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Cooperative Adaptive Cruise Control of Heterogeneous Vehicle Platoons

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Abstract: Road throughput can be increased by cooperative adaptive cruise control (CACC), which allows vehicles to drive at short inter-vehicle distances without compromising string stability by using wireless inter-vehicle communications. Practical application, however, may involve vehicles with different driveline dynamics, thus forming a heterogeneous platoon. This property potentially requires knowledge of other vehicle's driveline dynamics for implementation of CACC, which may not be available. As opposed to robust or adaptive approaches, the heterogeneity problem is solved here by revisiting an existing, widely adopted controller for homogeneous strings using an input-output linearization approach. As a result, a class of controllers is obtained which allows for vehicle strings that are heterogeneous with respect to driveline dynamics, without requiring knowledge of these dynamics. Furthermore, it is shown that the new controller represents a class of controllers that encompasses the original homogeneous controller. To illustrate the performance of the new controller, simulations of a heterogeneous platoon are presented and the string stability properties are assessed. From this analysis, it appears that the new controller performs at least as good as the original one, in terms of minimum string-stable time gap, settling time, and maximum jerk.

Keywords: Cooperative adaptive cruise control (CACC), string stability, heterogeneous platoons, input-output linearization, integrated vehicle highway systems (IVHS)

1. INTRODUCTION

Cooperative adaptive cruise control (CACC) aims to automate the longitudinal behavior of road vehicles by regulating the inter-vehicle distance to a desired value (Milanés and Shladover, 2014). An important requirement for the controller design is to realize string-stable behavior, which refers to the attenuation of the effects of disturbances in upstream direction. String stability contributes to safe vehicle behavior and ensures scalability of the string with respect to the number of vehicles; see Ploeg et al. (2014) and the literature references contained therein. Like its non-cooperative counterpart, known as adaptive cruise control (ACC), CACC also uses a forward-looking sensor, e.g., a radar, to measure distance and relative speed between the CACC-equipped vehicle and its directly preceding vehicle. In addition, however, CACC employs wireless inter-vehicle communications to obtain information otherwise unavailable. As a result, the distance to the preceding vehicle, commonly expressed in terms of time gap, at which still string-stable behavior is obtained, can be greatly reduced. Consequently, CACC has the ability to increase road capacity, particularly in case of highways.

Longitudinal vehicle dynamics, attributed to the vehicle driveline, play an important role in the controller design for CACC. To this end, the driveline may be modeled as a second-order system (Milanés and Shladover, 2014), but in the majority of literature, a linear first-order model is adopted, having desired acceleration as input and actual acceleration as output. It should be noted that such model can be obtained through a lower-level controller which linearizes the longitudinal dynamics involving engine characteristics, friction, and air drag (Sheikholeslam and Desoer, 1993).

In practical application of CACC, it is likely that a vehicle platoon will consist of vehicles with different driveline characteristics, thus composing a heterogeneous vehicle string. Although several publications exist regarding the definition of string stability for heterogeneous strings, see, e.g., the generic approach recently published by Rödönyi (2019), literature concerning controller design for vehicle strings that are heterogeneous with respect to the vehicle driveline, is very limited. A notable example of the latter is the publication by Shaw and Hedrick (2007), being one of the first papers on this topic. They present a controller design approach for heterogeneous vehicle strings based on robustness principles, i.e., design for worst-case situations. Along the same line of thought, Gao et al. (2016) model heterogeneous driveline dynamics by means of a nominal model with an additive dynamic uncertainty and subsequently design a robust controller adopting an $\mathcal{H}_\infty$ approach. Another robustness-inspired approach is presented by Al-Jhayyish and Schmidt (2018), who investigate robustness with respect to heterogeneous driveline dynam-

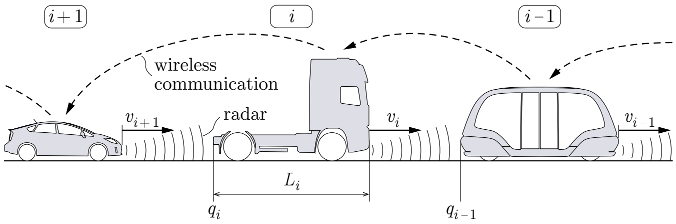

Fig. 1. CACC-equipped string of vehicles.

ics subject to various feedforward strategies, implemented through wireless inter-vehicle communication. An essentially different approach is adopted by Tao et al. (2019) and Harfouch et al. (2018), who present an adaptive controller, applying model reference adaptive control, while extending the scope with input saturation and robustness against communication losses, respectively. Finally, Zhu et al. (2019) also adopt an adaptive approach, based on optimal control theory, to cope with unknown driveline characteristics of the preceding vehicle in a CACC platoon.

