

# Robust Model Predictive Cooperative Adaptive Cruise Control Subject to V2V Impairments

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**Abstract**—To improve traffic throughput, Cooperative Adaptive Cruise Control (CACC) has been proposed as a solution. The usage of Vehicle-to-Vehicle (V2V) communication enables short following distances, thereby increasing road capacity and fuel reduction (especially for trucks). Control designs for CACC use the wirelessly communicated intended acceleration of a preceding vehicle as a feedforward action in a following vehicle. This feedforward action may determine approximately 80% of the total control action. In case of a communication failure, this feedforward is no longer available, and a larger time gap is needed to ensure high performance and robustness in terms of stability and safety. However, such a larger time gap is not instantly realizable. Therefore, a CACC design is needed which is robust against intermittent communication failures. This paper proposes to share model-based predictions of the intended acceleration via V2V communication, which are stored in a buffer of the following vehicle. This buffer is used in case a packet dropout occurs. Further, since the communication frequency is lower than the frequency of the control-platform, this buffer is also used to virtually upgrade the communication frequency. The design has been tested in experimental vehicles and shows an increased control performance, also in periods of packet dropouts.

**Index Terms**—Model Predictive Control, Cooperative Adaptive Cruise Control, Vehicle-to-vehicle communication, Packet loss

## I. INTRODUCTION

Cooperative Adaptive Cruise Control (CACC) is a promising application to increase road capacity, reduce fuel consumption, and increase safety [1], [2]. The usage of wireless vehicle-to-vehicle (V2V) communication enables short following distances, which, especially for trucks, results in the fuel consumption reduction [3], [4]. CACC aims to realize a desired inter-vehicle distance. The wireless link is used to share the intended acceleration, which may be used as a feedforward action in the CACC control design [5], [6], [7]. The total control action in terms of intended acceleration is heavily dependent on the feedforward signal, especially during transient behavior, as shown in Fig. 1. Here, measurement data of a PD-based CACC controller (as described in [5]) is analyzed. For a significant total control action  $u_i$  ( $|u_i| > 0.5 \text{ m/s}^2$ ), approximately 80% of the total control action is determined by the feedforward signal. This clearly shows the importance of reliably receiving a V2V message for CACC. Furthermore, packet losses lead directly to an unsafe situation, since the

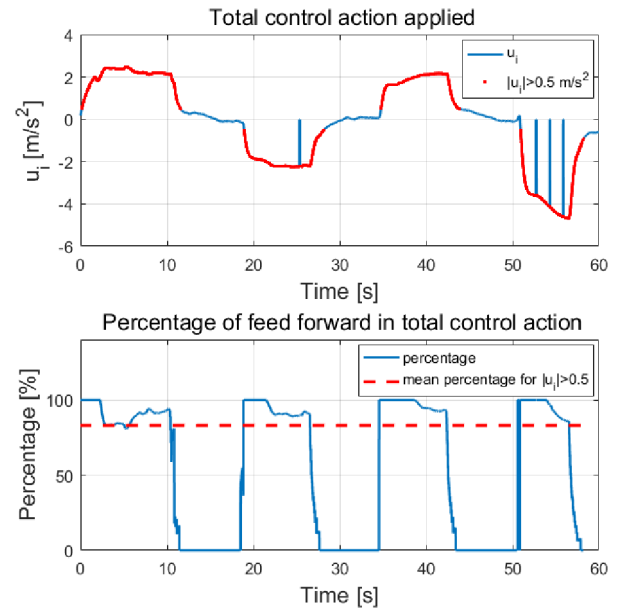


Fig. 1. Percentage of feedforward action in a CACC (with the feed back based upon a PD controller, [5]) with respect to total control action  $u_i$ . Only the significant total control action, ( $|u_i| > 0.5 \text{ m/s}^2$ ), marked in red, is used to determine the mean percentage of 80 %.

safe time gap when no V2V exists (i.e. ACC) is much higher ( $> 1 \text{ s}$ ) than the safe time gap when V2V is used (0.3 s), as analyzed in [8] and [9].

Several studies have shown that, especially with an increasing number of communicating nodes, the probability of packet losses increases, [10], [11], [12]. In order to overcome these scalability challenges, several solutions are proposed in the literature. For instance, [13] provides a solution at the level of the wireless communication protocol, where a lost packet is retransmitted. However, this leads to higher communication delays, which adversely influences the string stability aspects of the vehicle string [14].

[15] discusses the fact that general purpose network platforms were not originally designed for applications with critical timing requirements. To overcome the inherent packet dropouts and delays, it is proposed to sent packets containing

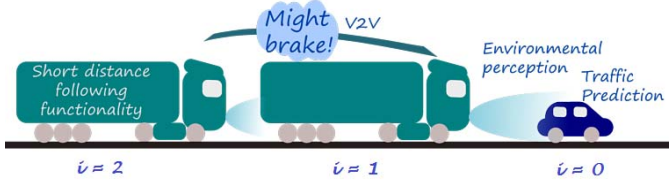


Fig. 2. Sharing look-ahead to allow for robust CACC with short inter-vehicle distances. The acceleration behavior of a preceding mixed-traffic participant may also be predicted, as proposed in [16].

optimizing sequences of control inputs over an unreliable communication network affected by data-loss. Scalability issues will also result in higher communication delays. To reduce the negative effect of communication delay, a switched control method for CACC was proposed in [17]. This approach requires a frequent alternation between throttle and brake, which will increase the fuel consumption. Others propose a dynamic spacing policy in case of packet loss [8]. However, during the transition towards a larger spacing policy, there is still a risk of a collision in case of a braking action of the preceding vehicle.

