A Consensus-based Approach for Platooning with Inter-Vehicular Communications and its Validation in Realistic Scenarios

Stefania Santini *Member, IEEE*, Alessandro Salvi,
Antonio Saverio Valente, Antonio Pescapè *Senior Member, IEEE*,
Michele Segata *Student Member, IEEE*, Renato Lo Cigno *Senior Member, IEEE*

***Abstract*—Automated and coordinated vehicles' driving (platooning) is very challenging due to the multi-body control complexity and the presence of unreliable, time-varying wireless Inter-Vehicular Communication (IVC). We propose a novel controller for vehicle platooning based on consensus and analytically demonstrate its stability and dynamic properties. Traditional approaches assume the logical control topology as a constraint fixed a priori, and the control law is designed consequently; our approach makes the control topology a design parameter that can be exploited to reconfigure the controller depending on the needs and scenario characteristics. Furthermore, the controller automatically compensates outdated information caused by network losses and delays. The controller is implemented in PLEXE, a state of the art IVC and mobility simulator that includes basic building blocks for platooning. Analysis and simulations show the controller robustness and performance in several scenarios, including realistic propagation conditions with interference caused by other vehicles. We compare our approach against a controller taken from literature, which is generally considered among the most performing ones. Finally, we test the proposed controller by implementing the real dynamics (engine, transmission, braking systems, etc.) of heterogeneous vehicles in PLEXE and verifying that platoons remain stable and safe regardless of real life impairments that cannot be modeled in the analytic solution. The results show the ability of the proposed approach to maintain a stable string of realistic vehicles with different control-communication topologies even in the presence of strong interference, delays, and fading conditions, providing higher comfort and safety for platoon drivers.**

***Index Terms*—platooning; V2V; multiple time-varying communication delays; distributed consensus; Lyapunov-Razumikhin; VANET**

I. INTRODUCTION

THE idea of automated and coordinated vehicles' driving goes back to the PATH project in California during the eighties' [1]. Coordinated driving can improve driving experience by relieving humans from some driving duties and at the same time, by letting an automated system control the vehicle, improve safety. Moreover, by reducing inter-vehicle distances, cooperative driving can improve traffic flow and reduce fuel consumption. As such goals are not achievable using standard sensor-based Adaptive Cruise Control (ACC), the community started considering Cooperative Adaptive Cruise Control (CACC). What differentiates a CACC from a standard ACC is the use of wireless communication to share information such as speed and acceleration among vehicles, enabling the possibility to reduce inter-vehicle distance without compromising safety.

A group of coordinated vehicles is called a *platoon*. Building and managing a platoon requires multiple technologies. Essential to guarantee vehicles' coordination are: *i)* a control algorithm that regulates the relative distance with respect to the vehicle ahead and coordinates all vehicles to stabilize the platoon; and *ii)* a communication network to exchange information between vehicles. The control algorithm can use data received from multiple vehicles in the platoon [2], defining the *control topology*. As an example, the CACC designed in [3] considers data from the preceding vehicle only, while the one in [4] exploits data from the platoon leader as well. Current approaches assume a static control topology, which means that the design of the controller is based on a fixed communication pattern. If the communication pattern is different from the designed one, for example due to network impairments or platoon strategy, the CACC is not able to safely control the platoon anymore. The choice of the control topology is a hot topic in platooning research because the topology itself drives the behavior of the controller, but it also dictates network requirements. In the literature, indeed, we find studies that investigate the impact of several different topologies on the characteristics of the controller [5].

In this paper, we overcome this problem by developing a flexible control system that can be reconfigured based on the actual communication capabilities. This paper extends the state of the art proposing, and proving the viability of, a control approach for vehicle platooning based on a consensus algorithm specifically designed to cope with Inter-Vehicular Communication (IVC) heterogeneous and time varying delays.

A. Contribution

The contribution of this work includes a theoretical part and a part built on realistic simulations. On the theoretical side

"Copyright (c) 2015 IEEE. Personal use of this material is permitted. However, permission to use this material for any other purposes must be obtained from the IEEE by sending a request to pubs-permissions@ieee.org."

S. Santini, A. Salvi, A. S. Valente, and A. Pescapè are with University of Napoli Federico II, Italy, Email: {stefania.santini, alessandro.salvi, antoniosaverio.valente, pescape}@unina.it

M. Segata is with the University of Trento, Italy, E-Mail: msegata@disi.unitn.it

R. Lo Cigno is with the University of Trento, Italy, E-Mail: locigno@disi.unitn.it

The work has been partially funded by the S^2-MOVE (PON04a3_00058) and SIRIO (PON01 02425) projects.

we contribute a novel control algorithm based on a distributed consensus, with the goal of coordinating all vehicles to reach an equal inter-vehicle gap [6]. Our approach is specifically designed to take into account the communication logical topology, as well as impairments as delay and losses. We provide the details of the control design, the control-loop dynamics, and the analysis of the stability of the proposed algorithm. On the simulation side, we implement the controller in PLEXE [7], an extension of Veins [8], and we carry out experiments with platoons of eight and sixteen cars in a $10\,\mathrm{km}$, 4 lanes stretch of highway exploring realistic network-related impairments. The communication delay and losses are intrinsically modeled in PLEXE communication device (IEEE 802.11p card). We include in the simulation model detailed physical characteristics of vehicle dynamics, modeling the mass of the vehicles, the powertrain (engine, transmission, gears, wheels) that actuates the control law, and the resistance forces (rolling and air drag). To the best of our knowledge, this is the first time that real dynamics of vehicles are included in a detailed communication-level simulation of platooning, a very important step toward implementation, as impairments in the actuation phase may lead to steady state errors or even instabilities if the controller is not well designed. The final part of the paper presents a comparison with the well known CACC algorithm presented in [4] and shows that our proposal is string-stable even for large Packet Error Rates (PERs); furthermore additional control-communication topologies are explored, showing that the platoon remains stable, but the actual dynamic performance obviously changes. The parameters settings in simulations are a useful indication on how they can be chosen in the stability space of the controller. This paper is an extension of our preliminary work presented in [9].

The rest of the paper is organized as follows. Sec. II reviews the literature and motivates our work. Sec. III defines our control algorithm and proves its characteristics. Sec. IV defines the simulation scenarios we use in experiments and presents the relative results. In Sec. V we describe the theoretical laws that define realistic engine (and braking) dynamics. The model described in Sec. V is then used in Sec. VI to perform the simulation analysis of our approach under realistic vehicle dynamics and with different control-communication topologies. Finally, Sec. VII concludes the paper.

II. Scenario, Motivation, and Related Work

We assume a standard Dedicated Short Range Communications / Wireless Access in the Vehicular Environment (DSRC/WAVE) [10], [11] access network with beaconing messages, and proper integration of different components of a cooperative driving system (emergency braking [12], anti-collision techniques, etc.) that are not discussed in this work. The paper focuses on the algorithm necessary to form and stabilize a platoon, seeking a robust technique that is tolerant to errors and impairments. The scenario and dynamic model are those described in [4]. The dynamic model will be refined to model real cars with limited power, gears, and resistance forces in Sec. V.

Usually, in CACC strategies the controller parameters are tuned to attenuate the propagation of motion signals toward the tail of the platoon, i.e., to guarantee the so called *string stable* behavior once the platoon is engaged. Predecessor-following architectures based on pairwise interactions were shown to be highly sensitive to external disturbances and number of vehicles resulting into instabilities [13]. At the same time it is known that a speed dependent spacing policy based on *headway time* leads to a string stable platoon for choices of the headway time consistent with the platooning application [14]. Control methods to ensure platoon string stability exist under the assumption of the use of IVC without delays, i.e., the analytical stability analysis is carried out under the hypothesis of ideal communication [15]. This is not a realistic assumption, and communication delays are known to create hardly manageable string instability [16]. Recent research activities design CACC strategies able to mitigate the effects of communication delays (see for example [17], [18] and references therein). Given that communication effects and limitations are not explicitly accounted for during the control design, they are numerically investigated through sensitivity analysis, usually performed in presence of fixed, unique, and constant communication delay [16], [19]. Often, the performance and the stability of CACC strategies with respect to communication characteristics (as delay, packet losses, reliability, traffic and mobility dynamics) are studied with proper simulation tools like [8]. As an example of this research direction, in [20] the performance of a CACC control algorithm (and its robustness with respect to periodic disturbances on the leader dynamics) are discussed in the presence of packet losses, network failures and beaconing frequencies. The simulation framework is built with a CACC controller prototype (designed in [21]), a traffic simulator (SUMO), and a network simulator (OMNeT++). The communication behavior (based on IEEE 802.11p) is modeled using OMNeT++.

Although platoon vehicles are in general modeled like a string, different control topologies may arise depending on the communication pattern among vehicles, and how the information is used by the control algorithm. If we consider generic control topologies, the problem of stabilizing a platoon naturally integrates in the more general framework of multi-agent systems control [22]–[24]. Further examples of this very recent research direction can be also found in [25], where a leaderless strategy is proposed for three autonomous vehicles ideally moving in a circle and sharing information on a broadcast communication channel with a constant and common delay. Platooning as a weighted and constrained consensus control problem is also discussed in [6], with the goal of understanding the influence of the control topology on the platooning dynamics by using a discrete-time Markov chain, but without considering the effect of time-varying delays on the ensemble stability. The DSRC/WAVE communication channel is affected by shadowing and fading, and the use of Carrier Sense Multiple Access (CSMA) technique in a highly concurrent channel access, can result in packet losses [26]–[28], and thus highly variable and time dependent delays at the application level, possibly leading to instabilities in the control system. According to the literature and IVC standards, the frequency at which each vehicle has to broadcast its data must be no lower than $10\,\mathrm{Hz}$ [3], a value that imposes tight communication constraints, stresses the channel (shared by all vehicles), but finds its justification in the vehicle's dynamics, and thus can be considered a hard physical requirement.

Within this scenario, this paper tackles and solves the platoon control as a high order consensus problem accounting for time varying communication delays and vehicles dynamics. Detailed simulations in PLEXE (an extension of Veins), including realistic details such as vehicles' masses and inertia, actuation lags, packet losses and interfering traffic, show the performance of the proposed approach and its advantages. The idea is to find a proper decentralized control algorithm so that the emerging platoon topology, depending on the communication links, is asymptotically stable without the need of pre-establishing (with respect to the controller design) the topology. The main goal of the proposed approach is to guarantee the platoon stability in presence of heterogeneous and time-varying communication delays. This feature can be very important also in case of emergencies, when the control of vehicles must be returned to drivers, giving more time to perform this delicate action as the platoon remains stable for longer times. The control algorithm significantly enhances the theoretical analysis in [29], as it embeds velocity-dependent spacing policy and standstill requirements [21]. Furthermore, it overcomes the limitations of the stability analysis in [29] in which, for each vehicle, a unique aggregate delay (resulting from the fusion of different delays from different sources) was assumed. Simulation studies that put together detailed and reliable model of the communication systems toghether with realistic model of vehicle dynamics (as e.g. [30], [31]) are necessary to show the effectiveness of platoon strategies in real environments. Despite its relevance, the problem has been only recently tackled in the current literature [32] with the different aim of optimizing fuel consumption in mixed traffic scenario.

