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Analysis and experimental verification of faulty network modes in an autonomous vehicle string

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***Abstract*— Advanced autonomous vehicle strings rely on inter-vehicle communication in order to decrease the necessary safety gap so that fuel consumption can be decreased and road capacity can be increased. In case of failures of some communication channels, the corresponding back-up control strategy must be switched on. Maximal spacing errors of such back-up modes are analyzed and compared. Robustness to platoon heterogeneity and communication delays are considered. The main conclusion we can draw is that, in the full communication mode, satisfactory spacing performance can be achieved by using simple output-feedback controllers designed without detailed knowledge on engine/brake characteristics, only utilizing the existing services available today in every commercial heavy trucks with automatic gearbox. Experimental verification of the designed controllers are presented.**

***Index Terms*— vehicle platoon, string stability, peak-to-peak norm**

I. INTRODUCTION

Organization of heavy vehicles in autonomous platoons with short, yet safe, gaps between the vehicles have several advantages including decrease in fuel consumption and driver's work time, and increase in road capacity [3], [11], [12]. One important ingredient allowing to achieve short safety gaps is the utilization of inter-vehicle communication applied in a constant spacing control strategy [9]. In case of communication failures back-up control modes can be switched on. The choice of the prescribed safety gaps for each mode are based on analysis of the potential spacing errors. Our goal is to provide three experimentally verified constant spacing control strategies, a normal and two back-up control modes, together with robustness analysis of the peak spacing errors along the platoon.

Very short safety gaps can be guaranteed, under certain constraints on lead vehicle maneuvers, when detailed engine, gearbox and brake system models are available, see, e.g., in references [5], [4], [2]. There is, however, some difficulties in the widespread applicability of these control methods. The required engine/gearbox/brake system models are usually not available and not reliable for every commercial heavy trucks. Beyond that, these controllers try to directly excite the brake cylinder pressures and throttle valve of the engine, which could also conflict with the existing control units, such as Electronic Brake System (EBS) and Engine Control Unit (ECU).

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In this paper, some experimental results of a recent project TruckDAS/Platooning (see [10], [6], [7]) is presented. The goal of the project is to explore the performance of an automated vehicle string consisting of several vehicles based on low cost investments, a few experiments and an appropriate control algorithm which, in contrast to the former solutions, exploits only the standardized and general services available on every modern commercial heavy trucks. Such services are the outer deceleration demand, provided by the (EBS), and the outer engine torque demand, provided by the ECU.

According to our experiences in a platoon of three vehicles with different types and properties, a safety gap of 3m can be safe if the following conditions hold. Deceleration of the leader vehicle is not greater than $2m/s^2$ and there is some dwell time between intensive acceleration and abrupt braking maneuvers so that transients can cease.

The peak norm of a signal $u(t)$ is denoted by $\|u\|_\infty = \sup_t |u(t)|$, the peak-to-peak norm of a system H is defined by $\|H\|_1 = \sup_{u\neq 0} \frac{\|Hu\|_\infty}{\|u\|_\infty}$.

In Section II the concept of the platoon and the control architecture is presented. The vehicle and the network models are described in Section III. The applied control strategies are introduced and analyzed in Sections IV and V, respectively. The experimental results are presented in Section VI.

II. PLATOON ARCHITECTURE

The control scheme of the platoon is plotted in Fig. 1. The lead vehicle is driven by a driver. In the other, follower vehicles, acceleration and braking tasks are carried out by on-board controllers based on information coming from a radar and a communication network. The radar provides relative speed and distance with respect to the preceding vehicle. Through the communication network, each vehicle transmits acceleration demand to its follower vehicle and the leader provides acceleration demand, speed and filtered GPS position for all. Acceleration demands are computed by the platoon controllers or based on pedal signals of the leader. Communication allows to quicken the reaction to maneuver changes.

The controllers, denoted by K_i, calculate acceleration reference u_i which is transmitted after scaling, checking its domain and rate to the EBS as deceleration demand, on the one hand, and to the motor control system in the form of engine torque demand, on the other hand.