Hence, a CACC controller with a high control performance, also during short periods of packet loss is needed. In this paper, we propose a novel approach for increasing the robustness and performance of a CACC control system, in the presence of short periods of packet losses, by sharing look-ahead information: the future intended acceleration over a prediction horizon, see Fig. 2. The importance of prediction is also emphasized in [18]. The intended acceleration over a prediction horizon is inherently determined by the Model Predictive Control (MPC), which may be shared via V2V.

For the design of ACC or CACC systems, including collision avoidance constraints, several Model Predictive Control approaches can be found in literature, see [19], [20], [21], [22]. [23] aims at equal velocities between the vehicles, while the focus of [24], [25] and [26] is on fuel reduction. Also the constraints used to formulate the MPC vary among different works. In [23], string stability is enforced in the MPC problem formulation, using the string stability definition of [27].

The proposed control method in this work is also based on MPC, for which the objective is to minimize the control errors over a prediction horizon, given certain constraints. The intended acceleration over a prediction horizon is determined by a Model Predictive Controller (MPC), which can then be shared via V2V. We note that none of the above mentioned approaches in the literature use the sharing of predicted intended accelerations via V2V as a means to increase robustness and performance of CACC against packet losses.

The main contributions of this paper are the design of a buffer and its application in the prediction of the disturbance and the estimation of the feedforward for CACC. Further, simulation and experimental results show that this design improves the control performance in situations with short communication losses, and also allows for a virtual upgrade of the communication frequency, thereby increasing the control

performance even further.

This paper is organised as follows. Sections II and III introduce the model and problem statement, respectively. Sections IV and V describe the MPC controller design and the buffer design, which is used to store the predictions as communicated by V2V. Simulation and experimental results with this design are presented in Sections VI and VII. Finally, the conclusions and recommendations for future work are described in Section VIII.

## II. SYSTEM MODEL

Consider a vehicle platoon of length  $N$ . The position, velocity and acceleration at time  $t$  of each vehicle  $i$ , with  $i \in P_N$  and  $P_N = \{i \in \mathbb{N} \mid 0 \leq i \leq N\}$ , are denoted by respectively  $p_i(t)$ ,  $v_i(t)$ , and  $a_i(t)$ . Here  $p_i$  represents the one-dimensional position of the center of the front bumper of vehicle  $i$ . It is assumed that  $p_i(t) < p_{i-1}(t)$  for all  $i \in \{1, 2, \dots, N\}$ . Vehicle  $i$  aims to maintain a desired inter-vehicle distance  $d_{r,i}$  between vehicle  $i$  and vehicle  $i-1$ , given by

$$d_{r,i}(t) = r_i + h_i v_i(t) \quad (1)$$

with  $r_i$  a constant standstill distance for vehicle  $i$  and  $h_i$  the desired time gap of vehicle  $i$ . The actual distance  $d_i$  satisfies

$$d_i(t) = p_{i-1}(t) - p_i(t) - L_{i-1} \quad (2)$$

with  $L_i$  the length of vehicle  $i$ .

The first following vehicle ( $i = 1$ ) drives with Adaptive Cruise Control, following a preceding mixed-traffic participant ( $i = 0$ ) with a certain desired distance,  $d_{r,1}$ . Typically, this desired distance  $d_{r,1}$  is chosen larger than  $d_{r,i}$  with  $i \geq 2$  due to safety reasons (since the preceding mixed-traffic participant does not communicate intentions). The control error  $e_i(t)$  is defined as in [5]:

$$e_i(t) = d_i(t) - d_{r,i}(t). \quad (3)$$

The vehicle model is described by

$$\dot{a}_i(t) = -\frac{1}{\tau_i} a_i(t) + \frac{1}{\tau_i} u_i(t - \phi_i), \quad (4)$$

with  $\tau_i = \tau$  a time constant representing driveline dynamics,  $\phi_i = \phi$  the actuator delay, and  $u_i$  the intended acceleration, i.e. the input to the driveline. A homogeneous string of vehicles is assumed:  $\tau_i = \tau_{i-1} = \tau$  and  $\phi_i = \phi_{i-1}$ , for all  $i \geq 2$ . Since  $u_{i-1}$  is communicated to vehicle  $i$ , the communication delay (which is assumed to equal the process delay due to the digital implementation of the communication unit)  $\theta$  needs to be included in the vehicle model of  $i-1$ :

$$\dot{a}_{i-1}(t) = -\frac{1}{\tau} a_{i-1}(t) + \frac{1}{\tau} u_{i-1}(t - \theta - \phi), \quad (5)$$

Define the state vector

$$x_i(t) = [e_i(t) \ \dot{e}_i(t) \ \ddot{e}_i(t) \ u_i(t - \phi)]^T. \quad (6)$$