In this paper, a different approach is taken for CACC design in case of vehicle strings that are heterogeneous with respect to the driveline dynamics. To this end, the homogeneous one-vehicle look-ahead controller (i.e., a predecessor-follower topology) from Ploeg et al. (2011) is revisited by proposing an alternative transformation of coordinates using an input-output linearization approach. It is shown that this approach yields a class of controllers that is suitable for heterogeneous strings without requiring knowledge of the driveline dynamics of the preceding vehicle. For a given set of controller parameters, the controlled vehicle string appears to have nearly identical string stability properties as the original homogeneous string, in the sense of minimum string-stable time gap. Finally, the original homogeneous controller appears to be a special case of this new class of controllers.

This paper is outlined as follows. First, Section 2 presents the problem statement in more detail by applying the original homogeneous controller in a heterogeneous setting. Next, Section 3 describes an alternative controller design, suitable for heterogeneous vehicle strings, and shows that this controller actually encompasses the structure of the original controller. The dynamic behavior of the controlled system is analyzed in Section 4, involving time responses and determination of the minimum string-stable time gap as a function of communication delay. Moreover, the results are compared with those obtained by a simplified controller applied in the new framework. Finally, Section 5 summarizes the heterogeneous controller design approach and proposes directions for further research.

2. PROBLEM SETTING

The CACC-controller design as introduced in Ploeg et al. (2011) for homogeneous platoons has been adopted in several publications, see, e.g., Aramrattana et al. (2019); Tao et al. (2019); Wu et al. (2019); Al-Jhayyish and Schmidt (2018); Harfouch et al. (2018) for recent ones. In this section, this approach is extended to platoons that are heterogeneous with respect to the driveline dynamics.

Consider to this end a string of m vehicles, see Fig. 1, where the vehicle dynamics are described by

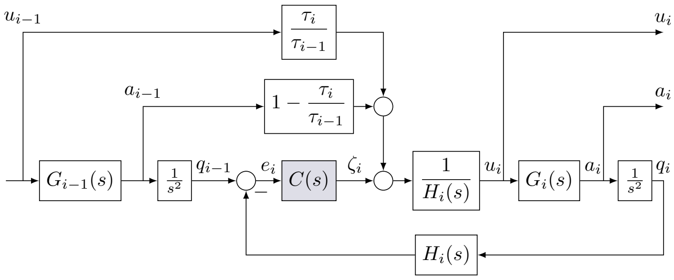

Fig. 2. Block diagram of controller (6).

$$\begin{aligned}\dot{q}_i &= v_i\\ \dot{v}_i &= a_i \qquad\qquad i = 1, 2, \ldots, m,\\ \dot{a}_i &= -\tfrac{1}{\tau_i}a_i + \tfrac{1}{\tau_i}u_i\end{aligned} \tag{1}$$

with q_i, v_i, and a_i denoting the position, velocity, and acceleration of vehicle i, respectively, and $m \in \mathbb{N}_+$ the number of follower vehicles in the platoon. The desired acceleration u_i is considered as input, and $\tau_i > 0$ denotes a time constant which represents the driveline dynamics of vehicle i. The model (1) can be obtained after feedback linearization of a more detailed model, cf. Sheikholeslam and Desoer (1993). Contrary to Ploeg et al. (2011), we allow for $\tau_i \neq \tau_j$.

The control objective is that each vehicle follows its predecessor at a desired distance $d_{\mathrm{r},i}$ using a constant time-gap policy:

$$d_{\mathrm{r},i} = r_i + h_i v_i, \quad 2 \le i \le m, \tag{2}$$

where $h_i > 0$ and r_i denote the time gap and the standstill distance, respectively. The spacing error e_i is then given by

$$e_i = (q_{i-1} - q_i - L_i) - (r_i + h_i v_i), \tag{3}$$

where L_i denotes the length of vehicle i; see also Fig. 1.