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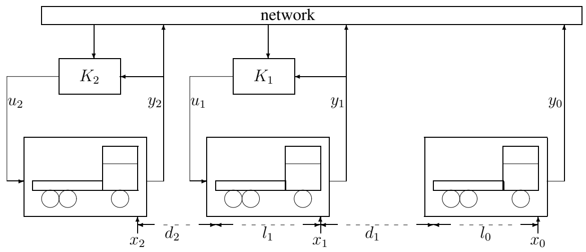

Fig. 1. Control structure of the platoon problem

III. Modelling vehicle strings

The acceleration of a vehicle can be described by the following equation

$$a = \frac{1}{m}\left[F_a + F_g + \frac{1}{r_e}(M_{rr} + \tau_b + \tau_e)\right]$$

where m denotes vehicle mass, M_{rr} is the rolling resistance, F_a and F_g are respectively the air drag and gravitational force due to road inclination, τ_e and τ_b stand for driving and, respectively, braking torques and r_e for effective wheel radius.

The longitudinal behavior of the drive-line is a highly nonlinear and hybrid dynamics due to the engine speed dependent motor torque characteristics, gear dependent torque transmission and the gear change process. Additionally, the control systems of both the automatic gear change and the engine are functioning as finite state automata. Intervention possibility for the platoon control software is given by a motor torque demand addressed to the engine control unit through CAN interface.

The dynamics between the prescribed brake pressure as input and the brake force as output can be described by an input delay necessary for building up the brake cylinder pressures, and a linear time-invariant system. For a given deceleration reference, the computation of the necessary brake pressure for each individual wheel requires knowledge of the vehicle mass, load distribution, resistances, wheel radius, incline angle of the road and tire-road adhesion characteristics. We can assume that all the necessary estimation problem is performed by the EBS which can receive a deceleration demand that is carried out by a finite state machine.

A. Simplified model of the longitudinal dynamics

Based on the above discussion and the proposed concept that existing services are used, the model of the longitudinal dynamics, including actuators, is approximated by the following model

$$\dot{a}_i(t) = -\frac{1}{\tau_i}a_i(t) + \frac{g_i}{\tau_i}u_i(t), \quad i = 0, 1, ..., n$$

where a_i and u_i denote the acceleration and acceleration demand of vehicle i, τ_i and g_i denote time constant and gain, respectively. Parameter g_i depends on the mode: braking or driving. It must be determined individually for each vehicle. It could be adaptively changed, see references [9], [8] where the control input is modified according to changes in load, air drag and rolling resistance. In our experiments g_i were kept constant. For vehicle index $i = 0$, u_0 is composed from the brake/gas pedal signals of the lead vehicle.

B. Platoon model in the state-space

The spacing error of the ith follower vehicle is defined by $e_i = x_i + L_i - x_{i-1}$ where L_i denotes the desired intervehicular spacing and without loss in generality it is assumed to be zero in the analysis.

For each vehicle, the spacing error dynamics can be written as follows

$$\begin{bmatrix} \dot{e}_i \\ \ddot{e}_i \\ \dot{a}_i \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau_i} \end{bmatrix} \begin{bmatrix} e_i \\ \dot{e}_i \\ a_i \end{bmatrix} + \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix} a_{i-1} + \begin{bmatrix} 0 \\ 0 \\ \frac{g_i}{\tau_i} \end{bmatrix} u_i$$

