A PLF-CACC Design with Robustness to Communication Delays

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Keywords: CACC, PLF, Communication Delays.

Abstract: In this paper, a new controller that makes a platoon of vehicles robust to large delays and loss of communication is proposed. The constant time headway spacing policy is adopted for the separations while the vehicles are allowed to exchange data according to the PLF communication pattern. Based on the SMC technique, the designed controller draw the platoon towards achieving the following and the string stability objectives. Semi strict L_2 string stability is proved to be achieved in this two-vehicle look ahead strategy with the propose controller. Simulation are run in order to confirm the theoretical findings and to assess the effectiveness of the proposed controller. The performances in terms of string stability and robustness against delays are compared to a baseline PLF-CACC from the literature.

1 INTRODUCTION

Cooperative autonomous vehicles, also known as CAVs are becoming more and more prevalent in today's world. These vehicles use advanced technology to drive themselves without human intervention. One of the main benefits of CAVs is their ability to communicate with each other and with infrastructure. This allows them to work together and avoid accidents, reducing traffic congestion and improving overall safety on the road. The development of effective control systems for cooperative autonomous vehicles is an important area of research, which involves designing algorithms and decision-making processes that enable multiple vehicles to work together in a coordinated manner towards a common goal. Cooperative adaptive cruise control (CACC) is an advanced form of cruise control that enables multiple vehicles to travel in a platoon, or convoy, while maintaining a desired separation from each other. Unlike traditional cruise control, CACC uses communication between vehicles to coordinate their movements and adjust their speed and distance based on the actions of surrounding vehicles. Therefore, the communication topology is a key aspect in the design of the driving strategy of the platoon.

Typical types of information flow topologies include predecessor following (PF), predecessor-leader following (PLF) and bidirectional (BD), among which PLF is the most prevailing CACC topology (Cui et al., 2021). Under this topology, an ego-vehicle takes in information, such as location, speed, and control input values from its predecessor and the leader. The PLF controller is more robust than PF since in the latter the vehicles respond only to their predecessors (Dey et al., 2015; Seiler et al., 2004).

Another key aspect is the selected spacing policy for the CACC system. It refers to the desired steady state spacing between two consecutive vehicles during vehicle following (Wu et al., 2020). The spacing policies can be classified into two major categories: constant spacing policy and variable spacing policies. The most typical variable spacing policy is the constant time gap (CTG) (Wu et al., 2020). The prevailing definition of the time gap denotes the period during which the rear bumper of the preceding vehicle and the front bumper of the ego vehicle pass a fixed position on the road. CTG is the strategy that fits the best the behaviour humans driver have when car-following, for this reason it is the most adopted spacing policy by commercially available CACC systems (Flores, 2018).

When designing a CACC system, the control law is another major concern which is our focus in this work. The latter regulates the error between desired and real spacing to drive the platoon towards achieving the desired inter-vehicles distances which are obtained according to the adopted spacing policy. In addition, the controller must ensure the string stability of the designed CACC system. The latter is said to be string stable if the disturbances are not amplified when propagating downstream along the vehi-

Besseghieur, K., Nemra, A. and Demim, F.
A PLF-CACC Design with Robustness to Communication Delays.
DOI: 10.5220/0012190500003543
In *Proceedings of the 20th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2023) - Volume 1*, pages 444-452
ISBN: 978-989-758-670-5; ISSN: 2184-2809

cle string. Along this direction, prevailing control laws in literature were proposed. Linear controllers in (Naus et al., 2010; Xing et al., 2018) and in (Xing et al., 2019) are designed. Although the string stability is simple to analyse, linear controllers present some limitations when it comes to satisfy state and input constraints. Optimal controllers solve an optimization problem to determine the control input for each vehicle of the platoon (Jin and Orosz, 2016; Dunbar and Caveney, 2011). Although they possess the capacity to handle state and input constraints, optimization-based controllers present a high computation burden. Both LQR and H_∞-based controllers that guarantee string stability were synthesized respectively in (Zhang et al., 2020a) and (Ploeg et al., 2013a) to drive the CACC system while minimizing a cost function. When the considered vehicle model is nonlinear or the adopted spacing policy is based on a variable time gap, nonlinear controllers are adopted as in (Besselink and Johansson, 2017) and (Liu et al., 2001). One drawback of these controllers is the fact that the string stability analysis is much more complex.

