Distributed Control And Reorganization Of Heterogeneous Vehicle Platoons Subject to Time Delay and Limited Communication Range

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Abstract. *Autonomous platoons have emerged as efficient alternatives for cargo transportation, and extensive research has been conducted to address safety and efficiency concerns. However, most existing literature assumes continuous connectivity among platoon vehicles, disregarding limited communication ranges and time-delay. In this paper, we focus on the challenge of maintaining connectivity and stability in platoons, even in the event of complete disconnection. Our objective is to enhance tolerance to various factors, including agent exits, external elements (e.g., traffic lights and human-driven vehicles), and non-ideal initial conditions, thereby improving traffic safety in mixed traffic scenarios. By treating the state alteration as a reference tracking problem, we propose a design procedure that ensures stability and zero spacing error in steady-state. Through agent-based and nonlinear simulations, we demonstrate the efficacy of our control protocol, allowing vehicles to achieve consensus with the platoon even when they start disconnected from others.*
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Resumo. *Pelotões autônomos surgiram como alternativas eficientes para o transporte de carga, e extensas pesquisas foram realizadas para abordar questões de segurança e eficiência. No entanto, a maior parte da literatura existente assume conectividade contínua entre veículos de pelotão, desconsiderando alcances de comunicação limitados e atrasos. Neste trabalho, focamos no desafio de manter a conectividade e a estabilidade nos pelotões, mesmo em caso de desconexão total. Nosso objetivo é aumentar a tolerância a vários fatores, incluindo saídas de agentes, elementos externos (por exemplo, semáforos e veículos conduzidos por humanos) e condições iniciais não ideais, melhorando assim a segurança do tráfego em cenários de tráfego misto. Ao tratar a alteração de estado como um problema de rastreamento de referência, propomos um procedimento de projeto que garante estabilidade e erro de espaçamento zero em estado estacionário. Por meio de simulações baseadas em agentes e não lineares, demonstramos a eficácia do nosso protocolo de controle, permitindo que os veículos cheguem ao consenso com o pelotão mesmo quando começam desconectados dos demais.*

1. Introduction

The study on autonomous vehicular platoons has grown recently due to high demand for efficient and safe transportation. Most literature focuses on control strategies, communica-

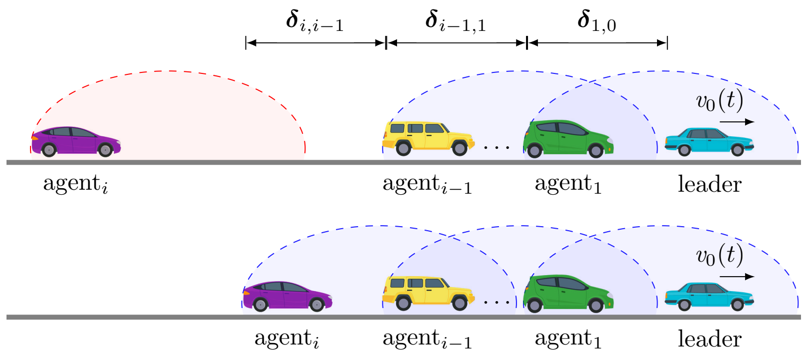

Figura 1. Heterogeneous platoons under limited communication range and time-delay: when a vehicle, or a subset of vehicles, loses connection with the team, it must be able to re-connect, maintaining the original formation.

tion protocols, and driver characterization, but few address robustness against unfavorable conditions, disruptions, failures, or attacks. In multi-agent systems, communication is an important topic. For platooning systems, researchers propose methods for robustness against communication delay, noise, or DoS attacks, but limited communication range in platoons is less studied. This paper explores scenarios of platoons with communication networks subject to connectivity constraints and time-delay.

