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An Adaptive Approach to Cooperative Longitudinal Platooning of Heterogeneous Vehicles with Communication Losses ⋆

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Abstract: Despite the progresses in Cooperative Adaptive Cruise Control (CACC), a crucial limitation of the state-of-the-art of this control scheme is that the string stability of the platoon can be proven only when the vehicles in the platoon have identical driveline dynamics (homogeneous platoons). In this paper, we present a novel control strategy that overcomes the homogeneity assumption and that is able to adapt its action and achieve string stability even with uncertain heterogeneous platoons with unknown engine performance losses and inevitable communication losses. Considering a one-vehicle look-ahead topology, we propose an adaptive switched control strategy: the control objective is to switch from an augmented CACC to an augmented Adaptive Cruise Control strategy when communication is lost based on a dwell time characterized switching law. The simulation of the proposed control strategy is conducted to validate the theoretical analysis.

Keywords: Cooperative adaptive cruise control, model reference adaptive control, string stability, heterogeneous platoon.

1. INTRODUCTION

Smart traffic is an active area of research striving to increase road safety, manage traffic congestion, and reduce vehicles' emission. Besides traffic light control (Baldi et al. (2107)), automated driving has proved to be a recognized solution for potentially improving road throughput by grouping vehicles into platoons controlled by one leading vehicle (Günther et al. (2016)). CACC is an extension of Adaptive Cruise Control (ACC) (Marsden et al. (2001)) where platooning is enabled by inter-vehicle communication in addition to on-board sensors. CACC has been studied to improve the string stability of vehicle platoons. The notion of string stability implies that disturbances in the form of sudden velocity changes of the leading vehicle are attenuated as they propagate upstream throughout the platoon.

Studies have been conducted to develop CACC strategies that guarantee the string stability of vehicle platoons. Under the assumption of vehicle-independent driveline dynamics (homogeneous platoon), Ploeg et al. (2014) used a performance oriented approach to define string stability and synthesized a one-vehicle only look-ahead cooperative adaptive cruise controller in order to stabilize the platoon. Moreover, Ariffin et al. (2015) developed a longitudinal controller based on a constant spacing policy (velocity-independent) and showed that string stability can be achieved by broadcasting the leading vehicle's acceleration and velocity to all vehicles in the platoon. Furthermore, Kianfar et al. (2015) worked on integrating safety and physical constraints in the vehicle platoon model by augmenting a linear controller by a model predictive controller (MPC) in order to satisfy the subjected constraints while maintaining the platoon's stability.

A review on the practical challenges of CACC was conducted by Dey et al. (2016). The paper highlights the importance of robust wireless communication that can account for highly dynamical environments. Due to unavoidable network delays and packet loss, Guo and Yue (2011) integrated parameter uncertainties, caused by the wireless network, to synthesize a H_∞ controller after feedback linearisation of the non-linear model. The controller was shown to satisfy the string stability criteria and robustness both in theory and in simulations. In addition, the work by Lei et al. (2011) investigates the effects of packet loss ratios, beacon sending frequencies and time headway on string stability. Santini et al. (2015) derived a controller that integrates inter-vehicle communication over different realistic network conditions which models time delays, packet losses, and interferences.

All the aforementioned works rely on the platoon's homogeneity assumption: however, in practice, having a homogeneous platoon is not feasible. A study conducted by Wang and Nijmeijer (2015) assessed the causes of heterogeneity of vehicles in a platoon and their effects on string stability. In fact, Han et al. (2013) designed a longitudinal CACC tracking controller of a heterogeneous platoon (i.e. different driveline dynamics) by assuming that the host

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vehicle can communicate over a wireless communication network with its preceding vehicle as well as with the platoon leader. Furthermore, external disturbances (e.g. vehicle accelerations, wind gust, network induced uncertainties, parametric uncertainties) are always present in practice: Guo et al. (2016) derived a distributed adaptive sliding mode controller for a heterogeneous vehicle platoon that guarantees string stability and adaptive compensation of disturbances based on constant spacing policy.