The open-loop model of the whole platoon is constructed by introducing the state vector $x^T = [a_0, \quad e_1 \quad \delta_1 \quad a_1, \cdots, e_n \quad \delta_n \quad a_n]$ where $\delta_i := \dot{e}_i$ for $i = 1, ..., n$, control input vector $u^T = [u_1 \cdots u_n]$ and disturbance $d = u_0$. With zero-order hold transformation, the open-loop, discrete-time platoon model with sampling time $T_s = 0.01s$ reveals the form

$$x(k+1) \quad = \quad A_d x(k) + B_d u(k) + E_d d(k)$$

C. Network model

The detailed description of the communication network is presented in Section VI-B. Here, we only note, that it has a sampling time of $T = NT_s$, $N = 10$, and the packet transmission takes about $h = 3T_s$. In certain conditions, no packet loss occurs and the transmission delay, h has small variation, it can be considered as constant. If $y(k)$ denotes the variable to be transmitted at the network input, then

$$\hat{y}(k) = \begin{cases} y(k-h) & \text{if } \frac{k-h}{N} \text{ is an integer} \\ \hat{y}(k-1) & \text{otherwise} \end{cases} \qquad (1)$$

denotes the network output at the receiver.

IV. Control design for vehicle platoons

A modified version of the constant spacing strategy presented in [9, Section 3.3.4] and its degraded modes when some network channels are broken are applied in the experiments. The modification of the basic strategy resides in that, instead of measured acceleration, control input is transmitted through the network. This has several advantages. 1.) The gear change has lower impact in the control signal than in the acceleration. Consequently, each vehicle can change gear without deceiving the followers[1] 2.) The vehicles react quicker to maneuver changes. 3.) Acceleration measurements are rather noisy contrary to control signals.

In the following sections the control strategy operating in normal mode, and the two strategies switched to in case of faulty network modes are compared.

[1] When acceleration is propagated to the follower vehicles, gear change and the end of an acceleration maneuver cannot be distinguished. The followers cease driving and stay in a lower gear for a while, which causes lagging.

A. Control strategies

The control strategy proposed in reference [9, Section 3.3.4], and also the modified version applied here, depend on four design parameters q_1, q_3, q_4 and λ. Let's define the following constants, $k_1 := \frac{q_1+q_4+\lambda+\lambda q_3}{1+q_3}$, $k_2 := \frac{\lambda(q_1+q_4)}{1+q_3}$, $k_{1\alpha} := \frac{q_4+\lambda q_3}{1+q_3}$, $k_{2\alpha} := \frac{\lambda q_4}{1+q_3}$, $k_{1\beta} := \frac{q_1+\lambda}{1+q_3}$ and $k_{2\beta} := \frac{\lambda q_1}{1+q_3}$.

Let control strategy $\mathcal{CS}_1$ operating in normal mode be defined by the following equations

$$u(k) \;:=\; u_L(k) + \hat{u}_N(k)$$

where $u_L = K_L x$ contains the locally available radar information. Gain matrix K_L can be constructed based on the following definition

$$\begin{aligned} u_{L,1}(k) &= -k_1\delta_1(k) - k_2 e_1(k) \\ u_{L,i}(k) &= -k_{1\beta}\delta_i(k) - k_{2\beta} e_i(k), \quad i > 1 \end{aligned}$$

where i stands for the vehicle index[2]. Control signal $u_N = K_N x + G_N d + Su$ is constructed from the information received from the network

$$\begin{aligned} u_{N,1}(k) &= u_0(k) \\ u_{N,i}(k) &= \frac{1}{1+q_3}u_{i-1}(k) + \frac{q_3}{1+q_3}u_0(k) \\ &\quad -k_{1\alpha}\sum_{j=1}^{i}\delta_j(k) - k_{2\alpha}\sum_{j=1}^{i}e_j(k), \quad i > 1 \end{aligned}$$

from which K_N, G_N and S matrices can be constructed[3]. Note, that $\sum_{j=0}^{i}\delta_j$ and $\sum_{j=0}^{i}e_j$ are respectively the relative speed and relative position between the ith vehicle and the leader.

Control strategy $\mathcal{CS}_2$ is applied, if the lead vehicle cannot send packets due to some faults. In this case the normal control strategy of the first follower vehicle ($i=1$) is applied in all follower vehicles

$$\begin{aligned} u(k) &:= u_L(k) + \hat{u}_N(k) \\ u_{L,i}(k) &= -k_1\delta_i(k) - k_2 e_i(k), \quad i \geq 1 \\ u_{N,i}(k) &= u_{i-1}(k), \quad i \geq 1 \end{aligned}$$

Again, K_N, G_N and S can be defined. Note, that $K_N = 0$.

