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Fault Tolerance of Cooperative Vehicle Platoons Subject to Communication Delay

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Abstract: Cooperative Adaptive Cruise Control (CACC) employs wireless intervehicle communication to allow for automatic vehicle following at small intervehicle distances while guaranteeing string stability. Inherent to the CACC concept, however, is its vulnerability to communication impairments, among which latency of the wireless link, which compromise string stability and, hence, safety. To investigate the sensitivity of the string stability property with respect to communication latency, two controllers are developed by means of $\mathcal{H}_\infty$ controller synthesis, employing a one-vehicle look-ahead and a two-vehicle look-ahead communication topology, respectively. The string stability properties of the controlled vehicle platoon are investigated, based on which it is proposed to switch from one- to two-vehicle look-ahead when the latency exceeds a certain threshold, thereby creating robustness against increasing communication delay by retaining string stability at the lowest possible time gap.

Keywords: Cooperative adaptive cruise control, H-infinity control, string stability, communication networks, vehicle platoons.

1. INTRODUCTION

Adaptive Cruise Control (ACC) is a longitudinal vehicle-following control system that keeps a desired distance to the preceding vehicle (Piao and McDonald, 2008). To this end, onboard sensors are employed, such as radar, which measure the intervehicle distance and its rate of change. When, in addition, information of the preceding vehicle(s) is cast through a wireless communication link, the control system is commonly referred to as Cooperative Adaptive Cruise Control (CACC). Employing wireless communication significantly enhances the performance compared to ACC, in terms of minimizing the intervehicle distance while guaranteeing string stability, i.e., shock wave attenuation in upstream direction (Seiler et al., 2004). As a result, traffic throughput is increased, while maintaining a sufficient level of safety (Shladover et al., 2012), although string-stable behavior *per se* does not guarantee the avoidance of collisions. In addition, significant fuel savings are possible, especially for trucks (Ramakers et al., 2009).

The wireless link is, however, subject to packet loss, e.g., due to obstruction of the line-of-sight or multi-path effects (Bergenhem et al., 2012). Another important impairment, being the focus of this paper, is latency, caused by message handling routines and asynchronicity of computers in different vehicles. This (possibly time varying) delay significantly compromises string stability, as shown in Naus et al. (2010). The relation between communication latency and CACC performance in terms of string stability already attracted interest, see, e.g., Liu et al. (2001), which investigates the effects of delay on string stability for a communication topology involving both the directly preceding vehicle the lead vehicle of the platoon. Employing the same communication topology, Fernandes and Nunes (2012) provide a detailed analysis of various information-updating schemes of the communication protocol subject to delay, whereas Öncü (2014) developed an analysis framework incorporating uncertain sampling intervals and delays in a sampled-data context.

The focus in this paper is on the design of CACC functionality for a one-vehicle look-ahead and a two-vehicle look-ahead communication topology, and on the subsequent analysis of the effects of a (slowly) varying communication delay on string stability for both topologies. In particular, the minimum time gap for which string-stable behavior can be achieved is determined, as a function of the communication delay. This forms the basis for a fault-tolerance strategy in case the actual communication delay exceeds the design value, which involves switching between the topologies. In addition, it is shown that above a certain delay threshold, the use of wireless communication is no longer beneficial in view of string stability. Here, an $\mathcal{H}_\infty$ optimal controller design approach is adopted, since this allows to *a priori* include the string stability requirement as a design specification, as opposed to, e.g., a consensus-seeking approach (Bernardo et al., 2015).

The outline of this paper is as follows. Section 2 introduces the vehicle model and formulates the control problem. Next, Section 3 presents the controller design for the aforementioned communication topologies. Section 4 then

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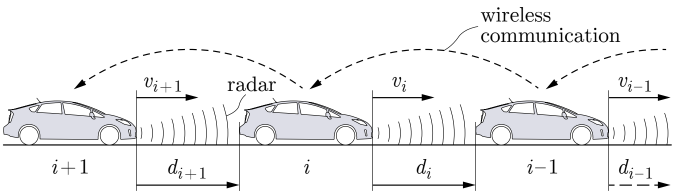

Fig. 1. CACC-equipped homogeneous vehicle platoon.

analyses the effects of communication delay on string stability and proposes a fault-tolerance strategy. Finally, Section 5 summarizes the main conclusions.

2. CONTROL PROBLEM FORMULATION

Consider a homogeneous platoon of m vehicles, as depicted in Fig. 1, where d_i is the distance between vehicle i and its preceding vehicle $i-1$, and v_i is the velocity of vehicle i. The main (tracking) control objective is to regulate d_i to a desired distance $d_{\mathrm{r},i}$. Adopting the constant time gap spacing policy, which is known to improve string stability (Naus et al., 2010), the desired distance is chosen as

$$d_{\mathrm{r},i}(t) = r_i + hv_i(t), \quad i \in S_m \backslash \{1\}, \tag{1}$$

where h is the time gap and r_i the standstill distance. The set of all vehicles in a platoon of length $m \in \mathbb{N}$ is denoted by $S_m = \{i \in \mathbb{N} \mid 1 \leq i \leq m\}$. This paper focusses on homogeneous platoons, which is why h does not depend on the vehicle index. The spacing error e_i is then equal to

$$\begin{aligned} e_i(t) &= d_i(t) - d_{\mathrm{r},i}(t) \\ &= \big(q_{i-1}(t) - q_i(t) - L_i\big) - \big(r_i + hv_i(t)\big), \end{aligned} \tag{2}$$

where q_i is the rear-bumper position of vehicle i, and L_i is its length. Consequently, the tracking objective is formulated as

$$a_1(t) = 0 \;\forall\, t \geq 0 \;\Rightarrow\; \lim_{t\to\infty} e_i(t) = 0 \;\forall\, i \in S_m \backslash \{1\}, \tag{3}$$

where a_1 is the acceleration of the lead vehicle. In other words, with the first vehicle driving at a constant velocity, the spacing errors e_i must converge to zero.

