Can Platoons Form on Their Own?

Lorenzo Ghiro*, Renato Lo Cigno*, Elena Tonini†, Stefano Fontana†, Michele Segata‡
*DII – University of Brescia and CNIT, Italy
†DII – University of Brescia, Italy
‡DISI – University of Trento and CNIT, Italy

***Abstract*—Research on platooning has tackled many different facets of the topic, from lateral and longitudinal control to algorithms for optimization of platoon size and coordination. However, very few works started addressing the following two foundational questions. The first: Given a stretch of road where platooning is enabled and some form of V2X communication is feasible, will vehicles be able to organize locally in platoons without the need of central intervention? The second: Is a coordination protocol for platoon formation possible, or will traffic dynamics prevent the efficient formation of platoons? This paper gives a first, positive answer to these questions: A platoon formation protocol is proposed and tested upon DSRC communications, though it can be implemented on top of any transmission technology. We assess the performance in terms of platoon formation efficiency, on a multi-lane highway, as a function of the penetration rate of platooning-enabled vehicles and traffic characteristics. Realistic simulation results highlight the properties of the protocol as well as the impact of different traffic parameters, foremost the traffic density and the maximum distance between vehicles considered to start a platoon negotiation. These initial results pave the road for more sophisticated analysis, enhancements of the protocol and evaluation of advanced –possibly centralized– approaches to improve platoon management to achieve safer roads with increased capacity.**

I. Introduction

Intelligent Transportation Systems (ITSs) have many components, and cooperative driving is one of them. Within cooperative driving applications, platooning [1], [2] is one of the most studied as it is easy to characterize and because it promises to increase safety, reduce fuel consumption (or stretch battery lifetime), and improve road utilization [3]–[5].

As we discuss in Sect. II, a lot of attention has been devoted to control algorithms, to coordination of platoons, and to coordinated maneuvers, while platoon formation and basic protocols to manage them attracted far less attention. We deem this is a gap in the study of cooperative driving, especially now that both the Volkswagen and Toyota groups have started deploying Direct Short Range Communications (DSRC) devices on some of their models.[1]

If vehicles are DSRC-enabled, they can send and receive standard Cooperative Awareness Messages (CAMs) (or Basic Safety Messages (BSMs)), but they can also seek for more advanced cooperation, at least if the vehicles are ready to do so. What we want to explore in this paper is the efficiency of local, spontaneous platoon formation in the presence of vehicles that are willing to cooperate and how these platoons interact with other vehicles, which we assume, as communication enabled, autonomous, and rationale, as explained in Sect. IV.

In light of these simple considerations, the contributions of this work are the following:

- We design a simple, yet complete and safety-proof, protocol to manage the discovery of other vehicles willing to platoon and build platoons on the fly. This simple and spontaneous system can is viable, and it also serves as a benchmark for the comparison of more sophisticated proposals;
- We evaluate the performance of the protocol in terms of efficiency of platoon formation and impact on other vehicles and the traffic, if any.

Performance is always evaluated as a function of the penetration rate of cooperative vehicles, so as to understand the impact and gains on the traffic of the progressive introduction of V2V-based ADAS. Simulations are carried out with Plexe [8]; the simulation code and the protocol definition is available in a specific branch of Plexe repository[2].

II. Background and Related Work

A vast part of literature on platooning concentrates on the longitudinal control, starting from systems based on classical control theory like Ploeg [9] and PATH [10], to algorithms inspired by a spring and damper mechanical coupling [11], to solutions based on consensus theory [12]–[14], to space-, instead of time-, based control algorithms [15], and many more. Two recent and fairly comprehensive surveys can be found in [1], [16] and we refer the reader to them for additional details on longitudinal control and other topics. Recently, also mixing different controllers was considered [17].

Regardless of the controller used to stabilize the platoon, a higher level protocol is needed to form and manage the platoon.

1. After years when regulatory bodies kept deferring the mandate to install DSRC on new models, in 2019 volkswagen in Europe and Toyota in Japan started installing 802.11p-based communication devices, even if no mandate exists. In Japan, there are also about 150 intersections equipped with Road Side Units (RSUs). Based on the sales of equipped models, we estimate that the number DSRC-enabled vehicles is, at the time of writing this paper, about 3 million in Europe, and 250,000 in Japan. Recently, the standard for next-generation DSRC Vehicle to Everything (V2X) communications has been released [6], and its improved capabilities will enhance chances for additional services to be implemented. In the US, the situation is more fluid, with no decision taken yet by any automaker, while a Cellular V2X (C-V2X) solution is being deployed in China [7], but more detailed information is difficult to collect. The hope is that other automakers will follow soon, and in the near future Vehicle to Vehicle communication (V2V) based Advanced Driver Assistance Systems (ADAS) will improve safety and road usage.

2. https://plexe.car2x.org/

The longitudinal control may influence maneuvers, and some approaches may be better than others, but the platoon formation is mostly control-agnostic. In this work we use PATH because it is widely accepted, easy to understand and maintain a constant, small inter-vehicle distance regardless of the platoon speed.

Cooperative platoon maneuvers, as discussed in [18]–[21], are part of the platoon management and formation procedures, but all the references we found assume that vehicles are willing to cooperate and/or they are already part of the platoon, or they are instructed from the infrastructure or some oracle to be part of a specific platoon. For instance [22] proposes a framework to simplify the definition and design of platoon maneuvers. In some sense, this framework can be used also for the formation of platoons, but the design of a proper protocol is not presented, and if and how platoons can be formed from independent vehicles is not discussed.

Closer to the specific field and contribution of this paper, we find works dealing with the assignment of cars to platoons (optimal or not), with algorithms that tackle global traffic coordination and optimization. A good overview of this is found in [23], [24] that analyze all factors influencing platoons formation and management, different strategies and objectives of platoons, and how they have been treated in the literature.

Concentrating on the assignment of vehicles to (and/or their position within) platoons we find works like [25], which proposes a co-evolutionary algorithm to optimize the trajectories of coordinated vehicles to achieve an energy-aware objective during the platoon formation process; the paper does not discuss how vehicles communicate, nor a protocol to implement the algorithm.