Now, the third derivative of  $e_i$  can be expressed as

$$\ddot{\ddot{e}}_i = -\frac{1}{\tau} \ddot{e}_i(t) - \frac{1}{\tau} (u_i(t - \phi) + h_i \dot{u}_i(t - \phi_i)) + \frac{1}{\tau} u_{i-1}(t - \theta - \phi).$$

Furthermore, by defining  $q_i(t - \phi)$  as

$$q_i(t - \phi) := u_i(t - \phi) + h_i \dot{u}_i(t - \phi), \quad (7)$$

the derivative of  $u_i(t - \phi)$  can be expressed as

$$\dot{u}_i(t - \phi) = \frac{1}{h_i} q_i(t - \phi) - \frac{1}{h_i} u_i(t - \phi). \quad (8)$$

Now the state-space representation of the closed-loop system is given by

$$\begin{aligned} \dot{x}_i(t) &= Ax_i(t) + B_1 q_i(t - \phi) + B_2 u_{i-1}(t - \theta - \phi), \\ y_i(t) &= Cx_i(t) \end{aligned} \quad (9)$$

with  $\theta$  the communication and process delay, and

$$A = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{1}{\tau} & 0 \\ 0 & 0 & 0 & -\frac{1}{h_i} \end{pmatrix}, \quad (10)$$

$$B_1 = \begin{pmatrix} 0 \\ 0 \\ -\frac{1}{\tau} \\ \frac{1}{h_i} \end{pmatrix} \quad \text{and} \quad B_2 = \begin{pmatrix} 0 \\ 0 \\ \frac{1}{\tau} \\ 0 \end{pmatrix},$$

with measured outputs  $y = [e_i(t) \ \dot{e}_i(t)]^T$  and

$$C = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}. \quad (11)$$

The outputs are based on measurements with a radar (for  $d_i$  and  $\dot{d}_i$ ), wheel encoders (for  $v_i$ ) and an accelerometer (for  $a_i$ ).

### III. PROBLEM DEFINITION

CACC is highly dependent on the intended acceleration  $u_{i-1}$ , which is sent over the network and is hence subject to packet loss. In this section, the control problem for designing a robust-CACC for V2V failure is introduced. The controller objective is to minimize the control errors  $e_i$ , as defined in (3), and its derivative  $\dot{e}_i$ , in the presence of packet loss, where we assume that packet loss never occurs for periods longer than  $\Delta T$  seconds. Furthermore, where possible, the controller should aim at comfort and reducing fuel consumption, i.e. the feedback control rate should be minimized. Safety should be realized by ensuring a positive distance between the vehicles over a certain prediction horizon of length  $\Delta T$ :  $d_i(\bar{t}) > 0$ , with  $\bar{t} \in [t, t + \Delta T]$ .

### IV. CONTROLLER DESIGN

We propose the following control law for  $q_i$ :

$$q_i(t - \phi) = u_{i-1}(t - \theta - \phi) + u_i^{MPC}(t - \phi), \quad (12)$$

which contains a (delayed) feedforward part ( $u_{i-1}(t - \theta - \phi)$ ) and an MPC-based feedback part  $u_i^{MPC}(t - \phi)$ . Substituting this control law in (7) and shifting time over  $\phi$ , yields

$$\dot{u}_i(t) = \frac{1}{h_i} (u_{i-1}(t - \theta) + u_i^{MPC}(t) - u_i(t)), \quad (13)$$

which leads to the following closed-loop dynamics, including the actuator delay and communication delay  $\theta$ :

$$\dot{x}_i(t) = Ax_i(t) + B_1 u_i^{MPC}(t - \phi) + B_3 u_{i-1}(t - \theta - \phi). \quad (14)$$

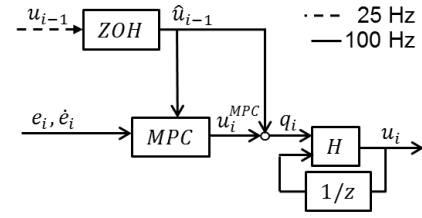


Fig. 3. The block scheme of the MPC controller of vehicle  $i$ . The intended acceleration of vehicle  $i - 1$  is received at a communication frequency of 25 Hz. The platform of the controller runs at 100 Hz.

with  $A$  and  $B_1$  defined above and

$$B_3 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{h_i} \end{pmatrix}. \quad (15)$$

Next, the continuous-time model formulation is discretized to support (the implementation of) the MPC-based controller design. Hereto, we denote discretized time by  $k$ , where  $t = k\Delta t$ , with  $\Delta t$  the sampling interval. Furthermore, the wireless communication frequency is often designed to be lower than the sampling frequency ( $1/\Delta t$ ) for the digital implementation of the controller. To resolve this, a zero-order hold (denoted by ZOH) is commonly applied. The blockscheme of the MPC controller is presented in Fig. 3. Discretization of (8) results in the following plant input at time  $k + 1$ :

$$u_i[k + 1] = \frac{\Delta t}{h_i} q_i[k] + (1 - \frac{\Delta t}{h_i}) u_i[k], \quad (16)$$

with the discretization of (12) shifted over time  $\phi$ :

$$q_i[k] = u_{i-1}[k - \theta_d] + u_i^{MPC}[k] \quad (17)$$

and  $\theta_d = \frac{\theta}{\Delta t}$ , with the assumption that  $\theta_d \in \mathbb{N}_0^+$ . In Fig. 3, this relation described in (16) is denoted with  $H : \mathbb{R}^2 \rightarrow \mathbb{R}$ ,  $u_i[k + 1] = H(q_i[k], u_i[k])$ . The approximated intended acceleration of the preceding vehicle, denoted by  $\hat{u}_{i-1}$ , will be used as an expected disturbance and as a feedforward action in a following vehicle.

