A Multi-layer Control Approach to Truck Platooning: Platoon Cohesion subject to Dynamical Limitations

Conference Paper · June 2017

DOI: 10.1109/MTITS.2017.8005652

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Presented at IEEE International Conference on Models and Technologies for Intelligent Transportation Systems, MT-ITS, 26-28 June 2017.

A Multi-layer Control Approach to Truck Platooning: Platoon Cohesion subject to Dynamical Limitations

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***Abstract*— This paper presents a multi-layer approach to Cooperative Adaptive Cruise Control (CACC) to improve the platoon cohesion subject to limited vehicle actuation capabilities. The objective of the design is to guarantee that the vehicles in the platoon keep their desired relative position, while maintaining desirable platoon properties in terms of disturbance attenuation. To this end, a multi-layered control architecture is proposed. On the lower layer, a unidirectional CACC is employed, involving information exchange in upstream direction. On the upper layer, a coordination variable is exchanged from each vehicle towards its direct preceding vehicle, thus yielding downstream information exchange. As a result, the leading vehicle is aware of the capabilities of the following vehicles, and therefore, is able to adapt its motion, if needed. Consequently, cohesion of a heterogeneous platoon is guaranteed, even in the case of physical limitations, like engine power limits. The developed technique is verified through simulations and experiments.**

I. INTRODUCTION

Nowadays, vehicular platooning receives a lot of attention in the research community [1], [2], [3], [4], [5]. When employing vehicle-2-vehicle communication, very short following distances can be reached, while still guaranteeing safety. Next to an increase in road throughput, this leads to a decrease in fuel consumption as a result of a reduction in air drag at short following distances. The latter mainly applies to truck platoons, since a truck suffers more from air drag compared to a passenger car. In many recent developments in platooning technology, the vehicles' homogeneity is an assumption [4]. However, in real-life applications, no two vehicles can behave exactly the same. This is particularly more critical when heavy-duty vehicles are dealt with. The vehicle behavior can be different as a result of different vehicle type reflecting both the dynamical properties due to, e.g., engine and braking characteristics [2], [3], and physical variations, such as weight [6]. In addition to these sources of heterogeneity, different communication network properties such as communication delay, or network connectivity [2], can bring in a different behavior for a vehicle in a platoon [7]. In [2], string stability of a heterogeneous platoon of vehicles subject to a constant distance spacing policy is guaranteed through choosing asymmetric feedback with respect to the following and preceding vehicles. This asymmetry is employed to avoid the string stability difficulties encountered in a bidirectional connectivity topology [8]. This idea of asymmetric feedback for a vehicle following problem, with constant distance spacing policy, is also used in [9]. Here, the vehicle model reflects the nonlinear dynamics of the drive-line and brake system, which is feedback linearized to a linear third-order dynamics. It is shown that the adverse effect of platoon size on stability margins can be compensated through connecting more vehicles directly to the leader or through choosing asymmetric control gains to feed back information to the leader. In many of these research papers, the motivation for having a bidirectional interaction topology is not clearly stated. The desire to guarantee platoon cohesion in case of heterogeneous vehicle capabilities could be a reason to do so. In [10], the authors try to redefine the notion of string stability for heterogeneous platoons. Since in a heterogeneous platoon, the disturbance attenuation cannot be expected to be uniform along the platoon, it is required to adapt the string stability definitions.

In this paper, heterogeneity in terms of the maximum acceleration capability is considered. For a heterogeneous truck platoon, such limitations in acceleration capability can lead to undesired behavior. For example, variations in terms of payload heavily affect the vehicle acceleration capabilities. In certain scenarios, e.g. dense traffic or hilly terrain, this can eventually lead to a platoon breakup or other vehicles cutting in between. Since it is desired for the vehicles in a platoon to stay together, it is required to have an enhancement in control strategy and communication topology design. To this end, this paper presents a multi-layer approach to Cooperative Adaptive Cruise Control (CACC). Here, the common platoon design strategies as in [4], [11] are enhanced in two aspects. To be able to keep the cohesion of the platoon, the one-vehicle look-ahead communication topology is changed to a bidirectional topology, i.e. information is sent from the rear vehicles in the platoon to the front of the platoon. However, to avoid the design complexities that might arise in introduction of symmetric bidirectional connections [3], [8], this additional information is exchanged through an information layer and is only used by the leader. Similar to [5], a multi-layered architecture is used to separate the platoon coordination objective from the low-level vehicle control goals. In contrast to [5], the upper layer is not estimating trajectories to be followed by the vehicles but information is shared between the vehicles by means of a coordination variable [12]. This information is passed along the platoon towards the leader. Therefore, the leading vehicle is continuously updated on the platoon's capabilities and adapts its behavior accordingly. To enforce more predictable behavior of the dynamical behavior of the controlled vehicles