To formulate the string stability requirement in the Laplace domain, the vehicle dynamics are also described in the Laplace domain by the transfer function $G(s)$, with $s \in \mathbb{C}$, according to

$$G(s) = \frac{q_i(s)}{u_i(s)} = \frac{1}{s^2(\tau s + 1)} e^{-\phi s}, \tag{4}$$

where τ is a time constant and ϕ a time delay, together representing the drive line dynamics. u_i is the vehicle input, which can be interpreted as the desired acceleration, whereas the position q_i is the output. This vehicle model is shown to adequately describe the dynamics of an acceleration-controlled vehicle in Ploeg et al. (2014). Note that, slightly abusing formal mathematical notation, $\cdot(s)$ denotes the Laplace transform of the corresponding time-domain variable $\cdot(t)$. Due to the homogeneity assumption, $G(s)$ is identical for all vehicles. Next, formulating the spacing error e_i in (2) in the Laplace domain yields

$$e_i(s) = q_{i-1}(s) - H(s)q_i(s) \tag{5}$$

with $H(s) = hs+1$. Without loss of generality, $r_i = L_i = 0$ is chosen.

Following Ploeg et al. (2014), the controller of each vehicle is designed according to

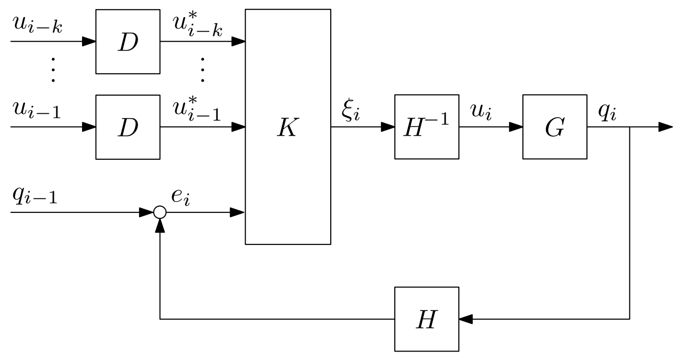

Fig. 2. CACC with k-vehicle look-ahead topology.

$$\begin{aligned} u_i(s) &= H^{-1}(s)K(s) \begin{pmatrix} e_i(s) \\ u^*_{i-1}(s) \\ \vdots \\ u^*_{i-k}(s) \end{pmatrix} \\ &=: H^{-1}(s)\xi_i(s) \end{aligned} \tag{6}$$

with $K(s) = \big(K_{\mathrm{fb}}(s)\; K_{\mathrm{ff},1}(s)\; \dots\; K_{\mathrm{ff},k}(s)\big)$, where $K_{\mathrm{fb}}(s)$ denotes the feedback control law and $K_{\mathrm{ff},j}(s)$, $j = 1, 2, \dots, k$, are the feedforward controllers. $\xi_i(s)$ is the output of the controller $K(s)$ and u^*_{i-j}, $j = 1, 2, \dots, k$, are the inputs of k preceding vehicles, obtained through wireless intervehicle communication. The wireless communication has a latency θ, i.e., $u^*_{i-j}(t) = u_{i-j}(t-\theta)$, which, in the Laplace domain, corresponds to $u^*_{i-j}(s) = D(s)u_{i-j}(s)$ with $D(s) = e^{-\theta s}$. This latency is independent of the vehicle index because messages are sent to all vehicles at the same time (i.e., broadcast), instead of forwarding them from one vehicle to the next (unicast). Obviously, (6) only holds for vehicles $i > k$. In case $i \leq k$, $K(s)$ is adapted to only take the $i-1$ preceding vehicles into account. Furthermore, $K(s)$ is desired to be independent of the vehicle index (for $i > k$), thus not requiring any specific order of the vehicles in the platoon. As a result, a CACC vehicle can be represented by the block scheme as shown in Fig. 2. As can be seen in this figure, $H(s)$ in (5) is located in the feedback loop, which is canceled by the precompensator $H^{-1}(s)$ in (6), such that the driver can select any time gap h without affecting the loop gain.

Since u_1 is the external input to the entire string, it is possible to formulate transfer functions $P_i(s)$, $i \in S_m$, from this input to any output of interest y_i, i.e.,

$$y_i(s) = P_i(s)u_1(s), \quad \forall\, i \in S_m. \tag{7}$$

In terms of input–output stability, the notion of string stability can then be described as a bounded response of the output y_i, for all $i \in S_m$, to the input u_1 for any string length $m \in \mathbb{N}$, thus including the infinite-length string (Ploeg et al., 2014). For vehicle platooning, a physically relevant choice for y_i would, e.g., be the spacing error e_i. In practice, however, the stronger requirement of attenuation in upstream direction of the response to disturbances in u_1 is imposed on vehicle platoons. To formulate this stronger requirement, referred to as *strict* string stability, a propagation transfer function $\Gamma_i(s)$ is introduced, according to

$$\begin{aligned} y_i(s) &= P_i(s)P^{-1}_{i-1}(s)y_{i-1}(s) \\ &=: \Gamma_i(s)y_{i-1}(s), \quad \forall\, i \in S_m, \end{aligned} \tag{8}$$