The brief overview of the state-of-the-art reveals the need to develop CACC with new functionalities, that can handle platoons of heterogeneous vehicles, while adapting to changing conditions. The main contribution of this paper is to address CACC for heterogeneous platoons with unreliable communication. The heterogeneity of the platoon is represented by different (and uncertain) time constants for the driveline dynamics. Using a Model Reference Adaptive Control (MRAC) augmentation method, we analytically prove the asymptotic convergence of the dynamics of a heterogeneous platoon to appropriately defined reference dynamics of a string stable homogeneous platoon. Furthermore, communication losses are handled by switching to a string stable augmented ACC controller with a different reference model. Bounded stability (in particular GUUB in the sense of Liberzon (2003)) is proven under slowly switching conditions.

The paper is organized as follows. In Section 2, the system structure of a heterogeneous vehicle platoon with engine performance losses is presented. Moreover, string stable reference dynamics are presented in Section 3. Section 4 presents an adaptive switched control strategy to stabilize the platoon in the heterogeneous scenario with engine performances losses while copping to inter-vehicle communication losses. Simulation results of the presented controller are presented in Section 5 along with some concluding remarks in Section 6.

2. SYSTEM STRUCTURE

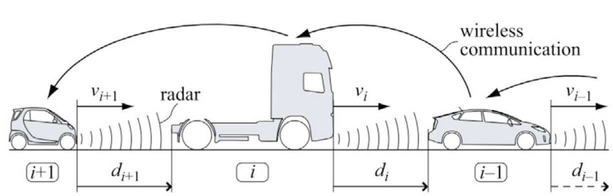

Fig. 1. CACC-equiped heterogeneous vehicle platoon Ploeg et al. (2014)

Consider a heterogeneous platoon with M vehicles. Fig. 1 shows the platoon where v_i and d_i represent the velocity (m/s) of vehicle i, and the distance (m) between vehicle i and its preceding vehicle $i-1$, respectively. This distance is measured using a radar mounted on the front bumper of each vehicle. Furthermore, each vehicle in the platoon can only communicate with its preceding vehicle via wireless communication. The main goal of every vehicle in the platoon, except the leading vehicle, is to maintain a desired distance $d_{r,i}$ between itself and its preceding vehicle.

A constant time headway (CTH) spacing policy will be adopted to regulate the spacing between the vehicles. The CTH is implemented by defining the desired distance as:

$$d_{r,i}(t) = r_i + hv_i(t) \ , \ i \in S_M, \tag{1}$$

where r_i is the standstill distance (m), h the time headaway (s), and $S_M = \{i \in \mathbb{N}| \ 1 \leq i \leq M\}$ with $i = 0$ reserved for the platoon's leader (leading vehicle).

It is now possible to define the spacing error (m) of the i^{th} vehicle as:

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

with q_i and L_i representing vehicle i's rear-bumper position (m) and length (m), respectively.

The control objective is to regulate e_i to zero for all $i \in S_M$, while ensuring the string stability of the platoon. The following model is used to represent the vehicles' dynamics in the platoon

$$\begin{pmatrix} \dot{e_i} \\ \dot{v_i} \\ \dot{a_i} \end{pmatrix} = \begin{pmatrix} 0 & -1 & -h \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau_i} \end{pmatrix} \begin{pmatrix} e_i \\ v_i \\ a_i \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} v_{i-1} + \begin{pmatrix} 0 \\ 0 \\ \frac{\Lambda_i}{\tau_i} \end{pmatrix} u_i, \tag{2}$$

where a_i and u_i are respectively the acceleration (m/s^2) and control input (m/s^2) of the i^{th} vehicle. Moreover, τ_i represents each vehicle's unknown driveline time constant (s) and Λ_i represents the engine's performance loss due to time depicted as an unknown constant input attenuation. Model (2) was derived for the special case of $\Lambda_i = 1$ $\forall i \in S_M$ in Ploeg et al. (2014). Furthermore, the leading vehicle's model is defined as

$$\begin{pmatrix} \dot{e_0} \\ \dot{v_0} \\ \dot{a_0} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau_0} \end{pmatrix} \begin{pmatrix} e_0 \\ v_0 \\ a_0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \frac{1}{\tau_0} \end{pmatrix} u_0. \tag{3}$$