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in the platoon, hereafter shortly referred to as closed-loop platoon dynamics, on the lower layer, a unidirectional CACC as described in [4], is employed. As a result of such multi-layer architecture as well as the bidirectional interaction topology, platoon cohesion is obtained in the case of engine power limitations, while the individual vehicle performances are not significantly affected.

In Section II, the definition of the vehicle's and platoon dynamics is elaborated. Next, in Section III, the design of the multi-layer control approach is explained. The approach is verified through simulations and experiments, of which the results are given in Section IV and Section V, respectively. Finally, the results are summarized in Section VI.

II. Problem Formulation

A. Vehicle Dynamics Model

Let $\mathcal{V} = \{1, \ \dots, \ n\}$ be a set containing all the vehicles in a platoon of size n. The longitudinal dynamics model for a vehicle i is defined as

$$\begin{cases} \dot{q}_i &= v_i \\ \dot{v}_i &= \frac{1}{m_i+m_{eq}}\Big(\frac{\eta_T i_d}{R_w}T_i - C_{rl}v_i^2 - m_i B_{rl} v_i - \\ & \qquad m_i A_{rl}\cos\alpha - m_i g \sin\alpha\Big) \\ \dot{T}_i &= -\frac{1}{\tau_i}T_i + \frac{1}{\tau_i}T_{ref,i}(t-\theta_G), \end{cases} \tag{1}$$

$\forall i \in \mathcal{V}$, where $q_i(t)$ and $v_i(t)$ denote the position and velocity, respectively, $T_i(t)$ is the drive torque, $T_{ref,i}(t)$ is the desired torque, τ_i is the actuation time constant, θ_G is the actuation response delay, m_i is the truck mass, A_{rl}, B_{rl}, and C_{rl} denote the road-load parameters involving road surface and internal friction, and drag force. Furthermore, η_T is the transmission efficiency, R_w is the wheel radius, g is the gravitational constant, α is the road slope angle, and i_d is the driveline ratio, being defined as

$$i_d = i_{axle} i_g \tag{2}$$

where i_{axle} is the final drive ratio and i_g is the current gear ratio. The equivalent mass m_{eq} of all the rotating parts of the truck is defined as

$$m_{eq} = \frac{i_d^2 J_e + J_w}{R_w^2} \tag{3}$$

where J_e is the mass moment of inertia of the engine and J_w is the mass moment of inertia of all wheels combined. Note that, in reality, the longitudinal actuation consists of an engine torque and a brake system torque with corresponding dynamics, as modeled in [13]. For simplicity, in this paper, the actuation dynamics is represented by a single time constant τ_i, as in (1). The actuation dynamics is feedback linearized using the following control law for the desired engine torque

$$\begin{aligned} T_{ref,i} = &\frac{R_w}{\eta_T i_d}\Big(C_{rl} v_i\left(2\tau_i \dot{v}_i + v_i\right) + \\ & m_i B_{rl}\left(\tau_i \dot{v}_i + v_i\right) + m_i A_{rl}\cos\alpha + m_i g \sin\alpha \ + \\ & \left(m_i + m_{eq}\right) u_{ref,i}\Big), \qquad \forall i \in \mathcal{V} \end{aligned} \tag{4}$$

where $u_{ref,i}(t)$ is the desired acceleration. Now, let $a_i(t) = \dot{v}_i$. Substitution of $T_{ref,i}(t)$ as in (4) into (1) results in the following linear longitudinal vehicle dynamics

$$\begin{cases} \dot{q}_i &= v_i \\ \dot{v}_i &= a_i \\ \dot{a}_i &= -\frac{1}{\tau_i}a_i + \frac{1}{\tau_i}u_{ref,i}(t-\theta_G), \end{cases} \tag{5}$$