III. PLATOONING CONTROL

A. Mathematical Preliminaries and Nomenclature

The inter-vehicle communication structure can be modeled by a graph where every vehicle is a node. Hence, a platoon of N vehicles is represented as a directed graph (digraph) $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{A})$ of order N characterized by the set of nodes $\mathcal{V} = \{1, \dots, N\}$ and the set of edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$. The topology of the graph is associated to an adjacency matrix with nonnegative elements $\mathcal{A} = [a_{ij}]_{N\times N}$. In what follows we assume $a_{ij} = 1$ in the presence of a communication link from node j to node i, otherwise $a_{ij} = 0$. Moreover, $a_{ii} = 0$ (i.e., self-edges (i, i) are not allowed unless otherwise indicated). The presence of edge $(i, j) \in \mathcal{E}$ means that vehicle i can obtain information from vehicle j, but not necessarily *vice versa*. A path in a digraph is a sequence $i_0, i_1, \dots, i_l$ of distinct nodes such that $(i_{h-1}, i_h) \in \mathcal{E}, h = 1, 2, \dots, l$. If there exists a path from node i to node j, we say that j is reachable from i.

In the rest of the paper we consider N vehicles together with a leader vehicle taken as an additional agent labelled with the index zero, i.e., node 0. We use an augmented directed graph $\overline{\mathcal{G}}$ to model the platoon topology based on the communication pattern desired by the consensus algorithm, i.e., the existence of edge (i, j) means that i uses the information received by j and not only that i is within the communication range of j. We assume node 0 is *globally reachable* in $\overline{\mathcal{G}}$ if there is a path in $\overline{\mathcal{G}}$ from every node i in $\mathcal{G}$ to node 0 [33].

Before proceeding to design the consensus controller, we recall some useful results on the stability of delayed systems.

Let $C([-r, 0], \mathbb{R}^n)$ be a Banach space of continuous functions defined on an interval $[-r, 0]$ and taking values in $\mathbb{R}^n$ with a norm $||\varphi||_c = \max_{\theta\in[-r,0]} ||\varphi(\theta)||$, $||\cdot||$ being the Euclidean norm. Given a system of the form:

$$\begin{aligned} \dot{x} &= f(x_t), t > 0, \\ x(\theta) &= \varphi(\theta), \ \theta \in [-r, 0], \end{aligned} \tag{1}$$

where $x_t(\theta) = x(t + \theta), \forall\theta \in [-r, 0]$ and $f(0) = 0$, it holds:

Theorem 1. *(Lyapunov-Razumikhin) [34]. Given system Eq.* (1)*, suppose that the function $f : C([-r, 0], \mathbb{R}^n) \to \mathbb{R}^n$ maps bounded sets of $C([-r, 0], \mathbb{R}^n)$ into bounded sets of $\mathbb{R}^n$. Let ψ_1, ψ_2, and ψ_3 be continuous, nonnegative, nondecreasing functions with $\psi_1(s) > 0, \psi_2(s) > 0, \psi_3(s) > 0$ for $s > 0$ and $\psi_1(0) = \psi_2(0) = 0$. If there is a continuous function $V(t, x)$ (Lyapunov-Razumikhin function) such that:*

$$\psi_1(||x||) \le V(t, x) \le \psi_2(||x||), t \in \mathbb{R}, x \in \mathbb{R}^n, \tag{2}$$

and there exists a continuous non decreasing function $\psi_4(s)$ with $\psi_4(s) > s, s > 0$ such that:

$$\begin{aligned} &\dot{V}(t, x) \le -\psi_3(||x||) \\ &\textit{when } V(t + \theta, x(t + \theta)) < \psi_4(V(t, x(t))), \theta \in [-r, 0], \end{aligned} \tag{3}$$

then the solution $x = 0$ is uniformly asymptotically stable.

B. Consensus based Control Design

The goal of the platoon control is to regulate speed and relative distance of each vehicle with respect to its predecessor and the leading vehicle [15], [35]. Hence, a platoon is composed of a string of N vehicles plus the additional leading vehicle acting as a reference for the ensemble. In our analysis each vehicle is equipped with on-board sensors to measure its absolute position, speed and acceleration, while an IEEE 802.11p radio enables vehicle to share information among neighbors and to receive the leading vehicle information.

To solve the problem according to the framework of consensus in dynamic networks [36], the generic i-th vehicle dynamics can be described as the following inertial agent ($i = 1, \dots, N$):

$$\begin{aligned} \dot{r}_i(t) &= v_i(t) \\ \dot{v}_i(t) &= \tfrac{1}{M_i} u_i(t), \end{aligned} \tag{4}$$

where r_i [m] and v_i [m/s] are the i-th vehicle absolute position and speed; M_i [kg] is the i-th vehicle mass and the propelling force u_i denotes the control input to be appropriately chosen to achieve the control goal. Note that this modeling approach is not so unconventional since it has been also used in the classical literature on interconnected vehicles [15]. Moreover, assuming that a constant velocity must be imposed to the platoon, the leader motion at steady state must fulfill:

$$\begin{aligned} \dot{r}_0(t) &= v_0; \\ \dot{v}_0 &= 0. \end{aligned} \tag{5}$$

Given Eqs. (4) and (5), the problem of maintaining a desired inter-vehicle spacing policy and a common speed can be rewritten as the following high-order consensus problem:

$$\begin{aligned} & r_i(t) \rightarrow \tfrac{1}{\Delta_i}\left\{\sum_{j=0}^{N} a_{ij}\cdot\left(r_j(t)+d_{ij}\right)\right\} \\ & v_i(t) \rightarrow v_0. \end{aligned} \tag{6}$$

where d_{ij} is the desired distance between vehicles i and j; a_{ij} (for $i = 1,\ldots,N$ and $j = 0,\ldots,N$) models the platoon topology emerging from the presence/absence of a communication link between vehicles i and j; $\Delta_i = \sum_{j=0}^{N} a_{ij}$ is the degree of vehicle/agent i, i.e., the number of vehicles establishing a communication link with vehicle i. Note that according to [37] the desired spacing d_{ij} can be expressed as $d_{ij} = h_{ij}v_0 + d_{ij}^{st}$, where h_{ij} is the *constant time headway* (i.e., the time necessary to vehicle $i-$th to travel the distance to its predecessor), and d_{ij}^{st} is the distance between the vehicles $i-$th and $j-$th at standstill. Furthermore we remark that a_{ij} are the nonnegative elements of the adjacency matrix associated to the platoon topology directed graph $\overline{\mathcal{G}}$. In what follows we also assume that $a_{0j} = 0$ ($\forall j = 0,\ldots,N$), since the leader does not consider data from any other vehicle.

The platoon high-order consensus problem in Eq. (6) is solved here with the following decentralized control action embedding the spacing policy information as well as all the time-varying communication delays

$$\begin{aligned} u_i = -b\left[v_i(t)-v_0\right] - \frac{1}{\Delta_i}\sum_{j=0}^{N} k_{ij}a_{ij}\Big[r_i(t) - r_j(t-\tau_{ij}(t)) - \\ \tau_{ij}(t)v_0 - h_{ij}v_0 - d_{ij}^{st}\Big], \end{aligned} \tag{7}$$

where $k_{ij} > 0$ and $b > 0$ are control gains to be opportunely tuned to regulate the mutual behavior among neighbor vehicles; $\tau_{ij}(t)$ and $\tau_{i0}(t)$ are the time-varying communication delays affecting the i-th agent when information is transmitted from agent j and from the leader respectively (in general $\tau_{ij}(t) \neq \tau_{ji}(t)$). The delays are all bounded by a generic τ: $\tau_{ij}(t) \leq \tau$ [38], [39]. When the information a message is used by the controller, $\tau_{ij}(t)$ is known, since each message is stamped with GPS-based time, whose precision is better than $100\,\mathrm{ns}$. The information relative to the predecessor is integrated with the same measures taken by on-board sensors (like radar, lidar, camera), thus improving the overall precision of measures.

C. Closed-loop Dynamics

In this section we analytically prove the closed-loop stability of the platoon under the action of the consensus-based control. The proof of stability is based on the recast of the closed-loop dynamics as a set of functional differential equations for which it is possible to find a quadratic Lyapunov-Razumikhin function [34] and, hence, asymptotic stability is proven in the presence of heterogeneous time-varying communication delays.

We define the position and speed errors of vehicle $i,\ i = 1,\ldots,N)$ with respect to position and speed of the leader $r_0(t), v_0$ respectively:

$$\begin{aligned} & \bar{r}_i = (r_i(t) - r_0(t) - h_{i0}v_0 - d_{i0}^{st}); \\ & \bar{v}_i = (v_i(t) - v_0). \end{aligned} \tag{8}$$

Re-writing the coupling control action u_i in terms of the state errors $\bar{r}_i$ and $\bar{v}_i$ and expressing headway constants h_{ij} and standstill distances d_{ij}^{st} with respect to the leading vehicle, namely $h_{ij} = h_{i0} - h_{j0}$ and $d_{ij}^{st} = d_{i0}^{st} - d_{j0}^{st}$, after some algebraic manipulation the closed-loop dynamics can be rewritten as:

$$\begin{cases} \dot{\bar{r}}_i = \bar{v}_i, \\ M_i\dot{\bar{v}}_i = -\frac{1}{\Delta_i}(k_{i0}a_{i0} + \sum\limits_{j=1}^{N} k_{ij}a_{ij})\bar{r}_i - b\bar{v}_i\left(t\right) + \\ \qquad + \frac{1}{\Delta_i}\sum\limits_{j=1}^{N} k_{ij}a_{ij}\left[\bar{r}_j\left(t-\tau_{ij}\left(t\right)\right)\right]. \end{cases} \tag{9}$$

To describe the platoon dynamics in presence of the time-varying delays associated to the different links in a more compact form we define the position and speed error vectors as $\bar{r} = \left[\bar{r}_1,\ldots,\bar{r}_i\ldots,\bar{r}_N\right]^\top$, $\bar{v} = \left[\bar{v}_1,\ldots,\bar{v}_i\ldots,\bar{v}_N\right]^\top$, and the error state vector as $\bar{x}\left(t\right) = \left[\ \bar{r}^\top\left(t\right)\bar{v}^\top\left(t\right)\ \right]^\top$. Moreover to exploit a compact notation we order all the different delays $\tau_{ij}(t)$ as elements of the set $\{\tau_{ij}(t) : i,j = 1,2,\ldots,N, i \neq j\}$. Each element in the set can be indicated as $\tau_p(t)$ with $p = 1,2,\ldots,m$ being $m \leq N(N-1)$; m is equal to its maximum, $N(N-1)$, only if the platoon topology is represented by a directed complete graph and all time delays are different.