To ensure the desired functionality, several constraints are introduced. The first constraint is to ensure a positive distance:

$$\begin{aligned} \forall \bar{k} \in [1, N_p] \text{ and } \forall v_i[k + \bar{k}] > 0 \quad : \\ -e_i[k + \bar{k}] &< r_i \\ \Rightarrow e_i[k + \bar{k}] + (h_i v_i[k + \bar{k}] + r_i) &> 0 \\ \Rightarrow d_i[k + \bar{k}] &> 0 \end{aligned} \quad (18)$$

with  $N_p$  the receding prediction horizon. The second constraint relates to the physical limitations of the acceleration actuator:  $a_{i,min} \leq u_i \leq a_{i,max}$ , with  $a_{i,min}$  the minimum acceleration of vehicle  $i$ ,  $a_{i,max}$  its maximum acceleration.

Based upon the problem definition, the MPC cost function is designed as follows, for  $\bar{k} \in 1, 2, \dots, N_p$ :

$$\begin{aligned} \min_{u_i^{MPC}[k+\bar{k}] \in U} & \sum_{k=1}^{N_p} (y_i[k+\bar{k}]^T Q y_i[k+\bar{k}] + \\ & u_i^{MPC}[k+\bar{k}]^T R u_i^{MPC}[k+\bar{k}] + \\ & \Delta u_i^{MPC}[k+\bar{k}]^T R_{\Delta u} \Delta u_i^{MPC}[k+\bar{k}]) \end{aligned}$$

subject to (14) and the constraints

$$\begin{aligned} e_i[k+\bar{k}] &> -r \\ a_{i,min} &\leq u_i[k+\bar{k}] \leq a_{i,max} \end{aligned}$$

with  $\Delta u_i^{MPC}[k] = u_i^{MPC}[k] - u_i^{MPC}[k-1]$ ,  $u_i^{MPC}[0] = 0$  and  $U = \{u \in \mathbb{R}\}$  and with weighting parameters:  $Q = \begin{pmatrix} q_1 & 0 \\ 0 & q_2 \end{pmatrix}$ ,  $R$  and  $R_{\Delta u}$ . The weighting parameters are tuned to avoid overshoot and to ensure a short settling time.

Remark: internal stability is not obviously realized by the cost function (since the full state is not represented in the cost function). However, internal stability is expected due to the following argument. The cost function minimizes  $e_i$ ,  $\dot{e}_i$  and  $u_i^{MPC}$ . If  $e_i$  and  $\dot{e}_i$  are bounded, then  $\ddot{e}_i$  is bounded as well. Further, if  $u_i^{MPC}$  (due to its inclusion in the cost function) and  $u_{i-1}$  is bounded, from (13) it follows that  $u_i$  is bounded as well.

The optimization problem is numerically solved via implementation in MATLAB, [28], which is based upon a specialized model predictive control quadratic programming (QP) solver, optimized for speed, efficiency, and robustness.

In case of packet loss one has to decide how to compute a suitable control action  $u_i$  given the fact that  $u_{i-1}$  is not available. The simplest design is to set the intended acceleration zero in case of packet loss. Alternatively, the acceleration of the preceding vehicle can be estimated (denoted by  $\hat{a}_{i-1}$ ) and applied as feedforward signal:  $\hat{u}_{i-1} = \hat{a}_{i-1}$ . In [29], a Singer model is described to estimate  $\hat{a}_{i-1}$ , based on-board sensor measurements (radar and accelerometer). Another possible solution to overcome packet loss for durations up to  $\Delta T$  seconds (or  $N_p$  sampling intervals) is described in the next section and is based on the MPC design in this section.

## V. BUFFER DESIGN

In the buffer design presented in this section, it is assumed that every vehicle in the platoon communicates a vector of predicted intended accelerations (based on MPC) to its following vehicle. The first objective of the buffer is to mitigate the effects of packet loss. Secondly, to further improve the control performance, this buffer is also used to compensate for the difference in communication frequency and the platform frequency at which the controller runs.

The output of the MPC controller at time  $k$  can be extended to a vector of length  $N_p$ , including the future predictions of the intended acceleration. The future prediction, at time  $k$ , of the control command at time  $k+j$  is represented by  $u_i^{MPC}[k+j|k]$ . The vector including all future predictions

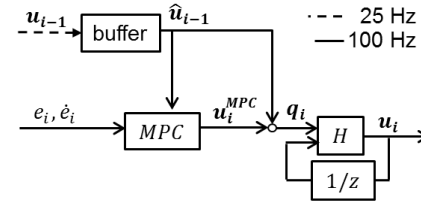


Fig. 4. A buffer is implemented in the control design to determine the feedforward and the expected system disturbance at the frequency of the control platform.

TABLE I  
SETTINGS USED FOR SIMULATION RESULTS.