In the control design, CACC systems which are designed without considering communication delay are likely to show poor performance in the real world under extreme communication delay and packet loss scenarios (Liu et al., 2001), (Lei et al., 2011). In (Ploeg et al., 2013b), L_p string stability of the platoon system is introduced and investigated under homogenous communication delay. It is shown that the L_∞ string stability is compromised and to ensure L_2 string stability of the system with a delay of 300 ms, the time gap is required to be as high as 1 s. In (Zhang et al., 2020b), authors proposed a semi-constant time gap (Semi-CTG) spacing policy that leads along with a linear controller to fully compensate heterogeneous communication delays. Under predecessor follower (PF) topology, linear controllers are employed and it is proved that the minimum time gap guaranteeing string stability equals the communication delay of the system. Under the same information flow pattern, the research in (Zhang et al., 2020a) adopts a space domain approach to design an optimal control-based CACC system. Both local and string stability are proven and robustness against communication failure is improved comparing to the state-of-the-art controllers proposed in (Ploeg et al., 2013a) and (Naus et al., 2010).

Communication delay and packet loss have rarely been addressed under PLF information flow topology. In (Zhang et al., 2020b), a semi-constant spacing policy is proposed to deal with communication and sensing delays. However, the authors did not take into consideration a constant time headway spacing policy. In (Fernandes and Nunes, 2012), strategies to mitigate communication delays are proposed under the PLF communication topology while considering a CS spacing policy again. In (Milanés et al., 2013), the authors considered a CTH spacing policy and the proposed controller is based on the PLF topology. However, the string stability analysis needs to be more detailed and the communication delays are not considered.

In our work, we propose a new controller that deals with communication delays under the CTH spacing policy and the PLF information flow topology. The proposed controller ensures the local and the string stability of the platoon and its capacity to deal with communication delays is shown. In order to assess the effectiveness of the proposed controller, we compare the performances with the work in (Milanés et al., 2013) which is set as a baseline.

The rest of this paper is organized as follows. Section 2 presents the robot modelling and problem formulation. In Section 3, the nominal controller is exposed and its robustness against delays is analysed. Section 4 proposes a new PLF-CACC controller and details its local and string stability. Section 5 includes simulations where the performance of the proposed system is assessed.

2 PROBLEM FORMULATION

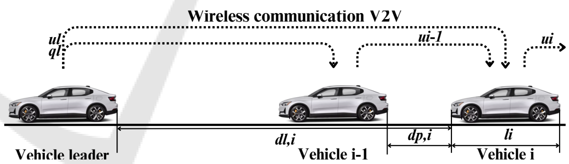

Figure 1: PLF platooning system.

In this section, the kinematic model of the vehicle is presented. The platoon modelling is exposed and the control problem is formulated under the PLF communication topology. To facilitate further discussion, definitions and notations are introduced here. As shown in Figure 1, the leader vehicle is indexed as l, the preceding vehicle is indexed as i–1 and the ego vehicle indexed as i. l_i, q_i, v_i and u_i denote the length, position, velocity, and control input of vehicle i, respectively. In our work, the string is assumed to be homogeneous .i.e. all vehicles of the platoon are identical. The following model is adopted (Milanés et al., 2013):

$$G(p) = \frac{k}{p^2 + 2\theta w_n p + w_n^2} \qquad (1)$$

with k, θ, w_n defined in Table 1.

Table 1: Vehicle model parameters.

k	θ	w_n
0.156	0.661	0.396

The main objective, under the CTH spacing policy and the PLF communication topology, is to regulate the subject vehicle's longitudinal motion to follow its predecessor and its leader with constant time gaps. The desired spacing between the ego vehicle and its predecessor, is formulated as:

$$d_{rp,i}(t) = r_i + h\,v_i(t) \tag{2}$$

Whereas, the desired spacing from the leader of the platoon is:

$$d_{rl,i}(t) = r_i + h_l\,v_i(t) \tag{3}$$

Where r_i, h and h_l denote the standstill distance, the desired time gaps to the predecessor and to the leader, respectively. This formulation leads to spacing error with respect to the preceding vehicle and the lead vehicle, respectively, as:

$$\begin{aligned} e_{p,i}(t) &= d_{p,i}(t) - d_{rp,i}(t) \\ &= (q_{i-1}(t) - q_i(t) - l_i) - r_i - h\,v_i(t) \end{aligned} \tag{4}$$

$$\begin{aligned} e_{l,i}(t) &= d_{l,i}(t) - d_{rl,i}(t) \\ &= (q_l(t) - q_i(t) - \sum_{j=1}^{i} l_j) - r_i - h_l\,v_i(t) \end{aligned} \tag{5}$$