$\forall i \in \mathcal{V}$. Note that, due to the linearization procedure, the longitudinal vehicle dynamics representation in (5) does not cover time-varying changes in the road slope α or changes in gear ratio i_g. In addition to this linear model, an upper limit on the actuation torque $T_i(t)$ is assumed to model the maximum engine torque $T_{max,i}$ of a vehicle i. It is assumed that the engine and gearbox are designed such that the maximum engine torque is always available. The maximum engine torque $T_{max,i}$ is modeled by limiting the acceleration setpoint $u_{ref,i}(t)$ of the linear model in (5) with the maximum acceleration $a_{max,i}(v_i)$ as follows

$$u_{ref,i} = \min\left(u_i, \ a_{max,i}(v_i)\right), \quad \forall i \in \mathcal{V} \tag{6}$$

where $u_i(t)$ is the intended acceleration setpoint of the cooperative control system, which will be explained below. The maximum acceleration is obtained by substitution of the maximum torque $T_{max,i}$ into the second equation in (1):

$$\begin{aligned} a_{max,i}(v_i) = &\frac{1}{m_i + m_{eq}}\Big(\frac{\eta_T i_d}{R_w}T_{max,i} - C_{rl}v_i^2 - \\ & m_i B_{rl} v_i - m_i A_{rl}\cos\alpha - m_i g\sin\alpha\Big), \ \forall i \in \mathcal{V}. \end{aligned} \tag{7}$$

B. Vehicular Platoon

The vehicular platoon is schematically depicted in Fig. 1. Let the inter-vehicle distance between two consecutive vehicles be defined as $d_i(t) = q_{i-1}(t) - q_i(t) - L_i$, where L_i is the length of vehicle i. The objective is to follow the preceding vehicle in the longitudinal direction satisfying the following distance spacing policy

$$d_{des,i}(t) := r + h v_i(t), \ \forall i \in \mathcal{V}\setminus\{1\} \tag{8}$$

with r and h being a standstill distance and the desired timegap, respectively. This spacing-policy is known to have favorable properties in terms of disturbance attenuation [4]. Given this, the distance error is defined as

$$\begin{aligned} e_i(t) &= d_i(t) - d_{des,i}(t) \\ &= \left(q_{i-1}(t) - q_i(t) - L_i\right) - \left(r + h v_i(t)\right), \ \forall i \in \mathcal{V}\setminus\{1\}. \end{aligned} \tag{9}$$

III. Controller Design

The design of the control system is based on two objectives. The first being the vehicle-following objective, i.e. $\lim_{t\to\infty} e_i(t) = 0, \ \forall i \in \mathcal{V}\setminus\{1\}$, even in case one of the vehicles is being limited in acceleration as a result of the upper limit on its engine torque. Second, disturbance attenuation in upstream direction of the platoon [4].

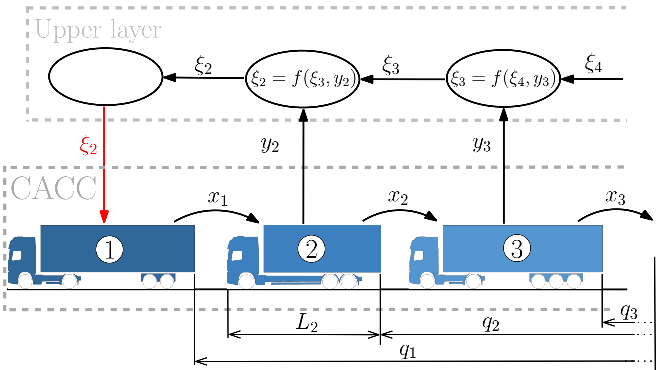

Fig. 1. Schematic overview of a heterogeneous vehicle platoon and the multi-layer information flow topology.