Our approach considers look-ahead topologies, where a platoon member receives information only from preceding vehicles. According to Feng et al. (2019), these topologies are classified as rPF. We propose a state machine focused on three main aspects. Firstly, under normal conditions, vehicles maintain constant speed, desired gap, and monitor the communication network. Secondly, temporary disturbances, like non-cooperative vehicles, trigger a state change where a control law regulates speed and gap while maintaining connectivity. Thirdly, severe perturbations, such as broken communication links due to red traffic lights, cause a split event. When compared to the state-of-the-art literature, our hybrid protocol offers, in steady-state conditions, the following contributions:

- relaxation of the initial conditions (a vehicle will reach the platoon even when disconnected from others since it starts anywhere behind the leader);
- re-connection of single agents (a vehicle will reach consensus with the team even under temporary disconnection);
- joining of platoon groups (separated parts of the platoon caused by external events, such as traffic lights, will be able to reconnect with the team);
- resilience under the failure of $n-1$ followers (a vehicle will be able to reach the leader even if all other platoon agents fail or intentionally leave the team).

2. Related work

Nowadays, *vehicular platoons* are one of the most studied problems in the field of transportation systems since road freight is a critical issue for many countries. In [Dey et al. 2016], the authors provide a compilation of the state-of-the-art literature about platoons, categorizing it into three issues: (i) *communication frameworks*, (ii) *driver interferences*, and (iii) *control strategies*. Regarding control, there are considerable subtopics, ranging from modeling to controller design, human interaction, structural changes in the team hierarchy, or fault tolerance. These real-world scenarios can impair the stability of the team, leading the discussion towards concepts of *resilience*.

In the seminal paper [Antonelli and Chiaverini 2006], the authors proposed a controller to deal with obstacles in multi-robot formation. Since then, *resilient platoons* have attracted the attention of the community, once there are many threats with the potential to compromise the team performance. The authors of [Parkinson et al. 2017], for example, describe a series of potential "cyber"threats, vulnerabilities, and mitigation strategies, on aspects like vehicle components, human interaction, and network infrastructure. On the other hand, effects of communication delay on platoons have been studied for second-order systems in [Ghaedsharaf et al. 2018], considering constant time-delay and exogenous noise, and in [Li et al. 2019, Zhang and Orosz 2016], considering heterogeneous time-varying delays and nonlinear spacing policies.

Another constraint is the limited communication ranges in mobile networks. Limited sensing capabilities are addressed in [Guo and Yue 2012], considering sensors like sonars and radars, which have sensitive and non-sensitive zones, both defined by their detection capability. The proposed conditions ensure string stability whenever some agents travel within the detection ranges of others. Similarly, [Middleton and Braslavsky 2010] investigates the effects of a limited range of forwarding and backward communication on string stability. However, both works do not handle disruptions, e.g., situations in which an agent leaves the platoon, purposefully or due to malfunction. Disconnection has been recently addressed in the context of Vehicular Ad-hoc Networks (VANETs) in [Huang and Tseng 2018], where authors use temporary relay information to keep the system connected, but the internal stability is neglected.

Finally, resourcefulness represents the main challenge in ensuring resilient autonomy in adverse environments. Changes in the platoon structure (planned or not) may lead to critical situations, such as collisions, lack of network connectivity, or internal instability. About structural reorganization of platoons, [Amoozadeh et al. 2015] presents a high-level management protocol that incorporates *merge* and *split* maneuvers with lane changes. The idea is to ensure traffic flow consistency by limiting the platoon length. Although simulation results are offered, discussions about low-level stability and other consequences of reorganization are out of scope. Similarly, [Paranjothi et al. lack] describes a protocol for the entrance of new vehicles in the platoon that neglects low-level control analysis. In [Maiti et al. 2020], the impact of merge and lane change operations in the front, middle, and tail of platoons is evaluated. The main conclusion is that, in the absence of traffic, agents entering in the middle of the team take more time than in the tail (or in the front), but no stability analysis is provided.

Concerning stability, a central point is the communication topology. Directed Acyclic Graph (DAG) models with homogeneous and heterogeneous platoons have been addressed in [Yan et al. 2012, Bian et al. 2019, Zheng et al. 2021], respectively, to improve the resilience of the team. Zhang et al. [Zhang et al. 2017] provide an evaluation of the Directed Acyclic Graphs (DAGs) on the performance of consensus algorithms. Directed graphs have also been considered in [Santini et al. 2019], where the authors formally prove the stability of a control law under topology changes to accommodate new vehicles or to disengage them. However, in the aforementioned cases, the authors assume there is always a communication link between involved vehicles.