Note that, under the assumption of a homogeneous platoon with no vehicle input attenuation (perfect engine performance), we have $\tau_i = \tau_0$ and $\Lambda_i = 1$, $\forall i \in S_M$. In this work, we remove the homogeneous assumption by considering that $\forall i \in S_M$, τ_i can be represented as the sum of two terms

$$\tau_i = \tau_0 + \Delta\tau_i \tag{4}$$

where τ_0 is a known constant representing the driveline dynamics of the leading vehicle and $\Delta\tau_i$ is an unknown constant deviation of vehicle i's driveline dynamics from τ_0. In fact, $\Delta\tau_i$ acts as an unknown parametric uncertainty. In addition, we remove the perfect engine performance assumption by considering Λ_i as an unknown input uncertainty. Using (4) in the third equation of (2) we obtain the following

$$\begin{aligned} \tau_i \dot{a_i} &= -a_i + \Lambda_i u_i \\ \dot{a_i} &= -\frac{1}{\tau_0} a_i + \frac{1}{\tau_0} \Lambda_i^* [u_i + \Omega_i^* \phi_i] \end{aligned} \tag{5}$$

where $\Lambda_i^* = \frac{\Lambda_i \tau_0}{\tau_i}$, $\Omega_i^* = -\frac{\Delta\tau_i}{\Lambda_i \tau_0}$, and $\phi_i = -a_i$.

Using (5) in (2), the vehicle model in a heterogeneous platoon with engine performance loss under the spacing policy defined in (1) can be defined as the following uncertain linear-time invariant system $\forall i \in S_M$

$$\begin{pmatrix}\dot e_i\\ \dot v_i\\ \dot a_i\end{pmatrix} = \begin{pmatrix}0 & -1 & -h\\ 0 & 0 & 1\\ 0 & 0 & -\frac{1}{\tau_0}\end{pmatrix}\begin{pmatrix}e_i\\ v_i\\ a_i\end{pmatrix} + \begin{pmatrix}1\\0\\0\end{pmatrix} v_{i-1} + \begin{pmatrix}0\\0\\\frac{1}{\tau_0}\end{pmatrix}\Lambda_i^*[u_i + \Omega_i^*\phi_i]. \quad (6)$$

In order to control the behavior of each vehicle in the platoon into keeping a desired distance or time gap between itself and its proceeding vehicle, ACC only utilizes the feedback from on-board sensors. CACC is an extension of this strategy which utilizes, in addition to the information from on-board sensors, information received from the proceeding vehicle over a communication network to produce the desired control action. Moreover, one way of handling the unavoidable communication losses in practice is by switching between CACC and ACC depending on the network's state. This networked switched control system is outlined in Fig. 2. In this aim, an adaptive switched control method is presented for the heterogeneous scenario with unknown control input attenuation (engine performance losses) and inter-vehicle communication losses that incorporates both an augmented CACC and an augmented ACC strategies in order to cope with each vehicle's unknown parametric and input uncertainties Ω_i^* and Λ_i^* while guaranteeing the string stability based on a dwell time (DT) switching approach.

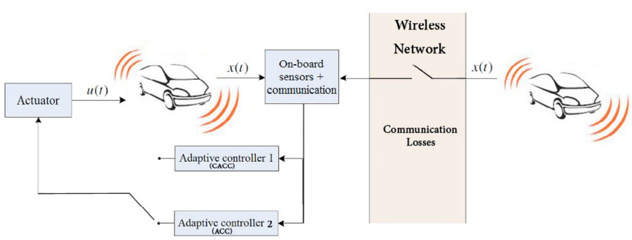

Fig. 2. Networked switched control system

3. STRING STABLE REFERENCE DYNAMICS

Communication losses are handled by switching from a CACC to an ACC strategy. By improving over previous work by the authors on heterogeneous platoons with ideal inter-vehicle communication (Abou Harfouch et al. (2017)), here the desired performance of the platoon is derived in terms of two reference models for the CACC and ACC respectively. Such reference models are based on string stability theory.