TABLE I

VALUES OF SIMULATION PARAMETERS

Parameter	Value	Unit	Parameter	Value	Unit
R_w	0.45	m	C_{rl}	1.25	kg/m
i_{axle}	2.5	$-$	g	9.81	m/s^2
J_w	232	kgm^2	$\tau_i\ \forall i$	0.1	s
J_e	2.5	kgm^2	θ_G	0.12	s
$T_{max,i}\ \forall i$	2500	Nm	k_p	0.2	$-$
η_T	1	$-$	k_d	0.7	$-$
$L_i\ \forall i$	18	m	r	2	m
A_{rl}	0.039	m/s^2	h	0.3	s
B_{rl}	0.0037	$1/s$	θ_C	0.02	s
α	0	rad			

As mentioned above, the proposed control solution consists of two layers. The purpose of the lower layer is to guarantee desired longitudinal vehicle-following behavior in terms of asymptotic stability of the error-dynamics and have attenuation of disturbances in upstream direction, i.e., satisfying the first and second control objective. The purpose of the upper layer is to share information to satisfy the vehicle-following objective in case one vehicle is being limited in acceleration. This information is shared using a coordination variable. The coordination variable represents the minimal amount of information needed to enable a specific cooperation objective [12]. First, the control structure of the lower layer is explained.

A. Lower Layer: Unidirectional CACC

To meet the vehicle-following and the disturbance attenuation objectives, on the lower layer, a unidirectional CACC as in [4] is employed. In this approach, the controller for the desired acceleration u_i of each vehicle is defined as

$$\dot{u}_i = -\frac{1}{h}u_i + \frac{1}{h}\big(u_{i-1}(t-\theta_C) + k_p e_i + k_d \dot{e}_i\big),\ \forall i \in \mathcal{V}\backslash\{1\} \tag{10}$$

where k_p and k_d are a proportional and derivative feedback gains, respectively. Furthermore, the feed-forward by means of the desired acceleration $u_{i-1}(t)$ of vehicle $i-1$, is obtained through wireless communication, and, therefore, subject to a communication delay θ_C. Let a state vector $x_i(t)$ be defined as

$$x_i = \begin{pmatrix} e_i & v_i & a_i & u_i \end{pmatrix}^T \quad \forall i \in \mathcal{V}\backslash\{1\}. \tag{11}$$

To be able to write the platoon dynamics in compact form, we assume that the communication and actuation delay, θ_C and θ_G, are both equal to zero. Furthermore, for now, it is assumed that the engine torque is unlimited, i.e., $T_{max,i} \equiv \infty$. As a direct result, the maximum acceleration $a_{max,i}(v_i)$, as in (7), is infinite as well. Under this assumption, the relation for $u_{ref,i}(t)$ in (6) reduces to $u_{ref,i}(t) \equiv u_i(t)$. Now, applying the controller (10) to the vehicle dynamics in (5), results in the following compact expression of the dynamics of vehicle i

$$\dot{x}_i = A_i x_i + A_p x_{i-1} \quad \forall i \in \mathcal{V}\backslash\{1,2\} \tag{12}$$

where

$$A_i = \begin{pmatrix} 0 & -1 & -h & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{1}{\tau_i} & \frac{1}{\tau_i} \\ \frac{k_p}{h} & -\frac{k_d}{h} & -k_d & -\frac{1}{h} \end{pmatrix}$$

and

$$A_p = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \frac{k_d}{h} & 0 & \frac{1}{h} \end{pmatrix}.$$

Obviously, the dynamics for the first vehicle are different. Let a state vector for the first vehicle be defined as $x_1 = \begin{pmatrix} q_1 & v_1 & a_1 \end{pmatrix}^T$. Furthermore, let a lumped state vector be defined as $x = \begin{pmatrix} x_1 & x_2 & \cdots & x_n \end{pmatrix}^T$. Now, the entire closed-loop platoon dynamics can be represented as

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \vdots \\ \vdots \\ \dot{x}_n \end{pmatrix} = \begin{pmatrix} A_1 & & & & O \\ A_{p,2} & A_2 & & & \\ & A_p & \ddots & & \\ & & \ddots & \ddots & \\ O & & & A_p & A_n \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} B_1 \\ B_2 \\ O \\ \vdots \\ O \end{pmatrix} u_1 \tag{13}$$

where

$$A_1 = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau_1} \end{pmatrix}, \quad B_1 = \begin{pmatrix} 0 \\ 0 \\ \frac{1}{\tau_1} \end{pmatrix},$$

$$A_{p,2} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{k_d}{h} & 0 \end{pmatrix}, \quad \text{and} \quad B_2 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{h} \end{pmatrix}.$$

For these platoon dynamics with τ_i being the same for all vehicles, the conditions for stability and string stability, i.e., disturbance attenuation, are the same as in [4].