Without loss of generality, $r_i = l_i = 0$ is assumed in the remainder of this paper. Formulating the spacing error $e_i(t)$ in the Laplace domain yields:

$$e_{p,i}(p) = q_{i-1}(p) - H(p)\,q_i(p) \tag{6}$$

$$e_{l,i}(p) = q_l(p) - H_l(p)\,q_i(p) \tag{7}$$

with the spacing policy transfer functions $H(p)$ and $H_l(p)$ defined as

$$H(p) = h\,p + 1 \tag{8}$$

$$H_l(p) = h_l\,p + 1 \tag{9}$$

The vehicle following objective is achieved when the inter-vehicle distance errors as defined in Equations (4) and (5) converge to zero. To achieve this, it is assumed in our work that the inter-vehicle spacing, the speed of the subject vehicle and the predecessor, and the acceleration of the subject vehicle are assumed to be detected by on-board sensors, including radar or camera, speedometer, and accelerometer. While, under the adopted PLF communication pattern, the accelerations, control inputs of both the predecessor and the leader and the position of the latter are collected by the V2V communication system and transmitted to the ego vehicle.

As shown earlier, it is of great importance to take into consideration heterogeneous communication and sensor delays and in the control design. We denote by $\tau_{x,i}$, the subject vehicle's on board sensor delay to obtain the preceding vehicle's acceleration, speed and position; $\tau_{u,i}$, the delay of the vehicle-to-vehicle (V2V) communication to obtain the predecessor's commands; all the information about the lead vehicle are obtained by V2V communication delayed by $\tau_{l,i}$.

Table 2: Controller parameters (Milanés et al., 2013).

k_1	k_2	k_3	k_4
0.45	0.25	0.15	0.1

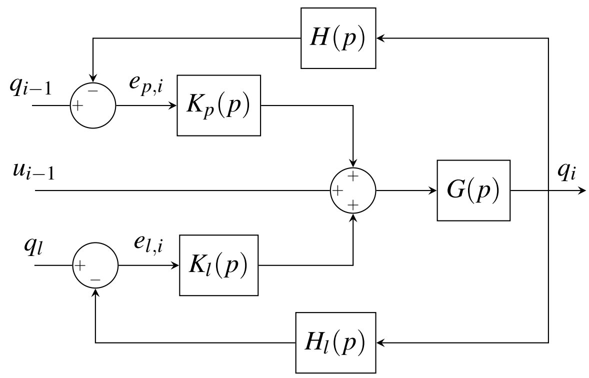

Figure 2: Nominal controller diagram.

3 NOMINAL CONTROLLER

In this section, the controller developed in (Milanés et al., 2013), which is set as a benchmark for this work, is briefly reviewed. As in this work, the authors adopted the CTH spacing policy and the PLF communication pattern in their strategy. We briefly analyse the controller design, its string stability and its robustness against delays.

3.1 Control Laws

In (Milanés et al., 2013), the gap regulation controller is composed of three main terms: two feedback-feedforward PD controllers that represent time-gap error regulation with respect to the preceding and the leading vehicles and the third term represents the preceding vehicle control inputs which is used as a feedforward term. The following control law was proposed:

$$u_i(t) = e_{p,i}\,k_2 + \dot{e}_{p,i}\,k_1 + e_{l,i}\,k_4 + \dot{e}_{l,i}\,k_3 + u_{i-1}(t) \tag{10}$$

where constants k_1, k_2, k_3 and k_4 are given in Table 2. The block diagram of the nominal CTH-PLF controller is shown in Figure 2. $K_p(p)$ and $K_l(p)$ representing the time-gap error regulation controller for the preceding and the leading vehicle respectively. Both terms correspond to a classic PD controller given by

$$K_p(p) = k_1 p + k_2 \tag{11}$$

$$K_l(p) = k_3 p + k_4 \tag{12}$$

3.2 String Stability Analysis

In addition to the vehicle following objective, a critical task of platoon control is to maintain string stability. It can be defined as the system's ability to attenuate the effects of disturbances introduced by downstream vehicles, in upstream direction. This allows the platoon to avoid amplifications of variations in accelerations, velocities and inter-vehicle distances along the vehicle platoon. Different analysis methods for string stability can be found in the literature (Feng et al., 2019). Adopting the performance oriented approach, the string stability criterion in (Milanés et al., 2013) is chosen as the transfer function from the positions of the ego to the preceding vehicle, respectively.

$$\Gamma_i(p) = \frac{q_i(p)}{q_{i-1}(p)} \tag{13}$$

According to (Ploeg et al., 2013b), a vehicle platoon is string stable if:

$$||\Gamma_i(p)||_{H_\infty} = sup \frac{||q_i(t)||_{L_2}}{||q_{i-1}(t)||_{L_2}} \leq 1 \,, \forall i \geq 1 \tag{14}$$

where $||.||_{H_\infty}$ and $||.||_{L_2}$ refer to the H_∞ and L_2 norms, respectively.