Parameter	value	Parameter	value
$\tau$	0.1 s	$N_p$	30
$\phi_1 = \phi_2$	0.2 s	$\Delta t$	0.01 s
$a_{min}$	-6 m/s <sup>2</sup>	$q_1$	0.4
$a_{max}$	3 m/s <sup>2</sup>	$q_2$	0.125
$\theta$	0.02 s	$R$	0.01
$h_1 = h_2$	0.3 s	$R_{\Delta u}$	0.005
$r_1 = r_2$	7.5 m		

will be denoted in bold as  $\mathbf{u}_i^{MPC}[k] = [u_i^{MPC}[k|k] \ u_i^{MPC}[k+1|k] \dots u_i^{MPC}[k+N_p-1|k]]^T$ . Maintaining a similar notation, the plant input-vector at time  $k+1$ ,  $\mathbf{u}_i[k+1]$  can be written as  $\mathbf{u}_i[k+1] = H(\mathbf{q}_i[k], \mathbf{u}_i[k])$ , with  $H$  as described in (16) updated towards  $H: \mathbb{R}^{N_p^2} \rightarrow \mathbb{R}^{N_p}$ . Here it is assumed that vehicle  $i-1$  has the same control design and communicates  $\mathbf{u}_{i-1}[k]$ . This vector can also be used in the MPC as a prediction on the disturbance and as a feedforward action, as shown in Fig. 4. Let us define index  $j \in \mathbb{N}_0^+$ , which counts the number of time samples since the last wireless message on the feedforward was received. Then, the output of the buffer is given by:

$$\hat{\mathbf{u}}_{i-1}[k] = \begin{cases} \begin{bmatrix} \mathbf{u}_{i-1}[k+j, \dots, k+N_p-1|k] \\ \mathbf{u}_{i-1}[k+N_p-1|k] \mathbf{J}_{j-1,1} \end{bmatrix} & \text{for } j < N_p \\ \hat{a}_{i-1}[k] \mathbf{J}_{N_p,1} & \text{for } j \geq N_p \end{cases} \quad (19)$$

with  $\mathbf{J}_{j-1,1}$  a vector of ones of length  $j-1$  and  $\hat{a}_{i-1}$  will be used after the prediction time has passed and still no new message is received. The first element of the intended acceleration vector  $\mathbf{u}_k^i(1)$  is applied as the plant input. In this way, if packet loss occurs, the MPC control commands computed at earlier times for vehicle  $i-1$  are used as feedforward for vehicle  $i$ . The rationale behind this design is that these predicted control commands will provide better performance than using the last received control commands, which may be outdated due to the occurrence of packet loss.

## VI. SIMULATION RESULTS

To demonstrate the performance of the proposed MPC and the buffer design, a simulation study is performed. In the simulation scenario, two vehicles are driving in a platoon at a constant velocity of 80 km/h, at the desired distance with a time gap of  $h_i = 0.3$  s. At  $t = 10$  s, the lead vehicle decelerates during 1 second with  $u_1 = -3$  m/s<sup>2</sup>. For these

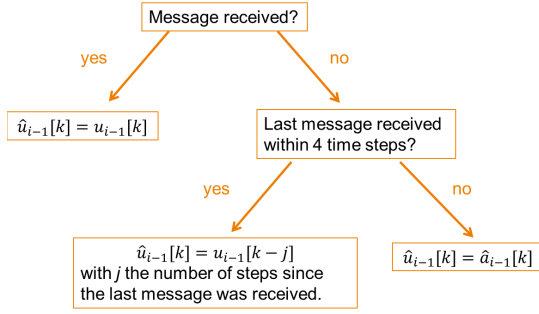


Fig. 5. The procedure to estimate  $\hat{u}_{i-1}$  for the MPC without buffer, based on the acceleration estimation proposed in [29].

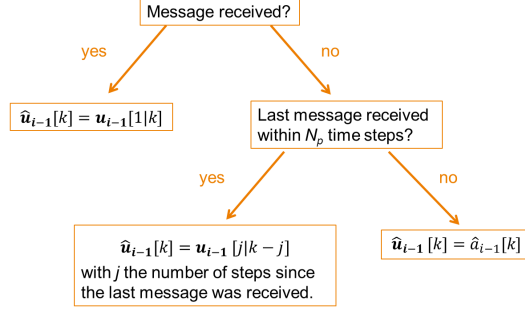


Fig. 6. The procedure to estimate  $\hat{u}_{i-1}^{i-1}(1)$  for the MPC with buffer.

short inter-vehicle distances, which amplify the aerodynamic benefits, a communication frequency of 25 Hz is needed to allow for string stability, [14]. Therefore, the communication frequency is chosen to equal 25 Hz, as also proposed by [5] and applied in the European i-Game project [30]. The controller runs at 100 Hz. So, the control platform expects to receive a communicated message every 4 samples as the expected communication delay equals  $\mathbb{E}(\theta) = \frac{1}{2}0.04 \text{ s} = 0.02 \text{ s}$ . Now three different feedforward designs are applied to estimate  $\hat{u}_{i-1}$  for the MPC design presented in Section IV:

- 1) The procedure for the estimation of  $u_{i-1}$  based on a ZOH (presented in Fig. 5) and, in case of packet loss, **no feedforward** is applied:  $\hat{a}_{i-1} = 0$ .
- 2) Also in this second feedforward design, a ZOH (presented in Fig. 5) is applied, but in case of packet loss a perfect acceleration **estimation** is assumed:  $\hat{a}_{i-1} = a_{i-1}$ .
- 3) The third feedforward design is based on the **buffer** design, as presented in (19). This procedure is also summarized in Fig. 6.