In this paper we propose a distributed control strategy for platoons that is resilient to some problems arising from mixed-traffic scenarios. Specifically, we focus on resourcefulness against unpredictable disconnections among the platoon agents. This can occur if a non-cooperative vehicle occupies a gap between vehicles in the platoon or if a red light splits the platoon.

3. Theoretical formalization

3.1. Longitudinal vehicle dynamics

Here, we consider the longitudinal dynamics of vehicles described in [Zheng et al. 2016], which considers rigid and symmetrical platforms free of pitch and yaw moments, wind effects, and sliding of the tires. With these conditions, the i-th vehicle in the platoon is given by:

$$v_i(t) = \dot{p}_i(t), \tag{1}$$

$$m_i a_i(t) = \frac{\eta_i}{r_i} T_i(t) - \frac{1}{2}\rho C_i v_i^2(t) - m_i g\mu, \tag{2}$$

where p_i is the position, v_i is the velocity and a_i is the acceleration. Also, we have the mass m_i, motor efficiency η_i, tire radius r_i, gravity acceleration g, friction constant μ, air density ρ, and drag coefficient C_i. By using feedback linearization, [Zheng et al. 2016] describes the longitudinal dynamics of i as the third-order linear time-invariant model:

$$\dot{\boldsymbol{x}}_i(t) = \mathbf{A}_i \boldsymbol{x}_i(t) + \mathbf{B}_i u_i(t), \tag{3}$$

with desired acceleration input $u_i(t)$ and matrices

$$\mathbf{A}_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\dfrac{1}{\varsigma_i} \end{bmatrix}, \ \mathbf{B}_i = \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{\varsigma_i} \end{bmatrix}, \text{ and } \boldsymbol{x}_i(t) = \begin{bmatrix} p_i(t) \\ v_i(t) \\ a_i(t) \end{bmatrix}.$$

3.2. Network model

The platoon connectivity is modeled as a Directed Acyclic Graph (DAG), which is a finite directed graph with no closed cycles that presents a topological ordering among the vertices. The DAG is described by a graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ composed of $n+1$ nodes $\mathcal{V} = \{\nu_0, \nu_1, \ldots, \nu_n\}$ and a set of edges $\mathcal{E} = \mathcal{V} \times \mathcal{V}$, where $\mathcal{V}$ represents the set of vehicles and $\mathcal{E}$ is the set of links connecting them. The graph $\mathcal{G}$ used to describe a communication topology, is associated with $n \times n$ matrices:

- Pinning matrix $\mathbf{P} = \sum_{i=1}^{n} \mathbf{P}_i = \sum_{i=1}^{n} \boldsymbol{\Omega}^{i,i} P_i \in \mathbb{R}^{n \times n}$ denotes the communication link between the leader and other vehicles.
- The Adjacency matrix $\mathbf{M} = \sum_{i=1}^{n} \sum_{j=1}^{n} \mathbf{M}_{ij} \in \mathbb{R}^{n \times n}$ indicates the sharing links among following vehicles, where $\mathbf{M}_{ij} = \boldsymbol{\Omega}^{i,j} M_{i,j}$ and

$$M_{i,j} = \begin{cases} 1, & \text{if } i \text{ receives information from } j; \\ 0, & \text{otherwise,} \end{cases}$$

in the topological order, the j-th vehicle precedes the i-th one, i.e. $i > j$.

- Degree matrix $\mathbf{D} = \sum_{i=1}^{n} \mathbf{D}_i = \sum_{i=1}^{n} \boldsymbol{\Omega}^{i,i} D_i \in \mathbb{R}^{n \times n}$ is a diagonal matrix with $D_i = \sum_{j=1}^{n} M_{i,j}$.
- Laplacian matrix $\mathbf{L} = \mathbf{D} - \mathbf{M}$.