On the other hand, while ignoring the communication delays and considering the fact that $q_0 = 0$, it is shown in (Milanés et al., 2013) that the obtained transfer function from the ego-vehicle to the preceding one is as follows:

$$||\Gamma_i(p)||_{H_\infty} = \frac{1 + G(p)K_p(p)}{1 + G(p)(K_p(p)H(p) + K_l(p)H_l(p))} \tag{15}$$

The magnitude of the transfer function defined above is analysed through its Bode diagram. In (Milanés et al., 2013), it is shown that the magnitude is maintained below the unity. However, many parameters of the considered transfer function are not precised. It is known that in the two-vehicle look-ahead topology, the desired time-gap h_l depends on the position of the ego vehicle in the platoon which implies that the function $H_l(p)$ and thus the transfer function $\Gamma_i(p)$ are not constants for all vehicles in the platoon (Ploeg et al., 2013a). Nevertheless, the position of the studied ego vehicle is not precised in (Milanés et al., 2013). In the presented Bode diagram, the authors did not mention which time-gap h_p was employed in the string stability analysis. In order to maintain the string stability, the employed PD controllers gains were tuned, as shown in Table 2.

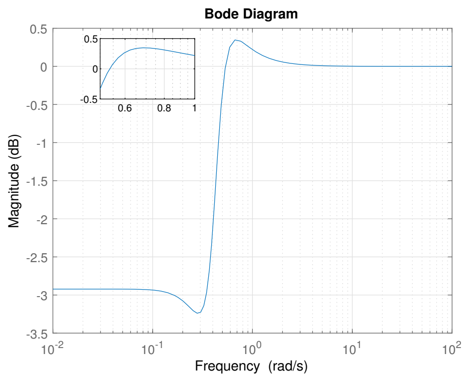

Figure 3: String stability analysis.

Figure 3 shows the frequency response magnitude of the ego vehicle with the same controllers parameters provided in Table 2 We consider a platoon of three vehicles with a leader, a predecessor and the subject vehicle. The desired time-gaps with respect to the predecessor and the leader are set to $h_p = 0.6$ and $h_l = 1.2$, respectively. Although no delays are incorporated, one can clearly notice that the magnitude of the transfer function surpasses the unity and thus the string stability of the platoon is not guaranteed while using the controllers parameters presented in Table 2.

3.3 Effects of Delays on the String Stability

In the controller design, it was assumed that the wireless communication system and on board sensors provide zero delay. The string stability of the CACC system is analysed when affected with the communication/sensor delays $\tau_{x,i}$, $\tau_{u,i}$, $\tau_{l,i}$ as defined earlier. The new block diagram of the delayed nominal system is shown in Figure 4. where $D_{x,i}(p) = e^{-\tau_{x,i}p}$, $D_{u,i}(p) = e^{-\tau_{u,i}p}$ and $D_{l,i}(p) = e^{-\tau_{l,i}p}$

As mentioned earlier, communication and sensors delays compromise string stability (Öncü et al., 2011). As shown in Figure 5, a platoon of four vehicles is considered. Sensors and communication delays are respectively set to $\tau_{x,i} = 0.2s$, $\tau_{u,i} = 0.5s$ and $\tau_{l,i} = 0.5s$. One can clearly notice that the second and the third followers amplify their predecessors perturbations and thus the strict L_2 string stability (Ploeg et al., 2013b) is not ensured. To this end, the objective of our work is to make the system robust against these communication/sensor delays.