Two use cases are simulated: in the first use case packet loss occurs at  $t = 10.2$  for a period of 0.24 s, while at the second scenario no communication failure occurs. The system and control parameters used in this simulation study are depicted in Table I.

#### A. Use case 1: packet loss

This use case shows the added value of the buffer for a short period of packet loss. In total 6 packets are lost, which corresponds to a time duration of 0.24 s.

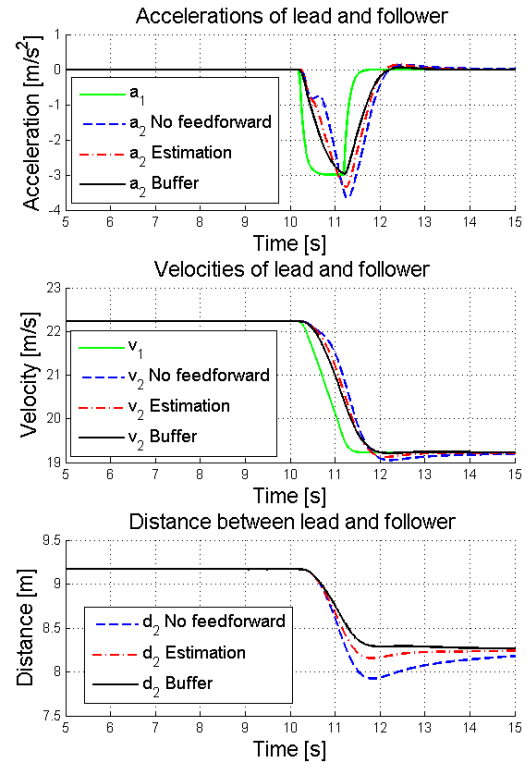


Fig. 7. Acceleration (upper plot), velocity profiles (center plot) and inter-vehicle distance (lower plot) based on the three feedforward designs for use case 1.

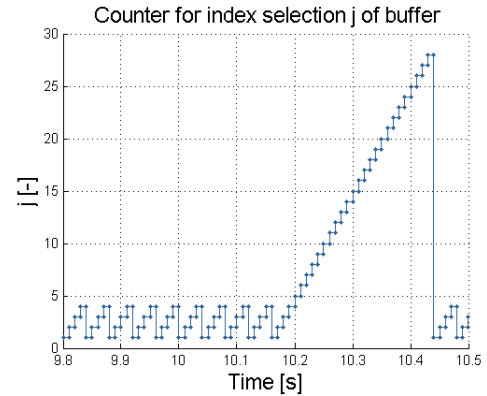


Fig. 8. Index  $j$  which counts the time steps since the last received packet for use case 1.

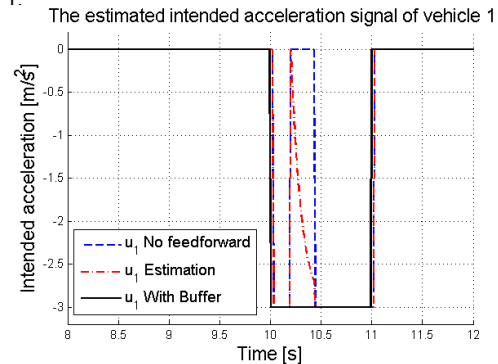


Fig. 9. Estimated intended acceleration of  $u_1$  for all three feedforward designs applied to use case 1.

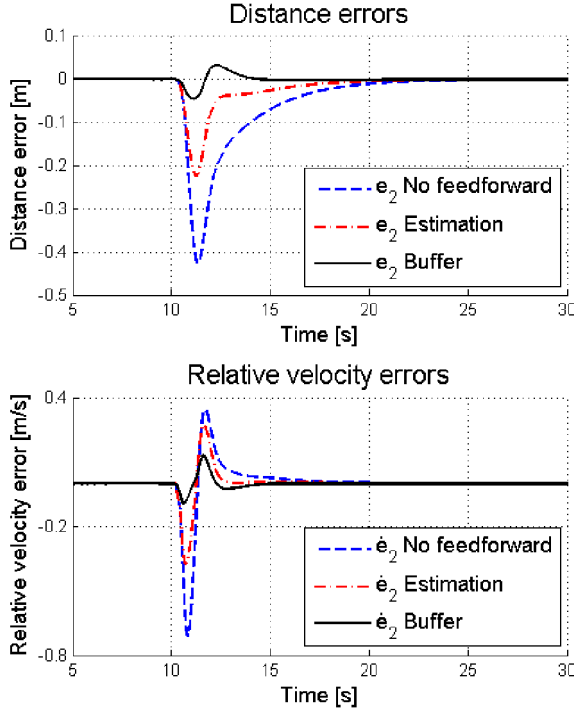


Fig. 10. Control errors for all three feedforward designs for use case 1.

