On the Progressive Introduction of Heterogeneous CACC Capabilities

Michele Segata*, Lorenzo Ghiro†, Renato Lo Cigno‡
*Faculty of Computer Science, Free University of Bolzano, Italy
†DISI – University of Trento, Italy
‡DII – University of Brescia, Italy

***Abstract*—Can we introduce Cooperative Adaptive Cruise Control (CACC) technologies on the road without separated road infrastructures? This simple question is often latent in works dealing with cooperative driving, especially in feasibility analysis of cooperative driving. As of today, the question has indeed received no definitive answer in the literature because it is hard to model analytically heterogeneous systems or to experiment with them. This work helps understanding how vehicles interact among each others when they do not run a single, a-priory defined, CACC algorithm, but rather each vehicle adopt its own one. We introduce the concept of *mixed platoon*, i.e., a string of vehicles where more than one CACC algorithm is used, and we experiment with mixed platoons in silico to study how the mixture of CACC algorithms affects efficiency and safety. For instance we analyze scenarios where we progressively introduce homogeneous and mixed platoons among standard Adaptive Cruise Control (ACC) vehicles, quantifying the positive or negative effects on traffic efficiency and safety induced by the introduction of CACC technologies as a function of their penetration rate. The obtained results encourage additional research on the topic, starting from theoretical analysis of mixed platoons down to performance evaluations of actual implementations.**

I. Introduction

Cooperative Adaptive Cruise Control (CACC), or vehicles' platooning, is one of the cooperative driving applications that received more attention from both academia and industry. However, its introduction is lagging behind, and experimental work has been so far limited only to small sets of vehicles with homogeneous control systems.

As we discuss in Sect. III, research focused on many properties of CACC looking for good longitudinal controllers, algorithms to properly follow a common trajectory, robustness to communication impairments and so forth, but very few works tackled the problem of heterogeneity and progressive introduction of CACC on the road. Standardization bodies, including the Society of Automotive Engineering (SAE)[1], have not (yet) released recommendations for CACC performance masks, let alone for a specific algorithm, thus it is legitimate to question what would happen if vehicles following different CACC algorithms and controllers mix up on the roads, and how these vehicles interact with vehicles following an automated Adaptive Cruise Control (ACC).

This question raises several issues. From an academic point of view one key issue is, for example, the elaboration of a theoretical framework to analyze distributed, multi-body systems where each of the actors is free to follow a locally chosen control law. To the best of our knowledge, the focus on heterogeneity has been so far directed mainly to the behavior of systems where agents with different characteristics follow a common control framework, while the problem of evaluating the performance of a distributed controlled system where individual agents obey different actuation strategies to achieve a common (or similar) goal has never been tackled. An exception in this directions is consensus under changing control topology, a topic started by the seminal paper [1], which spawned multiple research lines like [2], [3] and has been also exploited in networked vehicular control [4]–[6].

From a more practical point of view, and with the few exceptions discussed in Sect. III, no attempts has yet been done to evaluate what happens if Vehicle to Everything (V2X) enabled vehicles interact on a road when they follow different CACC algorithms: Can they safely coexist? Shall they all fallback to a common control algorithm (if ever possible)? Will the "performance of the road," for instance its throughput, be hampered or enhanced?

This work contributes to this effort, still in its infancy, in several ways. First, in Sect. II we formalize the possible contours of the problem, discussing what assumptions are reasonable and what should be avoided. Second, we introduce metrics that can help in the evaluation of the "feasibility and possible acceptance" of different scenarios and adoption strategies. Finally, we present results on experimental setups that we deem most interesting either because they represent credible CACC introduction strategies or because they allow gaining insights in the problem and explaining behaviors and results observed in more complex scenarios.

II. Scenario and Performance Metrics

The introduction of automated vehicles is well on its way, and in particular ACC systems are becoming ubiquitous. V2X communications are instead lagging behind, but they are essential for cooperation. In this work we are not interested in a specific communication technology such as 802.11p, Cellular V2X (C-V2X) or any other, but in understanding if and how heterogeneous CACC capabilities can be progressively introduced on the roads without destabilizing existing traffic

[1]An initial attempt by SAE to define requirements for CACC systems is stuck since 2015 as work in progress (www.sae.org/standards/content/j2945/6/). Although a standard CACC algorithm might look like the ideal solution, technical or commercial reasons going beyond the scope of this paper may force a different path to CACC introduction.

while possibly improving overall performance and road usage. For this reason we simply assume that V2X capable vehicles correctly communicate among themselves, as if using an 802.11p network without losses or congestion.

We consider a highway scenario where all vehicles are ACC capable, and investigate the progressive introduction of CACC capabilities, either all with the same controller or with two different controllers that mix together randomly.

A. Cooperative Driving Controllers

The Adaptive Cruise Control (ACC) we adopt is the classical one defined in [7, Chapter 6]. Its control law is defined as

$$\begin{aligned} u_i &= -\frac{1}{H}\left(\dot{\varepsilon}_i + \lambda\delta_i\right) \\ \delta_i &= x_i - x_{i-1} + l_{i-1} + Hv_i; \qquad \dot{\varepsilon}_i = v_i - v_{i-1} \end{aligned} \tag{1}$$

where l_i, u_i, x_i, v_i are the length, control command (desired acceleration), position, and speed of the i-the vehicle, respectively, and λ and H are the controller parameters that define the desired headway time. We consider $H = 1.2\,\text{s}$, a value ensuring string stability and comfort. In the rest of the paper we also call it the AC controller.

