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Improving the Performance of Cooperative Platooning with Restricted Message Trigger Thresholds

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ABSTRACT Cooperative Vehicular Platooning (Co-VP) is one of the most prominent and challenging applications of Intelligent Traffic Systems. To support such vehicular communications, the ETSI ITS G5 standard specifies event-based communication profiles, triggered by kinematic parameters such as speed. The standard defines a set of threshold values for such triggers but no careful assessment in realistic platooning scenarios has been done to confirm the suitability of such values. In this work, we investigate the safety and performance limitations of such parameters in a realistic platooning co-simulation environment. We then propose more conservative threshold values, that we formalize as a new profile, and evaluate their impact in the longitudinal and lateral behaviour of a vehicular platoon as it carries out complex driving scenarios. Furthermore, we analyze the overhead introduced in the network by applying the new threshold values. We conclude that a pro-active message transmission scheme leads to improved platoon performance, notably an increase greater than 40% in the longitudinal performance of the platoon, while not incurring in a significant network overhead.

INDEX TERMS Cooperative Awareness Messages; Cooperative Vehicular Platooning; ETSI ITS-G5; Safety; Vehicular Networks;

I. INTRODUCTION

INTELLIGENT Intelligent Transportation Systems (ITS) are key in meeting the transportation and mobility needs of the future in a safer and greener way. Connectivity among vehicles (V2V) and infrastructure (V2I) supports information sharing among road-users, in turn enabling a variety of advanced applications. Cooperative Vehicular Platooning (Co-VP) is one of such applications that will be enabled by wireless connectivity. In a connected platoon, vehicles can travel at higher speeds with inferior inter-vehicle distance, thus reducing fuel consumption by taking advantage of the slipstream while retaining all safety guarantees [1]–[3], such as improving longitudinal safety [4] and increasing the road capacity [5]. Co-VPs also the reduce risk for soldiers in military theaters by reducing the need for drivers on military convoys [6] and increase passenger capacity in public transport [7]. The development of connected platoons is present in the plans of automakers, developers and governments worldwide [8]–[10] with an agenda for implementation until 2030 [11].

The European Telecommunications Standards Institute (ETSI) ITS-G5 [12] and the Wireless Access in Vehicular Environments (WAVE) [13] have become the leading standards defining vehicular communication. These operate on top of existing PHY/MAC technologies, such as the IEEE 802.11p-based Direct Short Range Communications (DSRC) or the 3GPP's C-V2X (that englobates LTE-V2X and NR-V2X) [14], [15]. The ETSI ITS-G5 standard defines the transmission of Cooperative Awareness Messages (CAM) (similarly, WAVE defines Basic Safety Messages - BSM) to enable cooperative perception, augmenting the situational awareness and knowledge horizon of each vehicle. CAM messages can be transmitted periodically, at a pre-defined time interval, or can be event-triggered when a kinematic threshold is crossed, e.g., when speed or heading angle crosses a given value. While not referred as such in the standard, we call to a set of threshold values of kinematic events as a *service profile*.

In the absence of a dedicated communication protocol for sharing relevant platooning control information, vehicles can rely solely on received CAMs for setting up a platoon. In such case, the CAM trigger thresholds play a fundamental role in keeping the platoon's lateral and longitudinal coherence and stability. In this work, we investigate the behaviour of a platoon as we vary the threshold values of the CAM triggers over a selected range (organized into five candidate service profiles), in terms of efficiency and safety of the vehicles. Ultimately, from the five candidate service profiles, we select the one that performs best for the particular application of platooning and present as the Platoon Service Profile (PSP), to be considered for integration in the standard. PSP improves the performance of the Co-VP lateral and longitudinal controllers in scenarios with complex trajectories, such as a sequence of curves or while overtaking obstacles, reducing the distance and heading errors and increasing the platoon's stability. Finally, we evaluate the network overhead incurred by this new profile, in terms of throughput and inter-message delays. The Packet Delivery Rate (PDR) under PSP is also evaluated, specifically in congested network conditions. These results extend previous work [16], [17] by carrying out an integrated analysis of the control and networking perspective in four Co-VP scenarios.