B. Motivating Example for the Upper Layer

In the above, it is assumed that the engine torque is unlimited, i.e., $T_{max,i} \equiv \infty$. However, in the remainder of this paper, this is not the case. As explained by means of (6) and (7), the influence of the maximum engine torque $T_{max,i}$ is modeled by introducing an upper bound on the desired acceleration $u_i(t)$. Note that, due to the introduction of this limit, the platoon dynamics can no longer be modeled as a linear system, as in (13). Next, an example shows that a heterogeneous platoon can break up if only unidirectional interaction using the CACC control strategy, as described in Section III-A, is employed. In this example, a platoon of four trucks is considered. In principle, the trucks can be heterogeneous with respect to all parameters. However, in this paper, only the masses of the trucks are assumed to be different. The mass distribution in kilograms is as follows

$$(m_1 \quad m_2 \quad m_3 \quad m_4) = (25 \quad 20 \quad 20 \quad 40) \cdot 10^3,$$

which, in turn, leads to different levels of maximum acceleration $a_{max,i}(v_i)$ for each truck i, as can be seen in (7). The other parameters used for the simulation are given in Table I. The gear shifting strategy is simply modeled by changing the gear ratio i_g based on the actual velocity of the truck i. The correspondence between velocity ranges and gear ratios is listed in Table II. When the velocity reaches another velocity range, the gear ratio changes to the new gear ratio in 1.5 seconds with a constant rate. The simulated platoon response is depicted in Fig. 2. Initially, the four-truck platoon is moving at a velocity of 60 km/h at steady-state, i.e., zero initial spacing errors. At $t = 0$, the desired cruise speed of the leading truck is set to $v_{des} = 80$ km/h employing the following cruise controller

$$u_1(t) = k_v\left(v_{des} - v_1\right) \tag{14}$$

with $k_v > 0$. As a result, the leading truck increases its velocity towards the desired velocity subject to its own maximum levels of acceleration. At $t = 5$, the maximum acceleration $a_{max,1}(v_1)$ of the leading truck drops, as a result of a gear shift. Due to their lower weight, truck 2 and 3 do not reach their maximum acceleration limits and thus can easily follow, as can be observed from their response in Fig. 2. In contrast, truck 4 cannot reach such high levels of acceleration due to its larger weight, as can be observed in its acceleration response. Consequently, the spacing error $e_4(t)$ increases significantly, which is not desired. Eventually, the leader truck reaches its desired cruise speed of 80 km/h, and, after 45 seconds, the fourth truck has closed the gap towards the third truck. Especially in dense traffic, where a lot of acceleration and deceleration occurs, this leads to undesired platoon behavior. First, because the fuel saving is less due to a larger average following distance, and second, the possibility of other road traffic cutting in between the trucks increases. Another use-case is in hilly terrain with many sloped road segments. For trucks, even a small road

TABLE II

GEAR RATIOS OF SIMPLIFIED GEARBOX STRATEGY

Velocity range $[km/h]$	Gear ratio i_g [-]
0-10	9.6
10-20	5.9
20-30	3.5
30-45	2.1
45-70	1.2
> 70	1