3.3. Distributed control law

To stabilize the platoon, we have used a distributed control law based on a constant spacing policy between the vehicles. Basically, when agent i receives information from one or more teammates, it is governed by:

$$
\begin{aligned}
u_i(t) &= -\mathbf{K}_i \boldsymbol{u}_i(t), \\
&= -\mathbf{K}_i \sum_{j \in \mathcal{S}_i} \Big(\boldsymbol{x}_i(t) - \boldsymbol{x}_j(t - \tau_{ij}) + \boldsymbol{\delta}_{ij} - \tau_{ij} \mathbf{W} \boldsymbol{x}_i(t) \Big),
\end{aligned} \tag{4}
$$

where $\mathbf{K}_i = \begin{bmatrix} \kappa_1^i & \kappa_2^i & \kappa_3^i \end{bmatrix}$ represents the control gain vector, $\mathbf{W} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^{\intercal} \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}$, τ_{ij} is the heterogeneous constant delay in the communication link from vehicle j to the vehicle i, and $\boldsymbol{\delta}_{ij} = \begin{bmatrix} d_{ij} & 0 & 0 \end{bmatrix}^{\intercal}$, with d_{ij} being the constant desirable front bumper-to-rear bumper distance between the vehicle i and all $j \in \mathcal{S}_i$. The set $\mathcal{S}_i$ is defined as

$$
\mathcal{S}_i = \begin{cases} \mathcal{C}_i, & \text{if } i \text{ does not detect any obstacle in its trajectory;} \\ \emptyset, & \text{otherwise;} \end{cases}
$$

where the set $\mathcal{C}_i$ is composed of all vehicles that share information with the vehicle i along the transient regime. In the case when $\mathcal{S}_i = \emptyset$ the control law (4) is computed taking into account virtual reference states, see Thm. 1.

The proposed control law implies that fixed distances between vehicles must be ensured in a steady-state condition, independent of their speeds. However, since we are dealing with heterogeneous agents, this inter-vehicle distance may be different for every pair (i, j). The $\tau_{ij} \mathbf{W} \boldsymbol{x}_i(t)$ term was added to the control law (4) to compensate for the permanent regime spacing error caused by the delays, as addressed in [Souza et al. 2019] for homogeneous vehicles. To assemble the platoon control model, we initially apply the control law (4) in (3), which yields:

$$
\dot{\boldsymbol{x}}_i(t) = \mathbf{A}_i \boldsymbol{x}_i(t) - \mathbf{F}_i \boldsymbol{u}_i(t), \tag{5}
$$

with $\mathbf{F}_i = \mathbf{B}_i \mathbf{K}_i$. As $\mathbf{F}_i$ is independent for each agent, the results present in [Neto et al. 2019] are extended in this paper to a more general case of heterogeneous platoon. Therefore, the augmented longitudinal dynamics of the formation can then be described in the compact form:

$$
\dot{\boldsymbol{X}}(t) = \widehat{\mathbf{A}} \boldsymbol{X}(t) + \widehat{\mathbf{B}} \boldsymbol{U}(t) \tag{6}
$$

with $\boldsymbol{X}$(t) representing the vector augmented state, and $\boldsymbol{U}$(t) the control vectors of the n team members and matrices of constant parameters are:

$$
\widehat{\mathbf{A}} = \sum_{i=1}^{n} \left(\boldsymbol{\Omega}^{i,i} \otimes \mathbf{A}_i \right) \text{ and } \widehat{\mathbf{B}} = \sum_{i=1}^{n} \left(\boldsymbol{\Omega}^{i,i} \otimes \mathbf{F}_i \right).
$$

Further, the control law (4) can be vectorized, provided that $\boldsymbol{\delta}_{ij} = \boldsymbol{\delta}_{i0} - \sum_{j=i-1}^{1} (\boldsymbol{\delta}_{j,j-1} + \ell_j)$, where ℓ_j is the jth vehicle length, resulting in