As CACC controllers we consider PATH [7] and Ploeg [8] that are well known and well accepted by the community, while we leave alternative and possibly more performing CACC algorithms like [4], [9], [10] for future study.

Ploeg's controller, PL in the rest of the paper, also has a constant headway time as target, thus it is very similar to an ACC from the performance perspective point of view, but exploits V2X communications to know its future actions, i.e., the control input u_{i-1}, thus reducing the reaction time of the following vehicle because it discounts the actuation lag on the power train, eventually improving string stability. We model the actuation lag as a first order low pass filter with the pole at $0.5\,\text{s}$. Ploeg's control law is defined as:

$$\begin{aligned} \dot{u}_i = \frac{1}{H}\big(&-u_i + k_p\left(x_{i-1} - x_i - l_{i-1} - Hv_i\right) \\ &+ k_d\left(v_{i-1} - v_i - Ha_i\right) + u_{i-1}\big) \end{aligned} \tag{2}$$

with k_p and k_d additional parameters controlling how much distance and speed errors are weighted by the controller. We use the values originally proposed in the original paper which correspond to $H = 0.5\,\text{s}$.

PATH's controller, denoted as PA, is instead defined as:

$$\begin{aligned} u_i = \,& \alpha_1 u_{i-1} + \alpha_2 u_0 + \alpha_3(v_i - v_{i-1}) \\ &+ \alpha_4(v_i - v_0) + \alpha_5(x_i - x_{i-1} + l_{i-1} + d_d) \end{aligned} \tag{3}$$

where

$$\begin{aligned} \alpha_1 &= 1 - C_1; \quad \alpha_2 = C_1; \quad \alpha_5 = -\omega_n^2 \\ \alpha_3 &= -\left(2\xi - C_1\left(\xi + \sqrt{\xi^2 - 1}\right)\right)\omega_n \\ \alpha_4 &= -C_1\left(\xi + \sqrt{\xi^2 - 1}\right)\omega_n \end{aligned}$$

with parameters C_1, ξ, and ω_n controlling the apportioning of acceleration between leading and preceding vehicles, damping ratio, and bandwidth, respectively; d_d instead is the desired inter-vehicle distance and the remaining variables keep their already defined meaning. PA targets a constant inter-vehicle distance independent from the platoon speed, so it is quite different from AC and PL.

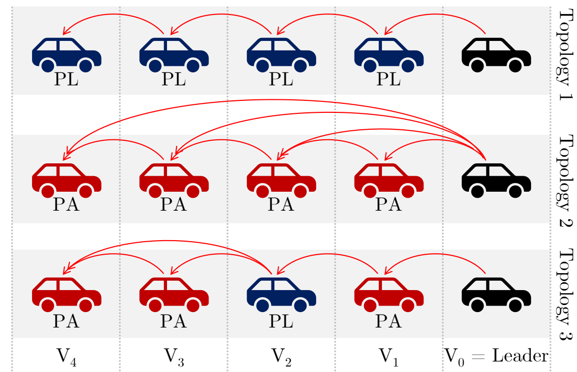

Figure 1: Examples of control topology in platoons of 5 vehicles: Top $\{\text{PL}, \text{PL}, \text{PL}, \text{PL}\}$; Middle $\{\text{PA}, \text{PA}, \text{PA}, \text{PA}\}$; Bottom $\{\text{PA}, \text{PL}, \text{PA}, \text{PA}\}$.

PL and PA are representative of two different approaches to CACC: mimicking an advanced ACC (Ploeg) or trying to maximize road usage reducing the vehicles' distance regardless of the speed (PATH). They also employ a different control topology: *predecessor-following only* (Ploeg), and *leader- plus precedessor-following* (PATH). Examples of different control topologies are illustrated in Fig. 1. In this regard Ploeg and PATH are good choices to initiate the study of mixed CACC because they do not assume potentially complex communication patterns like with controllers based on consensus theory [4], or with bidirectional topologies as in [9], a non-standard approach with interesting properties but possibly a less "socially acceptable" behavior.

B. Mixed Platoons and Metrics

For the sake of clarity we call a *platoon* a set of N_p vehicles that drive exploiting communication-based cooperation. Vehicles in a platoon $\mathcal{P}$ are numbered $V_0, \ldots, V_{N_p-1}$, with V_0 being the first one and always following an independent speed profile associated to a standard ACC to avoid accidents. The following vehicles implement an arbitrary mix of the PATH or Ploeg controllers.

With this definition, a generic platoon $\mathcal{P}$ is identified by the sequence of controllers implemented by all the $N_p - 1$ followers, as the leader V_0 specification is redundant. For instance the set $\{\text{PA}, \text{PL}, \text{PL}\}$ identifies a 4-vehicle platoon where V_1 implements PATH, while V_2 and V_3 implement Ploeg.

It is important to understand that the choice of the control algorithm of each vehicle in a platoon influences the communication pattern, or control topology, because each controller uses information only from a specific set of vehicles in the platoon, and thus uses only the information coming from these vehicles.

Fig. 1 reports the control-communication topology of three platoons of five vehicles each. V_0 does not implement a closed loop controller, at least with the control algorithms that define V_0 as leader and the others as followers. The platoon on the top is composed of homogeneous PL controllers, with the well-known predecessor-following control topology, the middle one refers to PA controllers, and the control topology includes direct communications from the leader. The bottom one depicts instead a mixed platoon, where V_1, V_3, V_4 implement PA, while V_2 implements PL. The control topology changes radically. V_3 and V_4 cannot use the information sent by V_0 even if they receive it, because the behavior of V_2 is not coherent with PA, thus there is a real risk of destabilizing the platoon. Instead, they can "elect" V_2 as their leader and successfully follow it, since by definition the leader behavior is independent from the followers' CACC. It is important to stress that this does not mean splitting the platoon in two, since V_2 is a follower of V_0 and V_1 and all the five vehicles behaves collectively coordinated by communications and CACC algorithms. We are aware that this heuristic reasoning is just one of the multiple possibilities, and we think it deserves attention in future studies; however, it seems a very reasonable assumption if one wants to study what happens if we allow CACC enabled vehicles to form platoons in presence of different control algorithms.