The contributions of our work are the following:

1) We assess the impact of the standard event-based Service Profiles (SPs), in scenarios of abrupt maneuvers (acceleration, deceleration) and sequential curves involving obstacle avoidance, on the performance of the platoon's stability (distance and heading errors). This was done by relying on a high-fidelity analysis of Co-VP lateral and longitudinal dynamics over a six-vehicle Co-VP over a realistic simulation framework called CopaDrive [18].
2) We identified a set of scenarios where standard settings provided decreased performance and could compromise the safety of the platoon. Hence, we explore new Service Profiles that can mitigate this problem with negligible implications to the standard. We assess these new SP and show that they increase the Co-VP overall safety, reducing lateral and longitudinal errors in multiple scenarios.
3) The network performance was analyzed to evaluate the impact of new profile in the occupation of the channel. We demonstrate that the proposed PSP does not increase network usage significantly, even under a heavy traffic environment, when compared with the ETSI ITS-G5 profiles.

The rest of this work is structured as follows. Relevant literature is reviewed in Section II. In Section III, we present our model for the connected platoon. A review of the ETSI ITS-G5 standard kinematic triggers and the description of tentative service profiles for platooning can be found in Section IV. Results of platoon safety and network usage over a range of scenarios is presented in Section V. Section VI presents conclusions and future work.

II. RELATED WORKS

Communication Impact on Cooperative Platoon Performance: The impact of vehicular communications on the performance of autonomous vehicle applications has been extensively studied [19]–[22], but not explicitly related to platooning applications. The works presented in [23], [24] analyze the performance of a cooperative platoon in a scenario of constant-time headway, with a multiple predecessor-follower Information Flow Topology (IFT) and a multiple preceding and following IFT including random packet losses. The authors determine the upper bound for communication delay for longitudinal control in order to guarantee the platoon stability. However, this work does not address communication standards and the trigger conditions presented in realistic scenarios. In [25], the authors investigate the impact of packet loss ratio and time message delay in the Co-VP controllers, considering DSRC and LTE C-V2X networks. In this work, a fixed inter-message delay and a packet loss model based on the Bernoulli distribution are assumed. The authors observed that longitudinal and lateral errors increase with both message delay and packet loss, and proposed a limit to both variables. However, the work does not investigate any scenario with both network conditions together. A similar strategy was applied in [26] to evaluate the impact of a deliberate communication failure in one of the vehicles and the consequences to platooning stability. This work used a simulated 14-vehicle platooning with WAVE communication, with fixed time delays. In contrast with usual steady-state communication analysis, the time-varying performance of IEEE 802.11p Co-VP communication is discussed in [27]. The authors consider the impact of a disturbance in the leader's behavior and derive the time-dependent states for the followers. The authors used the packet loss and the message delay as metrics, concluding that the IEEE 802.11p can keep the platooning stability under a disturbance. However, this work considers a leader-followers IFT, which reduces the number of sent messages. A similar evaluation was performed in [16], using ETSI ITS-G5 standard and the leader predecessor-followers IFT. This work identifies the phenomena that decrease communication performance based on the messages synchronization after sequential disturbances in Co-VP speed.

Trigger Thresholds for Message Transmission: The performance of the cooperative platoon also depends on the mes-

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sage trigger strategy: time-triggered and event-triggered. Although the ETSI ITS-G5 defines the event-triggered strategy as a standard, many implementations have been performed with time-triggered strategies [28]–[30]. Time-triggered messages can increase platoon safety if a high message frequency ratio is used, at the cost of increased packet collision probability due to a crowded medium [31]. In turn, the event-trigger solution reduces the network channel busy rate (CBR), enhancing vehicular network dissemination performances [21]. The event-triggered communication studied can be divided into two groups. The first group, such as presented in [32], assumes that the V2V communication is fully reliable. The authors of [32] developed a framework for event-triggered coordination of nonlinear vehicles dynamics with general controllers and a lower limit inter-event time. The second group investigates the impact of the network instabilities in event-triggered platooning [33]. In [34], an event-triggered message control is defined for a Co-VP application with time-varying delay and sensor faults. The event-triggering mechanism is a function of the present value of the sensor faults (and not the parameters defined in the ITS-G5 standard). In [35], it is proposed a flexible event-triggering strategy based on tunable parameters for each platooning vehicle, reducing the communication burden. An external observer is proposed in [36] to create a distributed and adaptive event-triggered control mechanism, based on the estimation of the leader state matrix. However, none of the above studies leverages an active ITS communication standard, which distances their conclusions from real deployment scenarios. An evaluation of the delay between messages in a cooperative platoon is conducted with ETSI ITS-G5 in [37]. The authors compare message delay using the ETSI event-triggered specifications against a fixed frequency of $10Hz$. In both modes, the authors consider a random transmission delay. The authors conclude that the platoon performance at fixed frequency outperforms the one with the ITS-G5 standard, especially at higher speeds. However, they do not address the CBR and its effects on the platoon.