According to the above definitions, the closed loop platoon dynamics can be represented as the following set of functional differential equations:

$$\dot{\bar{x}}\left(t\right) = A_0\bar{x}\left(t\right) + \sum_{p=1}^{m} A_p\bar{x}\left(t-\tau_p\left(t\right)\right), \tag{10}$$

where m is the total number of application level logical links and

$$A_0 = \begin{bmatrix} 0_{N\times N} & I_{N\times N} \\ -M\widetilde{K} & -M\widetilde{B} \end{bmatrix};\ A_p = \begin{bmatrix} 0_{N\times N} & 0_{N\times N} \\ M\widetilde{K}_p & 0_{N\times N} \end{bmatrix} \tag{11}$$

being

$$M = \mathrm{diag}\left\{\frac{1}{M_1},\ldots,\frac{1}{M_N}\right\} \in \mathbb{R}^{N\times N}; \tag{12}$$

$$\widetilde{B} = \mathrm{diag}\{b,\ldots,b\} \in \mathbb{R}^{N\times N}; \tag{13}$$

$$\widetilde{K} = \mathrm{diag}\left\{\tilde{k}_{11},\ldots,\tilde{k}_{NN}\right\} \in \mathbb{R}^{N\times N},\ \text{with}\ \tilde{k}_{ii} = \frac{1}{\Delta_i}\sum_{j=0}^{N} k_{ij}a_{ij}; \tag{14}$$

and $\tilde{K}_p = [\bar{k}_{pij}] \in \mathbb{R}^{N\times N}$ $(p = 1,\ldots,m)$ the matrix defined according to the formalism adopted in [40] as:

$$\bar{k}_{pij} = \begin{cases} \frac{a_{ij}k_{ij}}{\Delta_i}, & j \neq i, \tau_p(\cdot) = \tau_{ij}(\cdot), \\ 0, & j \neq i, \tau_p(\cdot) \neq \tau_{ij}(\cdot). \\ 0, & j = i. \end{cases} \tag{15}$$

D. Stability Analysis

From the Leibniz-Newton formula it is known that [41]:

$$\bar{x}\left(t-\tau_p(t)\right) = \bar{x}\left(t\right) - \int_{-\tau_p(t)}^{0} \dot{\bar{x}}\left(t+s\right)ds. \tag{16}$$

Hence, substituting Eq. (10) in Eq. (16) we have:

$$\bar{x}\left(t-\tau_p(t)\right)=\bar{x}\left(t\right)-\sum_{q=0}^{m}A_q\int_{-\tau_p(t)}^{0}\bar{x}\left(t+s-\tau_q\left(t+s\right)\right)ds, \tag{17}$$

where matrices $A_0, A_1, \dots, A_m$ are defined in Eq. (11) and $\tau_0\left(t+s\right)\equiv 0$. Using the above transformation, the time-delayed model (Eq. (10)) can be transformed into:

$$\begin{aligned}\dot{\bar{x}}\left(t\right)&=A_0\bar{x}\left(t\right)+\sum_{p=1}^{m}A_p\bar{x}\left(t\right)+\\ &-\sum_{p=1}^{m}\sum_{q=0}^{m}A_pA_q\int_{-\tau_p(t)}^{0}\bar{x}\left(t+s-\tau_q\left(t+s\right)\right)ds.\end{aligned} \tag{18}$$

From the definition in Eq. (11) it follows that $A_pA_q=0$ when $p=1,\dots m$ and $q=1,\dots,m$. Hence the system defined in Eq. (10) can be rewritten as:

$$\dot{\bar{x}}\left(t\right)=F\bar{x}\left(t\right)-\sum_{p=1}^{m}C_p\int_{-\tau_p(t)}^{0}\bar{x}\left(t+s\right)ds \tag{19}$$

where

$$C_p=A_pA_0=\begin{bmatrix}0_{N\times N} & 0_{N\times N}\\ 0_{N\times N} & M\widetilde{K}_p\end{bmatrix}, \tag{20}$$

and

$$F=A_0+\sum_{p=1}^{m}A_p=\begin{bmatrix}0_{N\times N} & I_{N\times N}\\ -M\widehat{K} & -M\widetilde{B}\end{bmatrix}, \tag{21}$$

with

$$\widehat{K}=-\sum_{p=1}^{m}\widetilde{K}_p+\widetilde{K}. \tag{22}$$

Furthermore the following Lemmas hold:

Lemma 1. *Supposing* $k_i=\frac{k_{i0}a_{i0}}{\Delta_i}\geq 0\ (i=1,\dots,N)$*, the matrix* $\widehat{K}$ *in Eq.* (22) *is positive stable if and only if node* 0 *is globally reachable in* $\overline{\mathcal{G}}$.

According to Lemma 1 the following matrix

$$\widehat{K}_M=M\widehat{K} \tag{23}$$

is also positive stable since $M>0$ (Eq. (12)).

Lemma 2. *Let* F *be the matrix defined in Eq.* (21)*.* F *is Hurwitz stable if and only if* $\widehat{K}_M$ *(Eq. (23)) in Lemma 1 is positive stable and*

$$b>b^{\star}=\max_i\left\{\frac{|Im(\mu_i)|}{\sqrt{Re(\mu_i)}}M_i\right\} \tag{24}$$

being μ_i *the i-th eigenvalue of* $\widehat{K}_M$ $(i=1,\dots,N)$.

Lemmas 1 and 2 can be proved extending the proof in [29] to the case of closed-loop matrices depending from $m\leq N(N-1)$ time-varying delays. Platoon stability can be now proved as follows.

Theorem 2. *Consider the system defined in Eq.* (10) *and take the control parameters in Eq.* (7) *according to Lemmas 1 and 2 so that matrix* F *in Eq.* (21) *is Hurwitz stable. Then, there exists a constant* $\tau^\star>0$ *such that, when* $0\leq\tau_p(t)\leq\tau<\tau^\star$ $(p=1,\dots,m)$,

$$\lim_{t\to\infty}\overline{x}(t)=0, \tag{25}$$

if and only if node 0 *is globally reachable in* $\overline{\mathcal{G}}$.

Proof. (*Sufficiency*). Since node 0 is globally reachable in $\overline{\mathcal{G}}$, from Lemma 1 it follows that the matrix $\widehat{K}_M$ is positive stable. Setting b as in Eq. (24), the hypothesis of Lemma 2 is satisfied, hence the matrix F defined in Eq. (21) is Hurwitz stable and from Lyapunov theorem there exists a positive definite matrix $P\in\mathbb{R}^{2N\times 2N}$ such that

$$PF+F^\top P=-Q;\quad Q=Q^\top>0. \tag{26}$$

Consider the following Lyapunov-Razumikhin candidate function (i.e., satisfying condition of Lyapunov-Razumikin Theorem 1)

$$V(\overline{x})=\overline{x}^\top P\overline{x}. \tag{27}$$

From Eq. (19), taking the derivative of V along Eq. (10) gives

$$\dot{V}(\overline{x})=\overline{x}^\top(PF+F^\top P)\overline{x}-\sum_{p=1}^{m}2\overline{x}^\top PC_p\int_{-\tau_p(t)}^{0}\overline{x}(t+s)ds. \tag{28}$$

Now for any positive definite matrix Ξ it is possible to show that $2a^\top c\leq a^\top\Xi a+c^\top\Xi^{-1}c$ according to [33]. Therefore, setting $a^\top=-\overline{x}^\top PC_p$, $c=\overline{x}(t+s)$, $\Xi=P^{-1}$, and integrating both sides of the inequality, we can write

$$\begin{aligned}\dot{V}(\overline{x})\leq{}&\overline{x}^\top(PF+F^\top P)\overline{x}+\sum_{p=1}^{m}[\tau_p(t)\overline{x}^\top PC_pP^{-1}C_P^\top P\overline{x}+\\ &+\int_{-\tau_p(t)}^{0}\overline{x}^\top(t+s)P\overline{x}(t+s)ds].\end{aligned} \tag{29}$$

According to the hypotheses of the Lyapunov-Razumikin Theorem [34], choose now the following continuous non decreasing function $\psi_4(s)=qs$ (for some constant $q>1$) and the continuous, non negative, non decreasing function $\psi_3(s)=(\lambda_{\min}(Q)-\tau\lambda_{\max}(H))s^2$; being $\lambda_{\min}(Q)$ the minimum eigenvalue of Q; $\lambda_{\max}(H)$ the maximum eigenvalue of the matrix H defined as $H=\sum_{p=1}^{m}PC_pP^{-1}C_P^\top P+qP$;

$$\tau<\tau^\star=\frac{\lambda_{\min}(Q)}{\lambda_{\max}(H)}. \tag{30}$$

After some simple algebraic manipulations, when

$$V(\overline{x}(t+\theta))<\psi_4(V(\overline{x}))=qV(\overline{x}(t)),\ -\tau\leq\theta\leq 0, \tag{31}$$

Eq. (29) becomes

$$\dot{V}(\overline{x})\leq-(\lambda_{\min}(Q)-\tau\lambda_{\max}(H))||\overline{x}||^2=-\psi_3(||\overline{x}||), \tag{32}$$

which proves sufficiency.
(*Necessity*). Eq. (10) is asymptotically stable for any time delay $\tau_p(t)<\tau^\star$, $p=1,\dots,m$. Letting $\tau_p(t)\equiv 0$ $(p=1,\dots,m)$ in Eq. (10), it follows from Eq. (19) that system $\dot{\overline{x}}=F\overline{x}$ with F defined in Eq. (21) is asymptotically stable. As all the eigenvalues of F have negative real parts, Lemma 2 implies that $\widehat{K}_M$ is positive stable. Now applying Lemma 1 the theorem is proven. □

We remark that Lemma 2 allows the computation of a lower bound $b^\star$ that delimits the tuning region of b for a given topology. As usual in tuning procedures the value of the

Table I
NETWORK SIMULATION PARAMETERS.

Parameter	Value
Path loss model	Free space ($\alpha = 2.0$)
Fading model	Nakagami-m ($m = 3$)
PHY/MAC model	IEEE 802.11p/1609.4 single channel (CCH)
Frequency	5.89 GHz
Bitrate	6 Mbit/s (QPSK R = 1/2)
Access category	AC_VI
MSDU size	200 B (byte)
Transmit power	20 dBm
Beacon frequency	10 Hz

Table II
TRAFFIC SIMULATION PARAMETERS FOR THE REALISTIC SCENARIO.

Freeway length	10 km
Lanes	4 (two-way)
Cars percentage (length 4 m)	50 %
Trucks percentage (length 20 m)	20 %
Vans percentage (length 5 m)	30 %
Inter-vehicle time	$\sim \exp(0.7276/\mathrm{s})$ ($\mathbb{E}[X] = 1.374\,\mathrm{s}$ [48]
Cars' speed	$\sim U(100\,\mathrm{km/h}, 160\,\mathrm{km/h})$
Trucks' speed	80 km/h
Vans' speed	100 km/h
Platoon size	8 and 16 cars
Platooning car max acceleration	$2.3\,\mathrm{m/s^2}$
Platooning car mass	1460 kg
Platooning car length l_i	4 m
Headway time h_{ij}	0.8 s
Control gains k_{ij}	$k_{10} = 460$, $k_{i0} = 80$ ($i \neq 0, i \neq 1$) $k_{ij} = 860$ otherwise
Control gain b	$b = 1800$
Distance at standstill d^{st}	15 m
Freeway fill-up time	500 s
Network warm-up time	10 s
Data recording time	50 s

control gain can be chosen by designers within the stability region (bounded by $b^\star$) so to achieve the desired dynamic performances. It is clear that during the implementation phases, the different lower bounds for every topology that may arise in the practice can be easily computed (according to Eq. (24)). Designers can consider the common lower bound (namely the maximum value assumed by $b^\star$) if they want to guarantee with a unique choice of the gain value the stability of the matrix F in all cases of interest. Here we follow this approach and we select a unique value for gain b suitable for all topologies where node 0 is globally reachable in $\bar{\mathcal{G}}$.