To improve the efficiency of the experiments we model a highway as a $10\,\mathrm{km}$ ring with N_L lanes. N_L changes depending on the specific experiments described in Sect. IV. The use of a ring instead of a linear stretch of road is justified by experimental and theoretical works [11], and simulated experiments to measure shockwaves [12]. We are interested in both safety and efficiency metrics to understand if and how the progressive introduction of CACC can improve the travel experience and the road usage at the same time. The actual formulation of metrics is described in Sect. IV where we detail the experiments we conduct but, in general, as a measure of the efficiency we use the throughput of the highway, while safety and travel comfort metrics are defined as speed and acceleration variations compared to standard scenarios.

We implement the scenarios in PLEXE [13], a framework for the simulation of CACC systems, easily modifying its logic to enable platoons with different CACC configurations coexisting with standard, homogeneous platoons. We plan to release such new logic to enable further research on the topic.

III. Related Work

The literature on longitudinal platoon controllers is vast, from the already cited PATH's and Ploeg's controllers to the many different proposals exploiting consensus theory (e.g., [4], [14], [15]) or delay compensated optimal control (see for instance [16]–[18]). In this paper, however, we are not concerned with the proposal of a new or different CACC, and not even with their robustness (studies in this direction are [9], [19], [20]).

The key contribution of our work deals with the impact of mixing different control techniques in CACC as well as assessing the impact on traffic of the progressive introduction of CACC. When we focus precisely on these aspects, the literature is far less abundant, and only a few works started tackling the problem in recent years. A first attempt to model large scale CACC traffic can be found in [5]. The goal of the authors is defining the global stability of M platoons that run in parallel on M lanes in the same road. The problem is tackled with a layered approach where stability is granted within platoons and also among the platoon leaders, thus granting overall stability, including lateral control, which is very important given the scenario sketched in the paper. All vehicles implement the same CACC controller. Another approach to understand the mixture of CACC, ACC, and human driven vehicles can be found in [21]. The goal of the paper is to define the risk of rear-end collisions when the CACC does not work due to communication failures, in which case the CACC falls back to ACC. The ACC considered is the same of our work (and indeed of most literature on the subject), and the CACC is PATH as we defined in Eq. (3); human driven vehicles follow an idealized model that does not take into account behavioral sciences, but only dynamics of the traffic. The paper highlights the risk of a too-early introduction of CACC systems without proper fall-back procedures when communications are unreliable.

A more explicit take at the stability of heterogeneous platoons is found in [22], where the explicit goal of the authors is the derivation of general conditions to ensure global string stable behavior of large platoons composed of a mixture of CACC controlled vehicles and human driven vehicles. The CACC considered is very similar to Ploeg's PL and is based on constant headway time. The stability of the system is assessed analyzing shockwaves (called stop-and-go disturbances in the paper), while the overall approach to improve stability is based on H_∞ norm with a frequency domain analysis. The approach is theoretical, with a sound modeling of the system, and numerical results based on Matlab and measured stop-and-go disturbances are provided, though, as also in the other papers analyzed here, no realistic discrete event simulations are provided to validate the model.

Finally [23] provides an approximated analysis of string stability for vehicles that mix human driven and PATH controlled vehicles as a function of the CACC penetration rate. The key approximations in this paper lies in considering only 50 vehicles, considering a small deceleration perturbation of the group of cars, and finally in the lack of definition of the vehicle string mixture, specifying only the fraction of vehicles that are controlled by CACC. This approximation (unfeasible in a realistic environment, as the mixture of human-driven, ACC and CACC defines specific control-communication patterns) leads to very interesting results, hinting to the necessity of tuning the CACC headway time to the CACC penetration rate. We dedicate a full set of experiments as described in Sect. IV-A to improve the understanding of small heterogeneous platoons that mix different CACC, while larger-scale experiments in Sect. IV-B investigate the global stability of traffic when CACC-enabled vehicles are introduced.

IV. Selected Experiments

Given the overall scenario sketched and explained in Sect. II, we need to choose a set of properly designed experiments to verify how different CACCs interact among themselves and with standard ACC systems. As mentioned, PATH and Ploeg are very different control algorithms, and we could not identify a possible theoretical framework to predict performance when mixing them, thus we resort to a purely experimental approach. In the following we describe the experiments we have selected and the reason of the choice. Sect. V presents and discusses the results obtained in each of the experiments. Indeed, each "experiment" corresponds to a setup where many different single experiments can be run, contributing to build a sufficient knowledge base to assess the performance we can expect when CACC systems will be introduced on the roads.