If we define the error state

$$\varepsilon_i = \begin{bmatrix}\varepsilon_{i,1}\\ \varepsilon_{i,2}\\ \varepsilon_{i,3}\end{bmatrix} := \begin{bmatrix}e_i\\ \dot{e}_i\\ \ddot{e}_i\end{bmatrix}, \tag{4}$$

we obtain

$$\dot{\varepsilon}_i = \begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & 0 & -\frac{1}{\tau_i}\end{bmatrix}\varepsilon_i + \begin{bmatrix}0\\ 0\\ -\frac{1}{\tau_i}\end{bmatrix}\zeta_i \tag{5a}$$

$$\zeta_i := h_i\dot{u}_i + u_i - \left(1 - \tfrac{\tau_i}{\tau_{i-1}}\right)a_{i-1} - \tfrac{\tau_i}{\tau_{i-1}}u_{i-1}, \tag{5b}$$

where ζ_i can be regarded as the external input of the system (5a). Hence, the control law $\zeta_i = [k_{\mathrm{p}}\ k_{\mathrm{d}}\ k_{\mathrm{dd}}]\,\varepsilon_i$, or

$$\dot{u}_i = -\tfrac{1}{h_i}u_i + \begin{bmatrix}\frac{k_{\mathrm{p}}}{h_i} & \frac{k_{\mathrm{d}}}{h_i} & \frac{k_{\mathrm{dd}}}{h_i}\end{bmatrix}\varepsilon_i + \tfrac{\tau_{i-1}-\tau_i}{h_i\tau_{i-1}}a_{i-1} + \tfrac{\tau_i}{h_i\tau_{i-1}}u_{i-1}, \tag{6}$$

stabilizes the ε dynamics, provided that $k_{\mathrm{p}} > 0$, $k_{\mathrm{dd}} > -1$, and $k_{\mathrm{d}} > \frac{k_{\mathrm{p}}\tau_i}{1+k_{\mathrm{dd}}}$. Fig. 2 shows a block diagram of vehicle i with controller (6), with $C(s) = k_{\mathrm{p}} + k_{\mathrm{d}}s + k_{\mathrm{dd}}s^2$, acceleration transfer function $G_i(s) = \frac{1}{\tau_i s+1}$, following from the third equation of (1), and spacing policy transfer function $H_i(s) = h_i s + 1$ according to (3). This figure clearly illustrates that both u_{i-1} and a_{i-1} are inputs of the controller and that τ_{i-1} must be available for the controller implementation.

Remark 1. The input u_{i-1} is actually the main reason for the application of wireless inter-vehicle communication, since u_{i-1} cannot be measured by on-board sensors, e.g., a radar, of the follower vehicle i.

Remark 2. Note that for $\tau_i = \tau_{i-1} = \tau$, the controller (6) reduces to

$$\dot{u}_i = -\tfrac{1}{h_i} u_i + \tfrac{1}{h_i} \left[k_\mathrm{p} \;\; k_\mathrm{d} \;\; k_\mathrm{dd}\right] \varepsilon_i + \tfrac{1}{h_i} u_{i-1}, \quad (7)$$

as presented in Ploeg et al. (2011).

Remark 3. The system (5), (6) is input-to-state stable (ISS) with respect to the input $\left[a_{i-1} \;\; u_{i-1}\right]^\mathrm{T}$. In particular, for bounded a_{i-1} and u_{i-1} we have that a_i and u_i are bounded, and for a_{i-1} and u_{i-1} converging to zero we have that a_i and u_i converge to zero.

Comparing (6) with (7), we can see some clear differences between the homogeneous and heterogeneous case. For the heterogeneous case we not only need u_{i-1}, but also a_{i-1} and τ_{i-1}. The former is not much of a problem as a_{i-1} can be communicated through the same wireless link as u_{i-1}. Knowledge of τ_{i-1}, however, may pose a problem, as this describes the preceding vehicle's driveline dynamics, which car manufacturers are not eager to disclose and/or which may not be exactly known.

Therefore, the problem we address in this paper is to determine (a class of) controllers that can be used for platoons that are heterogeneous with respect to the driveline dynamics. A possible way to address this problem is to use an adaptive controller which estimates the unknown τ_{i-1}, as done in Zhu et al. (2019). However, in this paper we take a different approach by revisiting the CACC controller design using a (static) input-output linearization approach. This results in a larger class of CACC controllers and it turns out that the controller (6) can be implemented without knowledge of the parameter τ_{i-1}.