The string stability can be analyzed in the frequency domain following the approach in [21], [42] by setting all the different time varying delays of each logical link to a unique and constant upper bound ($\tau^\star$ worst case analysis) and then deriving in the Laplace domain the complementary sensitivity functions exploiting a first-order Padé approximation for the delay. The gains can be selected inside the consensus region (defined by Lemmas 1 and 2) according to this approach. Limitations to the design of a string stable platoon arise with fixed spacing policy [43], [44] in the absence of information path with the leader, while this requirement is not necessary with a spacing policy that depends from the leader velocity [45]. Finally, note that in this work the specific value selected for the implementation (and reported in Tab. II) have been set with a trial and error approach. Future research work will be devoted to the design and the implementation of automatic tuning procedures, for example based on an LMI approach [46], [47], to optimize the gains choice with respect to delay bound, achievable performance and disturbance attenuation.

IV. EXPERIMENTAL ANALYSIS

A. Network and Vehicular Traffic Scenario

We use the PLEXE simulator described in [7], based on Veins [8], where the traditional CACC proposed in [4] is already available, and the actuation lag (i.e., the delay between the control decision and its actual realization in the vehicle due to inertial and mechanical limits) is accurately modeled. It permits the investigation of platooning systems by coupling realistic vehicle dynamics with realistic wireless network simulation. We extend the simulator by implementing Eq. (7) in the simulator as a new platoon control system. The simulation code is available to the community through the PLEXE website[1].

[1]http://plexe.car2x.org/

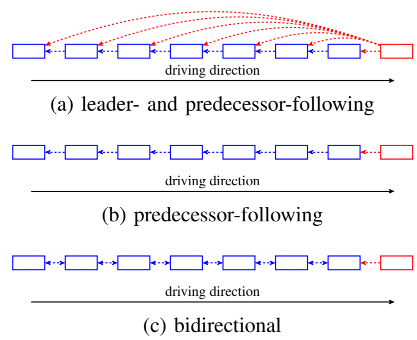


Figure 1. Control topologies selected for the simulations.

Regarding the channel models, in this work we test our approach using ideal communication (without losses) and in a realistic scenario where non-platoon vehicles transmit beacons generating interference. In [9] we considered a Bernoullian and a Gilbert-Elliott channel as well. For the sake of brevity, we omit those results. For the realistic scenario, the channel model is a free-space path loss coupled with Nakagami-m fading. We use a fully fledged IEEE 802.11p/1609.4 model configured with typical parameters, and consider a beacon frequency of 10 Hz, both for automated and human-driven vehicles. Note that the theoretical upper bound of the delay computed as in Eq. (30) is $\tau^\star = 1.5 \cdot 10^{-2}$ [s] which is above the typical bound of the IEEE 802.11p standard [17]. Concerning the road traffic simulation we consider different kind of vehicles traveling in both directions. The simulation includes cars, vans, and trucks with different percentages and speeds, which are injected with an exponentially distributed inter-vehicle time. At simulation time 500 s the platoon is injected in the middle of the freeway and communication is enabled. After a warm-up time of 10 s we start to record motion data about vehicles in the platoon. Tabs. I and II summarize all relevant parameters for both network and traffic simulation.

To show the stability and robustness of the proposed control strategy we perform an experimental analysis involving different driving leader maneuvers, in particular: (i) Consensus: starting from different initial conditions, the platoon has to

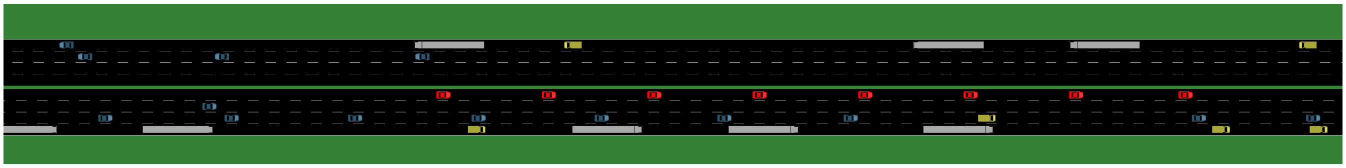
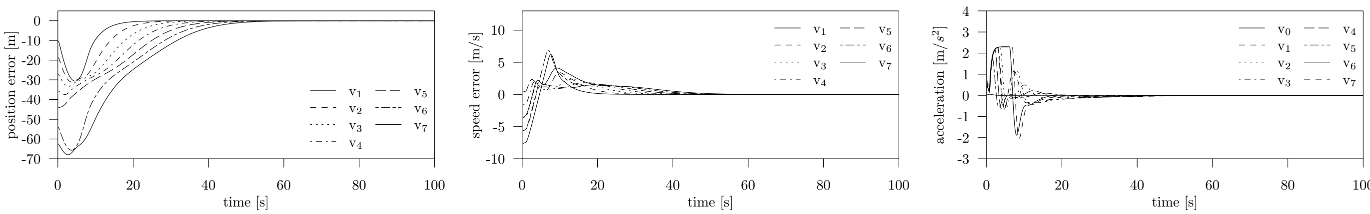


Figure 2. Screenshot of the realistic scenario. Human-driven vehicles in white, blue, and yellow, and platooning cars in red on the left-most lane.



(a) (b) (c)

Figure 3. Basic convergence analysis with $v_0 = 100\,\mathrm{km/h}$, $N+1=8$ vehicles. Platoon creation and maintenance: (a) time history of the position errors computed as $r_i(t) - r_0(t) - h_{i0}v_0 - d_{i0}^{st}$; (b) time history of the vehicle speeds error with respect to the leader computed as $v_i(t) - v_0$; (c) time history of the control effort in ms^{-2}.

reach and than maintain the reference behavior as imposed by the leader according to the desired spacing policy; (ii) Leader tracking: followers have to correctly track the time-varying leader speed; (iii) Sinusoidal: a periodic disturbance is acting on the leader motion. The chosen control topology is the one considered in [49] and coherent with [4], where the leader communicates with all the vehicles in broadcast, and every other vehicle also consider information from its predecessor to compute the control action (see Fig. 1a). We remark that the algorithm convergence is not restricted to the case of classical predecessor-following architecture based on pairwise interactions [3], but it ensures platoon stability for all those topologies that satisfy hypotheses of Theorem 2. We show this capability in Sec. IV-C by considering other two communication topologies. Moreover, we carry out a brief comparison with a classical CACC [4] control technique. Fig. 2 shows a screenshot of the simulation. In practice, vehicles in the platoon do not know the steady state values of the leader kinematic variables, but only their current measurements that they receive from the leader with some delay. Therefore, for the practical real-time computation of the desired spacing policy d_{ij} in the protocol Eq. (7), we consider in PLEXE the current measurement of the leader velocity $v_0(t)$.

B. Basic Convergence Analysis

We consider a platoon composed of 7 vehicles plus a leader with no packet losses. Control parameters are tuned inside the consensus region according to Theorem 2 to achieve acceptable transient performance and to guarantee string stability. The selected control parameters are reported in Tab. II. Figs. 3a and 3b show the results for the consensus scenario. The results confirm the ability of the proposed approach of creating and maintaining the platoon. All vehicles – starting from distances different from the one required by the spacing policy – reach the consensus and converge toward the desired positions and the leader speed, despite the presence of network delays during the information exchange. Furthermore, according to the theoretical derivation, the control effort (acceleration) reduces to zero

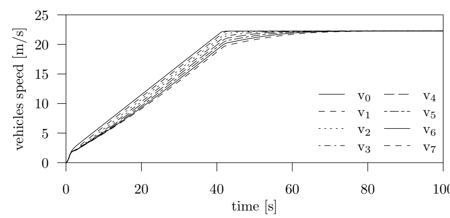


Figure 4. Leader tracking maneuver: time history of the vehicle speeds.

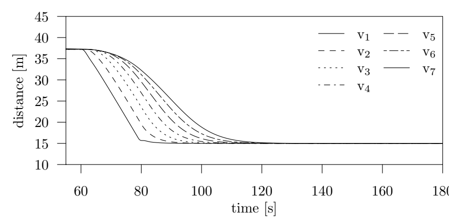


Figure 5. Braking maneuver: time history of bumper to bumper distances computed as $r_{i-1}(t) - r_i(t) - l_{i-1}$.

once the control goal is achieved, as depicted in Fig. 3c. The consensus is theoretically guaranteed for a constant leader speed, but to investigate control robustness w.r.t. different driving scenario, we test the ability of the proposed strategy in *tracking the leader*. As an example of this investigation, results in Fig. 4 show that the approach is able to achieve tracking by bringing all vehicles to the required speed and mutual positions (not shown), when the leader accelerates from $0\,\mathrm{km/h}$ to $90\,\mathrm{km/h}$ (with a constant acceleration of $0.5\,\mathrm{m/s^2}$).

To confirm the tracking performance of our algorithm, we test the controller in a braking scenario. Results in Fig. 5 show how the platoon reacts in the case of a braking maneuver performed by the leader from $100\,\mathrm{km/h}$ to a full stop. The platoon maintains the secure inter-vehicular distance, avoids collisions, and converges to stand-still distances at rest.

We dedicate further experiments to investigate if and how speed and acceleration fluctuations are attenuated downstream the string of vehicles of the platoon (*string stability*) when a periodic disturbance is acting on leader's speed. Results in

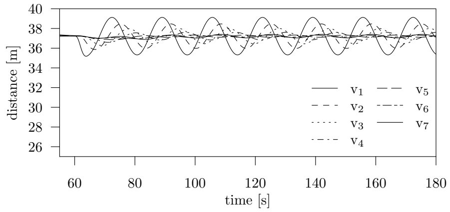


Figure 6. Robustness with respect to the sinusoidal disturbance (Eq. (33)) acting on the leader speed: time history of bumper to bumper distances computed as $r_{i-1}(t) - r_i(t) - l_{i-1}$.

Fig. 6, referring to a sinusoidal disturbance defined as

$$\delta(t) = A\ \cos\left(\frac{6}{100}\pi t\right), \quad A = 2.7\,\mathrm{m/s}, \tag{33}$$

confirm the string stable behavior of the platoon. The distance with respect to the preceding vehicle shows that the sinusoidal disturbance is attenuated downstream the string of vehicles.

As final test, we check the convergence for a platoon of 16 vehicles. The platoon still reaches the consensus conditions (Figs. 7a and 7b) and shows a string stable behavior (Fig. 7c). Moreover in this scenario we have re-tuned the controller to ensure a constant and very small (5 m) bumper to bumper distance and not a constant time headway.