A. Experiment 1

As a first controlled experiment we select a synthetic setup that allows stating initial results useful for subsequent analysis and research. We consider a single lane with a single platoon of length N_p. V_0 drives autonomously following a predefined speed pattern. The following vehicles implement an arbitrary mix of the PATH or Ploeg controllers, and we are interested in understanding if a string of CACC-enabled vehicles is stable and what is its performance when we mix PA and PL arbitrarily in presence of proper communication schemes. Recall that a vehicle implementing PA elects as platoon leader the first non-PA controlled vehicle it receives information from, because Ploeg is not a constant-space controller, and the actual positions of vehicles in the platoon would be incoherent with the expectation of the PATH controller. In the example reported at the bottom of Fig. 1, $\mathcal{P}$ is $\{\mathrm{PA}, \mathrm{PL}, \mathrm{PA}, \mathrm{PA}\}$; vehicles V_1 and V_2 elect as their leader V_0, while V_3 and V_4 elect V_2, which implements a Ploeg controller, and it is for these two vehicles the first "non-PA controlled vehicle" in front.

We consider platoons of $N_p = 4$, 8, and 16 vehicles. For $N_p = 4$ we consider all possible combinations of PL and PA, while for $N_p = 8$ and 16 we select only a few representative patterns, as detailed in Sect. V-A, because the 2^{N_p-1} combinations are clearly too many for an exhaustive study. For the sake of the analysis we assume that V_0 follows a sinusoidal speed pattern at $0.2\,\mathrm{Hz}$ between 95 and $105\,\mathrm{km/h}$, an extreme speed pattern usual in CACC performance studies. We compare the results against those of a string of N_p vehicles all following the ACC without communications, or, when appropriate for vehicle V_i, against those of an identical vehicle in the same position of a platoon where all vehicles implement the same CACC as V_i. We consider two metrics: One based on acceleration evaluating travel comfort, and one based on inter-vehicle distances evaluating the safety of the configuration. Furthermore, we also consider the total length of the platoon, which measures the potential increased efficiency in road usage.

Let $a_i^c(t)$ be the acceleration of vehicle V_i at time t in the configuration c, where for configuration we mean the assignment of control algorithms to the vehicles (i.e., the specific mix of PA and PL controllers of the $N_p - 1$ followers), while the apex AC refers to a string of N_p ACC-controlled vehicles. For a specific configuration c and vehicle i, we define the following metric

$$\Delta_a(c,i) = \max_t |a_i^{\mathrm{AC}}(t)| - \max_t |a_i^c(t)| \qquad (4)$$

as the deviation between the maximum acceleration in the ACC only configuration and the maximum acceleration measured in configuration c. A positive value of $\Delta_a(c,i)$ indicates that the maximum acceleration in configuration c is not larger than with a standard ACC, thus comfort is preserved, while a negative one indicates that there are stronger accelerations (or decelerations). In addition, we measure the minimum in the entire platoon

$$\Delta_a(c) = \min_{i\in\{1,\dots,N_p-1\}} \left(\Delta_a(c,i)\right) \qquad (5)$$

and the vehicle V_i that caused it.

We are also interested in measuring the difference in the minimum distance between a vehicle in a certain position in a mixed configuration with respect to a vehicle in the same position using a homogeneous configuration (i.e., where all vehicles use the same CACC). Let $d_i^c(t)$ be the distance of vehicle V_i from its predecessor at time t in the configuration c. We define the aforementioned metric as follows:

$$\Delta_d(c,i) = \min_t d_i^c(t) - \begin{cases} \min_t d_i^{\mathrm{PA}}(t), \text{if } V_i \text{ uses PA} \\ \min_t d_i^{\mathrm{PL}}(t), \text{if } V_i \text{ uses PL} \end{cases} \qquad (6)$$

where $d_i^{\mathrm{PA}}(t)$ and $d_i^{\mathrm{PL}}(t)$ refer to the distances measured for the same vehicle V_i, but in the experiment where the platoon is composed by vehicles all implementing the same CACC as V_i. A positive value of $\Delta_d(c,i)$ indicates that the minimum distance in configuration c is larger than in homogeneous conditions, hence we can assume safety is preserved, while a large negative one means that there might be safety issues in the given configuration. Similarly as in Eq. (5), we measure the minimum of the difference in the platoon and the vehicle that caused it

$$\Delta_d(c) = \min_{i\in\{1,\dots,N_p-1\}} \left(\Delta_d(c,i)\right) \qquad (7)$$

Finally we consider the following efficiency gain factor for all configurations:

$$\eta_c = \frac{L_{\max}^{\mathrm{AC}}}{L_{\max}^{c}} \quad (8) \qquad L_{\max}^{c} = \max_t \sum_{i\in\{1,\dots,N_p-1\}} d_i^c(t) \quad (9)$$

$L_{\max}^{\mathrm{AC}}$ is defined according to Eq. (9). η_c does not include vehicles' length, thus it allows comparison of platoons with different vehicles as well (not done in this paper), and indeed correctly accounts only for the space that platooning can reduce. For a platoon in isolation reducing the space between vehicles may look as an obvious and superfluous metric, but it helps interpreting results for more complex experiments where platoons and standard ACC driven cars are mixed in multiple lane roads. η_c grows as the platoon becomes more compact, for instance $\eta_c = 2$ when the average inter-vehicle distance in the platoon is halved.