$$
\begin{aligned}
\boldsymbol{U}(t) = &-\big[(\mathbf{P}+\mathbf{D})\otimes\mathbf{I}_3\big]\boldsymbol{X}(t) + \sum_{i=1}^{n}(\mathbf{P}_i\otimes\mathbf{I}_3)\boldsymbol{X}_0(t-\tau_{i0}) \\
&+ \sum_{i=1}^{n}\sum_{j=1}^{n}(\mathbf{M}_{i,j}\otimes\mathbf{I}_3)\boldsymbol{X}(t-\tau_{ij}) - \big[(\mathbf{P}+\mathbf{L})\otimes\mathbf{I}_3\big]\boldsymbol{\Delta}_0 \\
&+ \sum_{i=1}^{n}\Big[\big(\tau_{i0}\mathbf{P}_i + \boldsymbol{\Omega}^{i,i}\sum_{j=1}^{n}\tau_{ij}M_{i,j}\big)\otimes\mathbf{W}\Big]\boldsymbol{X}(t),
\end{aligned}
\tag{7}
$$

where $\boldsymbol{\Delta}_0 = \begin{bmatrix}\boldsymbol{\delta}_{10}{}^{\intercal} & \boldsymbol{\delta}_{20}{}^{\intercal} & \cdots & \boldsymbol{\delta}_{n0}{}^{\intercal}\end{bmatrix}$ concatenates the desired formation distances between all follower vehicles and the leader, while vector $\boldsymbol{X}_0{}^{\intercal}(t) = \begin{bmatrix}\boldsymbol{x}_0{}^{\intercal}(t) & \boldsymbol{x}_0{}^{\intercal}(t) & \cdots & \boldsymbol{x}_0{}^{\intercal}(t)\end{bmatrix}$ contains n copies of the leader vehicle states.

3.4. Formation error dynamics

To obtain the dynamics of the formation error, we initially started with the compact representation of the formation error:

$$
\widetilde{\boldsymbol{X}}(t) = \boldsymbol{X}(t) - \boldsymbol{X}^*(t), \tag{8}
$$

where $\boldsymbol{X}^*(t) = \boldsymbol{X}_0(t) - \boldsymbol{\Delta}_0$ is the reference value dependent on the difference between the leader states and the set-point distance. Since in this paper, we have look-ahead communication topologies, the dynamic of the leader is not governed by the control law (4). Thus, the formation error dynamics can be represented by:

$$
\dot{\widetilde{\boldsymbol{X}}}(t) = \dot{\boldsymbol{X}}(t) - \dot{\boldsymbol{X}}^*(t) = \dot{\boldsymbol{X}}(t) - \widehat{\mathbf{A}}_0\boldsymbol{X}^*(t), \tag{9}
$$

where $\widehat{\mathbf{A}}_0$ is a augmented matrix of the leader $\mathbf{A}_0$ matrix expressed by $\widehat{\mathbf{A}}_0 = \mathbf{I}_n \otimes \mathbf{A}_0$.

Based on the fact that $\mathbf{L} = \mathbf{D} - \mathbf{M}$, $\mathbf{P} = \sum_{i=1}^{n}\mathbf{P}_i$, and the sum of the line elements of the $\mathbf{L}$ is null, we add the null term $(\mathbf{L}\otimes\mathbf{I}_3)\boldsymbol{X}_0(t)$ to the control law (7) which is rewritten as:

3.5. Problem definition

The platoon reaches its main objective when all vehicles agree on an individual formation consensus with their neighbors. Concerning the aforementioned characteristics, we can formally define the scope of this paper according to the following problems:

Problem 1 (Resilient connection)**.** *Consider a heterogeneous platoon where each vehicle i is ruled by dynamic Eq.* (3) *and subjected to communication time-delay τ_{ij} and even communication breakdowns. In addition, assume that the vehicle i can start completely unplugged from the other ones, or it can be temporarily disconnected from the team due to failing vehicles or external disturbances (e.g., traffic lights). Then, the main problem is to compute an input command $u_i(t)$ such that i will join or rejoin the platoon (modeled as a DAG), even if lost communication with the preceding teammates.*

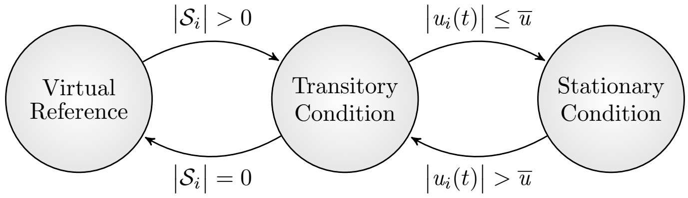

Figura 2. Switching protocol: in the *Virtual Reference* state, the vehicle is completely disconnected from the platoon; when it reaches one agent at its front, it switches to the *Transitory Condition*, using the state information provided by its new neighbor to reduce the state error; when the error is small enough, the vehicle goes to the *Stationary Condition*, following the entire platoon.