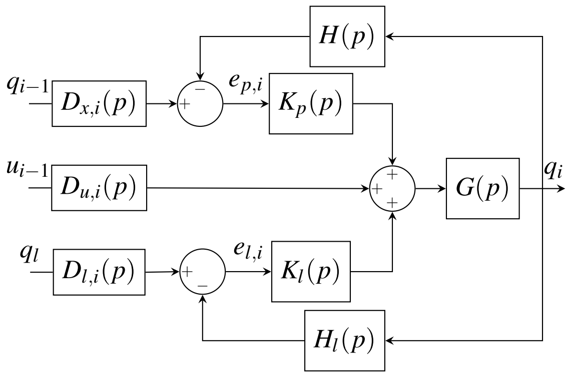

Figure 4: Nominal controller diagram with communication delays

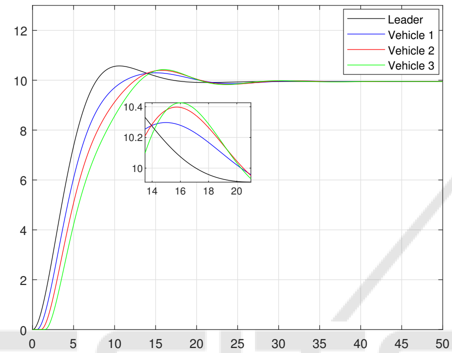

Figure 5: Time responses of the platoon vehicles with communication delays.

4 CONTROLLER DESIGN

In this section, we focus on the controller synthesis that drives the ego vehicle towards achieving the desired space with respect to its predecessor and to its leader. We note that the control of the lead vehicle is out of the scope of this paper. The errors dynamics with respect to the predecessor and to the leader are respectively formulated as

$$\begin{pmatrix} e_{1,i} \\ e_{2,i} \\ e_{3,i} \end{pmatrix} = \begin{pmatrix} e_{p,i} \\ \dot{e}_{p,i} \\ \ddot{e}_{p,i} \end{pmatrix} = \begin{pmatrix} q_{i-1} - q_i - hv_i \\ v_{i-1} - v_i - ha_i \\ a_{i-1} - a_i - h\dot{a}_i \end{pmatrix} \tag{16}$$

$$\begin{pmatrix} e_{4,i} \\ e_{5,i} \\ e_{6,i} \end{pmatrix} = \begin{pmatrix} e_{l,i} \\ \dot{e}_{l,i} \\ \ddot{e}_{l,i} \end{pmatrix} = \begin{pmatrix} q_l - q_i - hv_i \\ v_l - v_i - ha_i \\ a_l - a_i - h\dot{a}_i \end{pmatrix} \tag{17}$$

Deriving the state space representation of the system transfer function given in Equation 1, we obtain:

$$\begin{aligned} \dot{e}_{3,i} &= -2\theta w_n e_{3,i} - w_n^2 e_{2,i} - hk\dot{u}_i - ku_i + ku_{i-1} \\ \dot{e}_{6,i} &= -2\theta w_n e_{6,i} - w_n^2 e_{5,i} - h_l k\dot{u}_i - ku_i + ku_l \end{aligned} \tag{18}$$

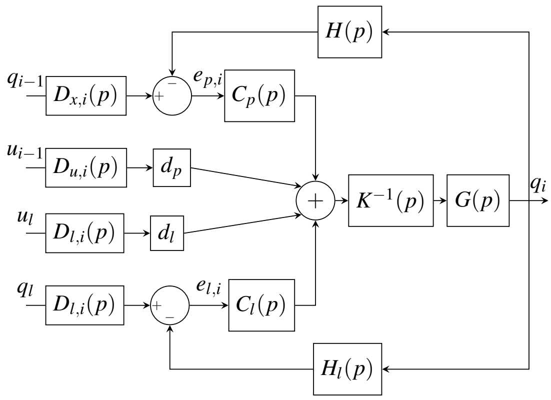

Figure 6: Proposed controller diagram.

An SMC surface is used in the controller design and defined as:

$$S = \begin{pmatrix} k_1 & k_2 & k_3 & k_4 & k_5 & k_6 \end{pmatrix} \begin{pmatrix} e_{1,i} \\ e_{2,i} \\ e_{3,i} \\ e_{4,i} \\ e_{5,i} \\ e_{6,i} \end{pmatrix} \tag{19}$$