We claim that event-triggered solutions can offer satisfactory platoon safety and efficiency performance, while improving the medium capacity and reducing network congestion. The later aspect is relevant on the account of co-existence: the platoon's internal communications should not become so intense as to degrade the communications of the other road-users around the platoon. While several works have studied event-triggered solutions, as far as we know none have evaluated their performance under the ETSI ITS-G5 standard, particularly in a realistic approach, which encompasses both control and kinematic properties of vehicles alongside the communication aspects. This work fulfills this gap by presenting a in-depth analysis of the ETSI ITS-G5 event-triggered message transmission and a microscopic evaluation of the platoon's longitudinal and lateral error under representative road scenarios.

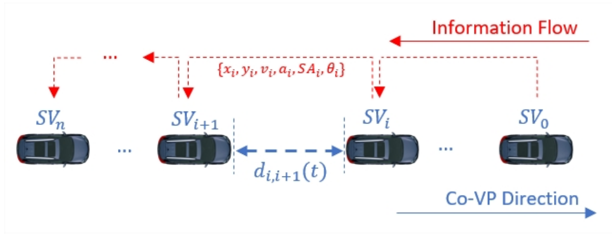

FIGURE 1. Co-VP Model with PF-IFT

TABLE 1. Terms & Corresponding Variables

Variable	Term
$m_{i,i+1}$	Message from SV_i to SV_{i+1}
$D_{SV_i,SV_{i+1}}$	Inter-vehicle distance
d_{ref}	Objective Distance
SD	Safety Distance
e_i^δ	Distance Error
e_i^θ	Heading Error
b_i	Bearing Error
α_i	Steering Angle

III. VEHICLE PLATOON MODEL & SAFETY METRICS

Table 1 presents some of the most used variables throughout this section and the paper.

A. CONTROL MODEL

We assume a platoon of $n+1$ vehicles under a ITS-G5 communication environment using a Predecessor-Follower IFT (PF-IFT) [38], [39], as presented in Fig. 1. Each vehicle has sensors to measure its global position, speed, acceleration, and heading. The vehicles in the platoon are referred to as *subject vehicles* and identified by SV_i (where $i \in \{0 \leq i \leq n, i \in \mathbb{N}\}$), with SV_0 being the platoon leader. Each SV_i can be both a local leader of SV_{i+1} and a follower of SV_{i-1}.

The vehicle controller is the Look-Ahead PID Controller [40], that manages the longitudinal and lateral behavior of the vehicle. In this Co-VP model, each follower (SV_{i+1}) decide their behaviour based solely on the CAM messages received from SV_i, transmitted upon activation of the kinematic triggers. Each SV_i sends a message $m_{i,i+1}(t)$ containing its current global position $(x_i(t), y_i(t))$, speed $(v_i(t))$, acceleration $a_i(t)$, steering angle $\alpha_i(t)$ and heading $\theta_i(t)$ to SV_{i+1}. The inter-vehicle spacing policy is the *Constant Time-Headway Policy* (CTHP) [41], that uses the current speed of SV_{i+1} to define the safety distance SD. In CTHP, the objective range d_{ref} is $d_{ref}(t) = SD + T_h v_{i+1}(t)$, where T_h is the defined time headway (typically between 0.5 and 2 seconds), and $v_{i+1}(t)$ is the follower's speed.