When we come to actual protocols for platoon formation, i.e., how vehicles discover each other, and how they can agree on the formation of platoons that will continue the travel together, the literature is far less generous of solutions.

Some works on this subject address optimization issues: travel time, consumption reduction, and others. The authors of [26] present centralized and distributed heuristic algorithms with the goal of forming platoons that are optimal according to a metric based on the difference between the vehicles position and desired speed. The paper also sketches the protocols to implement the studied algorithms on top of broadcast beacons. Results compare the efficiency of the algorithms in forming platoons with various metrics.

A recent work [27] sketches an algorithm to allow the formation of platoons in a situation where there is a centralized entity that knows all about the vehicles, their whereabouts and the roads graph. The approach is inherently centralized and no protocol or communication details are discussed or simulated. Similarly, [28] presents a framework to optimize and change the configuration of multi-lane platoons, idealizing the setting and communications, while disregarding the protocol to implement the proposed framework.

III. An Elementary Platoon Formation Protocol

The key concept of the protocol we propose is based on broadcasting the intention to form platoons. Single vehicles and leaders of already formed platoons continuously advertise, through *extended* CAM (`E-CAM`) messages, their characteristics and intentions, while listening to similar messages from other vehicles. Fig. 1 depicts the high-level logic of platoons management. The left-hand side describes the process of forming and merging platoons, while the right-hand side the process to let a vehicle leave the platoon. Detailed Finite State Machines (FSMs) of the platoon formation are described in Sect. III-A, while Tab. I reports possible extension parameters to be added in `E-CAM` to support platoons management; in the current implementation these are the one used.

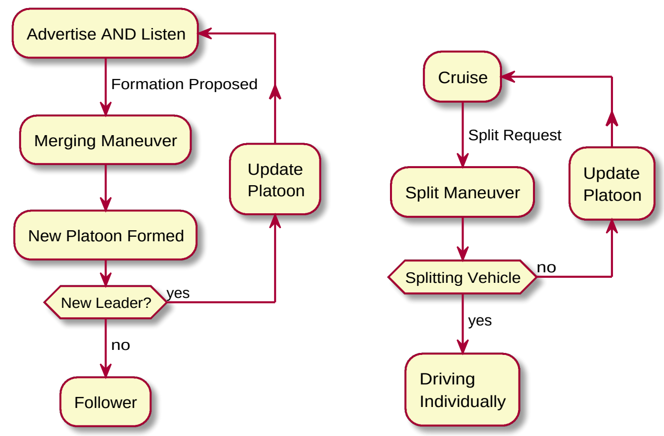

Figure 1: High-level global logic of the platoon management process: platoons formation and merge on the left-hand side, vehicles leaving the platoon on the right-hand side.

When a vehicle willing to form platoons receives `E-CAMs` advertising the presence of a platoon (or another single vehicle) compatible with the ego vehicle, it proposes to form a platoon as Requester. If the announcing vehicle (the Advertiser), accepts the proposal, the platoon formation can proceed and a merging maneuver is started as depicted on the left-hand side of Fig. 1. Details of the merging procedure are outside the scope of this contribution, as they can depend on many variables and situations. We use an implementation of a simple merge at the tail derived from the maneuvers proposed in [18] where we also enable the join of platoons and not only of single vehicles.

When the new platoon is formed, the Advertiser is the leader of the new platoon and the Requester is a simple follower, because the protocol ensures that the Requester has performed a complete merge of the platoons. After updating the platoon characteristics and stabilizing the cruising, the leader of the new platoon can go back to the 'Advertise AND Listen' state or stops Advertising because, e.g., the platoon has reached a target dimension. The protocol empowers the formation of platoons, but also the merging of already formed platoons.

A. Detailed FSM for Platoon Formation

The negotiation to form a platoon is executed in unicast on the service channel announced by the Advertiser, i.e., the protocol does not interfere with the CAMs (or `E-CAM`) sent on the safety channel. The protocol is initiated by the

Field	Format
CruiseMinSp	32 bits float [m/s]; minimum desired cruising speed, $0 < \texttt{CruiseMinSp} < \texttt{CruiseMaxSp}$
CruiseMaxSp	32 bits float [m/s]; maximum desired cruising speed, $\texttt{CruiseMinSp} < \texttt{CruiseMaxSp} < 100$
CurCruiseSp	32 bits float [m/s]; current desired cruising speed, $\texttt{CruiseMinSp} < \texttt{CurCruiseSp} < \texttt{CruiseMaxSp}$
CurLane	8 bits integer; lane of the ADVERTISER
PlatID	32 bits integer; unique identifier of the platoon
PlatCurSz	8 bits integer; current platoon size in no. of vehicles
PlatMaxSz	8 bits integer; maximum platoon size in no. of vehicles
ServCh	8 bits integer; channel for the formation protocol
Flags	16 bits; flags for capabilities, e.g., possibility to be platoon leader
NextWP	Geo Coordinates, variable length

Table I: Possible CAMs extension parameters to enable the platooning discovery and formation.

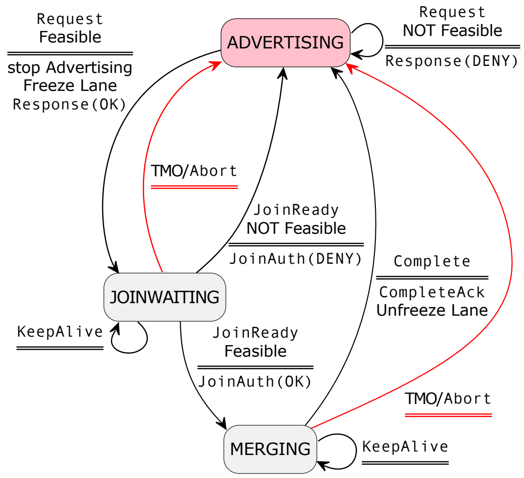

Figure 2: FSM of the ADVERTISER side of the protocol

REQUESTER. Working in unicast on a service channel helps streamlining the process, as unicast communications can use higher rates and the MAC-level ACKs simplify the design of the protocol making communications more reliable.