By setting: $\dot{S} = -\lambda S$ and combining Equations 4, 5, 16, 17, 18 and 19, the following control law is obtained:

$$\rho_i(t) = \alpha \dot{u}_i(t) + \beta u_i(t) \tag{20}$$

$$\rho_i(t) = \begin{pmatrix} c_1 & c_2 & c_3 & c_4 & c_5 & c_6 \end{pmatrix} \begin{pmatrix} e_{1,i} \\ e_{2,i} \\ e_{3,i} \\ e_{4,i} \\ e_{5,i} \\ e_{6,i} \end{pmatrix} + d_p u_{i-1} + d_l u_l \tag{21}$$

where $\alpha = hkk_3 + h_l kk_6$, $\beta = kk_3 + kk_6$, $c_1 = \lambda k_1$, $c_2 = k_1 - k_3 w_n^2 + \lambda k_2$, $c_3 = k_2 - 2\theta w_n k_3 + \lambda k_3$, $c_4 = \lambda k_4$, $c_5 = k_4 - k_6 w_n^2 + \lambda k_5$, $c_6 = k_5 - 2\theta w_n k_6 + \lambda k_6$, $d_p = kk_3$ and $d_l = kk_6$. The block diagram of the proposed CACC under the PLF topology is presented in Figure 6 where $C_p(p) = c_1 + c_2 p + c_3 p^2$, $C_l(p) = c_4 + c_5 p + c_6 p^2$ and $K(p) = \alpha p + \beta$.

The evaluation of string stability often involves analyzing the amplification of distance error, velocity, and/or acceleration in the upstream direction. As a result, a platoon model is created using these state variables. This leads to the following formulation of a homogeneous platoon model:

$$\begin{pmatrix}\dot{q}_i\\ \dot{v}_i\\ \dot{a}_i\\ \dot{u}_i\end{pmatrix}=\begin{pmatrix}0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & -\omega_n^2 & -2\theta\omega_n & 0\\ -\frac{k_{x_i}}{\alpha} & -\frac{k_{v_i}}{\alpha} & -\frac{k_{a_i}}{\alpha} & -\frac{k_{u_i}}{\alpha}\end{pmatrix}\begin{pmatrix}q_i\\ v_i\\ a_i\\ u_i\end{pmatrix} + \begin{pmatrix}0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ -\frac{c_1}{\alpha} & -\frac{c_2}{\alpha} & -\frac{c_3}{\alpha} & -\frac{d_p}{\alpha}\end{pmatrix}\begin{pmatrix}q_{i-1}\\ v_{i-1}\\ a_{i-1}\\ u_{i-1}\end{pmatrix} + \begin{pmatrix}0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ -\frac{c_4}{\alpha} & -\frac{c_5}{\alpha} & -\frac{c_6}{\alpha} & -\frac{d_l}{\alpha}\end{pmatrix}\begin{pmatrix}q_l\\ v_l\\ a_l\\ u_l\end{pmatrix} \tag{22}$$

Let $x_i = (q_i\, v_i\, a_i\, u_i)^T$ be the state vector, thus the following state representation is obtained:

$$\dot{x_i} = A_i x_i + A_p x_{i-1} + A_l x_l \tag{23}$$

We note that A_i is not constant since it depends on the parameter h_l which depends on the position of the vehicle in the platoon. A_p and A_l are constant for all the vehicles of index $i \geq 1$.

In the control structure shown in Figure 6, the Laplace function of the vehicle i position reads:

$$\begin{aligned} q_i(p) &= \frac{GC_pD_{x,i} + D_{u,i}}{K + G(H_lC_l + HC_p)} q_{i-1}(p) \\ &+ \frac{GC_lD_{l,i} + D_{l,i}}{K + G(H_lC_l + HC_p)} q_l(p) \\ &= \Theta_{i,i-1}(p) q_i(p) + \Theta_{i,l}(p) q_l(p) \end{aligned} \tag{24}$$

In (Milanés et al., 2013), the string stability is analysed through the magnitude of the transfer function from the the ego vehicle position q_i to the predecessor position q_{i-1} without taking into account that it is dependent on the index i. As defined in (Ploeg et al., 2013a), the semi strictly L_2 string stability of the platoon is considered in this work. It has been introduced to support the string stability analysis in the multi-vehicle look-ahead scheme. The semi strict L_2 string stability analysis is based on the transfer function from the ego vehicle position to the leader vehicle position which is given as:

$$\Phi_i(p) = \frac{q_i(p)}{q_l(p)} = \sum_{k=1}^{i-1} [(\Pi_{j=k}^{i-1} \Theta_{j+1,j}(p))\Theta_{k,l}(p)] \tag{25}$$

Since K and H_l depend on the vehicle's index in the platoon i, the semi strict string stability of the platoon is analyzed through multiple transfer functions $\Phi_i(p)$.

As illustrated in Figure 7, showing the gain $|\Phi_i(p)|$ for various values of i. No delays are considered, the desired time gap is set to $h = 0.8s$ and the controller parameters are given in Table 3. It can be noticed that the magnitudes of all the transfer functions are below the unity which confirms the semi strict L_2 string stability of the platoon.