3. ALTERNATIVE CONTROLLER DESIGN

One could interpret the derivation in Section 2 as a dynamic input-output linearizing approach with input $\dot{u}_i$ and output e_i. To this end, we view (5b) as a change of input:

$$\dot{u}_i = -\tfrac{1}{h_i} u_i + \tfrac{1}{h_i} \zeta_i + \tfrac{1}{h_i}\left(1 - \tfrac{\tau_i}{\tau_{i-1}}\right) a_{i-1} + \tfrac{1}{h_i}\tfrac{\tau_i}{\tau_{i-1}} u_{i-1}, \quad (8)$$

resulting in the linear system (5a), which should be stabilized by properly selecting the input ζ_i. Taking $\zeta_i = \left[k_\mathrm{p} \;\; k_\mathrm{d} \;\; k_\mathrm{dd}\right] \varepsilon_i$ yields the controller (6), whereas the resulting zero dynamics are given by

$$\dot{u}_i = -\tfrac{1}{h_i} u_i + \tfrac{\tau_{i-1} - \tau_i}{h_i \tau_{i-1}} a_{i-1} + \tfrac{\tau_i}{h_i \tau_{i-1}} u_{i-1}, \quad (9)$$

which are stable for a_{i-1} and u_{i-1} converging to zero, as mentioned in Remark 3.

However, instead of using a dynamic input-output linearizing approach, one can also apply static input-output linearization. Notice that the output e_i has relative degree $r = 2$ with respect to the input u_i. So, instead of differentiating the output three times, as was done to obtain (5a), we can also differentiate the output twice and investigate the resulting internal dynamics. To that end, it is also convenient to select a state describing these internal dynamics independently of the new input. These observations lead to the following alternative approach.

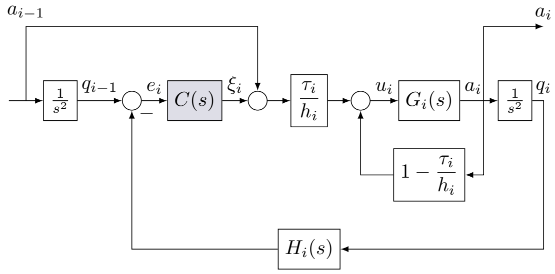

Fig. 3. Block diagram of controller (11) with PD implementation (13).

If we define the error state

$$\epsilon_i = \begin{bmatrix} \epsilon_{i,1} \\ \epsilon_{i,2} \end{bmatrix} := \begin{bmatrix} e_i \\ \dot{e}_i \end{bmatrix} \quad (10a)$$

and the internal dynamics state

$$z := v_{i-1} - v_i, \quad (10b)$$

while introducing the following change of input

$$u_i = \tfrac{\tau_i}{h_i}\xi_i + \tfrac{\tau_i}{h_i} a_{i-1} + \left(1 - \tfrac{\tau_i}{h_i}\right) a_i, \quad (11)$$

we obtain

$$\dot{\epsilon}_i = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \epsilon_i + \begin{bmatrix} 0 \\ -1 \end{bmatrix} \xi_i \quad (12a)$$

$$\dot{z} = -\tfrac{1}{h_i} z + \tfrac{1}{h_i}\epsilon_{i,2} + a_{i-1}. \quad (12b)$$

For the new input ξ_i we can use any controller which stabilizes (12a), such as the PD controller

$$\xi_i = k_\mathrm{p}\epsilon_{i,1} + k_\mathrm{d}\epsilon_{i,2}, \quad (13)$$

which yields the block diagram as depicted in Fig. 3, with $G_i(s)$ and $H_i(s)$ defined as in Fig. 2, and $C(s) = k_\mathrm{p} + k_\mathrm{d}s$.

Note that, due to the choice of (10b), the internal dynamics (12b) are independent of the choice for this input ξ_i. In particular, we have that the zero dynamics become

$$\dot{z} = -\tfrac{1}{h_i} z + a_{i-1}, \quad (14)$$

which is ISS with respect to the input a_{i-1}, i.e., for bounded a_{i-1} we have that z remains bounded, and for a_{i-1} converging to zero we have that z converges to zero. Since $h_i a_i = z - \epsilon_{i,2}$, we can draw the same conclusion for a_i with respect to the input a_{i-1}.

Remark 4. The change of input (11) does not depend on τ_{i-1} and also the system (12a) can be stabilized without knowledge of τ_{i-1}. Therefore, this new approach can also be used for platoons with heterogeneous driveline dynamics. Note that this result is the essential reason as to why the predictive controller developed by van Nunen et al. (2019) was suitable for heterogeneous platoons.