Problem 2 (Platoon stability)**.** *Assuming that vehicle i was capable of reaching the platoon, the following problem is to compute an input command $u_i(t)$ such that it will be able to achieve the steady-state condition with the neighbors. When any disturbance or event causes the complete disconnection of i with the agents ahead, we return to the scope of Prob. 1.*

4. Main results

4.1. Proposed approach

Typical consensus protocols in the literature generally assume that each team member always receives information from at least one neighbor. However, depending on the current platoon behavior or any adverse road condition, the i-th vehicle, or a subset composed of itself and its followers, can be completely disconnected from the preceding vehicles. For instance, this situation occurs when the platoon travels on a road devoid of connected infrastructure, and a traffic light changes when the platoon is passing by. Some vehicles keep going and others are stopped at the red light. Therefore, in this section, we propose a strategy that solves both, Prob. 1 and 2. Our method is based on the state-machine shown in Fig. 2, which is composed of three states and the transitions among them:

1. in the *Virtual Reference* state, there are two possibilities: i) no teammates are connected with the i-th vehicle or ii) there are teammates connected, but there are some obstacles ahead. In both cases, this vehicle will start to follow a virtual leader if, $\mathcal{S}_i = \emptyset$.
2. in the *Transitory Condition* state, i-th vehicle regains connectivity with another agent, which is enough for it to reduce its spacing error related to this neighbor. Here, however, a steady-state condition has not yet been achieved.
3. finally, in the *Stationary Condition* state, the error to its first predecessor neighbor is so small that it regains full connectivity with the platoon.

4.2. Reconnection protocol

To demonstrate that our approach ensures the *resilient* incorporation of agent i to the platoon, let us first consider the following assumption:

Assumption 1. *In steady-state, the leader travels at constant speed $0 < v_0 \leq \alpha v_{max}$, where v_{max} is the speed limit value for the road and $0 < \alpha < 1$ is a constant factor.*

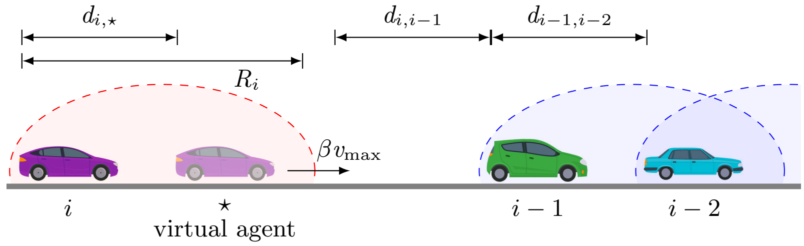

Figura 3. Virtual agent used to ensure connectivity with the platoon in the *Virtual Reference* state: when no communication is available and there is a free path, vehicle i uses a virtual neighbor traveling ahead to run the proposed control law. R_i represents the vehicle i communication range.

As previously stated, at the *Virtual Reference*, agent i has no feedback information about other members of the platoon, so it can not properly compute $u_i(t)$ to reduce the spacing error using Eq. (4). That can happen at the start, when the vehicle is powered on, or when its connection is temporarily lost due to system disturbances. Then, to solve Prob. 1, we propose the use of a *virtual agent*; an abstraction that emulates the communication of agent i with a forward neighbor. Figure 3 illustrates the idea when the preceding vehicles are outside the communication range and there is a free path. For simplicity in the following, we set $\boldsymbol{\delta}_{i\star} = 0$.