Table 3: Proposed controller parameters.

k_1	k_2	k_3	k_4	k_5	k_6	λ
10	1	0.05	10	1	0.01	100

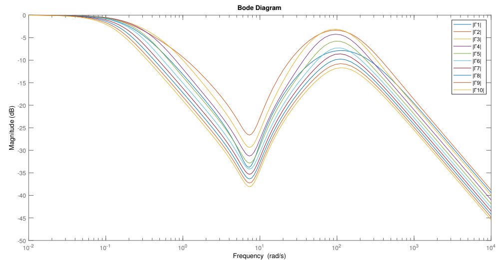

Figure 7: String stability analysis.

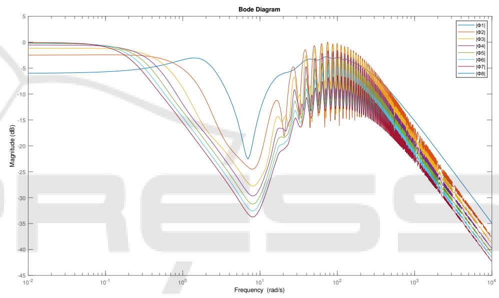

Figure 8: String stability analysis with communication delays.

Figure 8 shows that the semi strict L_2 string stability is still achieved under the following communication/sensors delays: $\tau_{x,i} = 0.2s$, $\tau_{u,i} = 0.4s$ and $\tau_{l,i} = 0.5s$. This confirms the robustness of the proposed controller against delays.

5 SIMULATION RESULTS

Simulations are performed using the proposed controller on a CACC string comprising of ten vehicles to verify the validity of the theoretical findings. In order to assess the robustness of the proposed controller against delays, two scenarios are considered: platoon control without and with communication/sensor delays. Based on these scenarios, two sets of simulations are carried out where the following settings are made for the experiments : A string of 20 vehicles is simulated with the desired speed profile of the lead vehicle is set as depicted in Figure 9. This leads to variable desired spacings between vehicles since in

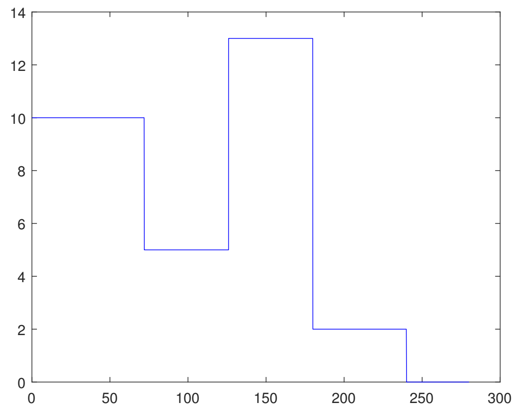

Figure 9: Desired speed for the lead vehicle.

the adopted CTH spacing policy, the desired distance varies with the ego vehicle's speed. In both scenarios, the simulation horizon is: $280s$ and all the vehicles initially are located at the origin with no initial speeds. The controller parameters for both scenarios are set as precised in Table 3 so as the semi strict string stability of the platoon is ensured.

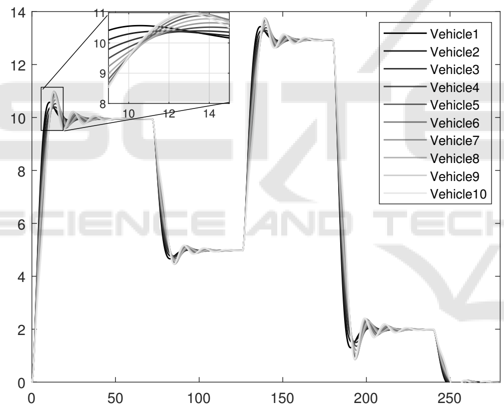

Figure 10: Time responses of the vehicles equipped with the nominal controller.