Remark 5. Any controller which stabilizes (12a) can be used for ξ_i. In particular, also a dynamic controller can be used, including the controller (6). To illustrate the latter, we write (6) as

$$h_i\dot{u}_i + u_i = \underbrace{\left[k_\mathrm{p} \;\; k_\mathrm{d} \;\; k_\mathrm{dd}\right] \varepsilon_i}_{\zeta_i} + \left(1 - \tfrac{\tau_i}{\tau_{i-1}}\right) a_{i-1} + \tfrac{\tau_i}{\tau_{i-1}} u_{i-1}. \quad (15)$$

Substituting (11), using the dynamics (1), and again substituting (11) results in

$$\begin{aligned} \dot{\xi}_i &= -\tfrac{1}{\tau_i}\xi_i + \tfrac{1}{\tau_i}\zeta_i \\ &= -\tfrac{1}{\tau_i}\xi_i + \tfrac{1}{\tau_i}\left[k_\mathrm{p} \;\; k_\mathrm{d} \;\; k_\mathrm{dd}\right] \varepsilon_i. \end{aligned} \quad (16)$$

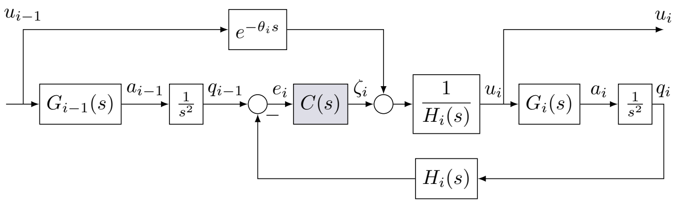

Fig. 4. Block diagram of controller (7) in an heterogeneous setting.

Consequently, instead of implementing (6), which requires knowledge of u_{i-1}, a_{i-1}, and τ_{i-1}, we can also implement (11), (16), which only requires knowledge of a_{i-1} (instead of u_{i-1}). In particular, this alternative implementation achieves the same dynamic behavior of ε_i as with the controller (6), but without requiring knowledge of τ_{i-1}.

In summary, the class of controllers (11) with ξ_i such that (12a) is stabilized, contains the class of controllers (6) with ζ_i such that (5a) is stabilized. However, the new class of controllers is richer, since other choices for ξ_i can also be made, such as the PD controller (13).

4. PERFORMANCE ANALYSIS

To illustrate the benefits of the newly proposed controller, we first consider the controller (7) as introduced in Ploeg et al. (2011). In addition, we also include latency of the wireless vehicle-to-vehicle communication which is induced by queueing, contention, transmission, and propagation. This latency plays an important role in the quality of the CACC performance. In particular, as will be shown in this section, the latency puts a bound on the time gap h_i below which the vehicle platoon becomes string unstable. Note that this latency can be taken into account in the controller design, see, e.g., Gao et al. (2016) and Zhang et al. (2018). This is, however, considered out of scope for this paper.

As in Ploeg et al. (2011), we let $\tau_i = 0.1\,\text{s}$, $h_i = 0.5\,\text{s}$, $k_\text{p} = 0.2$, $k_\text{d} = 0.7$, and $k_\text{dd} = 0$. In addition, we consider a communication delay $\theta_i = 0.02\,\text{s}$ between vehicles $i-1$ and i. These parameter values are adopted throughout this section, unless explicitly stated otherwise. Contrary to Ploeg et al. (2011), we allow $\tau_{i-1} \neq \tau_i$.

In Fig. 4, a block diagram is given of the controller (7) in this heterogeneous setting with communication delay. Here, $G_i(s)$ and $H_i(s)$ are defined as before, and $C(s) = k_\text{p} + k_\text{d}s + k_\text{dd}s^2$. The resulting *string stability complementary sensitivity* $\Gamma_i(s)$, which is the transfer function from "input velocity" v_{i-1} to "output velocity" v_i, or, equivalently, from "input acceleration" a_{i-1} to "output acceleration" a_i, is given by

$$\Gamma_i(s) = \frac{1}{h_i s + 1}\,\frac{e^{-\theta_i s}s^2(\tau_{i-1}s+1) + k_\text{dd}s^2 + k_\text{d}s + k_\text{p}}{s^2(\tau_i s+1) + k_\text{dd}s^2 + k_\text{d}s + k_\text{p}}. \tag{17}$$

For (strict) string stability, we need $\|\Gamma_i(s)\|_{\mathcal{H}_\infty} \leq 1$ (Ploeg et al., 2014), where $\|\cdot\|_{\mathcal{H}_\infty}$ denotes the $\mathcal{H}_\infty$ norm.