Control strategy $\mathcal{CS}_3$ is applied, if all network channels fail.

$$\begin{aligned} u(k) &:= u_L(k) \\ u_{L,i}(k) &= -k_1\delta_i(k) - k_2 e_i(k), \quad i \geq 1 \end{aligned}$$

[2] for $n=2$, $K_L = \begin{bmatrix} 0 & -k_2 & -k_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -k_{2\beta} & -k_{1\beta} & 0 \end{bmatrix}$

[3] $K_N = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -k_{2\alpha} & -k_{1\alpha} & 0 & -k_{2\alpha} & -k_{1\alpha} & 0 \end{bmatrix}$ $G_N = \begin{bmatrix} 1 \\ \frac{q_3}{1+q_3} \end{bmatrix}$, $S = \begin{bmatrix} 0 & 0 \\ \frac{1}{1+q_3} & 0 \end{bmatrix}$

B. Choice of control parameters

A simple way of tuning the four design parameters during experiments is to divide them into two groups. Ideally, the spacing error transients at maneuver changes are decreasing along the platoon. For this reason, first k_1 and k_2 are tuned from two-vehicle experiments. For all the parameters being positive real constants, it is required that $4k_2 \leq k_1^2$. In order to minimize steady-state spacing errors, $k_2 := \frac{1}{4}k_1^2$ is chosen. Parameter $k_1 = 0.7$ is selected so as to avoid input saturation due to meaningful initial errors $e_1(0)$ and $\delta_1(0)$.

Two of the parameters, λ and q_3, can be determined from k_1 and k_2 as $\lambda = k_1 - \alpha$ and $q_3 = \frac{q_1+q_4-\alpha}{\alpha}$, where $\alpha = \frac{1}{2}(k_1 + \sqrt{k_1^2 - 4k_2})$ and q_1 and q_4 are still unknowns.

Parameters q_1 and q_4 influence the decay rate of spacing errors along the platoon. Decreasing q_1 and increasing q_4 increase the decay rate. In the experiments $q_1 = q_4 = 5$ was applied.

V. Analysis of spacing performance

First, the closed-loop system with the delayed communication is modelled. The local part of the controllers run with the faster sampling rate $T_s = 0.01$s. Closing the loop with $u_L = K_L x$ results in

$$x(k+1) = A_L x(k) + B_L \hat{u}_N(k) + E_L d(k) \tag{2}$$

where $A_L = A_d + B_d K_L$, $B_L = B_d$, $E_L = E_d$. The networked system can be formulated when (2) is re-sampled with the greater, network sampling time $T = NT_s$. We follow a similar procedure to that presented in [1] for continuous-time systems. Assume, that $d(k) = d(k+1) = ... = d(k+N-1)$, then

$$\begin{aligned} x(k+N) &= A_L^N x(k) + \sum_{j=0}^{N-1} A_L^{N-1-j} B_L \hat{u}_N(k+j) \\ &\quad + \sum_{j=0}^{N-1} A_L^{N-1-j} E_L d(k) \end{aligned}$$

According to the network model (1), $\hat{u}_N(k+j) = u_N(k-N)$ for $j = 0,1,...,h-1$ and $\hat{u}_N(k+j) = u_N(k)$ for $j = h, h+1, ..., N-1$. Introducing a new state-variable $z(k) = \begin{bmatrix} x(k) \\ u_N(k-N) \end{bmatrix}$ and defining

$$\begin{aligned} B_1 &:= \sum_{j=0}^{h-1} A_L^{N-1-j} B_L, \quad B_0 := \sum_{j=h}^{N-1} A_L^{N-1-j} B_L \\ E_N &:= \sum_{j=0}^{N-1} A_L^{N-1-j} E_L \end{aligned}$$