The actual formation protocol starts when a listening vehicle decides that the E-CAM received from another vehicle represents a good opportunity to form a platoon or merge two existing ones. This condition is local and is not strictly part of the protocol; in the remainder of the paper we assume five conditions: *i)* 3 E-CAM are received from the same vehicle within a 3 s interval and the distance between the vehicles is between $D_{\min}$ and $D_{\max}$ m in front of the ego vehicle: a potential REQUESTER considers only ADVERTISERs in front of it for the sake of simplicity, the other case is left for future study; *ii)* the admitted cruising speed intervals of the advertising vehicle and the ego vehicle overlap by at least 10 km/h; *iii)* the NextWP is at least 5 km away; *iv)* the dimension of the platoon to be formed does not exceed the maximum platoon size (PlatMaxSz) advertised in the E-CAM; and *v)* the advertising vehicle is in the same lane or in one adjacent lane, i.e., we do not start a platoon formation if this requires changing more than one lane. When this happens the vehicle sends a Request message and becomes the REQUESTER (see Fig. 3).

Upon receiving the request the advertising vehicle becomes

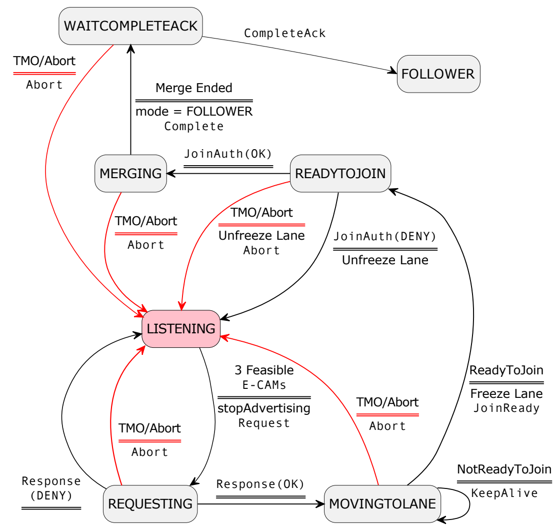

Figure 3: FSM of the REQUESTER side of the Protocol

the ADVERTISER. If the Request received by the ADVERTISER meets local conditions to form a platoon, then the ADVERTISER sends a positive Response message with the proposed platoon formation parameters, otherwise it sends a negative Response that ends the procedure. Reasons to deny a request can be many, the two foremost ones are: *i)* Another formation procedure just started, or *ii)* a vehicle in the platoon is performing a leaving procedure (not considered in this work).

When the ADVERTISER sends a positive Response, it moves to the JOINWAITING state where it remains while the REQUESTER prepares for the actual join maneuver and moves to the MOVINGTOLANE state. The ADVERTISER (and its platoon) will not change lane until the maneuver is finished to avoid inconsistent behaviors during the platoon formation; furthermore, the positive Response includes the identity of the last vehicle in the platoon, to allow the REQUESTER to properly identify the tail of the platoon for the merging procedure. The duration of this phase may be long, for instance because the merging platoon cannot change the lane, thus the REQUESTER periodically sends KeepAlive messages to inform the ADVERTISER that the joining is still active. Since it is not appropriate for these maneuvers to last too long, the REQUESTER sets a 20 s ($\pm 10\%$) timeout in the MOVINGTOLANE, if it expires the maneuver is aborted; 20 s is an arbitrary value we selected heuristically for this initial study.

When the REQUESTER is in the correct lane at the correct distance from the tail of the platoon, it sends a READYTOJOIN message and moves to the corresponding state. The ADVERTISER answers with a JoinAuth message and moves to the MERGING state. The REQUESTER also moves to the MERGING state upon receiving the JoinAuth. If any condition prevents the correct execution of these preliminary maneuvers either the ADVERTISER or the REQUESTER sends an Abort message and both vehicles return, after an appropriate timeout, to the base state of 'Advertise AND Listen' of Fig. 1.

The merging maneuver is handled by a specific protocol (we

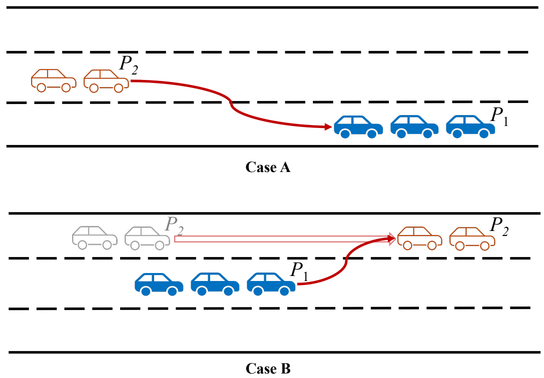

Figure 4: The two simple platoon merging maneuvers of **Case A** and **Case B**.

use a modification of the one presented in [18] as already mentioned) while the ADVERTISER and the REQUESTER remain in the MERGING state; the REQUESTER keeps sending `KeepAlive` periodic messages to confirm the ongoing merging maneuver. When the merging maneuver is completed, which implies that all the vehicles in the platoon of the REQUESTER have been notified of the merge and have changed their leader and platoon id, the REQUESTER sends a `Complete` message and moves to WAITCOMPLETEACK. The ADVERTISER acknowledges it with `CompleteAck` message, enables again the possibility to change lane and, after a proper timeout and if conditions permit, returns to the ADVERTISE state, otherwise behaves as a normal platoon leader without further advertising the will to form a larger platoon. Upon reception of the `CompleteAck`, the REQUESTER moves to a simple FOLLOWER state.

B. Protocol Verification

To verify the proposed protocol we present the elementary behavior of 2 platoons driving on a stretch of a 3-lane highway that decide to merge. We consider two elementary cases involving 2 already formed platoons, one with 3 vehicles (P_1) and one with 2 (P_2), that want to merge:

Case A: P_1 drives in the rightmost lane at 100 km/h, P_2 drives in the central lane at 110 km/h and its leader approaching P_1 decides to propose a merge;

Case B: P_1 drives in the central lane at 110 km/h, P_2 drives in the leftmost lane at 125 km/h: when P_2 overtakes P_1 the leader of P_1 decides to propose a merge.