B. Experiment 2

The second experiment we run envisages a situation where automated vehicles are introduced faster than communication and cooperative driving technologies, so that the background is a transportation system where all vehicles implement ACC

	Parameter	Value
mobility	No. of lanes	3
	Vehicles density*	10, 65 – 100 [car/km]
	Controllers used	AC, PA, PL (and mixed)
	Desired speeds	$\{100, 115, 130\}$ $\pm 5\,\mathrm{km/h}$
controllers	Powertrain lag	$0.5\,\mathrm{s}$
	ACC λ	0.1
	ACC H	$1.2\,\mathrm{s}$
	PATH C_1	0.5
	PATH ω_n	0.2
	PATH ξ	1
	PLOEG H	$0.5\,\mathrm{s}$
	PLOEG k_p	0.2
	PLOEG k_d	0.7

*the density refers to the road density, not per-lane density

Table I: Key parameters used in the experiments.

following Eq. (1), but are not equipped with V2X capabilities. We consider a 3-lane highway; single ACC vehicles (those that do not form platoons) drive by default in the rightmost free lane and are free to overtake. CACC enabled vehicles are progressively introduced and form platoons, but they are not free to overtake, thus they select the lane coherent with their desired speed and do not change it. For the sake of simplicity we assume platoons of constant size, and explore $N_p = 4$, 8, and 16 as in Sect. IV-A. The free-flow speed of vehicles is randomly distributed around three desired speeds: 100, 115, and $130\,\mathrm{km/h}$ with a uniform distribution $\pm 5\,\mathrm{km/h}$. Tab. I reports the parameters that characterize the experiment.

The main goal of this experiment is to explore the efficiency improvement in road usage in terms of vehicles per hour. It is clear that reducing the inter-vehicle distance should allow an increased vehicle density, but the actual gain as a function of the penetration rate of CACC is difficult to predict. Furthermore, this aspect has never been studied as a function of the CACC introduced, and definitely the impact of mixed platoons as defined in Sect. IV-A is a novel contribution. In this experiment we consider all three possibilities: CACC platoons use only PL or PA, or they are formed by mixed controllers. To measure the road throughput we added four equally spaced vehicles' counting devices in the highway ring, let's call them N-E-S-W. These devices measure the number of passing vehicles sampled every $15\,\mathrm{s}$, building 4 temporal sequences of throughput samples in cars / hour $\{\Theta_{\mathrm{N}}(t)\}$, $\{\Theta_{\mathrm{E}}(t)\}$, $\{\Theta_{\mathrm{S}}(t)\}$, $\{\Theta_{\mathrm{W}}(t)\}$. Out of these temporal sequences we can compute averages and other relevant metrics.

To assess the stability of traffic we compute the coefficient of variation of speed, often called also the *volatility* of traffic. The coefficient of variation ξ is the ratio between the standard deviation of a series and the absolute value of its average. Let $\sigma[s]$ and $\mathrm{E}[s]$ be the standard deviation and the average estimators over the series of speed measures $s = \{s_k\}$, respectively. $\xi(s)$ is computed as $\xi(s) = \dfrac{\sigma[s]}{|\mathrm{E}[s]|}$.

V. Performance Analysis

A. Results for Experiment 1

The first experiment is devoted to understand some basic properties of mixed platoons, with the goal of offering an

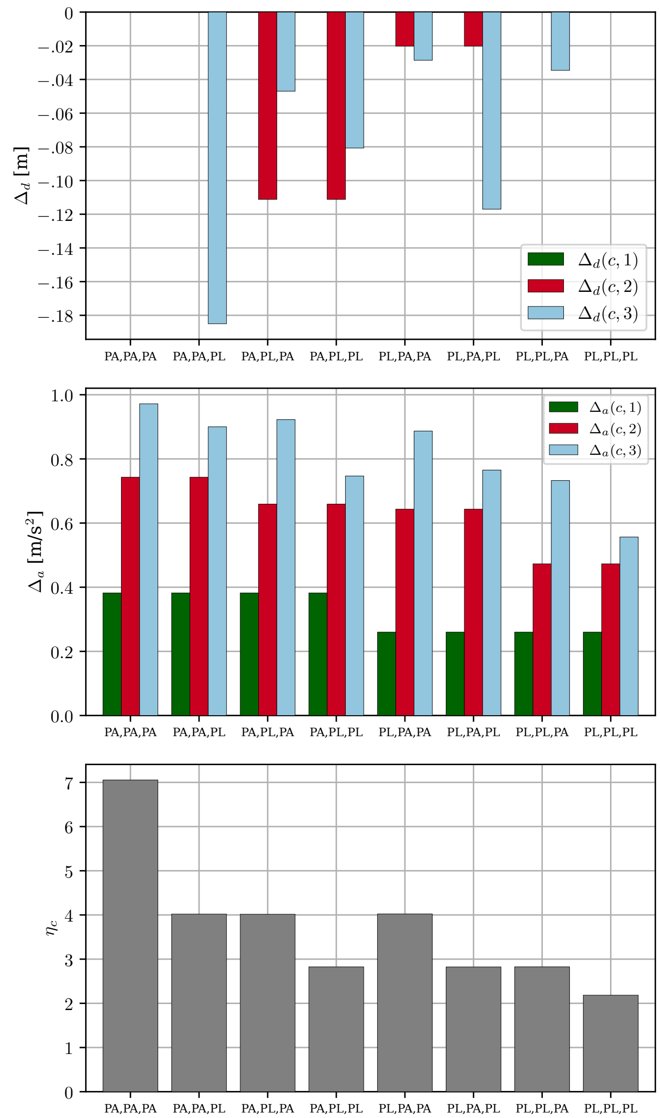

Figure 2: Top $\Delta_d(c, i)$, middle $\Delta_a(c, i)$, and bottom η_c metrics for all possible mixed CACC configurations of 4 cars.

interpretation key for more complex and larger experiments. Fig. 2 reports the three metrics defined defined by Eq. (6) ($\Delta_d(c, i)$), Eq. (4) ($\Delta_a(c, i)$), and Eq. (8) (η_c) for all possible combinations of 4-vehicle platoons.