3.1 CACC reference model

Under the baseline conditions of identical vehicles, perfect engine performance, and no communication losses throughout the platoon, Ploeg et al. (2014) derived, using a CACC strategy, a controller which proved to guarantee the string stability of the platoon. The baseline controller is defined as

$$h\dot u_{bl,i}^C = -u_{bl,i}^C + \xi_{bl,i}^C \ , \ \ i \in \{0\} \cup S_M$$
$$\xi_{bl,i}^C = \begin{cases} K_p^C e_i + K_d^C \dot e_i + u_{bl,i-1}^C & \forall i \in S_m \\ u_r & i = 0 \end{cases} \quad (7)$$

where the superscript C indicates that communication is maintained throughout the platoon. Moreover, u_r is the platoon input representing the desired acceleration of the leading vehicle. The cooperative aspect of (7) resides in $u_{bl,i-1}^C$ which is received over the wireless communication between vehicle i and $i-1$.

Therefore, we can now define the reference model for (6) as system (6) with $\Omega_i^* = 0$, $\Lambda_i^* = 1$, and control input $u_i = u_{i,m} = u_{bl,i}^C$. The reference model can be therefore described by

$$\begin{pmatrix}\dot e_{i,m}\\ \dot v_{i,m}\\ \dot a_{i,m}\\ \dot u_{i,m}\end{pmatrix} = \underbrace{\begin{pmatrix}0 & -1 & -h & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & -\frac{1}{\tau_0} & \frac{1}{\tau_0}\\ \frac{K_p^C}{h} & -\frac{K_d^C}{h} & -K_d^C & -\frac{1}{h}\end{pmatrix}}_{A_m^C}\underbrace{\begin{pmatrix}e_{i,m}\\ v_{i,m}\\ a_{i,m}\\ u_{i,m}\end{pmatrix}}_{x_{i,m}} + \underbrace{\begin{pmatrix}1 & 0\\ 0 & 0\\ 0 & 0\\ \frac{K_d^C}{h} & \frac{1}{h}\end{pmatrix}}_{B_w^C}\underbrace{\begin{pmatrix}v_{i-1}\\ u_{bl,i-1}^C\end{pmatrix}}_{w_i}, \ \forall i \in S_M \quad (8)$$

where $x_{i,m}$ and w_i are vehicle i's reference state vector and exogenous input vector, respectively. Consequently, (8) is of the following form

$$\dot x_{i,m} = A_m^C x_{i,m} + B_w^C w_i, \ \forall i \in S_M \quad (9)$$

Furthermore, using (7), the leading vehicle's model becomes

$$\begin{pmatrix}\dot e_0\\ \dot v_0\\ \dot a_0\\ \dot u_{bl,0}^C\end{pmatrix} = \underbrace{\begin{pmatrix}0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & -\frac{1}{\tau_0} & \frac{1}{\tau_0}\\ 0 & 0 & 0 & -\frac{1}{h}\end{pmatrix}}_{A_r}\underbrace{\begin{pmatrix}e_0\\ v_0\\ a_0\\ u_{bl,0}^C\end{pmatrix}}_{x_0} + \underbrace{\begin{pmatrix}0\\0\\0\\\frac{1}{h}\end{pmatrix}}_{B_r} u_r. \quad (10)$$

Reference model (8) has been proven in Ploeg et al. (2014) to be asymptotically stable around the equilibrium point

$$x_{i,m,eq} = (0 \ \bar v_0 \ 0 \ 0)^T \ \text{ for } x_0 = x_{i,m,eq} \text{ and } u_r = 0 \quad (11)$$

where $\bar v_0$ is a constant velocity, provided that the following Routh-Hurwitz conditions are satisfied

$$h > 0, \ \ K_p^C, K_d^C > 0, \ \ K_d^C > \tau_0 K_p^C. \quad (12)$$

3.2 ACC reference model

When communication is lost between at least two vehicles in the platoon, the reference dynamics (9) fail to guarantee the string stability of the platoon. Consequently, a new reference model for the heterogeneous platoon with engine performance loss (6) is derived in this section through an ACC strategy.