the networked control system can be formulated by

$$\begin{aligned} z(k+N) &= A_z(h) z(k) + E_z(h) d(k) \\ A_z(h) &= \begin{bmatrix} A_L^N + B_0(K_N + SK_L) & B_1 + B_0 S \\ K_N + SK_L & S \end{bmatrix} \\ E_z(h) &= \begin{bmatrix} E_N + B_0 G_N \\ G_N \end{bmatrix} \end{aligned}$$

which, through B_0 and B_1, depends on network delay h. The spacing errors are observed through matrixes C_i as $e_i(k) = C_i z(k)$, $i = 1, 2, ...n$.

Assume that the allowable input satisfies $\|u_0\|_\infty \leq u_{max}$, where u_{max} is a given bound. Then, the worst-case peaks of the spacing errors can be computed as follows (h-dependence is also revealed)

$$\varepsilon_i(h) \quad := \quad \|e_i(h,t)\|_\infty = \sum_{j=0}^{\infty} |C_i e^{A_z(h)t} E_z(h)| u_{max}$$

where the infinite sum can be well approximated by sufficiently large number of terms.

In the following numerical analysis performance indexes $\varepsilon_i(h)$ are computed for heterogeneous vehicle strings. Two sets of parameters are considered for the vehicle models. First, perfect estimation of gain coefficients $g_i := 1$ is assumed and only time constants τ_i can be different. The platoon is parameterized by

$$\theta_1 = [\tau_0 \ \tau_1 \ \dots \ \tau_n], \ \tau_i \in \{0.6, 0.8\}$$

that is each vehicle has a time constant of either 0.6 or 0.8. In the second case, gain parameters can also differ

$$\theta_2 = [\tau_0 \ g_0 \ \tau_1 \ g_1 \ \dots \ \tau_n g_n \ ], \quad \begin{array}{l} \tau_i \in \{0.6, 0.8\} \\ g_i \in \{0.9, 1.1\} \end{array}$$

Figures 2-6 show the worst and the best cases for ε_i in terms of vehicle index i, subject to platoon heterogeneity, i.e., $i \mapsto \sup_\theta \varepsilon_i(\theta)$ and $i \mapsto \inf_\theta \varepsilon_i(\theta)$, where $u_{max} = 2$. The lower bounds are achieved in case of homogeneous platoons ($\tau_i = \tau$, $g_i = g$ for all i). For a given set of allowable maneuvers, this analysis directly provides hints on choosing safety gaps between the vehicles in the different control modes, such as $L_i > \varepsilon_i$, assuming zero initial conditions. The analysis is carried out for a range of network delays from $h = 0$ to $h = 8T_s$.

In Figure 2, spacing error bounds for θ_1 and θ_2 are shown for control strategy $\mathcal{CS}_3$ which correspond to an adaptive cruise control (ACC) algorithm. Safety gaps must be increased along the platoon.

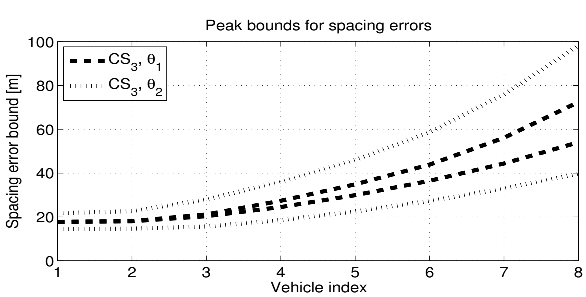

Fig. 2. Bounds on spacing errors, ε_i, in case of control strategy $\mathcal{CS}_3$. Upper and lower bounds are computed with respect to vehicle parametrization θ_1 (dashed) and θ_2 (dotted).