The top plot refers to Eq. (6), and all values are negative (or zero), meaning that in all possible cases of mixed platoons the distance between V_i and V_{i-1} is smaller or equal to the one measured in a homogeneous platoon implementing the same controller as V_i. This behavior is at the same time not surprising and not obvious. It is not surprising because one may expect that an heterogeneous mix of CACC, whose theoretical properties are not known, cannot behave as a homogeneous one with theoretically proven properties. It is not obvious for two reasons. First the differences could also be positive, meaning that vehicles are more widely spaced. Second and more important, the differences are minimal (at most $18\,\mathrm{cm}$ out of about $16\,\mathrm{m}$ for a PL vehicle following a PA one), hence

c = PA,PA,PA,PL,PL,PL,PL	$\Delta_d(c) = -0.23\,\mathrm{m}$ (V_4)	$\Delta_a(c) = 0.38\,\mathrm{m/s^2}$ (V_1)	$\eta_c = 3.10$
c = PA,PL,PA,PL,PA,PL,PA	$\Delta_d(c) = -0.19\,\mathrm{m}$ (V_4)	$\Delta_a(c) = 0.38\,\mathrm{m/s^2}$ (V_1)	$\eta_c = 3.59$
c = PL,PA,PL,PA,PL,PA,PL	$\Delta_d(c) = -0.16\,\mathrm{m}$ (V_7)	$\Delta_a(c) = 0.26\,\mathrm{m/s^2}$ (V_1)	$\eta_c = 3.10$
c = PL,PL,PL,PA,PA,PA,PA	$\Delta_d(c) = -0.05\,\mathrm{m}$ (V_4)	$\Delta_a(c) = 0.26\,\mathrm{m/s^2}$ (V_1)	$\eta_c = 3.59$
c = PA,PA,PA,PA,PA,PA,PA,PL,PL,PL,PL,PL,PL,PL,PL	$\Delta_d(c) = -0.34\,\mathrm{m}$ (V_8)	$\Delta_a(c) = 0.38\,\mathrm{m/s^2}$ (V_1)	$\eta_c = 3.26$
c = PL,PA,PL,PA,PL,PA,PL,PA,PL,PA,PL,PA,PL,PA,PL	$\Delta_d(c) = -0.21\,\mathrm{m}$ (V_{11})	$\Delta_a(c) = 0.26\,\mathrm{m/s^2}$ (V_1)	$\eta_c = 3.26$
c = PA,PL,PA,PL,PA,PL,PA,PL,PA,PL,PA,PL,PA,PL,PA	$\Delta_d(c) = -0.26\,\mathrm{m}$ (V_{12})	$\Delta_a(c) = 0.38\,\mathrm{m/s^2}$ (V_1)	$\eta_c = 3.49$
c = PL,PL,PL,PL,PL,PL,PL,PA,PA,PA,PA,PA,PA,PA,PA	$\Delta_d(c) = -0.02\,\mathrm{m}$ (V_9)	$\Delta_a(c) = 0.26\,\mathrm{m/s^2}$ (V_1)	$\eta_c = 3.49$
200 Random c; $N_p = 16$	$\Delta_d^{\min} = -0.41\,\mathrm{m}$	$\Delta_a^{\min} = 0.22\,\mathrm{m/s^2}$	$\eta_c = 2.44$

Table II: $\Delta_d(c)$, $\Delta_a(c)$, and η_c metrics for experiments with 8 and 16 cars.

safety is preserved. Indeed, this is a direct consequence of the different "elasticity" of PL and PA. PL actually mimics an improved AC, meaning that has the same qualitative behavior, just with reduced time headway and faster reaction of followers. PA instead mimics an almost rigid system, with all vehicles maintaining constant distance and, thanks to the knowledge of the leader behavior, also the same speed and acceleration, without delay and significant damping of the leader changes. Thus a PL vehicle following a PA one will oscillate around the average distance respect to it.

The middle plot of Fig. 2 reports Eq. (4). In all cases CACC controlled vehicles have a smaller acceleration ($\Delta_a(c, i) > 0$) than an ACC vehicle in the same situation, improving the passengers comfort. The difference in acceleration of V_i depends only the vehicles in front of it, and this can be expected given the control topology of all the CACC considered. Results are remarkably constant independently of the complete configuration c, with vehicles more distant from the leader having a larger gain.

Finally, the bottom plot of the figure reports Eq. (8) showing that, regardless of the configuration, any mix of CACC grants a higher road efficiency which is proportional to the specific mix of CACC implemented. When many PA controllers are involved the efficiency gain can be quite large, but also PL grants fairly high gains. This baseline result is useful to analyze the throughput improvement obtained in Experiment 2.

Tab. II presents values of $\Delta_d(c)$ and $\Delta_a(c)$ for some configurations of platoons with $N_p = 8$ and 16, namely alternating the controllers PL and PA and grouping them in blocks: PA first and then PL or vice-versa. In these cases presenting the values for all the vehicles in the platoon is not feasible for space reasons, this is why we present the minimums only (Eq. (5) and (7)), which are the most critical values in the entire platoon, and the efficiency η_c. Results fully confirm the analysis with $N_p = 4$ with numerical values that are very close to the "most similar" 4-vehicle configuration;

	PA			PL			Mix		
	.25	.5	.75	.25	.5	.75	.25	.5	.75
$N_p = 4$	1128	1144	1137	1125	1138	1136	1130	1137	1136
$N_p = 8$	1137	1148	1160	1142	1136	1162	1141	1149	1161

Table III: Throughput in cars/hour with density 10 cars/km for $N_p = 4$ and 8 and $R = 0.25$, 0.5, and 0.75; free-flow throughput = 1150 cars/hour, throughput with AC = 1134 cars/hour.