The acceleration and velocity profiles are shown in Fig. 7. The index  $j$ , which counts the time steps since the last received packet, for the case where a buffer is used, is visualized in Fig. 8. The estimated feedforward signals for all three feedforward designs are shown in Fig. 9. The intended acceleration  $\hat{u}_1$  as estimated by the buffer design follows the step to  $-3 \text{ m/s}^2$  during  $t = 10 \text{ s}$  to  $t = 11 \text{ s}$  perfectly. The other two feedforward designs estimate a higher intended acceleration, which could lead to a overshoot in inter-vehicle distance (as shown in the lower plot in Fig. 7). In Fig. 10 the control errors ( $e_i$  and  $\dot{e}_i$ ) of the following vehicle ( $i = 2$ ) are displayed for all three feedforward designs. The usage of the buffer significantly reduces the control errors during time intervals of V2V failure. Especially the negative part of the distance error, which is most dangerous since then the realized distance is closer than the desired distance, is significantly decreased by the buffer design.

#### B. Use case 2: no packet loss

This use case shows the benefits of the buffer above the zero-order hold, even in the case that no packet loss occurs. The communication frequency is chosen to be 25 Hz, while the controller runs at 100 Hz. Thus, every 0.04 s vehicle  $i$  expects to receive  $\mathbf{u}_k^{i-1}$ . The buffer virtually upgrades the communication frequency to 100 Hz. Fig. 11 shows the control errors for the estimation based on a zero-order hold and the buffer. Compared to a ZOH, the buffer design reduces the control errors significantly.

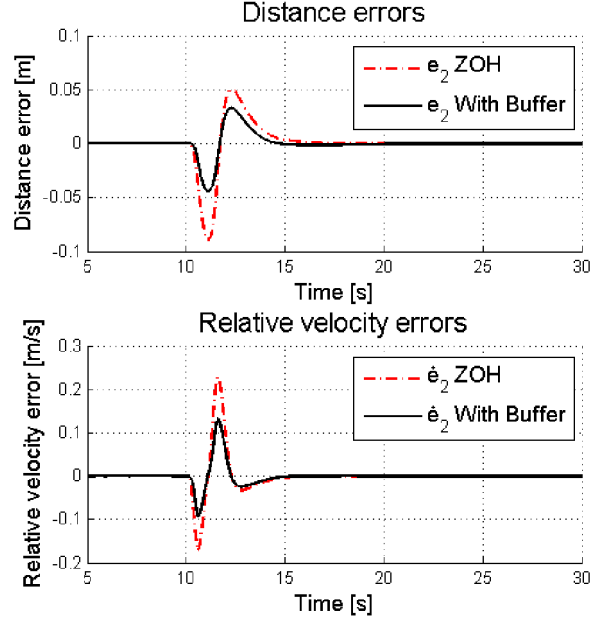


Fig. 11. Control errors for use case 2, with ZOH and buffer design, without any packet loss.

## VII. EXPERIMENTAL RESULTS

The goal of the experimental tests is to evaluate the robustness and performance of the MPC (and buffer) design against packet losses. The control performance is evaluated by the variance of the control error and the minimum control errors (i.e. the most negative errors, since these are most hazardous). The proposed control design including communication of the buffer is implemented at a TOYOTA Prius test-vehicle, which is further described in [5]. The communication message content is updated such that the MPC-based predictions can be shared over the wireless link, as presented in the following section.

#### A. V2V messages

The V2V communication used for the experimental setup is based on the 802.11p protocol. A 'CAM like message is used with a single-hop broadcast at 25 Hz. Furthermore, (dynamic) fields for robustness are added, based on basic, low-frequency, high-frequency and optional containers. Since  $\mathbf{u}_k^i$  and its accuracy need to be communicated, the message size increases linearly with the prediction horizon length. An increased message size may lead to a higher probability of packet loss, as shown in [11], [12]. In order to evaluate the risk of packet losses, the total message size  $M_{total}$  (in bytes) is determined as function of the prediction horizon length as:  $M_{total} = 52.5 + 2.25N_p$ . The expected maximum message size for which the probability of packet loss is still acceptable for  $M_{total}$  of around 500B, [12]. It can be concluded that, although the message size increases by adding a prediction horizon, the probability of a packet loss is still at an acceptable level, even up to predictions of length  $N_p = 200$ .



TABLE II  
PERFORMANCE OF THE IMPLEMENTED CONTROLLERS.

	MPC without buffer	MPC with buffer
$\text{var}(e_2)$ [ $m^2$ ]	0.1391	0.0212
$\text{var}(\dot{e}_2)$ [ $m^2/s^2$ ]	0.0268	0.0109
$\min(e_2)$ [m]	-0.87	-0.22
$\min(\dot{e}_2)$ [m/s]	-0.81	-0.56

### B. Vehicle test setup

To enable the comparison for the evaluation of robustness and performance the proposed MPC controller is implemented for two cases: with and without the usage of a buffer (respectively applying the procedure in Fig. 6 and in Fig. 5). For the MPC without usage of a buffer, the difference in frequency of the control platform (which equals 100 Hz) and the communication frequency (25 Hz) is compensated by a zero-order hold to estimate the feedforward signal  $\hat{u}_{i-1}$ . For a wireless failure a Singer model, as described in [29], is used to estimate the acceleration of the preceding vehicle based on on-board sensor measurements (radar and accelerometer). The feedforward signal is estimated by  $\hat{u}_{i-1} = \hat{a}_{i-1}$ .