Assuming accurate estimation of gain parameters g_i, Figures 3 and 4 present the bounds for control strategy $\mathcal{CS}_2$ and $\mathcal{CS}_1$, respectively. The robustness against the network delay can be observed in case of control strategy $\mathcal{CS}_1$. The loss of information from the leader vehicle (Figure 3) causes sensitivity to network delays, still, spacing errors reduced to about 20% as compared to controller $\mathcal{CS}_3$. Control strategy $\mathcal{CS}_1$ can maintain a uniform spacing error of 1.5m. Similar conclusions can be drown in case of platoon parametrization θ_2, when gain parameters g_i are uncertain as well, see Figures 5 and 6. Note, that network delays in the tested range have no significant effects on control strategy $\mathcal{CS}_1$.

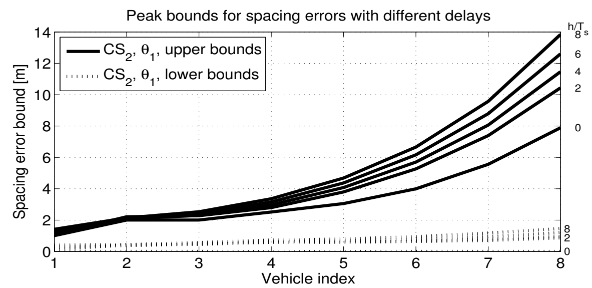

Fig. 3. Bounds on spacing errors, ε_i, in case of control strategy $\mathcal{CS}_2$. Upper and lower bounds for different network delays are computed with respect to vehicle parametrization θ_1.

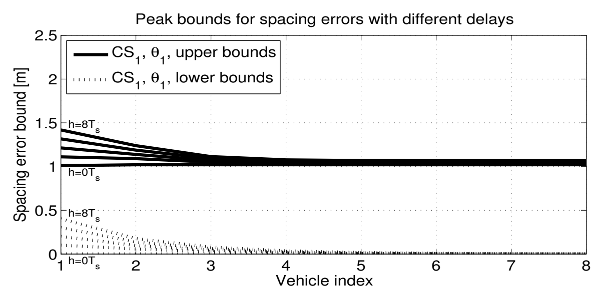

Fig. 4. Bounds on spacing errors, ε_i, in case of control strategy $\mathcal{CS}_1$. Upper and lower bounds for different network delays are computed with respect to vehicle parametrization θ_1.

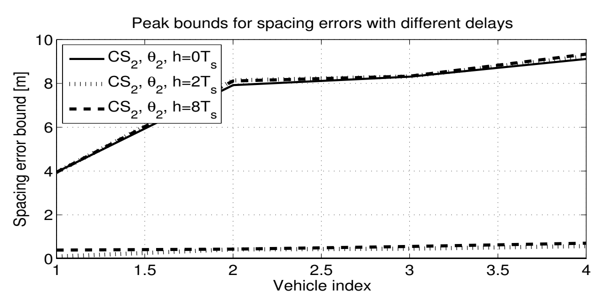

Fig. 5. Bounds on spacing errors, ε_i, in case of control strategy $\mathcal{CS}_2$. Upper and lower bounds for different network delays are computed with respect to vehicle parametrization θ_2.

VI. Experimental Results

A. Set of vehicles

Control strategies $\mathcal{CS}_1$, $\mathcal{CS}_2$ and $\mathcal{CS}_3$ are implemented on a platoon of three heavy trucks and tested on a 3km

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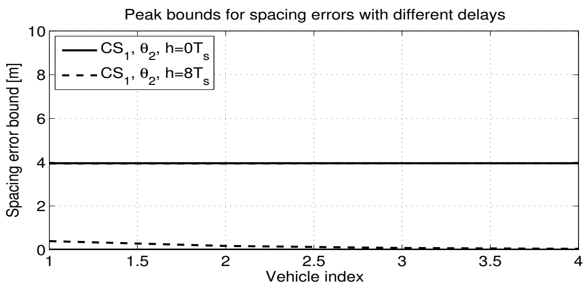

Fig. 6. Bounds on spacing errors, ε_i, in case of control strategy $\mathcal{CS}_1$. Upper and lower bounds for different network delays are computed with respect to vehicle parametrization θ_2.

long flight-strip. The leader vehicle, driven by a driver, is a MAN TGA two-axle tractor of 18 tonne with load cage. The second vehicle is a Volvo FH 24 tonne three-axle truck. The third one is a Renault Magnum two-axle tractor of 18 tonne with a semitrailer, See Fig. 7. It is important to remark that all vehicles are equipped with automatic gear change, thus acceleration can be attained purely by software.