$\Delta_d(c)$ and $\Delta_a(c)$ may refer to different vehicles in the platoon, and in general they do, as it is rare that the same vehicle experiences the strongest acceleration and also the minimum distance. Efficiency gains are also quite good: recall that we are measuring all the metrics in extreme dynamic conditions when the platoon leader continuously changes speed following a $0.2\,\mathrm{Hz}$ sinusoid between 95 and $105\,\mathrm{km/h}$. The last line of Tab. II presents the results for random configurations of 16-vehicle platoons, meaning that when forming the platoon the controller of each V_i is chosen at random between PL and PA. We explored 200 configurations and the values refer to the absolute minimum of both $\Delta_d(c)$ and $\Delta_a(c)$ (i.e., $\Delta_d^{\min}$ and $\Delta_a^{\min}$) observed across all configurations c explored. $\Delta_d^{\min}$ and $\Delta_a^{\min}$ may refer to different platoons and a different vehicle in the platoon, thus reporting the vehicle position is irrelevant. Also in all these cases the results are very encouraging. We can observe that in random configurations $\Delta_d^{\min}$ is only slightly smaller than those observed in selected ones with less vehicles: The absolute value ($41\,\mathrm{cm}$) does not hamper security as the minimum safety distance we consider is $5\,\mathrm{m}$. Remarkably, also in these case Δ_a remains positive, indicating that even platoons of 16 vehicles with mixed CACC ensure a higher comfort compared to standard ACC.

B. *Results for Experiment 2*

The second experiment is devoted to understand if and how the introduction of CACC techniques improves the road usage, checking at the same time that safety is not hampered. Understanding the behavior of such large and complex scenarios can be difficult and it is necessary to proceed step-by-step. Tab. III reports the throughput measured for a fairly low traffic density, i.e., 10 cars/km, which means, for a single lane, roughly one vehicle every $300\,\mathrm{m}$ on average. With this setting the free-flow throughput, i.e., the throughput obtained if every vehicle follow its intended speed, is $= 1150$ cars/hour, because the average speed is $115\,\mathrm{km/h}$. Experimental results however slightly differ from this theoretical value for two reasons. First, vehicles interact on the road and during interactions they can only slow their speed, never accelerating beyond the 'desired' one. Second, the random distribution of desired speeds can lead to an average speed for the experiment slightly different from the theoretic one. This is evidenced by the fact that for $N_p = 8$ and $R = 0.75$ the measured throughput is higher than the free-flow one, because a single 8-car platoon assigned a high speed can have a significant impact, and the actual CACC has almost no impact. Averaging over multiple simulations would most probably correct these small variations, but the

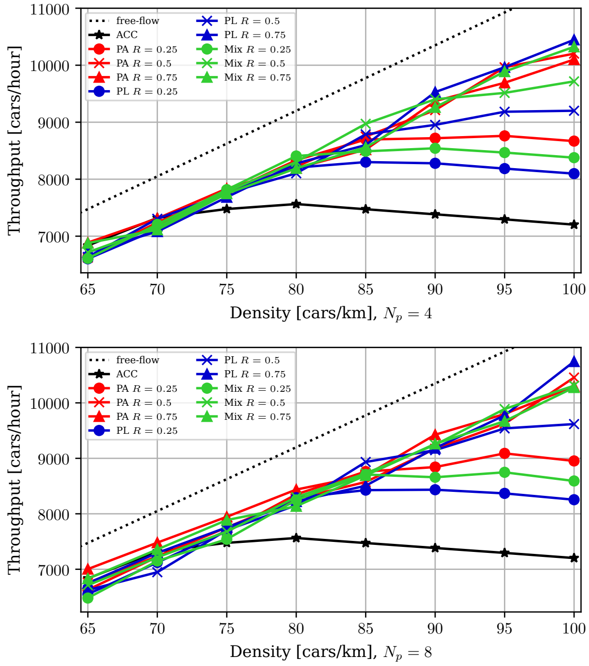

Figure 3: Road throughput as a function of the vehicles density in cars/km with $R = 0.25$, 0.5, and 0.75 and different platoons composition; $N_p = 4$ top plot and $N_p = 8$ bottom plot.

experiments related to this scenario (including $N_p = 16$ not shown here for lack of space) already take a few days of CPU, and we deem that reducing these variations is not relevant. This basic experiment shows that at low density platooning has no impact on the throughput independently of the CACC mix, and the throughput achieved is practically the expected free-flow, but interactions on the road slightly lowers it.

Fig. 3 reports the throughput of the road in cars per hour as a function of the vehicles density, ranging from 65 to 100 cars per km. Experiments refer to the baseline case of all vehicles implementing ACC and to the presence of 25%, 50% , and 75% of CACC-enabled vehicles, organized in platoons of size $N_p = 4$ (top plot) and $N_p = 8$ (bottom plot) with homogeneous PA or PL controllers or a random mix (Mix-curves) of them. The black dotted line in all plots reports the free-flow expected throughput, increasing linearly with the density of vehicles as the average free-flow speed of the vehicles is not changed.

As indicated by the results in Tab. III, the real throughput of the road is always smaller than the free-flow one and, as long as the road capacity is not reached, the throughput loss is small and linear with the density. Neglecting random effects it is also independent of the use of ACC-only or mix of CACC. These results indicate that platoons of mixed CACCs remain stable and also that all platoons, homogeneous or mixed, do not disrupt traffic behavior and increase the road capacity. The capacity gain is proportional to the penetration rate of CACC-enabled vehicles and to the efficiency η_c discussed in Sect. V-A. Consider also that, given a penetration rate, larger platoons imply a slightly larger gain: a platoon of $2N$ cars has in fact $2N-1$ controlled cars, while 2 platoons of N cars have $2(N-1)$ controlled cars only.