B. METRICS OF PLATOON SAFETY

Distance error (or Longitudinal Error) e_i^δ: between the current and the desired inter-vehicle distance is defined simply as:

$$e_{i+1}^\delta(t) = d_{i,i+1}(t) - d_{ref} \tag{1}$$

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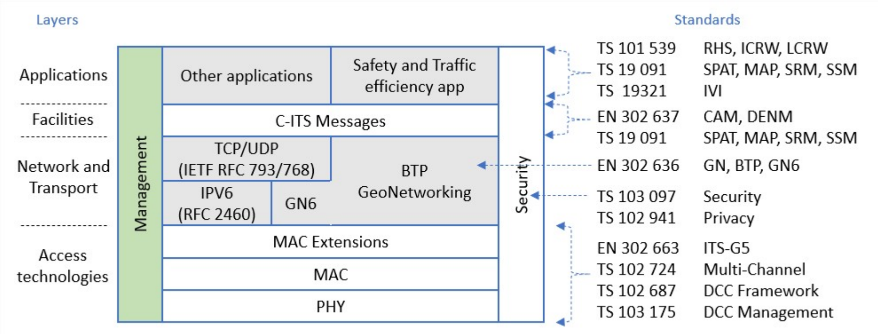

FIGURE 2. ETSI ITS-G5 Stack

where $d_{i,i+1}(t)$ is the Euclidean distance between $SV_i(t)$ and $SV_{i+1}(t)$.

Stability: We consider the **local platoon stability**, described by the following transfer function of the steady state error:

$$H(s) = e^{\delta}_{i+1}/e^{\delta}_{i}, \tag{2}$$

based on the $\mathcal{L}_2$ norms. The platoon stability is guaranteed if $\|H(s))\|_{\infty} \leq 1$ and $h(t) > 0$, where $h(t)$ is the impulse response corresponding to $H(s)$ [42]. In [43], the authors define the stability of the platoon as $\mathcal{L}_{\infty}$, guaranteeing the non-overshoot for a signal while it propagates throughout the platoon as a *global platoon stability*. This metric defines the worst case performance in the sense of measuring the peak magnitude of the spacing distance between vehicles.

Heading Error (or Lateral Error) e^{θ}_i**:** in the platooning application, SV_{i+1} should perform the same path as SV_i based only on the received information (in the form of a message $m_{i,i+1}$). In a longitudinal-only Co-VP application, the controller of vehicle SV_{i+1} uses $m_{i,i+1}(t)$ to define and correct $e^{\delta}_{i+1}(t)$. If longitudinal and lateral control is considered, vehicle SV_{i+1} compares $\theta_{i+1}(t)$ with $\theta_i(t-T_0)$, where T_0 is the time that SV_{i+1} takes to reach a similar position to SV_i when $m_{i,i+1}(t-T_0)$ was sent. This means that, as $d_{ref}(t) \geq SD$, when SV_i is in position $(x_i(t), y_i(t))$, SV_{i+1} is in position $(x_{i+1}(t), y_{i+1}(t))$, with a speed of $(v_{i+1}(t)\cos(\theta_{i+1}(t)), v_{i+1}(t)\sin(\theta_{i+1}(t)))$, the $m_{i,i+1}(t)$, sent by SV_i, will be received by SV_{i+1} in $t+\zeta$, where ζ is the message delay between the sent and receiving time. The information contained in $m_{i,i+1}(t)$ will be immediately used to calculate $e^{\delta}_{i+1}(t)$, while $m_{i,i+1}(t-T_0)$ will be used to calculate the **heading error** ($e^{\theta}_{i+1}(t)$), defined as:

$$e^{\theta}_{i+1}(t) = \theta_i(t-T_0) - \theta_{i+1}(t) \tag{3}$$

IV. EXPLORING TRIGGER THRESHOLDS FOR CAM MESSAGES

A. CURRENT ETSI ITS TRIGGERS

The ETSI ITS stack is described as a family of ETSI standard, with the key one being ETSI EN 302.665 [44], as it describes the communication architecture. Fig. 2 (adapted from [45]) presents the protocol stack and reference architecture for ETSI ITS-S, and lists the key standards of the European ITS standard. The Cooperative Awareness Messages (CAMs), defined in ETSI EN 302 637-2 [46], can be event-triggered or periodic. The CAM event-triggered mechanism is kinematic-dependent: each vehicle generates new CAMs depending on updates of its current position, speed, and heading [16]. In other words, an On-board Unit (OBU) adjusts the periodicity of CAM messages to the vehicle's dynamics, increasing the frequency as it accelerates or decelerates, at high speeds, or when performing abrupt maneuvers.