C. Behavior under Different Topologies

To prove the flexibility of the controller, we test the algorithm for three control topologies, namely leader- and predecessor-following (Fig. 1a), predecessor following (considering only front vehicle information, Fig. 1b), and bidirectional (considering information from the vehicles directly in front and behind, Fig. 1c). In particular, we test standard convergence (i.e., constant speed) and the behavior under a sinusoidal disturbance. Fig. 8 shows the performance in terms of speed error with respect to the leading vehicle for standard convergence. The figure shows that, independently from the chosen topology, the algorithm converges to the desired speed value with, however, different behaviors. Comparing the bidirectional topology (Fig. 8b) with the leader- and predecessor-following one (Fig. 8a) we can see a lower speed error but a larger convergence time. Namely bidirectional topology shows better performance during transient while it discloses a very small residual steady state error with respect to the consensus goal. This difference occurs because of the selfish behavior of the leader- and predecessor-following topology. With a bidirectional topology each vehicle action considers the distance error to the previous vehicle as well. On the other hand, the predecessor topology behaves similarly to the leader- and predecessor-one, with only minor differences.

Concerning the sinusoidal scenario, Fig. 9 shows speed as a function of time for the three topologies. Independently from the topology, the algorithm shows a stable behavior. As for the convergence scenario, the bidirectional topology causes the algorithm to consider what the following vehicle is doing, resulting in a much more coherent action. Better performance are instead obtained in the case of leader- and predecessor-following and predecessor-following. Indeed, all vehicles behave similarly in terms of absolute speed.

Even though the high-level characteristics change with the control topology, the results show that the algorithm can safely be re-configured depending on networking performance.

D. Simulations in High Density Traffic Scenario

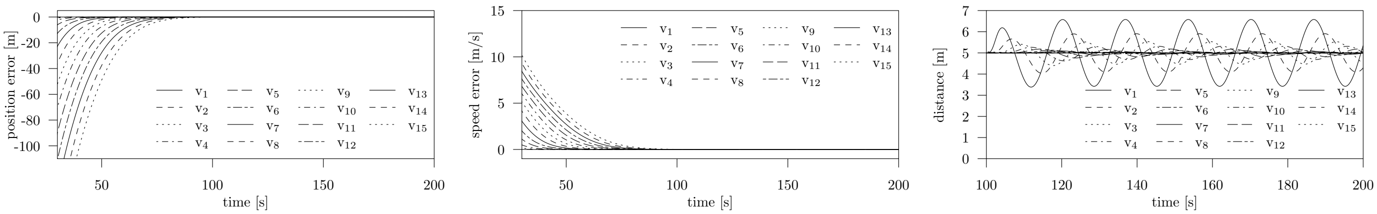
In the realistic freeway scenario described in Sec. IV-A, we simulate the consensus, the leader tracking, and the sinusoidal disturbance, but for the sake of brevity we report the results of the tracking and the sinusoidal ones only. Fig. 10 shows the speed profiles as function of time for the vehicles in the platoon for the leader tracking scenario. The leader accelerates from $80\,\mathrm{km/h}$ to $130\,\mathrm{km/h}$ with a constant acceleration of $1.5\,\mathrm{m/s^2}$. Despite the interferences caused by other vehicles, all cars in the platoon correctly track the leader's maneuver, and the differences with Fig. 4 are minor. In the second scenario, the leader accelerates and decelerates in a sinusoidal fashion around the average speed of $110\,\mathrm{km/h}$ with a frequency of $0.2\,\mathrm{Hz}$. Fig. 11 reports the bumper-to-bumper distance for all the cars in the platoon. As in Fig. 6, the controller successfully maintains string-stability by attenuating the error along the platoon. Indeed, the oscillation is barely noticeable already at vehicle number 3. Nevertheless, there are minor imperfections caused by packet losses. For example, between simulation times $602\,\mathrm{s}$ and $606\,\mathrm{s}$, it can be noticed that vehicle 7 looses its reference position. The error is however in the order of $20\,\mathrm{cm}$, thus the system can still be considered safe and robust.

E. A Brief Comparison with a Traditional Controller

We compare the performance of our approach against the CACC of the PATH project [4, Chapter 7], which is considered one of the most performing controllers in the literature. We experimentally compare the algorithms in terms of string-stability under Bernoullian packet losses for the sinusoidal disturbance scenario (Eq. (33)). While the consensus algorithm well preserves its performance with PERs up to $60\,\%$, the CACC becomes string unstable (see Fig. 12). This depends from the ability of our approach to explicitly compensate outdated information using timestamps in packets to estimate the delay (without approximating it to a constant unique nominal value), thus correcting the measurements in case of packet losses.

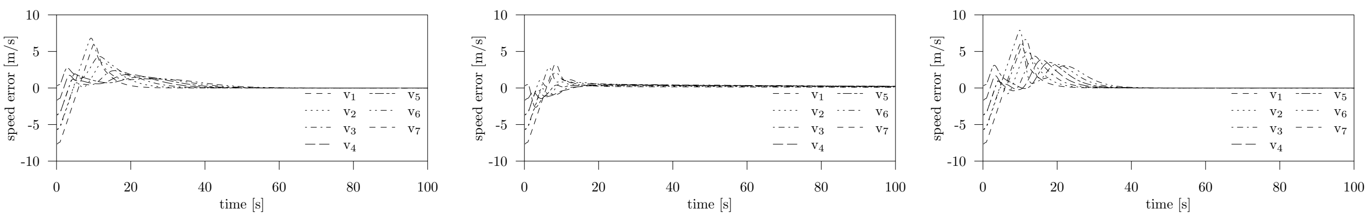
V. Realistic Vehicle Dynamics

Platoon performance strongly depends on the ability of the vehicles to actuate the accelerations as planned by the control strategy. The required vehicle acceleration is imposed by using either the throttle or the braking system according to a hierarchical architecture composed by an upper-level and a lower-level controller [4], [50]. The former, which is the formation control strategy (in our case the consensus-based controller), determines the desired acceleration exploiting positions and velocities information collected from the neighbors. The latter is instead locally used to generate the throttle and/or the brake commands required to exactly track the acceleration trajectories planned by the upper-level strategy. In this work we consider the classical two-component architecture, but in the literature other architectures exist [51].



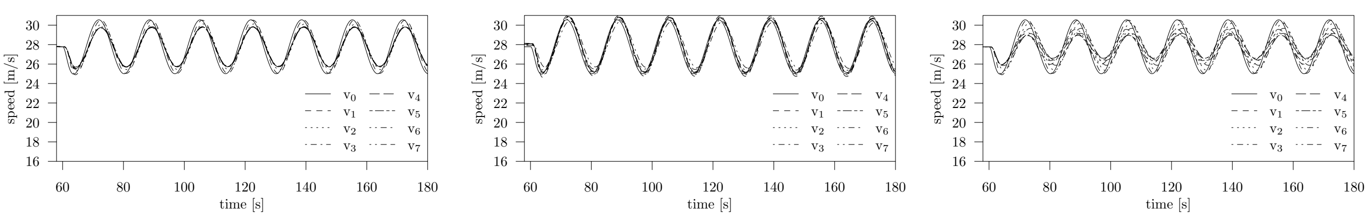
(a) (b) (c)

Figure 7. Platoon of $N+1=16$ vehicles. (a) Platoon creation and maintenance: time history of the position errors computed as $r_i(t)-r_0(t)-h_{i0}v_0-d_{i0}^{st}$; (b) time history of the vehicles' speed error with respect to the leader computed as $v_i(t)-v_0$. (c) Robustness with respect to the sinusoidal disturbance (Eq. (33)) acting on the leader speed: time history of bumper to bumper distance computed as $r_{i-1}(t)-r_i(t)-l_{i-1}$.



(a) leader- and predecessor-following (b) bidirectional communication (c) predecessor-following

Figure 8. Consensus performance in terms of speed error for the standard convergence scenario and three different control topologies.



(a) leader- and predecessor-following (b) bidirectional communication (c) predecessor-following

Figure 9. Consensus performance in terms of speed for the sinusoidal scenario and three different control topologies.

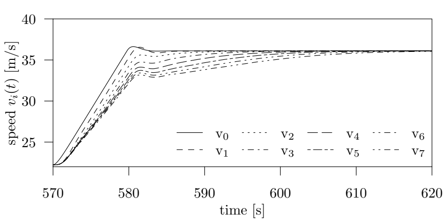


Figure 10. Leader tracking maneuver in the realistic network scenario: time history of vehicles' speed.

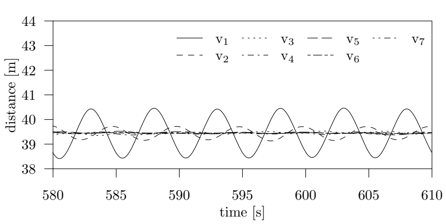
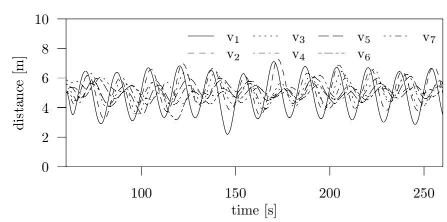
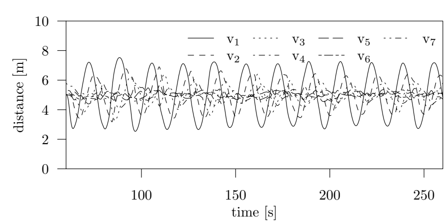


Figure 11. Sinusoidal disturbance on leader motion in the realistic network scenario: bumper to bumper distances computed as $r_{i-1}(t)-r_i(t)-l_{i-1}$.



(a) PATH's CACC



(b) Consensus

Figure 12. Bumper to bumper distances for the sinusoidal scenario in presence of Bernoullian packet losses (PERs of 60 %).

Realistic vehicular traction force, which is clearly bounded and depends on the mechanical and aerodynamic vehicular characteristics, limits the achievable acceleration and velocity profiles in practical scenarios and, hence, induces large transients during maneuvers and degrades performance. The theoretical derivation ensures upper-level control stability, but it is fundamental to test robustness using detailed non-linear models of the vehicle dynamics on the road. In the following we investigate the platoon behavior in presence of non-linear vehicles dynamics (e.g., engine dynamics, gear box status, friction and inertial forces) that are not explicitly considered during the design of the upper-level strategy. We conduct a simulation campaign with a non homogeneous platoon composed of four types of vehicles, randomly assigning the different traction characteristics to the 8 vehicles of the platoon. We take the real parameters for an Audi A3 2.0 TDI, a BMW 1 Series 2.0, a Mini Cooper 1.6, and an Alfa Romeo 147 1.6 Twin Spark. For the sake of brevity, we do not list all the parameters (gear ratios, engine power, ...) as they can easily be found online. We perform the experimental analysis involving the same maneuvers proposed in Sec. IV-B.

A. Realistic Vehicle Model in PLEXE

By default in PLEXE the engine-to-wheel (the drivetrain for short) dynamics are simulated with a first order linear filter, as commonly assumed in platooning literature [3], [4]. The longitudinal dynamics are approximated assuming that the actual acceleration $\ddot{r}$ of the vehicle tracks the desired acceleration $\ddot{r}_{\text{des}}$ provided by the control strategy u following the simple law [4], [13]:

$$\ddot{r} = \frac{1}{1+\tau_a s}\ddot{r}_{\text{des}}, \tag{34}$$

where r is the actual longitudinal position of the vehicle and τ_a the actuation lag (fixed to $0.5\,\text{s}$). This implies that the actual acceleration $\ddot{r}$ is not bounded by realistic actuation constraints as, for instance, imposed by the gear box status.