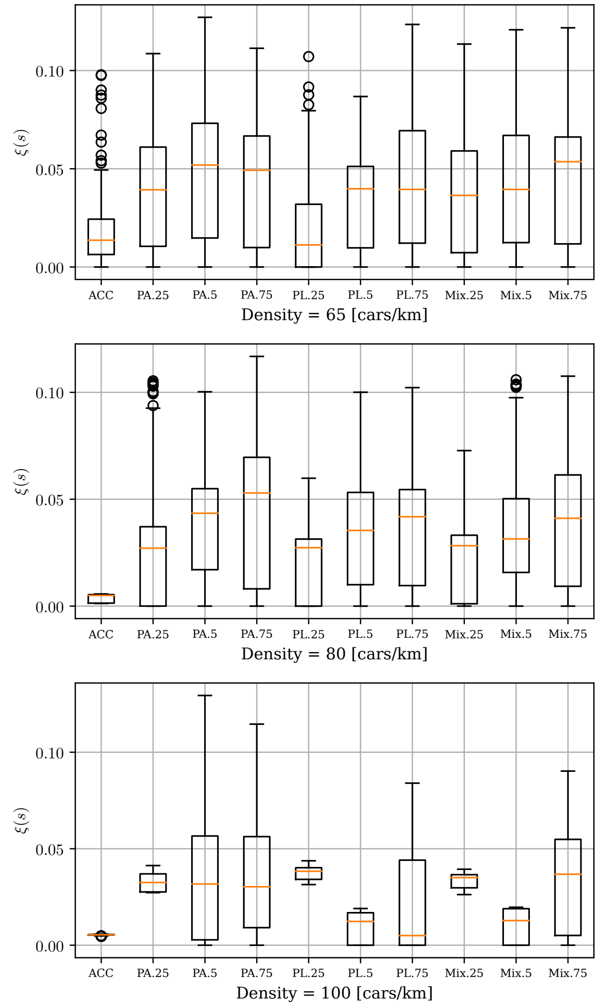

Figure 4: Traffic volatility ($\xi(s)$) of all the tested configurations for $N_p = 8$, traffic density 65 (top), 80 (middle) and 100 (bottom) cars/hour.

It is now important to understand if the capacity gain comes at some cost. Fig. 4 reports the volatility of the traffic estimated by $\xi(s)$ for traffic density 65, 80, and 100 cars/km, $N_p = 8$, for all the experimented configurations. The boxplots in the figure report the 25th–75-th percentiles as boxes and the median as orange line; whiskers are set to the last available measure within the 1.5 inter-quartile range and outliers are isolated circles. The first observation is that, overall, the speed becomes less volatile as the density increase, a confirmation that the introduction of CACC-enabled vehicles does not produce shockwaves. This observation must be coupled with the very low values of $\xi(s)$, that always remain below 0.11, very close to the coefficient of variation of the free-flow speed mix defined in the simulations that is $\frac{135-95}{\sqrt{3}\cdot 230} \simeq 0.1$, but the bulk of the vehicles experience a much lower speed volatility. Besides these general considerations, the extreme stability of ACC-controlled vehicles is remarkable and indicates the complete absence of shockwaves or other traffic irregularities. This is expected as the ACC parameters and lane-changing decisions were tuned to obtains extremely smooth behavior. The presence of platoons increases volatility mainly because they leave more free space on the road, so that ACC-based vehicles can overtake and change their speed, but the volatility does not trigger shockwaves, as shown by the high throughput in Fig. 3 and the low $\xi(s)$. Results for $N_p = 4$ and 16, not reported for lack of space, support the encouraging conclusions we draw.

VI. Discussion and the Work Ahead

The analysis and results presented in this paper are clearly preliminary; nevertheless, they open interesting questions suggesting at least three new research directions.

The first one regards the composition of messages and the communication capabilities of vehicles. Cooperative Awareness Messages (CAMs) are not assumed to carry information on CACC capabilities, still, the results of this paper indicate that ACC and CACC enabled vehicles can actually cooperate on the road if they are all V2X capable. Our results in Experiment 2 assume that isolated ACC vehicles are not equipped with V2X capabilities, thus the penetration rate of CACC vehicles refer to platoons that are already formed. However, the preconstruction of platoons is feasible in a simulation environment but it is not in reality, so it would be worth extending our current study exploring what happens if all vehicles are V2X enabled and if they cooperate to form strings of vehicles. Early experimental works like [24] have (correctly) focused mainly on the safety interaction of small, homogeneous platoons with human driven vehicles; now its time to look further in the future when CACC vehicles will start entering the market.

The second investigation path is a more theoretical one and deals with the properties of mixed platoons. As we discussed in Sect. III, the studies on the properties of strings of cars implementing different CACCs are very few, prompting the need of developing theoretical frameworks able to model such heterogeneous systems. These frameworks would be fundamental to determine performance bounds and in turn guide novel modeling efforts and simulations studies. Furthermore, they would also support the optimal design of CACC-enabled vehicles whose mix with traditional traffic leads to the theoretically maximum improvement of the road transportation quality.

The third regards the analysis of additional CACCs potentially with different control topologies, e.g., bi-directional or many-to-many. This topic also relates to the investigation of spontaneous formation of platoons as opposed to a centrally-optimized one, which might be too complex or simply useless at low market penetration rates.

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