The CAM trigger threshold values are defined in [46]; for convenience, we refer to this set of values as the **Basic Service [*Transmission Trigger*] Profile** (BSP), following [17]. The threshold values triggers are defined within an upper (T_{max}) and lower (T_{min}) messages bound times and kinematics triggers to check e^{δ}_{i+1} and e^{θ}_{i+1} comparing SV_{i+1} data with the received one from SV_i. These rules are checked latest every $100ms$, which is defined as $\Delta =$*T_CheckCamGen*, and are stated as follows:

- Maximum time (T_{max}) interval between CAM generations: $1s$;
- Minimum time (T_{min}) interval between CAM generations: $0.1s$;
- Heading difference (τ_{Head}): absolute difference between current and last heading provided in a CAM; a CAM is triggered if $\tau_{\text{Head}} > 4°$;
- Position difference (τ_{Pos}): a CAM is triggered if $\tau_{\text{Pos}} > 4m$;
- Speed difference (τ_{Speed}): a CAM is triggered if $\tau_{\text{Speed}} > 0.5m/s$;

In [12], ETSI defines some ITS use cases, including a Co-VP situation, where it reduces T_{max} to $0.5ms$. This use case is defined as BSP for platooning (BSP-P) in [17]. This change causes that, in a straight line, a platoon member whose constant velocity is greater than or equal to $6.67m/s$ will transmit a CAM by trigger τ_{Speed} instead of T_{max}, unless another trigger is detected. The ETSI standard [46] also specifies that T_{max} of a kinematic trigger assumes the value elapsed between the last two CAMs ($T_{max} = t_{CAM}$), until one new trigger is fired or until three messages limited

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TABLE 2. Service Profiles

Profile	BSP	BSP-P	SP_1	SP_2	SP_3	SP_4	SP_5
T_{max} (s)	1.0	0.5	1.0	1.0	1.0	1.0	1.0
T_{min} (s)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
τ_{Head} $(°)$	> 4	> 4	> 2	> 1	> 4	> 2	> 1
τ_{Pos} (m)	< 4	> 4	> 4	> 4	> 2	> 2	> 2
τ_{Speed} (m/s)				< 0.5			

by the new T_{max} are sent. If all three messages are sent, and no trigger is activated, T_{max} returns to the original value defined in the communication profile.

B. TENTATIVE SERVICE PROFILES

In related works, the performance of communication profiles specified in the ETSI ITS architecture have been evaluated in cooperative platooning conditions typically following straight lines without obstacles. In such scenarios, platoon safety is evaluated solely on its ability to keep the distance between vehicles as the leader changes its speed. In such conditions, the safety and stability of the platoon are usually guaranteed since τ_{Speed} is, even in its default value, very conservative.

However, a natural condition to analyze the performance of the Co-VP application suggests the presence of curves and obstacles on the track. Keeping speed constant, the trigger values τ_{Head} and τ_{Pos} must assume a more significant role in the controller response. Thus, we propose the analysis of different trigger values than the ones proposed by ITS-G5, defining five Service Profiles (SPs), as shown in Table 2. Considering that the value of τ_{Speed} in the ETSI ITS is already quite restrictive, we chose to analyze the impact of reducing the values of τ_{Head} and τ_{Pos} in these SP. So, initially, in SP_1 and SP_2, we reduced the τ_{Head}, respectively, to 2° and 1° to check their influence over the heading error. Nevertheless, in SP_3, SP_4, and SP_5, we changed τ_{Pos} to $2m$, reducing the maximum speed for triggering by t_{min} from $144km/h$ to $72km/h$. Thus, it is possible to analyze the network congestion caused by this condition by the increased messages concerning the expected increase in performance. For complete analysis, SP_3, SP_4, and SP_5 mirror the values of τ_{Head} from BSP, SP_1, and SP_2, respectively.