Fig. 7. Experimental vehicles in project TruckDAS

B. Communication network

The communication network specified in this section is applied only for experimental purposes, because of its nice properties. It consists of radio transceivers operating on the open 868MHz ISM narrow-band. On the physical layer of the network model GFSK modulation and Manchester coding is used, while the data link layer is based on 4 byte device addressing and CRC-based data protection. In the network and data layers broadcast messaging is applied which means that there is no peer-to-peer socket communication and classic network topology. With proper timing strategy, all peers receive all messages of the other network nodes. The channel access is achieved by time division multiple access (TDMA): The leading vehicle initiates the broadcast, and the two followers accept it. As soon as the channel turns disengaged after the end of this broadcast, the second vehicle sends its message and so the cycle is restarted. In the top network layer, compact data description is utilized where the data is stored in the form similar to the representation of the CAN network protocol. Thus, the data packet is only 30 bytes long, which is extended with packet identifier for further data-protection purposes.

C. Experimental scenarios

The model parameter identification was performed based on several braking and accelerating experiments, individually for each vehicles. The worst case performance can then be analyzed based on the models obtained. Once the maximal spacing errors are determined platooning tests can be carried out, where the design of the experimental scenarios are confined to the design of the leader vehicle maneuvers.

The platoon control algorithms are tested with three heavy trucks shown in Figure 7. The experimental scenario is started with a 'joining in' maneuver in which the leader vehicle passes the others which are travelling at constant speed. When the last vehicle in the platoon is caught by the radar of the joining vehicle and its driver enables the joining maneuver by pressing a deadman-button, the joining vehicle is accelerated and braked by given constant values and for sufficient time so that the vehicle arrives approximately at the prescribed distance with speed near that of the platoon. After the braking period the spacing controller is switched on. When both joining maneuvers are finished, the leader vehicle can accelerate and decelerate and finally stop.

D. Results

Typical experiments of each kind are presented in Figures 8-10 for the three controllers. In every experiments the driver of the platoon applied approximately the same maneuvers and maximal acceleration and deceleration towards a fair comparison. This is shown in the plots of velocity profiles and control signals (with black lines). It can be observed as comparing the control signals in cases of control with and without communication, that the reactions of the follower vehicles to changes at the front vehicle are much faster in the case of direct acceleration feed-through. (You can see this at the heavy braking events.) It also can be concluded by comparing the spacing errors of the third vehicle (blue dotted lines in Figures 9 and 10) that additional information from the leader greatly improve the tracking performance.

Concerning platoon performance with controller $\mathcal{CS}_1$, nine experiments of similar maneuvers were carried out on a 3km long pathway. The maximum spacing error was not greater than 3m during braking, i.e. in the direction of collision danger. During driving maneuvers, the maximum leg was not greater than 8m.

VII. Conclusions

It has been demonstrated that the nowadays available on-board services of commercial heavy tracks are applicable for creating new platooning services. Without detailed vehicle models, output-feedback controllers can be designed that provide satisfactory tracking performance for heterogenous platoons. The feed-through of control inputs, speeds and filtered GPS positions has the benefit of shortening the safety gaps between the vehicles. Degraded controller modes corresponding to network channel faults have been also presented,