In this context, let us present the following statement:

Theorem 1. *Suppose a platoon at the equilibrium point accordingly with Assumption 1 and let the virtual reference states be given by* $\boldsymbol{x}_\star(t) := \begin{bmatrix} p_i(t) & \beta v_{max} & 0 \end{bmatrix}^\intercal$. *Then a vehicle i in the* Virtual Reference *state governed by the control law* (4)*, setting* $j = \star$, $\boldsymbol{\delta}_{i\star} = \tau_{i\star} = 0$*, will reach the* Transitory Condition *state as* $t \to \infty$ *if it has a free path to its first predecessor neighbor and the following conditions hold*

$$k_2 > 0, \quad \kappa_3^i > -1 \;\; and \;\; \alpha < \beta \frac{\kappa_3^i + 1}{\kappa_2^i} \leq 1; \tag{10}$$

where β is a tuning parameter to adjust the final speed of the vehicle in the Virtual Reference *state and αv_{max} defines the platoon speed.*

thm. 1. Setting $j = \star$ in (4) and $\boldsymbol{\delta}_{i\star} = \tau_{i\star} = 0$ we get

$$\begin{aligned} u_i(t) &= -\mathbf{K}_i \Big(\boldsymbol{x}_i(t) - \boldsymbol{x}_\star(t) + \boldsymbol{\delta}_{i\star} \Big), \\ &= \kappa_2^i \Big(\beta v_{\max} - v_i(t) \Big) - \kappa_3^i a_i(t), \end{aligned} \tag{11}$$

which reveals that the control law (4) plugged with the virtual reference states provides a positive acceleration command. In the Laplace domain, focusing on the speed output, we have

$$v_i(\lambda) = G(\lambda) \frac{v_{\max}}{\lambda} \;\; with \;\; G(\lambda) = \frac{\beta(\lambda + (\kappa_3^i + 1)/\varsigma_i)}{\lambda^2 + (\kappa_3^i + 1)/\varsigma_i \lambda + \kappa_2^i/\varsigma_i}.$$

Thus the first two inequalities in the theorem statement ensure vehicle stability. The final value theorem yields the third one that guarantees $\alpha v_{\max} < v_i(t)|_{t\to\infty} \leq v_{\max}$. Then, if the conditions in the theorem hold, a vehicle commanded by (11) decreases its spacing error to its predecessor neighbor up to switch to the *Transitory Condition* because the platoon speed in steady-state is higher than $\alpha v_{\max}$, the leader vehicle speed (Asm.1). $\square$

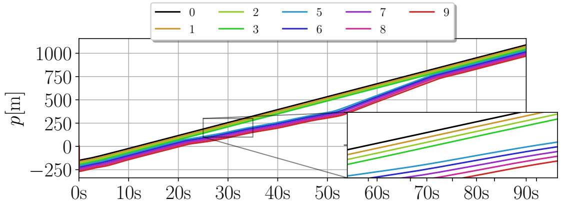

Figura 4. (experiment 3) position of the vehicles in the *CARLA*. In the experiment, all agents start connected. After 20 s, the HDV splits the platoon, leaving the road at 50 s and allowing its predecessors to recover communication after about 70 s.

5. Simulation results and analysis

In this section, we present the results of our control protocol. Here, we evaluate characteristics such as agent exits, mixed-traffic external disturbances, and nonlinear simulations. The protocol and the linear model of the agents have been calculated using the *Numpy* library for *Python* language, running at *Ubuntu 20.04*. Meanwhile, for the nonlinear example, the dynamic of the vehicles was emulated using the *CARLA* simulator.

In this last experiment, we have implemented our strategy with a heterogeneous team composed of the leader and 9 followers, but this time in the *CARLA* simulator[1] [Alexey Dosovitskiy et al. 2017], an open-source tool for autonomous driving research that provides a client/server interface allowing for external communication with many languages, including Python. Here, also, we set the fourth follower in the team to behave like an Human-driven Vehicle (HDV), whose time-varying speed is given by

$$v_4(t) = \big(0.8 + 0.1 \sin 0.5t\big) \alpha v_{\text{max}},$$

for $t \geq 20\,\mathrm{s}$, the instant in which the platoon is interrupted. Also, to make the simulation more realistic, we have used typical values for the time-varying communication delay, i.e a uniform random distribution $\tau_{ij}(t) \in [0{,}1, 0{,}3]$ [s] [Abdelgadir et al. 2016].