V. EVALUATION OF THE SERVICE PROFILES

We use the CopaDrive framework [18], that integrates a 3D robotic simulator (Gazebo) with an ETSI ITS stack provided by the Artery project [47], running on the network simulator OMNET++. The communication between Gazebo and Artery is made through messages exchanged under Robotic Operating System (ROS). CopaDrive allows simultaneously for a realistic evaluation of the platoon behaviour at microscopic scale and accurate simulation of network events, thus enabling us to study the impact of different trigger conditions in more complex settings. The architecture of

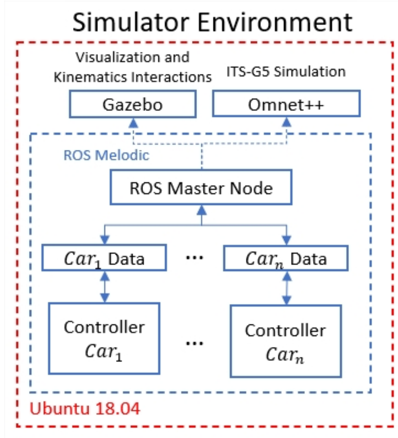

FIGURE 3. CopaDrive Framework Architecture

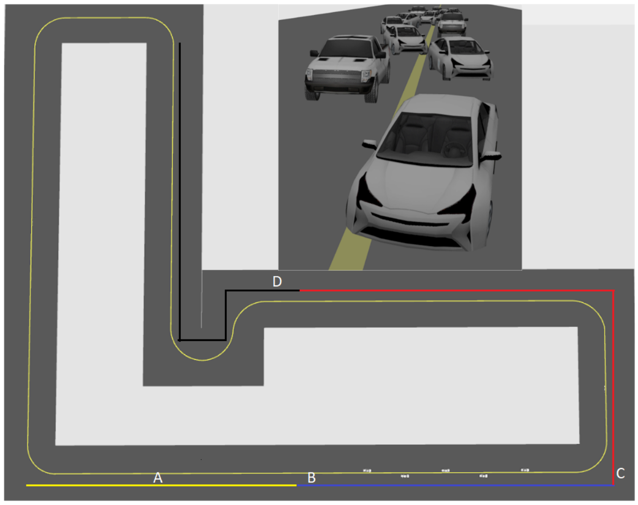

FIGURE 4. Track for Simulations

CopaDrive is presented in Fig. 3. Furthermore, the possibility of integration with a robotic testbed [48] for future validation of the obtained data was seen as an advantage in choosing the tool. In this work, CopaDrive operates in a Linux Ubuntu 18.04.6 Bionic, with Gazebo 9.0 and ROS Melodic. The PC running the simulations is an Intel® Core® i7-975H CPU, with 16 GB RAM memory and a NVIDIA Geforce GTX 1650.

A. EVALUATED SCENARIOS

We defined four scenarios, each involving different challenges for platoon's safety. In all scenarios, the vehicles carry out a trajectory in the track presented in Fig. 4; the track is divided into four sections to facilitate the discussion of the platoon performance in each scenario: A (*yellow*), B (*blue*), C (*red*) and D (*black*). In scenarios 1, 2 and 3, we consider a platoon composed of six autonomous vehicles was used, the first being SV_0, platoon leader, and the last SV_5. In all scenarios, the leader performs its trajectory by following a line drawn in the track and applying a line following algorithm. In all scenarios, each profile was evaluated by means of a sequence of five tests, and the values presented are the average of these evaluations.

Straight Line Scenario (Scenario 1) was developed to analyze the Co-VP performance while the vehicles travel on a straight road, without obstacles. This scenario encompasses sections A (*yellow*) and B (*blue*) of the track. In this scenario, the leader start moving, increasing speed from 0 m/s to 16 m/s, after which it maintains a constant speed for approximately $500m$, until a full brake occurs. A video of the SC1 simulation of BSP and SP3 can be found in https://youtu.be/TEiSW1XFLJg.