In fact, since $u_{bl,i-1}^C$ is no longer present for measurement for at least one $i \in S_M$, we define a new baseline controller $\forall i \in S_M$ as follows

$$h\dot u_{bl,i}^L = -u_{bl,i}^L + \xi_{bl,i}^L \ , \ \ i \in \{0\} \cup S_M$$
$$\xi_{bl,i}^L = \begin{cases} K_p^L e_i + K_d^L \dot e_i & \forall i \in S_m \\ u_r & i = 0 \end{cases} \quad (13)$$

where the superscript L indicates that communication has been lost. Similar to the CACC case, the reference model is defined as system (6) with $\Omega_i^* = 0$, $\Lambda_i^* = 1$, and control input $u_i = u_{i,m} = u^L_{bl,i}$. Therefore, the reference model can be described by

$$\begin{pmatrix}\dot{e}_{i,m}\\ \dot{v}_{i,m}\\ \dot{a}_{i,m}\\ \dot{u}_{i,m}\end{pmatrix} = \underbrace{\begin{pmatrix}0 & -1 & -h & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & -\frac{1}{\tau_0} & \frac{1}{\tau_0}\\ \frac{K^L_p}{h} & -\frac{K^L_d}{h} & -K^L_d & -\frac{1}{h}\end{pmatrix}}_{A^L_m}\underbrace{\begin{pmatrix}e_{i,m}\\ v_{i,m}\\ a_{i,m}\\ u_{i,m}\end{pmatrix}}_{x_{i,m}} + \underbrace{\begin{pmatrix}1 & 0\\ 0 & 0\\ 0 & 0\\ \frac{K^L_d}{h} & 0\end{pmatrix}}_{B^L_w}\underbrace{\begin{pmatrix}v_{i-1}\\ u^C_{bl,i-1}\end{pmatrix}}_{w_i},\ \forall i \in S_M \tag{14}$$

which is of the form

$$\dot{x}_{i,m} = A^L_m x_{i,m} + B^L_w w_i,\ \forall i \in S_M. \tag{15}$$

The leading vehicle's model is the same as (10).

The asymptotic stability of the reference model (15) around equilibrium point (11) can be guaranteed by deriving conditions on K^L_p and K^L_d through the Routh-Hurwitz stability criteria. These conditions were found to be the same as (12). String stability of (15) can be additionally guaranteed by deriving sufficient conditions on the gains of controller (13) using a string stability definition provided in Liang and Peng (1999). The additional conditions are found to be:

$$\begin{aligned}\frac{2}{h^2} &\le K^L_p\\ \frac{\tau_0 + \sqrt{\tau_0^2 + 3h^2}}{h^2} &\le K^L_d \le \frac{\tau_0^2 + h^2}{2\tau_0 h},\end{aligned} \tag{16}$$

The derivation of conditions (16) is presented in the Appendix.

4. MAIN RESULT FOR PLATOONING WITH INTER-VEHICLE COMMUNICATION LOSSES

In this section, reference models (9) and (15) will be used to design the piecewise continuous control input $u_i(t)$ such that the uncertain platoon's dynamics described by (3) and (6) converge to string stable dynamics under communication losses.

With this scope in mind, we will augment a baseline controller controller with an adaptive term, using a similar architecture as proposed in Lavretsky and Wise (2013). To include the adaptive augmentation, the input $u_i(t)$ is split, $\forall i \in S_M$, into two different inputs:

$$u_i(t) = u_{bl,i}(t) + u_{ad,i}(t), \tag{17}$$

where $u_{bl,i}$ and $u_{ad,i}$ are the baseline controller and the adaptive augmentation controller (to be constructed), respectively. Moreover, we define

$$u_{bl,i}(t) = \begin{cases} u^C_{bl,i}, \text{ when communication is present}\\ u^L_{bl,i}, \text{ when communication is lost}\end{cases} \tag{18}$$

then using (17) in (3) and (6), we get the leading vehicle model

$$\dot{x}_0 = A_r x_0 + B_r u_r \tag{19}$$

where $x_0 = \begin{pmatrix}e_0 & v_0 & a_0 & u_{bl,0}\end{pmatrix}^T$, and the uncertain switched linear system vehicle model

$$\begin{aligned}\dot{x}_i(t) = A_{m,\sigma(t)}x_i(t) + B_{w,\sigma(t)}w_i(t) + B_u\Lambda^*_i\big[u_{ad,i}\\ + \Theta^{*T}_i\Phi_i(x_i, u_{bl,i})\big],\ \forall i \in S_M,\ \sigma(t) \in \mathcal{M} = \{1, 2\}\end{aligned} \tag{20}$$