The setup is illustrated as follows, Fig. 7(a) shows the start when all vehicles are connected to their neighbors, and the HDV is in the parallel lane. After 20 s, the external vehicle performs a lane change maneuver, and one can observe that its subsequent lower velocity, below the leader's speed, forces a split in the platoon. Then, after 50 s, the non-cooperative agent leaves the road, as illustrated in Fig. 7(b), the moment in which the fifth follower is allowed to accelerate until it reaches the team in Fig. 7(c). Once again, by applying our heuristics, we can recover the communication and reach a stable condition, even in mixed traffic scenarios. Figures 4, 5, and 6 show in detail the position, spacing error, and speed of the vehicles over time. Particularly with the speed profile, it is possible to see the effects of the time-varying delay (small fluctuations) and the oscillatory behavior of the HDV, but our controller shows to be a string and internally stable to such conditions.

6. Conclusion and future work

In this paper, we have addressed the problem of resilient connectivity maintenance and stability for a team of vehicles in a linear formation. Our hybrid control strategy ensures

[1] `https://carla.org/`

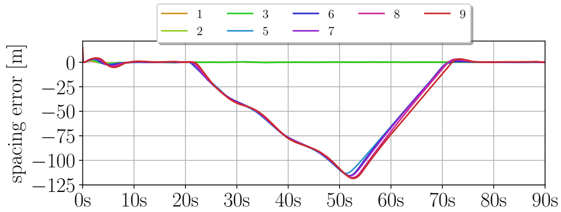

Figura 5. (experiment 3) spacing error of the vehicles (according to the leader) in the *CARLA*. After the platoon's stationary condition at the beginning, the HDV enters and leaves the road, but the disturbance is completely rejected by the proposed protocol.

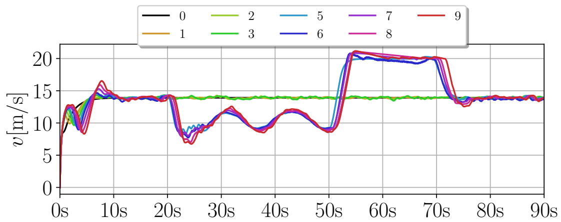

Figura 6. (experiment 3) vehicles speed in the *CARLA*. All followers tracked the leader's speed before and after the exit of the HDV.

the mission even under the complete disconnection of the platoon members, caused by vehicle failures, external disturbances, or abrupt leader accelerations. The main conclusion is that our approach allows an autonomous vehicle to connect to a platoon independently of its initial state, communication range, or information delay. Also, we have demonstrated that, under certain conditions, the formation is stable, even if it is temporarily separated by traffic lights, human-driven vehicles, or if a great number of teammates exit simultaneously.

In future work, we intend to evaluate other approaches to different communication topologies in addition to the DAGs approach. Other network imperfections, such as Denial-of-Service (DoS) or time-varying delays can also be studied. Finally, we intend to provide better syntheses of the control gains to improve robustness and make the platoon less susceptible to road friction, sloping terrains, and other disturbances.

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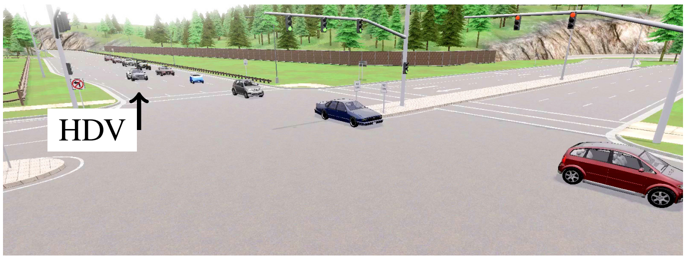

(a) the HDV laterally approaches the platoon and splits it at 20 s.

(b) the HDV leaves the road at 50 s.

(c) platoon stabilization at 85 s, after the disruption.

Figura 7. (experiment 3) platoon composed of the leader and 9 followers implemented in the *CARLA* simulator: (a) the robots start connected, but the fourth follower (an HDV) delays its predecessors with a low speed; (b) the HDV leaves the road; and (c) the last agents recover connection and reaches null spacing error.

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