We extend the default vehicle model embedded in PLEXE by adding friction, vehicle inertial forces, effective traction characteristics, gear box status, actuator dynamics and speed-depended lags. The model assumes only longitudinal motion of vehicles, thus neglecting roll, pitch, and yaw of the vehicle chassis. These assumptions are not restrictive because we are focusing on the longitudinal control of the platoon. We derive fundamentals equations for the vehicle dynamics using the generalized Newton's second law and the D'Alembert's principle.

Consider the following force balance:

$$F_i = \lambda m\dot{v} = F_u - F_F, \tag{35}$$

where F_i is the inertial force acting on the vehicle, m and v are the vehicle mass and speed, respectively, and λ is the mass factor that takes into account the rotational inertia of the drivetrain. F_u is the effective traction force and F_F is the total friction force acting on the vehicle. The latter is defined as [30], [52]:

$$F_F = F_A + F_R + F_G, \tag{36}$$

where F_A is the air drag [30], F_R is the rolling resistance [31], and F_G is the gravitational force:

$$F_A = \frac{1}{2}c_{\text{air}}A_L\rho_a v^2, \tag{37}$$

$$F_R = mg\left(c_{r1} + c_{r2}v^2\right), \tag{38}$$

$$F_G = mg\sin\left(\theta_{\text{road}}\right), \tag{39}$$

where c_{air} is the air drag coefficient; A_L is the maximum vehicle cross section area; ρ_a is the air density; c_{r1} and c_{r2} are parameters that depend on the kind of tires and tire pressure; g is the gravitational acceleration; and θ_{road} the slope of the road expressed in degrees.

From Eq. (35) and by taking into account the unavoidable actuation lag, the model describing the longitudinal motion can be written as:

$$\begin{cases} \dot{r} = v \\ \dot{v} = \frac{1}{\lambda m}\frac{1}{1+\tau(v)s}F_u - \frac{1}{\lambda m}F_F, \end{cases} \tag{40}$$

where $\tau(v)$ is the speed-dependent lag during acceleration and braking maneuvers.

The traction force F_u in Eq. (40) can be either a propelling or a braking force according to the acceleration/deceleration requirements $\ddot{r}_{\text{des}}$ imposed by the upper-level control u during automatic driving. In the first case F_u is generated by the engine, while in the second case it is originated by the friction between disks and pads:

$$F_u = \begin{cases} -F_{\text{brake}} & \text{if} \quad \ddot{r}_{\text{des}} \leq 0 \\ F_{\text{eng}} & \text{if} \quad \ddot{r}_{\text{des}} > 0. \end{cases} \tag{41}$$

F_u is bounded ($F_{u\text{min}} \leq F_u \leq F_{u\text{max}}$) due to the limits of the propelling and braking forces that can be effectively provided in each operating condition depending from the actual vehicle speed and gear box status ($F_{\text{eng}\text{min}} \leq F_{\text{eng}} \leq F_{\text{eng}\text{max}}$ and $F_{\text{brake}\text{min}} \leq F_{\text{brake}} \leq F_{\text{brake}\text{max}}$). Furthermore, as accelerations and decelerations are alternatively imposed to the vehicle by the engine or the braking system, we need to consider two different actuation lags, i.e.:

$$\tau(v) = \begin{cases} \tau_{\text{brakes}} & \text{if} \quad \ddot{r}_{\text{des}} \leq 0 \\ \tau_{\text{eng}} & \text{if} \quad \ddot{r}_{\text{des}} > 0. \end{cases} \tag{42}$$

In the following sections we provide a mathematical description for both F_{eng} and F_{brake}.

B. Engine Tractive Effort: F_{eng} and τ_{eng}

The maximum force that the engine can supply depends on its power. The traction effort F_{eng} depends on the engine power output P_{eng} at each given rotation speed [30]

$$F_{\text{eng}} = \frac{\eta P_{\text{eng}}(N_{\text{eng}})}{v} \qquad [\text{N}], \tag{43}$$

where P_{eng} is the power output in [W], N_{eng} is the engine speed in [rpm], η is the engine efficiency, and v is the vehicle velocity expressed in [m/s]. Engine power curves $P_{\text{eng}}(N_{\text{eng}})$ are available as results of the dyno tests done by manufacturers or by other institutions[2] and they are usually available on-line.

The engine speed can be expressed as a function of the vehicle velocity [52]

$$N_{\text{eng}} = \frac{60 i_d i_g v}{d_{\text{wheel}}\pi} \qquad [\text{rpm}], \tag{44}$$

where i_d is the differential transmission ratio, i_g is the gear ratio for the current engaged transmission, and d_{wheel} is the diameter of the tractive wheels in [m]. By substituting Eq. (44)

[2]http://rototest-research.eu/

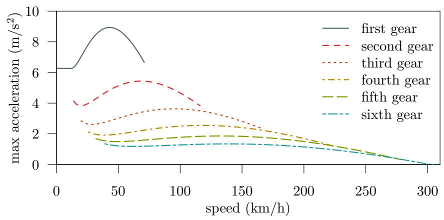


Figure 13. Maximum acceleration curves computed according to Eq. (45) as a function of vehicle velocity and parametrized with respect to the different gears in the real case of an Audi R8 4.2 FSI Quattro car (2007).

into Eq. (43) we can compute F_{eng} as a function of the vehicle velocity v for all possible gear ratios.

The minimum engine speed $N_{\text{eng}_{\text{min}}}$ is always different form zero (for engine velocities smaller than $N_{\text{eng}_{\text{min}}}$ the engine is shut down). Thus, for the sake of simplicity, we do not include clutch dynamics and we assume that a minimum vehicle velocity, associated to the first gear, corresponds to the minimum engine speed $N_{\text{eng}_{\text{min}}}$ rpm.

According to the above considerations, to account for starting maneuvers from rest, we rewrite Eq. (43) as:

$$F_{\text{eng}}(v) = \begin{cases} \frac{\eta P_{\text{eng}}(v_{\text{min}})}{v_{\text{min}}} & \text{if} \quad v \leq v_{\text{min}} \\ \frac{\eta P_{\text{eng}}(v)}{v} & \text{if} \quad v > v_{\text{min}}. \end{cases} \tag{45}$$

Fig. 13 shows, as an example, the maximum acceleration curves computed according to Eq. (45) as a function of vehicle velocity for different gears in the real case of an Audi R8 4.2 FSI Quattro car (2007). According to the propelling model, the system can provide any desired acceleration values $\ddot{r}_{\text{des}}$, but only below the corresponding maximum acceleration curve.

As already mentioned, due to the engine combustion process, system dynamics are affected by an actuation lag τ_{eng} (see Eqs. (40) and (42)). This lag depends from the fuel injection time τ_{inj}, the combustion time τ_{burn} and the transport delay τ_{exh}, i.e, the time needed for exhaust gases, moving along the exhaust manifold, to reach the pre-catalyst UEGO-sensor. This delay can be estimated as in [30]

$$\tau_{\text{eng}}(n) = \tau_{\text{inj}}(n) + \tau_{\text{burn}}(n) + \tau_{\text{exh}}, \tag{46}$$

where $\tau_{\text{inj}}(n) = \frac{2(N_C-1)}{n \cdot N_C}$, $\tau_{\text{burn}}(n) = \frac{3}{2n}$; n is the engine speed is expressed in [rps], and N_C is the number of cylinders. The transport delay τ_{exh} is approximated, for the sake of simplicity, to a mean value of $100\,\text{ms}$ [30, Sec. 4.1.3].

C. Brakes Model: F_{brake} and $\tau_{\,brake}$

An accurate mathematical derivation of the braking force acting on a wheel equipped with a brake disk depends on the description of all the physical components of the system (which include geometry of the brake disks and pads, friction effects and very detailed physic-based equations to describe the hydraulic pressure dynamics inside the master cylinder) and it is clearly related to the specific features of the braking device under exam. For these reasons, we disregard these aspects, which are clearly behind the scope of the vehicular network simulations, and we assume that the braking system has enough force to lock the wheels and that the vehicle is equipped with an Antilock Braking System (ABS) able to optimize the braking performance. Moreover, we also neglect possible aerodynamic forces and non uniform weight distribution on wheels. Given these simplifying assumptions, it is possible to estimate the maximum braking force as [53]

$$F_{\text{brake}_{\text{max}}} = \mu m g, \tag{47}$$

where μ is the average coefficient of friction between the road and the tyre. Hence, the braking force that can effectively be imposed to the vehicle due to braking system constraints can be computed as

$$F_{\text{brake}_{\text{max}}} = \min(\lambda m \ddot{r}_{\text{des}}, \mu m g). \tag{48}$$

Concerning the actuation lag (τ_{brakes} in Eq. (42)), we fix it to a constant value of $200\,\text{ms}$ [50].

VI. Experimental Results using Realistic Vehicles

Here we present the same analysis we provided in Sec. IV but using realistic vehicles as discussed in Sec. V.

A. Convergence Analysis

The fist evaluation concerns the platoon robustness with respect to non-linear vehicles dynamics and non homogeneous platoons. Results in Fig. 14 confirm the ability of the proposed approach in *creating and maintaining* the platoon (with a negligible position error at steady state around $\simeq 1\%$, see Fig. 14a) despite the presence of air drag, rolling resistance and bounded traction efforts that limit the achievable accelerations profiles of the different vehicles according to their traction characteristics.

Good performance is also achieved during transient maneuvers when the platoon, starting from the equilibrium conditions, has to *track the leader* while it accelerates/decelerates. Fig. 15a reports the speed of the leader (that performs first and acceleration, and then, when the transient is over a deceleration until complete stop) and the speed of all other cars. Figs. 15b and 15c report the relative distances and accelerations. Again, despite the significant presence of friction the platoon maintains the secure inter-vehicular distance, avoiding collisions and converging to standstill distances at rest with position errors within 1%. The platoon is also string stable, but we skip these results for the sake of brevity.

B. High Traffic Density Scenario

This final analysis considers the realistic vehicles models in the high traffic density scenario, with fading and accurate car-to-car communication. For each setup experiments are repeated five times randomly changing the ordering of the vehicles. All the results obtained confirm stability, convergence and noise rejection properties. For the sake of brevity, we show the results of a single run. Fig. 16 shows that all followers correctly track the leader maneuver without overshooting the speed of the vehicle they have in front, thus showing that the controller counteracts both realistic network impairments, real car dynamics, and non homogeneous platoons. Results depicted in Fig. 17, instead, show the time history of the inter-vehicle

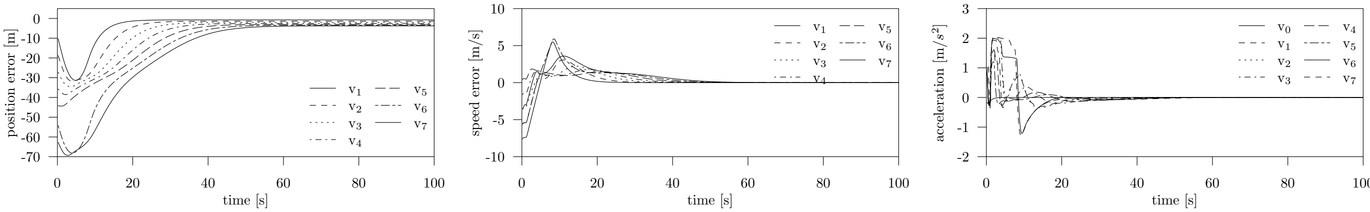
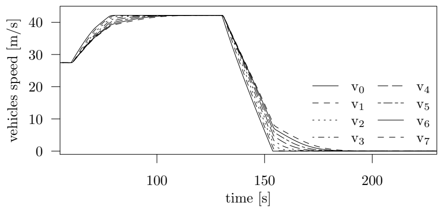
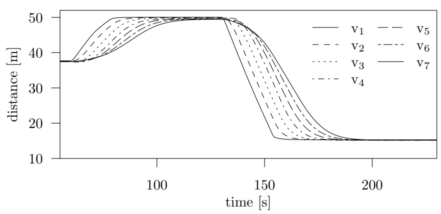


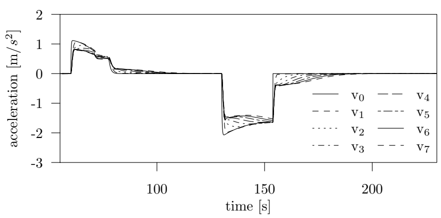
Figure 14. Platoon creation and maintaining: convergence analysis with realistic vehicles models ($N+1=8$ and $v_0 = 100\,\text{km/h}$). Platoon *creation and maintenance*: (a) time history of the position errors computed as $r_i(t) - r_0(t) - h_{i0}v_0 - d_{i0}^{st}$; (b) time history of the vehicle speed errors with respect to the leader computed as $v_i(t) - v_0$; (c) time history of the control effort in ms^{-2}.