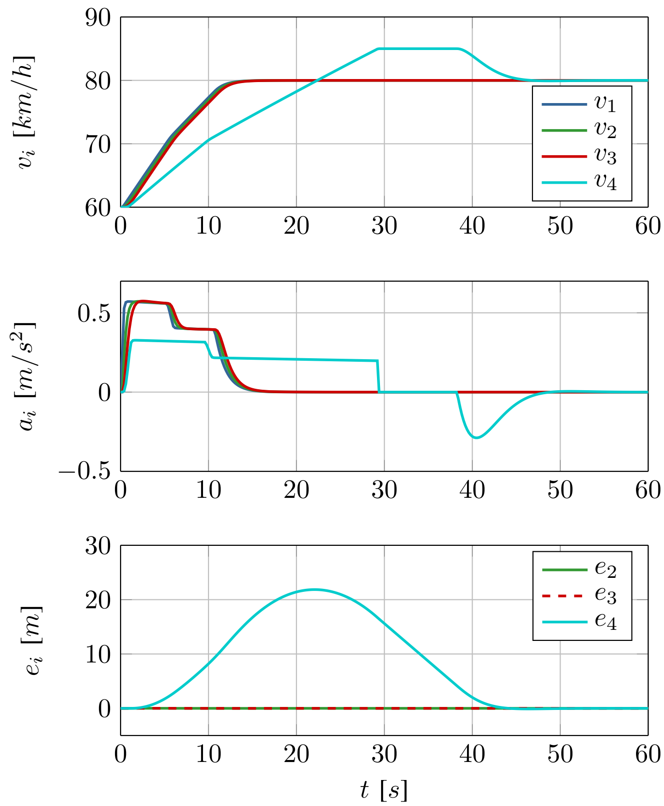

Fig. 2. Velocity v_i, acceleration a_i and spacing error e_i response of a four-truck platoon during acceleration from 60 km/h to 80 km/h. For the acceleration a_i response, the same indices as for the legend of the velocity v_i apply.

slope can lead to severe limitations in maximum acceleration and velocity. Note that, in reality, when a truck changes gear, and thus the clutch is released, there is a dip in the acceleration. However, this phenomenon is not included in the model since this is not the focus of this paper.

C. Multi-layer Control Approach

As shown above, to achieve platoon cohesion in the presence of heterogeneity, information from rearward vehicles is required. Next, a multi-layer control method for solving this problem is proposed. Fig. 1 shows a schematic overview of the multi-layer control layout. On the lower-layer, each vehicle has interaction with its direct predecessor by means of $x_i(t)$, i.e., unidirectional CACC as explained in Section III-A is employed. Furthermore, each vehicle i sends an information vector $y_i(t) \in \mathbb{R}^3$ to its node on the upper layer. Let a coordination variable $\xi_i(t) \in \mathbb{R}$ be defined as

$$\xi_i = f\left(\xi_{i+1}, y_i\right), \quad \forall i \in \mathcal{V}\setminus\{1, n\} \tag{15}$$

$$\xi_n = f\left(\xi_n\right). \tag{16}$$

Meaning, the coordination variable $\xi_i(t)$ of vehicle i is updated based on the coordination variable $\xi_{i+1}(t)$ of the following vehicle and information from vehicle i by means of $y_i(t)$. In particular, the following nonlinear algorithm is proposed

$$\xi_i = \min\left(\xi_{i+1}, Ky_i\right), \quad \forall i \in \mathcal{V} \setminus \{1, n\} \tag{17}$$

$$\xi_n = Ky_n \tag{18}$$

where $K = (1 \quad -\gamma_p \quad -\gamma_d)$, and γ_p and γ_d are a proportional and derivative gain, respectively. In this way, the coordination variable ξ_2 arriving at the leading vehicle, contains the maximum allowable acceleration of the slowest vehicle in the platoon. In addition, this maximum acceleration is lowered with respect to the spacing error $e_i(t)$, and its derivative $\dot{e}_i(t)$ for damping, corresponding to the slowest vehicle. By defining $u_{ref,1}$ as

$$u_{ref,1} = \min\left(u_1, a_{max,1}, \xi_2\right), \tag{19}$$

the coordination variable $\xi_2(t)$ is used by the leading vehicle as an additional limit on the desired acceleration $u_1(t)$. In this way, the acceleration of the leading vehicle is limited as a result of the maximum acceleration $a_{max,k}(v_k)$ of the slowest vehicle in the platoon having index k. Furthermore, to guarantee that the spacing error $e_k(t)$ is being regulated to zero during acceleration of the platoon, a linear feedback-term is added, as in (17). As mentioned above, by introduction of the maximum engine torque $T_{max,i}$, the platoon dynamics is not a linear system anymore. Furthermore, the use of the minimum function adds another nonlinearity. In fact, the entire closed-loop platoon dynamics can modeled as a nonlinear switched system [14]. However, the resulting closed-loop platoon dynamics are not given here. Using the approach explained above, the cohesion of the vehicular platoon improves significantly, which is shown in the next section.