Multi-curve Scenario (Scenario 2) extends SC1 with four curves, as presented in https://youtu.be/MCDcIEtaF8Y. This scenario encompasses sections A, B, C and D *black* of the track, with the two closed curves. In this scenario, the leader accelerates in the same way as in SC1, running through a straight line and performing three left curves and a sharp right curve. Then, it will run for $400m$ and then stop altogether. The main idea of this scenario is to evaluate the Co-VP capacity to follow the leader's trajectory, including sharp curves in $90°$ and one of $180°$. In this case, the lateral error increases its importance since it will demonstrate the followers' ability to perform the same path as the leader. We can assume that the Co-VP speed error performance is similar to the one presented in SC1 since the acceleration and deceleration time is the same in both scenarios. However, as the trajectory diverges and the path is different, the e_5^δ tends to increase.

Obstacle Scenario (Scenario 3) adds five static obstacles on the track, represented by *pickups*. This scenario encompasses sections A, B and C of the track. Such obstacles are placed on different sides of the track, as shown in Fig. 4 and their function is to *force* the platoon leader and his followers to perform a *slalom* maneuver. Thus, the vehicles must perform maneuvers with minimum error to avoid collisions with each other and with obstacles, receiving as information only the data from the SV_{i-1}. Thus, the leader follows the same acceleration profile presented in SC1 and SC2, reaching the desired speed, maintaining a constant speed to avoid obstacles, and aligning himself again to perform the curves indicated in the red color path, performing complete braking at the end of this excerpt. This scenario is presented in https://youtu.be/F3zGpP2XBBU.

High Medium Occupation (Scenario 4) encompasses sections A, B and C of the track. In Scenario 4, we repeated the SC3 trajectory, but with increased vehicles number, from 10 to 100, to evaluate the network congestion due to the proposed profiles.

The main scenario, kinematic and control parameters enforced in the scenarios are presented in Table 3:

B. METRICS

As Co-VP errors propagate and accumulate from the first to the last follower, we focus our discussion on the performance

TABLE 3. Model Parameters

Parameters	Definition
Vehicles (Scen. 1 to 3)	6
Max steering angle	0.52 rad
Safety distance (DS)	5.5 m
Time headway (TH)	0.5 s
Leader speed	58 Km/h
Longitudinal: K_P, K_I, K_D	2.0 , 0.005 , 2.0
Lateral: K_P, K_I, K_D	2.5 , 0.001 , 1.0

of subject vehicle SV_5. It is important to note that the triggers are analyzed individually car-by-car and that there is a difference in the subsequent processing of triggering the CAMs of each vehicle belonging to the platoon. Due to this option, on one hand, the effects of synchronization analyzed in [16] are practically mitigated due to the decoupling between vehicles. On the other hand, this effect makes the reaction times of each vehicle slightly different and consequently more complex to be analyzed. Finally, we analyze the error between SV_{i+1} and SV_i or between SV_{i+1} and SV_0. The different trigger conditions happen because, although slight, there are variations in the trajectory of SV_0 in each simulation, which affect the movements and activation of their followers' triggers. In each scenario, the behavior of the network was analyzed in terms of **throughput**, **number of sent messages**, and **inter-message delay (IMD)**. The throughput is defined as presented in eq. 4.

$$Throughput = \frac{ReceivedMessages * MessageSize}{time * BitRate} \tag{4}$$

C. STRAIGHT LINE SCENARIO - SC1

Platoon Safety: Fig. 5 presents the quantiles of the speed error for SV_5 throughout the duration of Scenario 1. The median speed error is close to zero in all profiles, while maximum velocity errors approach $2.0m/s$. The distance error of SV_5, e_5^δ, is depicted in Fig. 6. We observe that the median of the distance errors tends to be under-estimate (vehicle is farther than estimate). 50% of BSP errors fall in a limited range (-0.1 to $0m$), but it is also the profile that overestimates the most. This justifies the introduction of BSP-P, in which the behaviour is inverted: distances tend to be underestimated. SP1 to SP5 also tend to underestimate distances and have an inferior range of occurrence of error w.r.t. BSP-P, with SP3 having the smallest range (-0.4 to $0m$). Finally Fig. 7 presents the local stability condition for all SPs, demonstrating that the platoon stability is guaranteed since $\mathcal{L}_\infty(e_5^\delta) < \max_1^4(\mathcal{L}_\infty(e_i^\delta))$. These results show that the new profiles do not degrade performance with respect to the established profiles (BSP/-P), but even improve it as SP3, SP4, and SP5 reduce e_5^δ in 28% (Fig. 6), as a consequence of the reduction of $\tau_{\mathrm{P}os}$ in these specific profiles.