First, we consider the case without communication delay, i.e., $\theta_i = 0$. Then, for string stability we need

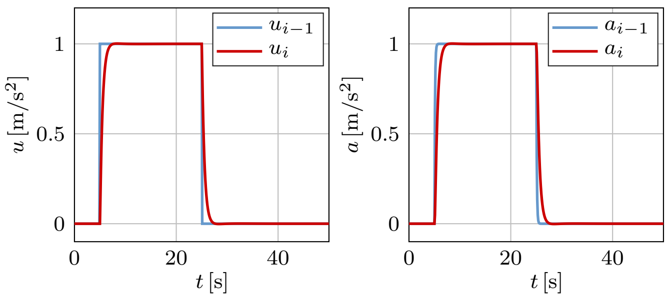

Fig. 5. Time response of controller (7) in homogeneous setting, i.e., $\tau_i = \tau_{i-1} = 0.1$.

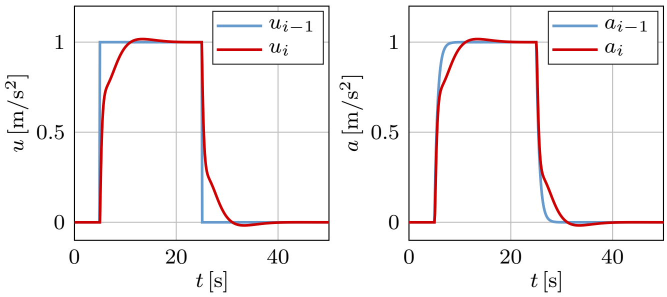

Fig. 6. Time response of controller (7) in heterogeneous setting, i.e., $\tau_i = 0.1$, $\tau_{i-1} = 0.6$.

$$\|\Gamma_i(j\omega)\|_{\mathcal{H}_\infty} = \sup_{\omega\in\mathbb{R}} \sqrt{\frac{(k_\text{p}k_\text{d} - \tau_{i-1}\omega^2)^2 + \omega^2}{(1+h_i^2\omega^2)\big((k_\text{p}k_\text{d} - \tau_i\omega^2)^2 + \omega^2\big)}} \leq 1, \tag{18}$$

taking into account that $k_\text{dd} = 0$. Notice that for given k_p, k_d, h_i, τ_i, and ω in (18), the expression under the square-root becomes an increasing function of τ_{i-1} for $\tau_{i-1} \geq k_\text{p}k_\text{d}/\omega^2$. In particular, we have that by increasing τ_{i-1}, we can make the $\mathcal{H}_\infty$ norm of Γ_i arbitrarily large, ultimately resulting in string instability, already in the case without communication delay. For instance, for the parameters given above and $\theta_i = 0$, we obtain for $\tau_{i-1} = 0.6$ that $\|\Gamma_i(j\omega\|_{\mathcal{H}_\infty} = 1.8 > 1$.

To illustrate that the homogeneous controller (7) becomes sting unstable, we consider the response of vehicle i to a step change in the input u_{i-1} of vehicle $i-1$ at times $t = 5\,\text{s}$ and $t = 25\,\text{s}$, while including the communication delay $\theta_i = 0.02\,\text{s}$ again. The time responses for the homogeneous case, with $\tau_i = \tau_{i-1} = 0.1$, and for a heterogeneous case, with $\tau_i = 0.1$ and $\tau_{i-1} = 0.6$, are depicted in figures 5 and 6, respectively. We see that for the heterogeneous case, the response of vehicle i has a larger settling time and exhibits overshoot. Therefore, we can conclude that the controller (7) is not suitable for heterogeneous platoons.

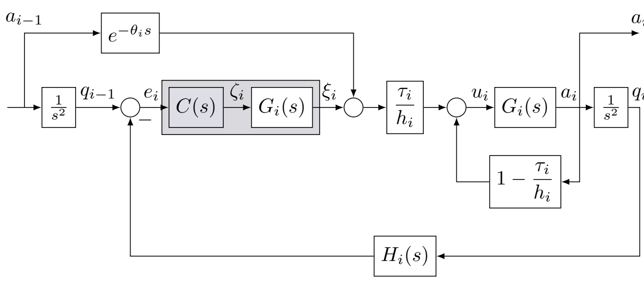

Fig. 7. Block diagram of controller (11), (16).