IV. Simulation Results

In this section, the scenario treated in Section III-B is repeated with exactly the same platoon and controller parameters. However, now employing the multi-layer control structure as is explained in Section III-C, with the values for the gains being $\gamma_p = 0.1$ and $\gamma_d = 0.5$. The simulation results are depicted in Fig. 3. Initially, the platoon is traveling at 60 km/h in steady-state. At $t = 0$ s, the leading truck changes its desired cruise speed to $v_{des} = 80$ km/h. By comparing the acceleration response in Fig. 3 with the response in Fig. 2, it can be observed that the acceleration of the leading truck is limited by a lower value than its own acceleration limit. In fact, it is limited by the coordination variable $\xi_2(t)$, which by means of propagation equals the coordination variable of the limited truck

$$\xi_4 = a_{max,4}(v_4) - \gamma_p e_4 - \gamma_d \dot{e}_4. \tag{20}$$

As a result, the spacing error $e_4(t)$ remains very small compared to the response with only unidirectional platoon interaction, i.e., CACC only, as depicted in Fig. 2. At $t = 10$ s, the fourth truck shifts up its gear, leading to a lower gear ratio i_g and thus a lower acceleration limit $a_{max,4}(v_4)$. Consequently, the spacing error towards the third truck slightly starts to increase. However, as a result of

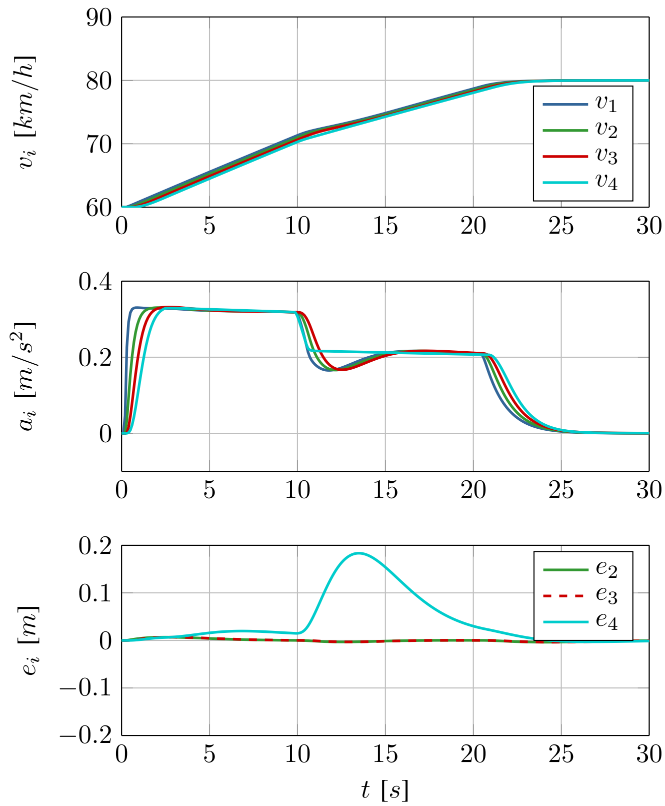

Fig. 3. Velocity v_i, acceleration a_i and spacing error e_i response of a four truck platoon during acceleration from 60 km/h to 80 km/h. For the acceleration a_i response, the same indices as for the legend of the velocity v_i apply.

the negative contribution of the spacing error $e_4(t)$ towards the information variable ξ_4 in (20), the leading truck's acceleration is slightly decreased such that the spacing error converges to zero. Furthermore, note that the acceleration undershoot of truck 1-3 around $t = 12$ s is attenuating in upstream direction, which is in correspondence with the second control objective.

The approach is also verified through experiments, which are elaborated upon in the next section.