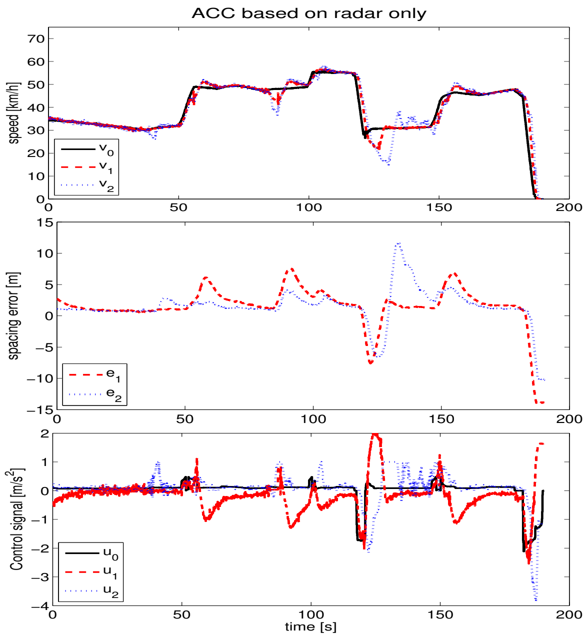

Fig. 8. Adaptive Cruise Control based on radar information only (controller $\mathcal{CS}_3$)

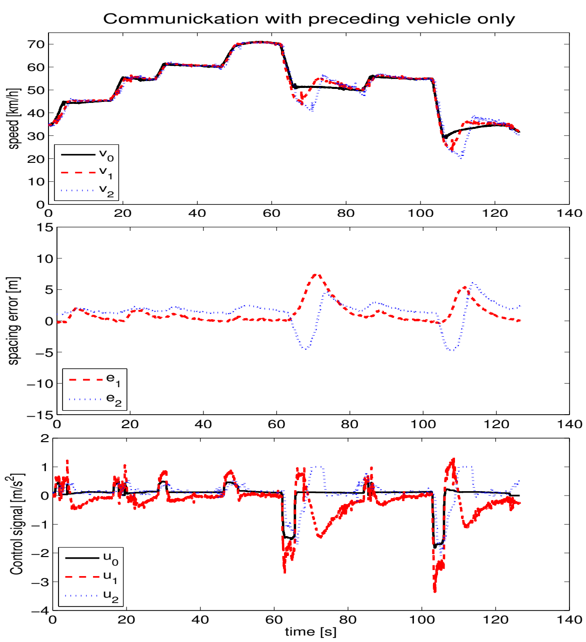

Fig. 9. Control based on radar and communication with the preceding vehicle (controller $\mathcal{CS}_2$)

analyzed and experimentally verified. Upper bounds on the worst case spacing errors has been computed for platoons of heterogeneous dynamics and communication delays, which can support the selection of the safety gaps.

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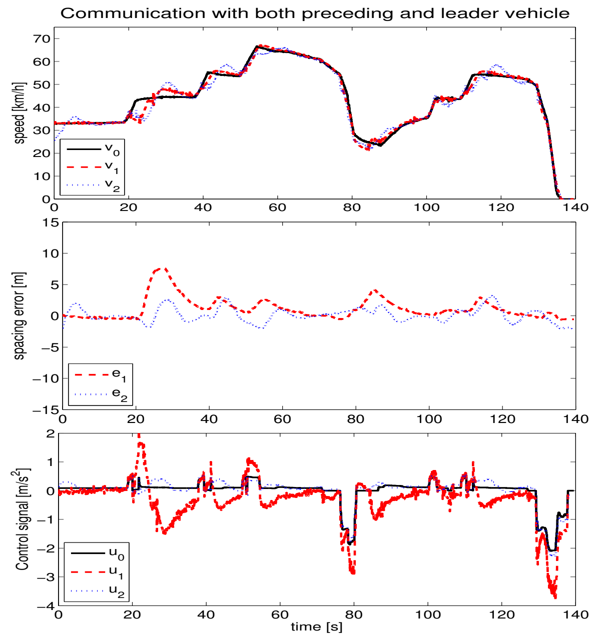

Fig. 10. Platoon control (controller $\mathcal{CS}_1$)

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