In the first scenario, no communication delays are taken into consideration and the desired time gap is set to $0.2s$ which is considered a relatively short time gap. Figure 10 depicts the time responses of the first ten vehicles of the platoon where the nominal controller in (Milanés et al., 2013) is adopted. It shows that the perturbations are amplified downstream the platoon direction which indicates the string instability of the platoon. With the same desired time gap, Figure 11 presents the time responses of the first ten vehicles of the platoon equipped with the proposed controller. In this case, it is shown that the amplitudes are not amplified along the downstream direction of the platoon which confirms the theoretical findings concerning the semi strict L_2 string stability. The lo-

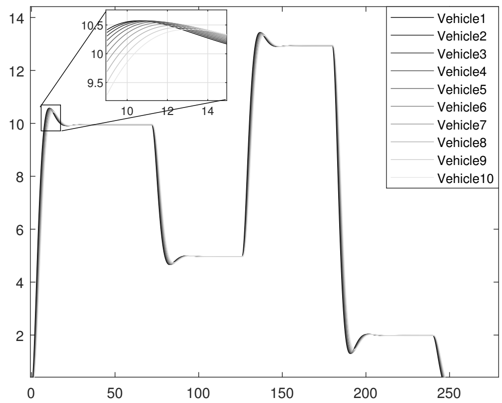

Figure 11: Time responses of the vehicles equipped with the proposed controller.

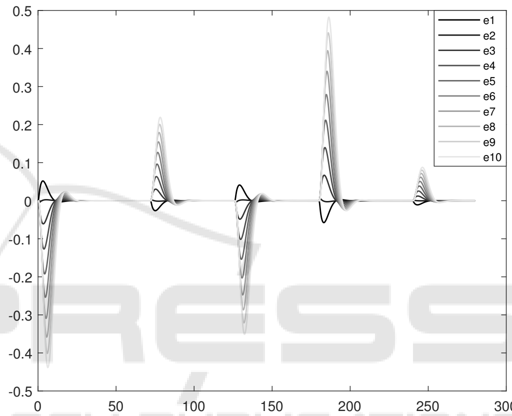

Figure 12: Distance errors of the vehicles equipped with the nominal controller.

cal stability of the platoon is illustrated in Figure 12, where the vehicles errors converge to zero which indicates that the vehicle following objective is achieved and the desired spaces are maintained.

In the second scenario, the desired time gap is considered to be $h = 0.6$ with communication and sensors delays set to be: $\tau_{x,i} = 0.2s$, $\tau_{u,i} = 0.5s$ and $\tau_{l,i} = 0.5s$. Figures 13 and 14 show the performance of both the nominal and proposed controller in dealing with the delays. Clearly, the latter presents robustness against delays and the semi strict L_2 string stability is ensured. While, the baseline CACC shows that the delays have compromised its string stability.

6 CONCLUSION

Robustness against communication and sensors delays in order to maintain the string stability of the CACC equipped platoons is the object of study in this paper. The considered CACC scheme is based on the

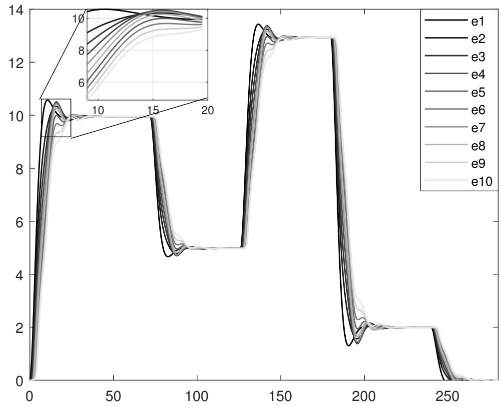

Figure 13: Time responses of the vehicles equipped with the nominal controller.

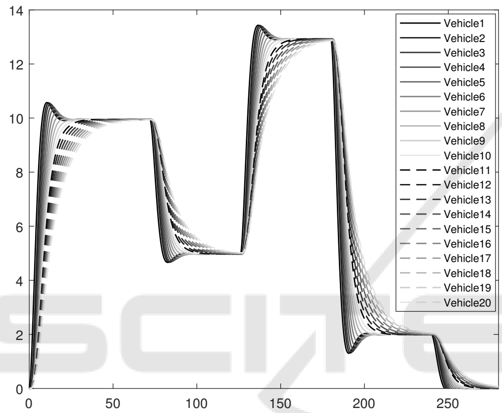

Figure 14: Time responses of the vehicles equipped with the proposed controller.

PLF communication topology and the CTH spacing policy is adopted in this work. A new controller is proposed and is proved to ensure the semi strict L_2 strict stability of the platoon. A nominal controller is briefly reviewed and set as a baseline for this work. In order to confirm the theoretical results, simulations are carried out and the proposed controller shows better performance than the nominal controller in terms of string stability and robustness against communication and sensors delays. Future works include extensive analyse of the proposed controller in terms of assessing the traffic flow performance and a comparison to the PF CACC controllers needs to be carried out.

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