where $\sigma(t)$ is the switching law (defined by the communication losses), $A_{m,p}$ and $B_{w,p}$ are known matrices, defined in (9) and (15), with $p \in \mathcal{M}$ representing the two subsystems in our system, and $B_u = \begin{pmatrix}0 & 0 & \frac{1}{\tau_0} & 0\end{pmatrix}^T$. In fact, subsystem $p = 1$ is activated by $\sigma(t)$ when communication is maintained throughout the platoon. On the other hand, subsystem $p = 2$ is activated by $\sigma(t)$ when communication is lost between at least two vehicles in the platoon. The uncertain ideal parameter vector is defined as $\Theta^*_i = \begin{pmatrix}K^*_{u,i} & \Omega^*_i\end{pmatrix}^T$, where $K^*_{u,i} = 1 - \Lambda^{*-1}_i$. The regressor vector is defined as $\Phi_i(x_i, u_{bl,i}) = \begin{pmatrix}u_{bl,i} & \phi_i\end{pmatrix}^T$. Therefore, the heterogeneous platoon with engine performance loss with (17) can be defined as the cascaded system (19)-(20).

Furthermore, define the group of reference models representing the desired behavior of each subsystem, $\forall i \in S_M$ and $\sigma(t) \in \mathcal{M}$, as

$$\dot{x}_{m,i}(t) = A_{m,\sigma(t)}x_{m,i}(t) + B_{w,\sigma(t)}w_i(t), \tag{21}$$

where $x_{m,i} = \begin{pmatrix}e_{m,i} & v_{m,i} & a_{m,i} & u_{bl,i}\end{pmatrix}^T$.

The adaptive control input is defined as

$$u_{ad,i}(t) = -\Theta^T_{i,\sigma(t)}\Phi_i(x_i, u_{bl,i}), \tag{22}$$

where $\Theta_{i,p}$ is the estimate of Θ^*_i. Moreover, the state tracking error is defined as

$$\tilde{x}_i = x_i - x_{m,i},\ \forall i \in S_M.$$

Replacing (22) in (20) and subtracting (21) we obtain, $\forall i \in S_M$ and $\sigma(t) \in \mathcal{M} = \{1, 2\}$, the following state tracking error dynamics

$$\dot{\tilde{x}}_i(t) = A_{m,\sigma(t)}\tilde{x}_i(t) - B_u\Lambda^*_i\tilde{\Theta}^T_i\Phi_i(x_i, u_{bl,i}) \tag{23}$$

where $\tilde{\Theta}_{i,p} = \Theta_{i,p} - \Theta^*_i$. Moreover, define (t_{p_l}, t_{p_l+1}) as subsystem p's switch-in and switch-out instant pair with $p \in \mathcal{M}$ and $l \in \mathbb{N}^+$.

Problem 1: Design the adaptive laws for (22) and the switching law $\sigma(t)$, without the knowledge of the vehicles' parametric and input uncertainties, such that (19)-(20) tracks the behavior of a string stable platoon under communication losses.

In fact, since $A_{m,p}$ is stable, there exist $P_p = P^T_p > 0$ and $Q_p = Q^T_p > 0$ of every subsystem $p \in \{1, 2\}$ such that

$$A^T_{m,p}P_p + P_pA_{m,p} + Q_p \le 0. \tag{24}$$

Define $\bar{\lambda}_p$ and $\underline{\lambda}_p$ as the maximum and minimum eigenvalue of P_p respectively. Moreover, define $\alpha = \max_{p\in\mathcal{M}}\{\bar{\lambda}_p\}$ and $\beta = \min_{p\in\mathcal{M}}\{\underline{\lambda}_p\}$. Furthermore, assume a known upper and lower bounds for Θ^* such that $\Theta^* \in [\underline{\Theta}, \bar{\Theta}]$.

Moreover, define the adaptive law for every $p \in \{1, 2\}$ and $S_p = S^T_p > 0$ as

$$\dot{\Theta}_{i,p}(t) = -S_pB^T_uP_p\tilde{x}_i(t)\Phi^T_i(x_i, u_{bl,i}) + F^T_{i,p}(t), \tag{25}$$

where $F_{i,p}(t)$ is a parameter projection term, defined in Sang and Tao (2012), that guarantees the boundedness of the estimated parameters in $[\underline{\Theta}, \bar{\Theta}]$.