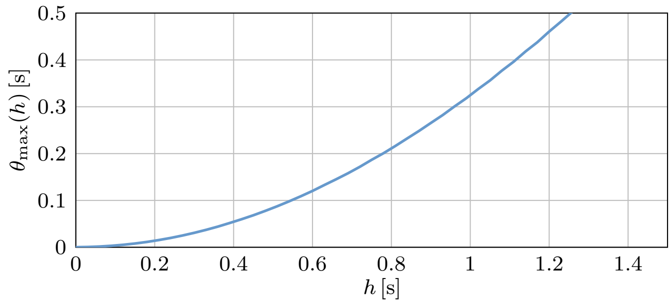

Fig. 8. The maximum string-stable communication delay $\theta_{\max}(h)$ for the controller (11), (16) with $\tau_i = 0.1$.

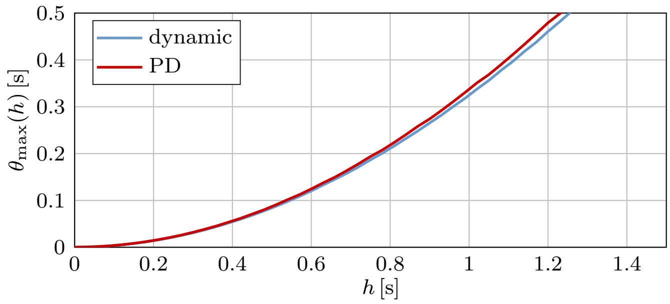

Fig. 10. The maximum string-stable communication delay $\theta_{\max}(h)$ for the dynamic controller (11), (16), with $\tau_i = 0.1$, and for the PD controller (11), (13).

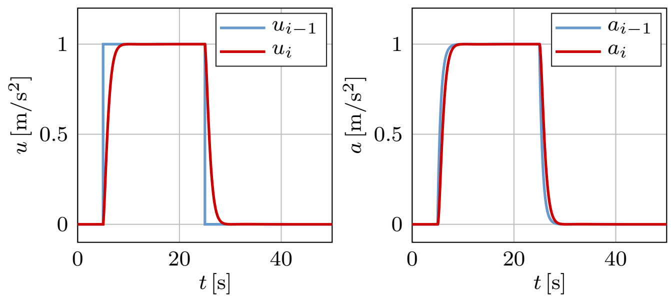

Fig. 9. Time response of controller (11), (16) in a heterogeneous setting ($\tau_i = 0.1$, $\tau_{i-1} = 0.6$).

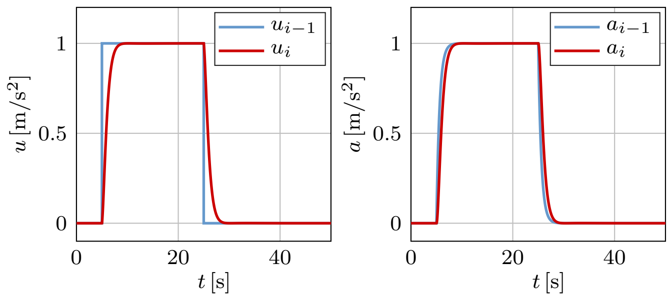

Fig. 11. Time response of controller (11), (13) in a heterogeneous setting ($\tau_i = 0.1$, $\tau_{i-1} = 0.6$).

Instead of (7), we could implement the controller (11), (16), for which a block diagram is depicted in Fig. 7, with $C(s) = k_\mathrm{p} + k_\mathrm{d}s + k_\mathrm{dd}s^2$. Recall that this controller is equivalent to the controller (6), as shown in Fig. 2, but only needs a_{i-1} as input and does not need knowledge of τ_{i-1}. The resulting string stability complementary sensitivity $\Gamma_i(s)$ is given by

$$\Gamma_i(s) = \frac{1}{h_i s + 1} \frac{e^{-\theta_i s} s^2(\tau_i s + 1) + k_\mathrm{dd}s^2 + k_\mathrm{d}s + k_\mathrm{p}}{s^2(\tau_i s + 1) + k_\mathrm{dd}s^2 + k_\mathrm{d}s + k_\mathrm{p}}. \tag{19}$$

Without delay, i.e., $\theta_i = 0$, we have that $\|\Gamma_i(j\omega)\|_{\mathcal{H}_\infty} = 1$ and therefore string-stable behavior. However, by increasing the delay θ_i, string stability will be compromised at a certain point. This can be seen in Fig. 8, which shows the maximum communication delay $\theta_{\max}$ as a function of the time gap h for which string stability is still guaranteed, determined using (19) with $\tau_i = 0.1\,\mathrm{s}$. Note that this is the exact same graph as obtained for controller (6), since the latter also has Γ_i as in (19). Equivalently, controller (7), with Γ_i as in (17), yields the same result when using the homogeneous setting $\tau_{i-1} = \tau_i = 0.1$.