The goal of these two elementary cases, depicted in Fig. 4, is to show the elementary behavior during the platoon formation process.

Figs. 5 and 6 report the speed and acceleration of every vehicle in the two platoons during the negotiation to merge, the subsequent merge maneuver, and the final phase of the formation of the new 5-vehicles-platoon for **Case A** and **Case B** respectively. The vertical dotted lines correspond to the key phases of the maneuver as reported in the caption of Fig. 5 and highlight, as expected, that the longer phase is the one when platoons actually merge, while the protocol itself does

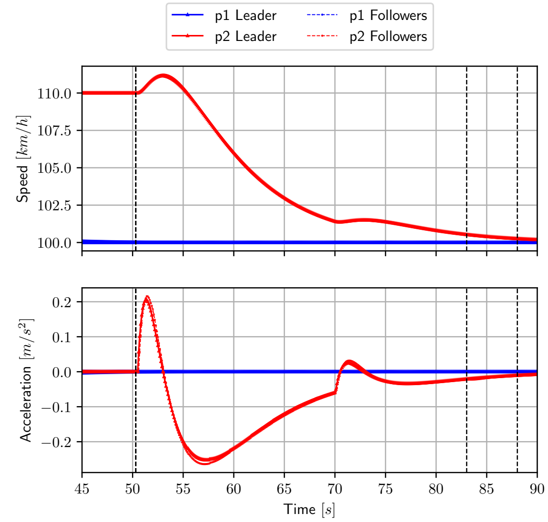

Figure 5: Speed and acceleration of vehicles during the platoon merging of **Case A**; vertical dotted lines correspond to the 4 fundamental phases of the platoon formation protocol: `Request` sent, `JoinReady` sent, `CompleteAck` sent, and the actual end of the maneuver when the ADVERTISER starts sending `E-CAM`s again.

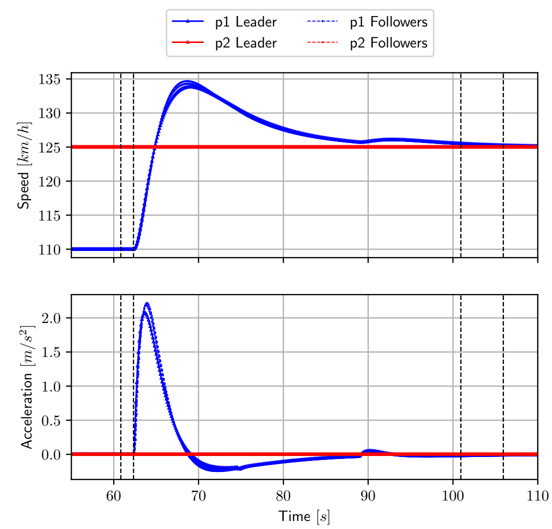

Figure 6: Speed and acceleration of vehicles during the platoon merging of **Case B**; vertical dotted lines as described in Fig. 5.

not introduce large delays. In Fig. 5 P_2 first change lane (not shown in the plots as they refer the longitudinal dynamics), then accelerates to get closer to P_1 and start decelerating until, at second 70, the distance between P_2 leader and the tail vehicle of P_1 is compatible with the PATH controller, which is activated and induces again a small acceleration to regulate the distance and speed. Approximately at 84 s the maneuver is completed and the `CompleteAck` sent, while the last vertical dotted line marks the moment when the new platoon is stable and the leader starts again sending `E-CAM`s. In Fig. 6 P_1 sends the `Request`, then waits for P_2 to complete the overtaking before sending the `JoinReady`. When this happens P_1 changes lane

	Parameter	Value
Road & Traffic	No. of lanes	$N_L = 3$
	Road length	$10\,\mathrm{km}$ of effective observation
	Observed vehicles	> 1000
	A_r	$\{5, 10, 15, 20, 25, 30\}$ veh./min./lane
	V_i Desired speed	$s_i = U[100, 105, 110, 115, 120, 125, 130]\,\mathrm{km/h}$
	V_i platooning speed range	$s_i \pm \delta_s$, $\delta_s = 10\,\mathrm{km/h}$
	Platooning Penetration Rate R	{0.25, 0.50, 0.75, 1.0}
Controllers	Powertrain lag	$0.5\,\mathrm{s}$
	Standstill distance	$d = 2\,\mathrm{m}$
	ACC headway time	$H_a = 1.2\,\mathrm{s}$
	ACC gain	$\lambda = 0.1$
	PATH apportioning coeff.	$C_1 = 0.5$
	PATH damping	$\omega_n = 0.2$
	PATH bandwidth	$\xi = 1$
	PATH inter vehicle distance	$5\,\mathrm{m}$
Comm.	L2-technology	dual radio 802.11p
	Tx power	$500\,\mathrm{mW}$
	Broadcast MCS	$3\,\mathrm{Mbit/s}$
	Unicast MCS	$12\,\mathrm{Mbit/s}$
	Rx sensitivity	$-94\,\mathrm{dBm}$
Protocol	$D_{\min}$	$20\,\mathrm{m}$
	$D_{\max}$	$\{50, 100, 150, 200\}\,\mathrm{m}$
	$N_P^{\max}$ =`PlatMaxSz`	{6, 8, 10, 25}
	Wait after Success / Abort	5 s / 20 s
	Req. Feasible Adv.	3

Table II: Parameters characterizing vehicles and communications in the simulation experiments.

and accelerates to join P_2. The remaining part of the procedure is similar to **Case A**; the PATH controller is activated around second 88.