Furthermore, we define the switching law $\sigma(t)$ based on a DT strategy as follows

$$t_1 - t_0 > T_1,\ k = 0$$
$$t_{k+1} - t_k \geq T_{DT} = \max\{T_0, T_d\},\ \forall k \geq 1, \tag{26}$$

where $\{t_k\}_{k=1}^{\infty}$ are $\sigma(t)$'s switching instants between the two subsystems, and T_0, T_1, and T_d are constants defined in Sang and Tao (2012).

Theorem 1. Consider the heterogeneous platoon model (6) with reference models (9) and (15) in the CACC and ACC mode respectively. Then, the adaptive input (22) with adaptive laws (25) makes the platoon GUUB stable, provided that the switching between CACC and ACC satisfies the DT (26). The following state tracking error upper bound is derived

$$\|\tilde{x}_i(t)\|^2 \leq (\frac{4}{\beta} - \frac{1}{\alpha})M,\ \forall t > t_0 + T_1,\ \forall i \in S_M,$$

where $M = \max_p \mathrm{tr}\big[(\bar{\Theta} - \underline{\Theta})S_p^{-1}(\bar{\Theta} - \underline{\Theta})^T\big]$.

Proof. See Sang and Tao (2012).

Remark 1. Since reference models (21) were chosen to provide the desired string stable dynamics of the platoon under both network conditions as shown in Sections 3.1 and 3.2, then the heterogeneous platoon with engine performance losses tracks, with a bounded tracking error, the behavior of a string stable platoon under communication losses. Please note that the bounds in Theorem 1 could be quite conservative, especially in the presence of large uncertainty, as shown in Section 5.

Remark 2. Finally, a more realistic networked communication model would consider average dwell time in place of dwell time. Dwell time has the appealing feature that asymptotic stability can be achieved also in the presence of large uncertainty (Yuan et al. (2017)). Extension to average dwell time will be the object of future work.

5. AN ILLUSTRATIVE EXAMPLE

To validate the switched controller (17), we simulate in SIMULINK a heterogeneous vehicle platoon with vehicles' engine performance loss of 3+1 vehicles (including vehicle 0) under communication losses. Table 1 presents the platoon's characteristics as well as the chosen time headway constant.

Table 1. Platoon parameters, M=3, h=0.9s

i	0	1	2	3
$\tau_i(s)$	0.1	0.4	0.25	0.3
Λ_i	-	0.6	0.75	0.7

The desired platoon acceleration $a_0(t)$ is shown in Fig. 3, and the baseline controllers' gains are chosen, for $h = 0.9$, as $K_p^C = 1.5$ and $K_d^C = 2$ for $u_{bl,i}^C$, and $K_p^L = 2.5$ and $K_d^L = 2$ for $u_{bl,i}^L$ in order to respect both string stability conditions (12) and (16).

Consequently, having the numerical values of $A_{m,1}$ and $A_{m,2}$ one can now calculate the conditions (26) on the switching signals which guarantees the overall stability of the switched system. We choose $Q_1 = Q_2 = 10^2 I$ to solve the linear matrix inequalities (24). As a result, we have $\bar{\lambda}_1 = 31.09$, $\underline{\lambda}_1 = 3.90$, $\bar{\lambda}_2 = 31.41$, and $\underline{\lambda}_2 = 3.75$. Therefore, $\alpha = 31.41$ and $\beta = 3.90$ and consequently the DT characteristics are found to be $T_1 = T_{DT} = 6.67s$.

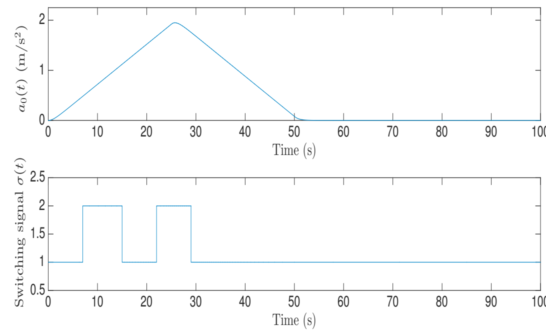

Fig. 3. Top: Desired platoon acceleration $a_0(t)$; Bottom: Switching signal $\sigma(t)$

In addition, the adaptive gain matrices are set to $S_1 = S_2 = 10^2 I$. The state tracking upper bound was found to be $\|\tilde{x}_i(t)\|^2 \leq 1.84$, or $\|\tilde{x}_i(t)\| \leq 1.35$.