(a) time history of the vehicle speeds



(b) time history of bumper to bumper distances computed as $r_{i-1}(t) - r_i(t) - l_{i-1}$



(c) time history of the vehicles acceleration

Figure 15. Leader tracking maneuver with realistic vehicle model.

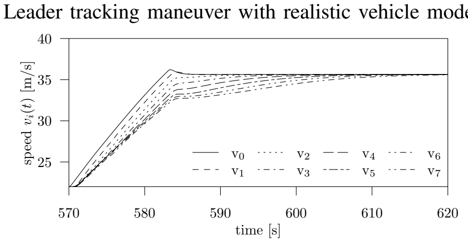


Figure 16. Leader tracking maneuver with realistic network scenario and vehicle model. Time history of vehicles' speed.

distance when a sinusoidal disturbance is acting on the leader motion. Also in this case, although attenuation of distance error is less pronounced (compared to Fig. 11) due to the impact of vehicles limitations and non homogeneity, the platoon is stable and relative errors well below any dangerous situation.

VII. Conclusion

This paper proposes a novel, distributed, consensus-based control approach for vehicle platoons that compensate by design communication delays and the topology of the agents network

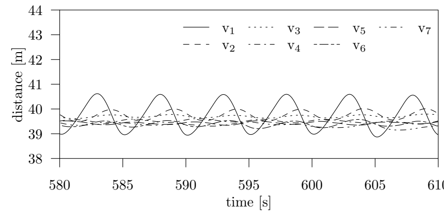


Figure 17. Sinusoidal disturbance acting on leader motion with realistic network scenario and vehicle model: Time history of bumper to bumper distances computed as $r_{i-1}(t) - r_i(t) - l_{i-1}$.

that implements the algorithm. Topology becomes a design parameter and not a constraint as in traditional control theory. The stability and convergence of the platooning algorithm in presence of time-variable heterogeneous delays is proven theoretically, giving a sound ground for application development. The resulting algorithm was implemented in Plexe on top of a beaconing protocol consistent with DSRC/WAVE standards. Simulations confirm the theoretical properties and comparison with a classic CACC well known in literature hints to superior performance of our proposal. Finally, the flexibility of Plexe allows us to validate the entire system under realistic communication scenarios, complex road (highway) conditions including vehicles generating interference, and, most of all, real dynamics of vehicles together with platoons of mixed, non homogeneous vehicles. This latter contribution is a milestone in feasibility studies of platooning without infrastructure support in realistic scenarios, and it paves the road toward further experiments and, we hope, implementations that will save human lives.

VIII. Acknowledgments

This work is partially funded by the Regione Campania (Italy) with the Piattaforma Mobilitá [CUP B68C12000460007] project, in the context of POR CAMPANIA FESR 2007/2013 O.O. 2.1.

References

[1] S. Shladover, C. Desoer, J. Hedrick, M. Tomizuka, J. Walrand, W.-B. Zhang, D. McMahon, H. Peng, S. Sheikholeslam, and N. McKeown, "Automated Vehicle Control Developments in the PATH Program," *IEEE Trans. on Vehicular Technology*, vol. 40, no. 1, pp. 114–130, Feb. 1991.

[2] U. Montanaro, M. Tufo, G. Fiengo, M. di Bernardo, A. Salvi, and S. Santini, "Extended cooperative adaptive cruise control," in *2014 IEEE Intelligent Vehicles Symposium Proceedings*, 2014, pp. 605–610.

[3] J. Ploeg, B. Scheepers, E. van Nunen, N. van de Wouw, and H. Nijmeijer, "Design and Experimental Evaluation of Cooperative Adaptive Cruise Control," in *IEEE Int. Conf. on Intelligent Transportation Systems (ITSC 2011)*, Washington, DC, Oct. 2011, pp. 260–265.

[4] R. Rajamani, *Vehicle Dynamics and Control*, 2nd ed. Springer, 2012.

[5] Y. Zheng, S. Eben Li, J. Wang, D. Cao, and K. Li, "Stability and Scalability of Homogeneous Vehicular Platoon: Study on the Influence of Information Flow Topologies," *IEEE Trans. on Intelligent Transportation Systems*, vol. 17, no. 1, pp. 14–26, Jan. 2016.

[6] L. Y. Wang, A. Syed, G. G. Yin, A. Pandya, and H. Zhang, "Control of Vehicle Platoons for Highway Safety and Efficient Utility: Consensus with Communications and Vehicle Dynamics," *Journal of Systems Science and Complexity*, vol. 27, no. 4, pp. 605–631, Aug. 2014.

[7] M. Segata, S. Joerer, B. Bloessl, C. Sommer, F. Dressler, and R. Lo Cigno, "PLEXE: A Platooning Extension for Veins," in *6th IEEE Vehicular Networking Conf. (VNC 2014)*, Paderborn, Germany, Dec. 2014, pp. 53–60.

[8] C. Sommer, R. German, and F. Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," *IEEE Trans. on Mobile Computing*, vol. 10, no. 1, pp. 3–15, Jan. 2011.

[9] S. Santini, A. Salvi, A. S. Valente, A. Pescapè, M. Segata, and R. Lo Cigno, "A Consensus-based Approach for Platooning with Inter-Vehicular Communications," in *34th IEEE Conf. on Computer Communications (INFOCOM 2015)*, Hong Kong, China, Apr. 2015, pp. 1158–1166.

[10] IEEE, "IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-channel Operation," IEEE, Std 1609.4-2010, Feb. 2011.

[11] ——, "Wireless Access in Vehicular Environments," IEEE, Std 802.11p-2010, Jul. 2010.

[12] M. Segata and R. Lo Cigno, "Automatic Emergency Braking - Realistic Analysis of Car Dynamics and Network Performance," *IEEE Trans. on Vehicular Technology*, vol. 62, no. 9, pp. 4150–4161, Oct. 2013.

[13] H. Hao and P. Barooah, "Stability and Robustness of Large Platoons of Vehicles with Double-integrator Models and Nearest Neighbor Interaction," *Int. Journal of Robust and Nonlinear Control*, vol. 23, no. 18, pp. 2097–2122, Dec. 2013.

[14] K. Santhanakrishnan and R. Rajamani, "On Spacing Policies for Highway Vehicle Automation," *IEEE Trans. on Intelligent Transportation Systems*, vol. 4, no. 4, pp. 198–204, Dec. 2003.

[15] D. Swaroop and J. Hedrick, "String Stability of Interconnected Systems," *IEEE Trans. on Automatic Control*, vol. 41, no. 3, pp. 349–357, Mar. 1996.

[16] X. Liu, A. Goldsmith, S. Mahal, and J. Hedrick, "Effects of Communication Delay on String Stability in Vehicle Platoons," in *IEEE Intelligent Transportation Systems Conf. (ITSC 2001)*, Oakland, CA, Aug. 2001, pp. 625–630.

[17] P. Fernandes and U. Nunes, "Platooning With IVC-Enabled Autonomous Vehicles: Strategies to Mitigate Communication Delays, Improve Safety and Traffic Flow," *IEEE Trans. on Intelligent Transportation Systems*, vol. 13, no. 1, pp. 91–106, Mar. 2012.

[18] L. Zhang and G. Orosz, "Motif-based Design for Connected Vehicle Systems in Presence of Heterogeneous Connectivity Structures and Time Delays," *IEEE Trans. on Intelligent Transportation Systems*, vol. 17, no. 6, pp. 1638–1651, Jan. 2016.

[19] P. Fernandes and U. Nunes, "Platooning of Autonomous Vehicles with Intervehicle Communications in SUMO Traffic Simulator," in *IEEE Int. Conf. on Intelligent Transportation Systems (ITSC 2010)*, Madeira Island, Portugal, Sep. 2010, pp. 1313–1318.

[20] C. Lei, E. van Eenennaam, W. Wolterink, G. Karagiannis, G. Heijenk, and J. Ploeg, "Impact of Packet Loss on CACC String Stability Performance," in *11th Int. Conf. on ITS Telecommunications (ITST 2011)*, Saint Petersburg, Russia, Aug. 2011, pp. 381–386.

[21] G. J. Naus, R. P. Vugts, J. Ploeg, M. Van de Molengraft, and M. Steinbuch, "String-stable CACC Design and Experimental Validation: A Frequency-domain Approach," *IEEE Trans. on Vehicular Technology*, vol. 59, no. 9, pp. 4268–4279, Nov. 2010.

[22] R. Olfati-Saber, J. A. Fax, and R. M. Murray, "Consensus and Cooperation in Networked Multi-agent Systems," *Proceedings of the IEEE*, vol. 95, no. 1, pp. 215–233, Jan. 2007.

[23] M. di Bernardo, A. Salvi, S. Santini, and A. S. Valente, "Third-order consensus in vehicles platoon with heterogeneous time-varying delays," *IFAC-PapersOnLine*, vol. 48, no. 12, pp. 358–363, 2015.

[24] M. di Bernardo, P. Falcone, A. Salvi, and S. Santini, "Design, Analysis, and Experimental Validation of a Distributed Protocol for Platooning in the Presence of Time-Varying Heterogeneous Delays," *IEEE Transactions on Control Systems Technology*, vol. 24, no. 2, pp. 413–427, Mar. 2016.

[25] R. Szalai and G. Orosz, "Decomposing the Dynamics of Heterogeneous Delayed Networks with Applications to Connected Vehicle Systems," *Physical Review E*, vol. 88, no. 4-040902(R), pp. 1–5, Oct. 2013.

[26] K. Karlsson, C. Bergenhem, and E. Hedin, "Field Measurements of IEEE 802.11p Communication in NLOS Environments for a Platooning Application," in *76th IEEE Vehicular Technology Conf. (VTC2012-Fall)*, Quebec City, Canada, Sep. 2012, pp. 1–5.