IV. Test Scenario and Selected Experiments

We consider a 3-lane highway of arbitrary length. Vehicles enter the highway as autonomous vehicles following the standard SUMO lane change model. Non cooperative vehicles follow the standard SUMO Krauss model [29]. Platooning vehicles use the Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) (PATH) defined in [10][3] and are capable of changing lane to overtake or maintain the right-most free lane. The first vehicle of a platoon, when this forms, is always an autonomous vehicle controlled by an ACC. A generic vehicle is named V_i, while vehicles within a platoon are identified as $V_j^p, j = 0, \ldots, N_P^{\max} - 1$, where $N_P^{\max}$ = `PlatMaxSz` is the maximum number of vehicles admitted in a platoon and the apex p is a platoon identifier. If a vehicle is willing to participate in a platoon, it also has a speed range around its desired speed, named δ_s, that defines if it can form a platoon with other cars within communication range; δ_s is identical for all vehicles, while the desired speed of vehicles, when they enter the road, is a discrete uniform distribution on $[100, 105, 110, 115, 120, 125, 130]\,\mathrm{km/h}$.

Vehicles arrive at the highway following a simple Poisson process for each lane, with rate α vehicles/s. For the sake of simplicity, we assume vehicles with a constant length of $4\,\mathrm{m}$ and a stand-still distance of $2\,\mathrm{m}$. All vehicles enter the road at $90\,\mathrm{km/h}$, and the Poisson process is translated by $1.44\,\mathrm{s}$ to guarantee that vehicles enter the road with a distance from the preceding vehicle larger than the safety headway time H_a plus the stand-still distance. In other words, given α, the inter generation time between vehicles is defined as:

$$\Delta_t = 1.44 + e^{\frac{t}{\alpha'}}; \quad \alpha' = \frac{\alpha}{1 - 1.44\alpha} \tag{1}$$

which limits α in the interval $(0, \frac{1}{1.44})$. For readability, in plots we express the average arrival rate in vehicles per minute per lane: $A_r = 60 \cdot \alpha$. The fraction of vehicles that are communication-enabled and willing to form a platoon is $0 \leq R \leq 1$. Simulations end when at least 1000 platoon-enabled vehicles exit at the end of the road. Each experimental scenario is repeated seven times with different seeds to collect independent samples.

Even if the scenario proposed is minimal, the number of actual configurations, cases and conditions is very large: traffic arrival rate A_r, penetration rate R, desired speed ranges, the minimum and maximum negotiation distances $D_{\min}$, $D_{\max}$, and so forth, all influence results and make a systematic exploration unfeasible. Thus we present selected results that highlight interesting features of the protocol and give insight in the dynamics of platoon formation.

The key metrics we use are the fraction of vehicles η that are part of a platoon, and the distribution $\mathbf{N_P}$ of the platoon size as a function of the observation point along the road. The stretch of highway under observation is $10\,\mathrm{km}$, preceded by $500\,\mathrm{m}$ where vehicles reach their steady state after entering the simulation, and followed by a $500\,\mathrm{m}$ stretch where vehicles stop the platoon formation protocol to avoid having 'pending' procedures when the vehicles exit the simulation[4].

The first analysis we present shows the trend of vehicles to form and join platoons. Fig. 7 reports the fraction η of vehicles that have joined a platoon along the highway for $R = 1$, $N_P^{\max} = 8$, and all the traffic densities A_r; in other terms the swiftness of platoon formation as the vehicles proceed on the highway. We report the two cases $D_{\max} = 50$ and $200\,\mathrm{m}$; the other two values $D_{\max} = 100, 150\,\mathrm{m}$ confirm the trend. First of all, it is clear that in $10\,\mathrm{km}$ most vehicle form a platoon independently from any condition or parameter, although $D_{\max} = 50\,\mathrm{m}$ somehow limits the platoon formation: Since $D_{\min} = 20\,\mathrm{m}$ the actual 'space' to request a platoon formation is only $30\,\mathrm{m}$ so it is reasonable that platoon formation is slowed down. Next, we have to note that even if vehicles entering the road activate communications and go in the 'Advertise AND Listen' state, the first platoons complete their formation only after roughly $1\,\mathrm{km}$. This is mostly due to time spent in the MOVINGTOLANE and MERGING states, where the vehicles dynamics and road conditions require spending several tens of seconds, enough to drive $1\,\mathrm{km}$ or more at the speeds we consider. Carefully observing the bottom plot of Fig. 7, one can notice a peculiar behavior of the curves for $A_r = 20, 25, 30$ between $2\,\mathrm{km}$ to

3. As the focus of this paper is not on the platoons controllers performance. Tab. II reports all the parameters that allow reproduction of results, even if they are not explained in detail here.

4. This is needed to avoid inconsistencies in the communication protocols, for instance one vehicle trying to communicate in unicast with a vehicle that has already exited the simulation.

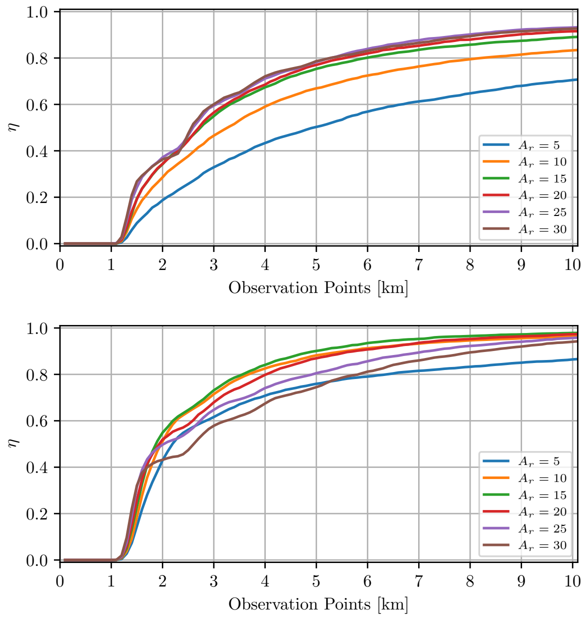

Figure 7: Fraction η of vehicles that joined a platoon as a function of the position in the road for $R = 1$, $N_P^{\max} = 8$, and all the traffic densities A_r. Top $D_{\max} = 50$; bottom $D_{\max} = 200$.