The tests are organized as follows:

- A reference acceleration profile is designed for a virtual first vehicle ( $i = 0$ ), such that the behavior is reproducible and the test results can be compared.
- Two test vehicles are used. The first test vehicle ( $i = 1$ ) follows this virtual vehicle based on the MPC implementation with buffer. The second test vehicle ( $i = 2$ ) follows at the desired distance using sequentially one of the two above mentioned controllers.
- V2V failures between vehicle 1 and 2 are introduced at  $t = 10$  s,  $t = 18$  s and  $t = 50$  s and for durations of 0.3 s. These failure profiles are coupled to the reference acceleration profile such that the test results are exactly reproducible.

### C. Test results

The results of the tests for both control approaches are shown in Fig. 12 and Fig. 13. When comparing the packet loss profiles in the upper plots of Fig. 12 and Fig. 13, it can be observed that some unintended (natural) V2V failures occurred around 9.5 s, 12 s and 49 s (in the test with the MPC without buffer), these losses also caused a few missing velocity instants (zeros) plotted in the middle plot.

The variances of the control errors and the minimum control errors are calculated for the time interval between 10-57 s (to compensate for different initial errors) and are shown in the first column of Table II. The MPC design with buffer improves the control performance compared to the design without usage of a buffer. The control performance is improved in short periods of packet loss. Additionally, the MPC-based approach with buffer also improves the estimation of  $\hat{u}_{i-1}$  compared to a zero-order hold approximation, resulting in a significantly improved performance also when no packet loss occurs.

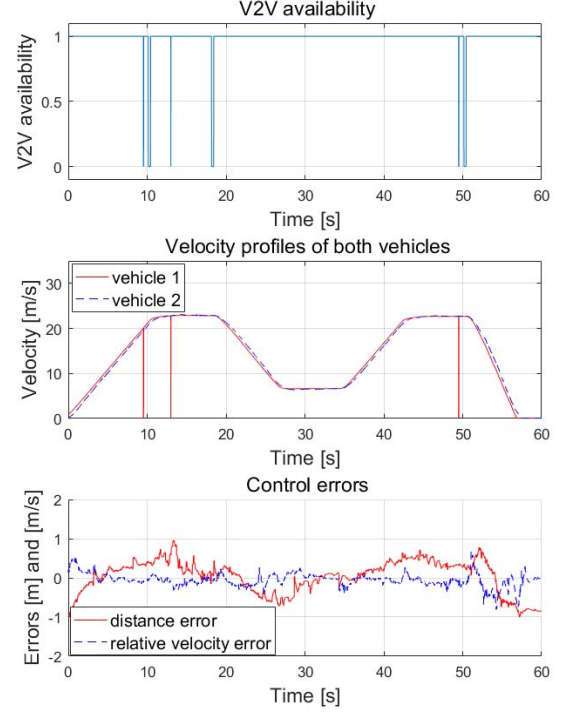


Fig. 12. Experimental test results using the MPC design without usage of a buffer, the top figure represents the packet losses, the middle shows the velocity profiles and the bottom figure presents the control errors.

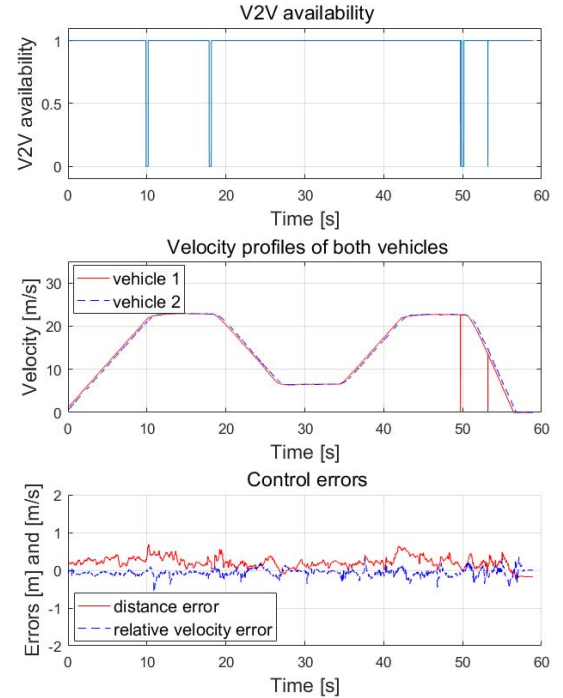


Fig. 13. Experimental test results using the MPC design including the buffer, the top figure represents the packet losses, the middle shows the velocity profiles and the bottom figure presents the control errors.

## VIII. CONCLUSIONS AND FUTURE WORK

This paper proposes to share the intended acceleration for a certain prediction horizon, with the aim to improve the robustness and performance of the CACC control in the presence of intermittent packet losses. An MPC controller is proposed, which shares its future predictions. Further, a buffer is implemented to be used when no message is received. The applied method thereby also compensates for the difference in communication frequency and the frequency at which the control algorithm runs. This method is evaluated by comparison to a MPC controller without using a buffer. Results shown here prove that the usage of a buffer, in combination with a MPC controller, has the potential to improve the CACC control performance, both for situations of packet losses as well as situations in which the V2V communication is fully operational. Future work will include an analysis on the relevance of packet loss in an emergency situation, as well as an analysis on the effects of inaccurate predictions on safety.

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