Furthermore, the platoon undergoes communication losses modeled as a switching signal $\sigma(t)$, shown in Fig. 3, with DT characteristics T_1 and T_{DT}.

Simulating the platoon with vehicle control input (17) $\forall i \in S_3$, Fig. 4 shows the state tracking error $\|\tilde{x}_i(t)\|$ of vehicles 1, 2, and 3. In fact it is clear that $\|\tilde{x}_i(t)\|$ is bounded and less than 1.35.

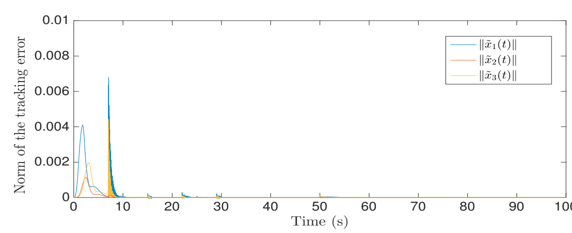

Fig. 4. Norm of the state tracking error of vehicles 1-3: $\|\tilde{x}_i(t)\|$, $i \in S_3$

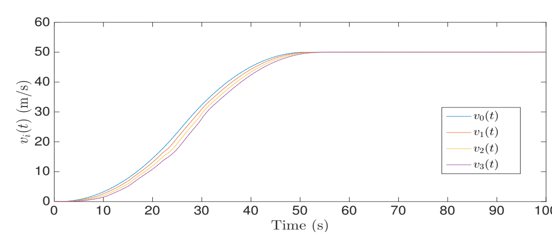

Fig. 5. Velocity response of vehicles 0-3 $v_i(t)$, $i \in \{0, S_3\}$

Fig. 5 shows each vehicle's velocity as a response to the desired acceleration $a_0(t)$. String stability is clearly maintained throughout the heterogeneous platoon and all velocities reach a common equilibrium velocity of 50 m/s.

6. CONCLUSION

A novel switched control strategy to stabilize a platoon with non-identical vehicle dynamics, engine performance losses, and communication losses was considered. The proposed control scheme comprises a switched baseline controller (string stable under the homogeneous platoon with perfect engine performance assumption) augmented with a switched adaptive term (to compensate for heterogeneous dynamics and engine performance losses). The derivation of the string stable reference models and augmented switched controllers were provided and their stability and string stability properties were analytically studied. When the switching respects a required dwell time, the closed-loop switched system is stable and signal boundedness is guaranteed. Numerical results demonstrated the string stability of the heterogeneous platoon with engine performance losses under the designed control strategy. Future works will aim at enhancing the heterogeneous control strategy's robustness to unmodelled dynamics (Ioannou and Baldi (2010)) and considering switching communication topologies using robust switching control techniques (Baldi et al. (2012)).

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Appendix A. ACC STRING STABILITY CONDITIONS

The authors in Liang and Peng (1999) provide the following string stability condition:

$$|\frac{R_i(jw)}{R_{i-1}(jw)}| \leq 1, \ \forall w \geq 0 \tag{A.1}$$

where $R_i(s) = q_{i-1}(s) - q_i(s)$, and $q_i(s)$ is the Laplace transform of vehicle i's position $q_i(t)$. Using this definition on system (14), R_i is found to be:

$$R_i(s) = \frac{K_p^L + K_d^L s}{s^2(\tau_0 s + 1)(hs + 1)}[R_{i-1} - R_i - hsR_i] \tag{A.2}$$

Rearranging (A.2) leads to

$$\frac{R_i(s)}{R_{i-1}(s)} = \frac{K_p^L + K_d^L s}{\tau_0 h s^4 + (\tau_0 + h)s^3 + (1 + hK_d^L)s^2 + (hK_p^L + K_d^L)s + K_p^L}$$

Using definition (A.1), sufficient conditions on $\{K_p^L, K_d^L\}$ for the string stability of the reference model (15) in the ACC scenario are found to be conditions (16).