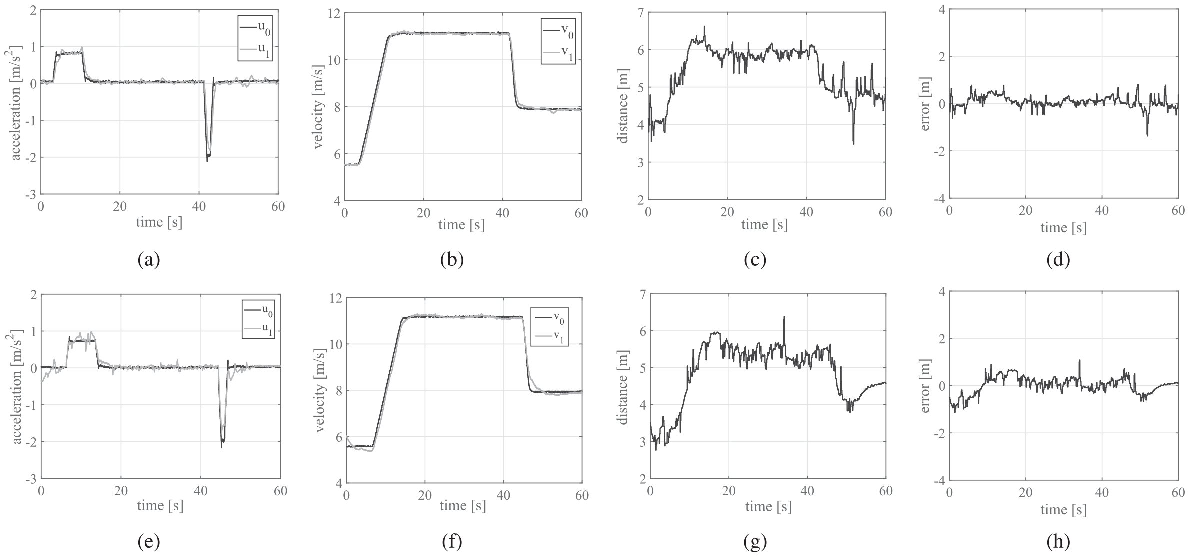


Fig. 12. Measured time responses with the original CACC system of (a) the acceleration and (b) the velocity (black: first vehicle, gray: follower), (c) the intervehicle distance, and (d) the intervehicle distance error; and responses with the Smith predictor (e) the acceleration and (f) the velocity (black: first vehicle, gray: follower), (g) the intervehicle distance, and (h) the intervehicle distance error.

and the actual acceleration a_i, the disturbance δ_i appears to be a constant offset, approximately, with a magnitude of $0.05\,\mathrm{m/s}^2$, which is mainly due to effects of the rolling resistance.

V. Conclusion and Discussion

In this paper, a Smith predictor has been applied to compensate for the vehicle actuator delay in a homogeneous CACC system, in order to improve the potential of CACC. With the proposed scheme, individual vehicle stability can be considered independently of the vehicle actuator delay. Moreover, the minimum string-stable time gaps have been presented with both the original and the Smith predictor-based CACC schemes. The actual minimum string-stable time gap for the Smith predictor-based scheme is derived, considering the effect of the tracking latency which is due to fact that the actual intervehicle distance is larger than the predicted distance. Thereby, the potential reduction of the string-stable intervehicle distance is theoretically analysed. In our CACC configurations, the minimum string-stable time gap has been decreased by more than 15%. In addition, the Smith predictor-based scheme has been modified to be robust to exogenous acceleration disturbances. Experimental results validate the theoretical analysis with frequency and time responses.

Potential future works include considering uncertain vehicle dynamics and heterogeneous platoons. In addition, application of the Smith predictor on the communication delay is expected to result in a further reduction of the string-stable intervehicle distance.

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