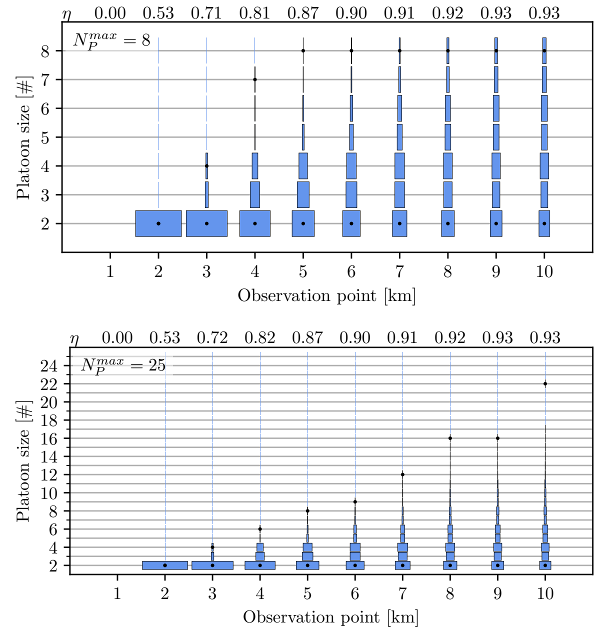

Figure 8: Distribution of the platoon size $\mathbf{N_P}$ as a function of the observation point for $A_r = 15$, $R = 1$, $D_{\max} = 200$, and $N_P^{\max} = 8, 25$.

$4\,\text{km}$, particularly evident for $A_r = 30$ because the curve does not overlap with others in this area. The curves have a non uniform increment rate, and this is due to the fact that at these high road loads at the beginning many vehicles form platoons of dimension 2, more or less synchronized, then move in the 'Advertise AND Listen' state and, again more or less synchronized, form platoons of dimension 3 and 4 (see also Fig. 8).

Fig. 8 presents the distribution of the platoon size $\mathbf{N_P}$ as discrete violinplots in 10 observation points equally spaced along the road from km 1 to km 10 for $N_P^{\max} = 8, 25$ and the other simulation parameters reported in the caption. The number reported above the violinplots indicate η, the fraction of vehicles that are part of a platoon at the specific observation point. The sum of all the bars of the violinplots is constant, correctly representing a distribution. Obviously the larger η the more vehicles are accounted for in the distribution. As expected, platoon sizes increase as vehicles organize along the road, but they do not tend to become all of the maximal size allowed. This is particularly evident in the bottom plot, where no platoon reaches the size of 25, and the bulk of them remains below 10. This may be due to many reasons, but we think that the dominating one is the difficulty of completing maneuvers with large platoons, so that these maneuvers, even if initiated will abort as discussed commenting Fig. 10. However, as very large platoons create large blockages area on the road (in the examined case a 22-vehicles platoon is roughly $200\,\text{m}$ long, but a different controller and bigger vehicles can easily make large platoons much longer), we do not report any other detailed result for $N_P^{\max} = 25$.

Focusing on the top plot, one can follow the evolution of platoons. Starting at km 2 we observe that all platoons have dimension 2, as the first round of platoon formation lasts more than 1 km (and this is obviously true also for $N_P^{\max} = 25$). At the observation point at km 3 the bulk of platoons have dimension 2, 3, and 4, but some larger platoons already merged into platoons as large as 7. The platoon size keep increasing, but even at km 10 the dimensions 2, 3, and 4 are the most likely to be found. The size will keep increasing with the road length, but we think it is not realistic to characterize the size of platoons at 'steady state,' as on normal roads there are always entry-exit points.

In closing this first analysis, we remark that the platoon formation strategy is "First Detected First Requested," thus what we observe is a basic behavior of the protocol. Better strategies to start negotiations may benefit the dynamics of platoon formation.

Tab. III presents η and $\overline{\mathbf{N_P}}$ as measured at the end of the road for several different sets of parameters (reported in the caption). The takeaway of this analysis is that platoons can form autonomously almost regardless of the scenario, even with a penetration rate as small as $R = 0.25$. Only when the range considered to start a platoon formation session is very small $D_{\max} = 50$ and $R = 0.25$ the fraction of vehicles in a platoon remains small: $\eta = 0.32$. The average platoon size $\overline{\mathbf{N_P}}$ grows together with η, indicating that as more vehicles enter platoons these becomes larger, as we already observed for specific sets of parameters. This trend and the general considerations we did on results presented are confirmed by the analysis of all results we obtained in the explored space of parameter (see Tab. II), not reported here to avoid repetitive patterns.

Tab. III quantify how much the penetration rate of platooning

$A_r = 5$							
R	$D_{\max}$	η	$\overline{\mathbf{N_P}}$	R	$D_{\max}$	η	$\overline{\mathbf{N_P}}$
$R = 0.25$	50	0.32	2.15	$R = 0.5$	50	0.48	2.24
	100	0.39	2.25		100	0.59	2.48
	150	0.43	2.27		150	0.64	2.49
	200	0.47	2.30		200	0.66	2.56
$R = 0.75$	50	0.61	2.35	$R = 1.0$	50	0.68	2.49
	100	0.71	2.75		100	0.78	2.94
	150	0.76	2.81		150	0.83	3.04
	200	0.78	2.84		200	0.85	3.15
$A_r = 25$							
R	$D_{\max}$	η	$\overline{\mathbf{N_P}}$	R	$D_{\max}$	η	$\overline{\mathbf{N_P}}$
$R = 0.25$	50	0.62	2.40	$R = 0.5$	50	0.76	2.64
	100	0.70	2.73		100	0.85	3.37
	150	0.72	2.63		150	0.82	3.31
	200	0.67	2.65		200	0.82	3.17
$R = 0.75$	50	0.82	2.88	$R = 1.0$	50	0.84	3.03
	100	0.89	3.98		100	0.90	4.30
	150	0.89	4.11		150	0.88	4.18
	200	0.87	3.71		200	0.88	4.26

Table III: Fraction η of platooning-enabled vehicles that have formed a platoon and average dimension of the platoons $\overline{\mathbf{N_P}}$ at the end of the road for all penetration rates R, $A_r = 15$, $N_P^{\max} = 8$ and all tested $D_{\max}$.