[27] M. Segata, B. Bloessl, S. Joerer, C. Sommer, R. Lo Cigno, and F. Dressler, "Vehicle Shadowing Distribution Depends on Vehicle Type: Results of an Experimental Study," in *5th IEEE Vehicular Networking Conf. (VNC 2013)*, Boston, MA, Dec. 2013, pp. 242–245.

[28] M. Segata, B. Bloessl, S. Joerer, C. Sommer, M. Gerla, R. Lo Cigno, and F. Dressler, "Towards Communication Strategies for Platooning: Simulative and Experimental Evaluation," *IEEE Trans. on Vehicular Technology*, vol. 64, no. 12, pp. 5411–5423, Dec. 2015.

[29] M. di Bernardo, A. Salvi, and S. Santini, "Distributed Consensus Strategy for Platooning of Vehicles in the Presence of Time Varying Heterogeneous Communication Delays," *IEEE Trans. on Intelligent Transportation Systems*, vol. 16, no. 1, pp. 102–112, Sep. 2014.

[30] U. Kiencke and L. Nielsen, *Automotive Control Systems: For Engine, Driveline, and Vehicle*, 2nd ed. Springer, 2005.

[31] J. Y. Wong, *Theory of Ground Vehicles*, 3rd ed. John Wiley & Sons, 2001.

[32] S. E. Li, K. Deng, Y. Zheng, and H. Peng, "Effect of Pulse-and-Glide Strategy on Traffic Flow for a Platoon of Mixed Automated and Manually Driven Vehicles," *Computer-Aided Civil and Infrastructure Engineering*, vol. 30, no. 11, pp. 892–905, Aug. 2015.

[33] R. A. Horn and C. R. Johnson, *Matrix Analysis*. Cambridge Univesity Press, 1987.

[34] J. K. Hale, *Introduction to Functional Differential Equations*, ser. Applied Mathematical Sciences. Springer, 1993, vol. 99.

[35] E. Coelingh and S. Solyom, "All Aboard the Robotic Road Train," *IEEE Spectrum*, vol. 49, no. 11, pp. 34–39, Oct. 2012.

[36] G. Chen and F. L. Lewis, "Leader-following Control for Multiple Inertial Agents," *Int. Journal of Robust and Nonlinear Control*, vol. 21, no. 8, pp. 925–942, Aug. 2011.

[37] S. Darbha and K. R. Rajagopal, "Intelligent Cruise Control Systems and Traffic Flow Stability," *Transportation Research Part C: Emerging Technologies*, vol. 7, no. 6, pp. 329–352, Dec. 1999.

[38] A. Botta, A. Pescapè, and G. Ventre, "Quality of Service Statistics over Heterogeneous Networks: Analysis and Applications," *European Journal of Operational Research*, vol. 191, no. 3, pp. 1075–1088, Dec. 2008.

[39] R. P. Karrer, I. Matyasovszki, A. Botta, and A. Pescapè, "Magnets-experiences from Deploying a Joint Research-operational Next-generation Wireless Access Network Testbed," in *3rd Int. Conf. on Testbeds and Research Infrastructures for the Development of Networks & Communities (TRIDENTCOM 2007)*, Orlando, FL, May 2007, pp. 1–10.

[40] W. Yang, A. L. Bertozzi, and X. Wang, "Stability of a Second Order Consensus Algorithm with Time Delay," in *47th IEEE Conf. on Decision and Control (CDC 2008)*, Cancun, Mexico, Dec. 2008, pp. 2926–2931.

[41] K. R. Stromberg, *An Introduction to Classical Real Analysis*. Wadsworth International, 1981.

[42] E. Shaw and J. K. Hedrick, "Controller Design for String Stable Heterogeneous Vehicle Strings," in *46th IEEE Conf. on Decision and Control (CDC 2007)*, New Orleans, LA, Dec. 2007, pp. 2868–2875.

[43] P. Seiler, A. Pant, and K. Hedrick, "Disturbance Propagation in Vehicle Strings," *IEEE Trans. on Automatic Control*, vol. 49, no. 10, pp. 1835–1842, Oct. 2004.

[44] S. E. Li, Y. Zheng, K. Li, and J. Wang, "Scalability Limitation of Homogeneous Vehicular Platoon under Undirected Unformation Flow Topology and Constant Spacing Policy," in *34th IEEE Chinese Control Conf. (CCC 2015)*, Hangzhou, China, Jul. 2015, pp. 8039–8045.

[45] R. H. Middleton and J. H. Braslavsky, "String Instability in Classes of Linear Time Invariant Formation Control with Limited Communication Range," *IEEE Trans. on Automatic Control*, vol. 55, no. 7, pp. 1519–1530, Feb. 2010.

[46] T. Ryan and H. J. Kim, "LMI-Based Gain Synthesis for Simple Robust Quadrotor Control," *IEEE Trans. on Automation Science and Engineering*, vol. 10, no. 4, pp. 1173–1178, Jun. 2013.

[47] E. B. Muhando, T. Senjyu, A. Uehara, and T. Funabashi, "Gain-scheduled Control for WECS via LMI Techniques and Parametrically Dependent Feedback Part II: Controller Design and Implementation," *IEEE Trans. on Industrial Electronics*, vol. 58, no. 1, pp. 57–65, Mar. 2011.

[48] N. Wisitpongphan, F. Bai, P. Mudalige, and O. K. Tonguz, "On the Routing Problem in Disconnected Vehicular Ad-hoc Networks," in *26th IEEE Conf. on Computer Communications (INFOCOM 2007)*, Anchorage, AK, May 2007, pp. 2291–2295.

[49] T. Murray, M. Cojocari, and H. Fu, "Measuring the Performance of IEEE 802.11p using NS-2 Simulator for Vehicular Networks," in *IEEE Int. Conf. on Electro/Information Technology (EIT 2008)*, Ames, IA, May 2008, pp. 498–503.

[50] J. Gerdes and J. Hedrick, “Vehicle Speed and Spacing Control via Coordinated Throttle and Brake Actuation,” *Control Engineering Practice*, vol. 5, no. 11, pp. 1607–1614, 1997.

[51] S. E. Li, Y. Zheng, K. Li, and J. Wang, “An Overview of Vehicular Platoon Control under the Four-component Framework,” in *IEEE Intelligent Vehicles Symposium (IV 2015)*, Seoul, Korea, Jun. 2015, pp. 286–291.

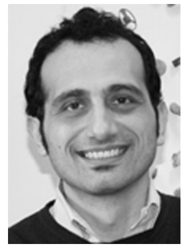
[52] T. D. Gillespie, *Fundamentals of Vehicle Dynamics*. Society of Automotive Engineers, 1992, vol. 400.

[53] A. Day, *Braking of Road Vehicles*. Elsevier, Mar. 2014.

Stefania Santini is an Associate Professor of automatic control with the Department of Electrical Engineering and Information Technology, University of Naples Federico II. Stefania Santini received the M.Sc. degree in electronic engineering and the Ph.D. degree in automatic control from the University of Naples Federico II, Naples, Italy, in 1996 and 1999, respectively. Dr. Santini’s Ph.D. research work was supported by the Engine Institute of the National Research Council. She is involved in many projects with industry, including small- and medium-sized enterprises (SMEs) operating in the automotive field. Her research interests include the area of the analysis and control of non-linear systems with applications to automotive engineering, transportation technologies, and, more recently, computational biology.

Alessandro Salvi received the M.Sc. degree in control systems engineering and the Ph.D. degree in computer science and control systems engineering, with the thesis entitled ”Cooperative Control for Vehicle Platooning: A Complex Network Approach,” from the University of Naples Federico II, Naples, Italy, in 2010 and 2014, respectively. He was a Visiting Ph.D. student with Universitat Politècnica de Catalunya, Barcelona, Spain, in 2011 and with the Chalmers University of Technology, Göteborg, Sweden, in 2013. He is currently with the Department of Electrical Engineering and Information Technology, University of Naples Federico II. His research interests include the distributed control of complex networks with applications to automotive engineering and power systems.

Antonio Saverio Valente received his M.Sc. degree in Control Systems Engineering in 2010. In 2015 he got the Ph.D. degree in Computer Science and Control Systems engineering from the University of Naples Federico II, with the thesis entitled “Cooperative Driving in Inter-Vehicular Communication Network”. He is currently with the Department of Electrical Engineering and Information Technology (DIETI), University of Naples Federico II. His research interests focus on the distributed control of complex networks with applications to automotive engineering and on the monitoring of fleets of vehicles via floating car data.



Antonio Pescapé [SM ’09] is an Associate Professor at the Department of Electrical Engineering and Information Technology of the University of Napoli Federico II (Italy) where he teaches courses in Computer Networks, Computer Architectures, Programming, and Multimedia and he has also supervised and graduated more than 160 among BS, MS, and PhD students. His research interests are in the networking field with focus on Internet Monitoring, Measurements and Management and on Network Security. Antonio Pescapé has co-authored over 170 journal (IEEE ACM Transaction on Networking, Communications of the ACM, IEEE Communications Magazine, JSAC, IEEE Wireless Communications Magazine, IEEE Networks, etc.) and conference (SIGCOMM, NSDI, Infocom, Conext, IMC, PAM, Globecom, ICC, etc.) publications and he is co-author of a patent. He has served and serves as workshops and conferences Chair (including IEEE ICC (NGN symposium)) and on more than 170 technical program committees of IEEE and ACM conferences. For his research activities he has received several awards, comprising a Google Faculty Award, several best paper awards and two IRTF (Internet Research Task Force) ANRP (Applied Networking Research Prize). Antonio Pescapé has served and serves as independent reviewer/evaluator of research and implementation projects and project proposals co-funded by the EU Commission, Sweden government, several Italian local governments, Italian Ministry for University and Research (MIUR) and Italian Ministry of Economic Development (MISE). Antonio Pescapé is a Senior Member of the IEEE.

Michele Segata received his B.Sc. and M.Sc. in Computer Science from the University of Trento in 2009 and 2011, respectively. In 2016 he got a double PhD in Computer Science from the Universities of Innsbruck and Trento. His research mainly focuses on the development of communication protocols and highly realistic simulation models for platooning. He also worked on vehicular networking-based safety application and a software defined radio implementation of the IEEE 802.11p physical layer. He volunteered in the organization of international conferences such as VNC and WONS. Since April 2016 he is a Postdoctoral Research Fellow with the Advanced Networking Systems group in Trento, leaded by Prof. Renato Lo Cigno.

Renato Lo Cigno (SM’11) is an Associate Professor at the Department of Computer Science and Telecommunications (DISI) of the University of Trento, Italy, where he leads a research group in computer and communication networks. He received a degree in Electronic Engineering with a specialization in Telecommunications from Politecnico di Torino in 1988, the same institution where he worked until 2002. From June 1998 to February 1999, he was with the Computer Science Department, University of California, Los Angeles, as Visiting Scholar. His current research interests are in performance evaluation of wired and wireless networks, vehicular networks, modeling and simulation techniques, congestion control, P2P networks and networked systems in general. Renato Lo Cigno has been Area Editor for Computer Networks for five years, and has been involved in the organization of several IEEE and ACM Conferences, including Infocom and P2P, He is senior member of IEEE and ACM and has co-authored more than 150 papers all in international, peer reviewed venues.