V. Experimental Results

To verify the practical feasibility, the multi-layered approach is implemented. For practical reasons, for the experiment, passenger cars are used instead of trucks. The

TABLE III

Parameter values for the experimental set-up

Parameter	Value	Unit	Parameter	Value	Unit
R_w	0.2	m	$\tau_i\ \forall i$	0.1	s
i_{axle}	1	$-$	θ_G	0.2	s
$T_{max,3}$	170	Nm	k_p	0.2	$-$
η_T	1	$-$	k_d	0.7	$-$
$L_i\ \forall i$	4.46	m	r	2.5	m
A_{rl}	0.094	m/s^2	h	0.6	s
B_{rl}	0	$1/s$	θ_C	0.02	s
C_{rl}	0.47	kg/m	$m_i + m_{eq}\ \forall i$	1625	kg
α	0	rad			

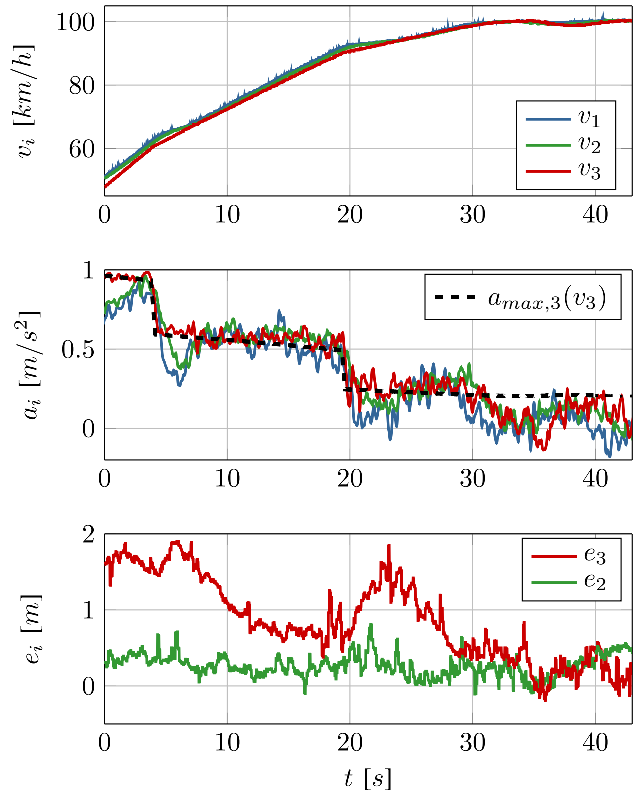

Fig. 4. Velocity v_i, acceleration a_i and spacing error e_i response of an experiment with a three vehicle platoon during acceleration from 55 km/h to 100 km/h. For the acceleration a_i response, the same indices as for the legend of the velocity v_i apply.

three passenger vehicles are equipped with radar-based forward sensing and IEEE 802.11p-based wireless inter-vehicle communication [4]. The three vehicles have almost identical limits in terms of maximum acceleration. Therefore, a virtual limit is implemented on the third vehicle. This virtual acceleration limit $a_{max,3}(v_3)$ is determined using the relation in (7), and is computed based on the model parameters given in Table III. In Table IV, the virtual gear shifting strategy that is implemented for the gear ratio i_g during the experiment is reported. Vehicle 1 and 2 do not reach their maximum acceleration limit. The experimental results are shown in Fig. 4. At $t = 0$ s, the platoon is driving at 55 km/h, however, already accelerating. Around $t = 4$ s and $t = 20$ s, the third vehicle shifts gear, leading to a lower maximum acceleration $a_{max,3}(v_3)$. At these moments, the spacing error $e_3(t)$ slightly increases. However, due to the influence of the upper layer, the leading vehicle reduces its acceleration

TABLE IV
GEAR RATIOS OF GEARBOX STRATEGY FOR THE EXPERIMENTAL SET-UP

Velocity range [km/h]	Gear ratio i_g [-]
0-20	4
20-60	2.1
60-90	1.5
> 90	1

accordingly, and this spacing error converges back to zero. It can be observed that, while adapting the acceleration, the undershoot of the acceleration response is again decreasing in upstream direction, similar as for the simulation response in Fig. 3. Eventually, the platoon reaches the desired velocity of 100 km/h.

VI. Conclusions

In this paper, a novel multi-layer control strategy is proposed. The approach has been proven to be an effective solution to deal with heterogeneous vehicles having limited acceleration capabilities. The performance in terms of a small spacing error, i.e., platoon cohesion, has been shown to improve significantly. The proposed algorithm is verified through simulations and experiments.

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