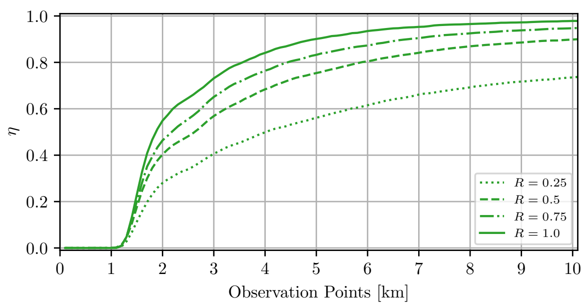

Figure 9: Fraction η of platooning-enabled vehicles that have joined a platoon as a function of the position in the road for $N_P^{\max} = 8$, A_r = 15, $D_{\max} = 200$ and all penetration rates R.

vehicles influences the platoon formation mainly for small $D_{\max}$. Fig. 9 supports this conclusion showing η for $N_P^{\max} = 8$, A_r =15, $D_{\max} = 200$ and all penetration rates: the fraction of vehicles that are part of a platoon decreases as the penetration rate decreases, but even with $R = 0.25$ at the end of the road nearly 80% of enabled vehicles are part of a platoon.

Figs. 10 and 11 report measures on the platoon formation protocol itself. Namely Fig. 10 reports the total number of protocol sessions that ended with a success (blue) with an abort (red) or with a deny (gray), while Fig. 11 reports boxplots of the duration of the sessions ended successfully or aborted; those ended with a deny are not reported because they all end within a few milliseconds. The first observation on Fig. 10 is that session denied by the ADVERTISER far outnumber successful ones. Albeit they are sort of irrelevant as they only imply the exchange of a few massages, a better session initiation strategy may help reducing unsuccessful sessions. More difficult may be to reduce the number of aborted sessions, as these are mostly due to other traffic interfering with the merging vehicles, as we can extrapolate also observing that they grow in number

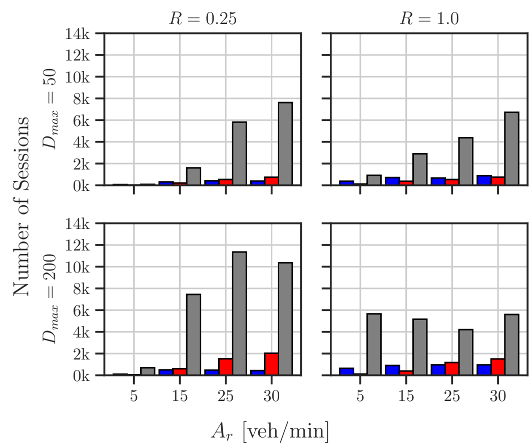

Figure 10: Total number of protocol sessions in the experiments (mean on all the repetitions) for $N_P^{\max} = 8$, $D_{\max} = 50, 200$, $R = 0.25, 1$, and $A_r = 5, 15, 25, 30$ divided between those that ended with success (blue), abort (red) or deny (gray).

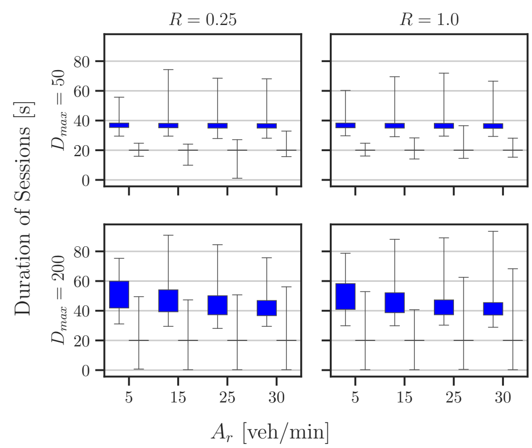

Figure 11: Boxplots of the successful (blue) or aborted sessions duration in seconds. Same parameters ad Fig. 10.

with increased traffic density, while successful ones remain roughly constant. Denied one also increase with traffic when $D_{\max} = 50$, but this is due to the increase of interactions when the traffic increase with short $D_{\max}$, as with light traffic sessions are simply not initiated. Overall, sessions are just a few per vehicle, so that they do not represent a large load for the communication layer.

Fig. 11 highlights that successful sessions last in general slightly less than one minute with some extending close to two minutes, with longer sessions when $D_{\max} = 200$ as the session starts when vehicles are farther away. The reason is obviously not in the communication itself, but is rooted in the dynamics of the vehicles on the road. Additional insight is needed to understand if this duration can be reduced or not. Aborted sessions are dominated by the 20 s timeout in the MOVINGTOLANE state, so that boxplots collapse onto this value and only whiskers are visible. We recall that the value of this timeout is arbitrary and deserves further investigation.

Short sessions, close to $0\,\mathrm{s}$ are due to interference from other vehicles soon after the procedure is started.

V. Conclusions and Future Work

Platoons formation and management is fundamental for smart mobility infrastructures. This work introduced a baseline protocol to negotiate the formation of platoons and the merge of small platoons into larger ones. The protocol is implemented on 802.11p, but can be implemented on any communication infrastructure, including C-V2X.

The protocol behavior has been explored on a 3-lane highway with a large set of different traffic and protocol parameters (see Tab. II) for a total of 384 possible configurations. Indeed, and unfortunately, this is still a small portion of the space of parameters, as we fixed several of them with heuristic considerations. The results presented are very encouraging, as platoons form spontaneously with high probability, even if we considered only an elementary strategy to propose the platoon formation: First Detected First Requested, i.e., a vehicle contacts another one as soon as it receives 3 E-CAMs, which leave space for much smarter strategies.

The presented protocol is a baseline against which the community can compare better, centralized or distributed optimization strategies that can be implemented having a real protocol for the platoon formation management. Even centralized optimization algorithms will notify vehicles on what platoon to form, but then the vehicles have to coordinate to form it on the road. Future work include, besides these interesting questions, completing the system with a protocol to let vehicles leave platoons and analyzing the fundamental behavior, as we did here, in presence of enter and exit ramps. Furthermore, analysis and performance of the communication layer, not presented here, is of the utmost importance to understand scalability and safety of the system.