As opposed to the controller (7), however, the controller (11), (16) can also be used in the heterogeneous case. This is illustrated in Fig. 9, which shows the response of this controller for the heterogeneous case where $\tau_i = 0.1$ and $\tau_{i-1} = 0.6$ (with $\theta_i = 0.02\,\mathrm{s}$). We see a behavior of the follower vehicle i which is comparable to that in Fig. 5. This shows that the newly proposed controller is able to deal with heterogeneous platoons, even without requiring knowledge of τ_{i-1}, and achieves the same level of performance in the heterogeneous setting as the controller (7) in the homogeneous setting. Moreover, the class of new controllers is richer: Instead of the dynamic controller (11), (16), we can also use the static controller (11), (13) with suitably selected k_p and k_d.

The dynamic controller (11), (16), with parameters as described at the start of this section, was tuned for homogeneous platoons to have minimal jerk and settling time. After a step on u_{i-1}, this controller achieves a settling time of 1.81 s with a maximum jerk of 1.35 m/s^3. Taking the same controller gains for the PD controller (11), (13), i.e., $k_\mathrm{p} = 0.2$ and $k_\mathrm{d} = 0.7$, appears to result in very similar performance, namely a settling time of 1.82 s with a maximum jerk of 1.35 m/s^3.

The PD controller (11), (13) corresponds to replacing the two blocks in Fig. 7 containing $C(s) = k_\mathrm{p} + k_\mathrm{d}s + k_\mathrm{dd}s^2$ and $G_i(s) = \frac{1}{\tau_i s + 1}$, respectively, by a single block, containing only the PD controller $C(s) = k_\mathrm{p} + k_\mathrm{d}s$. This yields the following string stability complementary sensitivity:

$$\Gamma_i(s) = \frac{1}{h_i s + 1} \frac{e^{-\theta_i s} s^2 + k_\mathrm{d}s + k_\mathrm{p}}{s^2 + k_\mathrm{d}s + k_\mathrm{p}}. \tag{20}$$

As before, we can determine the maximum string-stable communication delay $\theta_{\max}(h)$. This relation is shown in Fig. 10, from which we conclude that the PD controller (11), (13) allows for a slightly larger communication delay than the dynamic controller (11), (16), thus yielding comparable string stability properties. The time response of the PD controller (11), (13) is depicted in Fig. 11 for the heterogeneous setting, i.e., $\tau_i = 0.1$, $\tau_{i-1} = 0.6$. Clearly, the response is almost identical as with the dynamic controller (see Fig. 9), even though we do not know τ_{i-1}.

In summary, we can see that the PD controller (13) is simpler than the dynamic controller (16), while achieving very similar performance in terms of maximal jerk, settling time, and maximum string-stable communication delay.

5. CONCLUSION

The presented one-vehicle look-ahead controller for CACC allows for vehicle platoons that are heterogeneous with respect to the vehicle driveline, without requiring knowledge about the driveline dynamics of the preceding vehicle. Moreover, the new controller structure was shown to encompass the baseline controller for homogeneous systems, thus providing a larger class of controllers. In addition, a specific implementation of the new controller illustrated that it is possible to retain the performance of the baseline controller in terms of settling time, maximum jerk, and maximum string-stable communication delay.

Inherent to the heterogeneity property of the new controller is that it relies on communication of the actual acceleration of the preceding vehicle, i.e., an output, as opposed to communication of the vehicle's input, which was required in the baseline controller. Obviously, this requires measurement of the longitudinal acceleration, locally in the transmitting vehicle, which generally suffers from a rather low signal-to-noise ratio. Hence, a direction of further investigation concerns the application of an acceleration filter or observer and the consequences thereof for CACC performance. Another line of research concerns graceful degradation of CACC under persistent communication loss. Estimation of the preceding vehicle's acceleration using on-board sensors, instead of using wireless communication, would then provide a degraded mode, without the need to switch to a different type of controller.

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