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References

[1] B. Häfner et al., "A survey on cooperative architectures and maneuvers for connected and automated vehicles," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 1, Firstquarter 2022.

[2] R. Lo Cigno et al., "Cooperative driving: A comprehensive perspective, the role of communications, and its potential development," *Elsevier Computer Communications*, vol. 193, Sep. 2022.

[3] V. Turri et al., "Cooperative Look-Ahead Control for Fuel-Efficient and Safe Heavy-Duty Vehicle Platooning," *IEEE Trans. on Control Systems Technology*, vol. 25, no. 1, Jan. 2017.

[4] Z. Yang et al., "Collision-Free Ecological Cooperative Robust Control for Uncertain Vehicular Platoons With Communication Delay," *IEEE Trans. on Vehicular Technology*, vol. 70, no. 3, Mar. 2021.

[5] G. Guo et al., "Distributed Trajectory Optimization and Fixed-Time Tracking Control of a Group of Connected Vehicles," *IEEE Trans. on Vehicular Technology*, vol. 72, no. 2, Oct. 2023.

[6] 802.11bd-2022, *Telecommunications and Information Exchange between Systems, Local and Metropolitan Area Networks, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Next Generation V2X.*

[7] T. Cui et al., "C-V2X Vision in the Chinese Roadmap: Standardization, Field Tests, and Industrialization," in *Vehicular Networks - Principles, Enabling Technologies and Perspectives*, D. A. Haidine, Ed., Rijeka: IntechOpen, 2022, ch. 3.

[8] M. Segata et al., "Multi-Technology Cooperative Driving: An Analysis Based on PLEXE," *IEEE Trans. on Mobile Comp. (TMC)*, Feb. 2022.

[9] J. Ploeg et al., "Design and Experimental Evaluation of Cooperative Adaptive Cruise Control," in *14th IEEE Intelligent Transportation Systems Conf. (ITSC 2011)*, Washington, D.C., USA, Oct. 2011.

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

[11] G. Giordano et al., "The joint network/control design of platooning algorithms can enforce guaranteed safety constraints," *Elsevier Ad Hoc Networks*, vol. 94, Nov. 2019.

[12] S. Santini et al., "A Consensus-based Approach for Platooning with Inter-Vehicular Communications and its Validation in Realistic Scenarios," *IEEE Trans. on Vehicular Technology*, vol. 66, no. 3, Mar. 2017.

[13] Y. Li et al., "Nonlinear finite-time consensus-based connected vehicle platoon control under fixed and switching communication topologies," *Elsevier Transportation Research Part C: Emerging Technologies*, vol. 93, Aug. 2018.

[14] Y. Zheng et al., "Development of Connected and Automated Vehicle Platoons With Combined Spacing Policy," *IEEE Trans. on Intelligent Transportation Systems (TITS)*, vol. 24, no. 1, Jan. 2023.

[15] B. Besselink et al., "String Stability and a Delay-Based Spacing Policy for Vehicle Platoons Subject to Disturbances," *IEEE Transactions on Automatic Control*, vol. 62, no. 9, Sep. 2017.

[16] Z. Wang et al., "A Survey on Cooperative Longitudinal Motion Control of Multiple Connected and Automated Vehicles," *IEEE Intelligent Transp. Systems Mag.*, vol. 12, no. 1, Spring 2020.

[17] M. Segata et al., "On the Progressive Introduction of Heterogeneous CACC Capabilities," in *13th IEEE Vehicular Networking Conference (VNC 2021)*, Virtual Conference, Nov. 2021.

[18] M. Segata et al., "Supporting platooning maneuvers through IVC: An initial protocol analysis for the JOIN maneuver," in *11th IEEE/IFIP Conference on Wireless On-demand Network Systems and Services (WONS)*, Obergurgl, AT, Apr. 2014.

[19] S. Maiti et al., "The Impact of Flexible Platoon Formation Operations," *IEEE Trans. on Intelligent Vehicles*, vol. 5, no. 2, Jun. 2020.

[20] Häfner, Bernhard and Schmitt, Georg A and Ott, Jörg, "Evaluating Participation in Cooperative Maneuvers among Connected and Automated Vehicles," in *IEEE 96th Vehicular Technology Conference (VTC2022-Fall)*, London, UK, Sep. 2022.

[21] M. Strunz et al., "CoOP: V2V-based Cooperative Overtaking for Platoons on Freeways," in *2021 IEEE Int. Intelligent Transportation Systems Conference (ITSC)*, Indianapolis, IN, USA, Sep. 2021.

[22] J. Ivanchev et al., "A Hierarchical State-Machine-Based Framework for Platoon Manoeuvre Descriptions," *IEEE Access*, vol. 9, Aug. 2021.

[23] T. Sturm et al., "A taxonomy of optimization factors for platooning," *IEEE Trans. on Intelligent Transp. Systems*, vol. 22, no. 10, Oct. 2021.

[24] V. Lesch et al., "An overview on approaches for coordination of platoons," *IEEE Trans. on Intelligent Transp. Systems*, vol. 23, no. 8, Aug. 2022.

[25] Z. Deng et al., "A coevolutionary algorithm for cooperative platoon formation of connected and automated vehicles," *IEEE Trans. on Vehicular Technology*, vol. 71, no. 12, Dec. 2022.

[26] J. Heinovski et al., "Platoon Formation: Optimized Car to Platoon Assignment Strategies and Protocols," in *IEEE Vehicular Networking Conference (VNC)*, Taipei, Taiwan, Dec. 2018.

[27] H. Yair et al., "Automatic Real-Time Platoon Formation Using the Road Graph," *SN Computer Science*, vol. 5:18, 2024.

[28] R. Firoozi et al., "Formation and reconfiguration of tight multi-lane platoons," *Control Engineering Practice, Elsevier*, vol. 108, 2021.

[29] S. Krauss, "Microscopic modeling of traffic flow: investigation of collision free vehicle dynamics," Apr. 1998.