Network Performance: The inter-message delay (IMD) is shown in Fig. 9 for SV_0 (top) and SV_5 (bottom). The IMD of SV_0 at the start of the trajectory is small for all profiles

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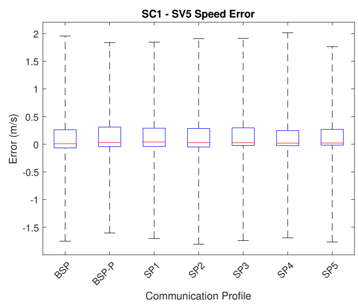

FIGURE 5. SC1 - SV_5 Speed Error Comparison

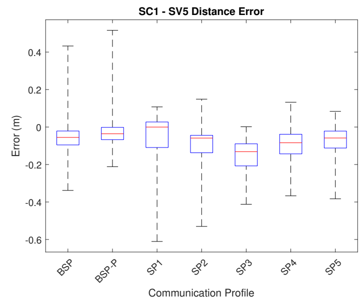

FIGURE 6. SC1 - SV_5 Distance Error Comparison (e_5^δ)

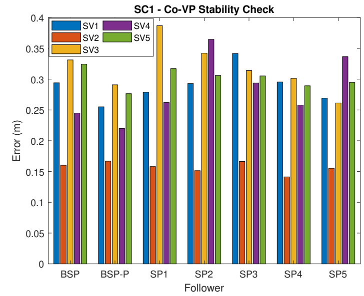

FIGURE 7. SC1 - Co-VP Stability Check

FIGURE 8. SC1 - Total Triggers per Profile

Profile	τ_{Head}	τ_{Pos}	τ_{Speed}	T_{max}	Total
BSP	435	79	292	508	1314
BSP-P	652	47	239	538	1476
SP1	621	64	285	400	1370
SP2	775	60	270	382	1487
SP3	16	639	253	390	1298
SP4	22	644	253	389	1308
SP5	19	650	245	391	1305

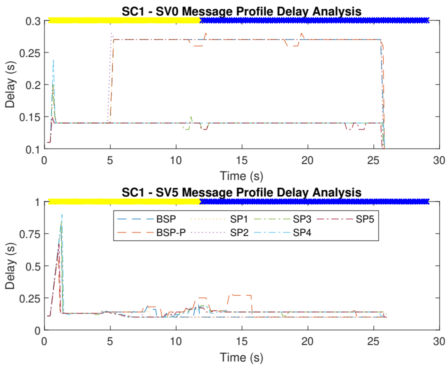

FIGURE 9. SC1 - Message Profile Delay Analysis

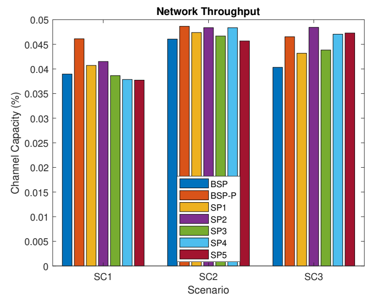

FIGURE 10. Scenarios Throughput

since it is the speed difference threshold τ_{Speed} that triggers the CAMs. After $5s$, when the speed stabilizes, the profiles with higher values of τ_{Pos} trigger messages with inferior frequencies. This means that the leader is occupying less the transmission medium in the BSP, BSP-P, SP1, and SP2. However, the bottom of the figure shows that the IMD of SV_5 is nearly the same for all the profiles. This similarity confirms that all the profiles for this vehicle's quantities produce a similar network load. Fig. 10 shows the vehicle's throughput, calculated with eq. 4, with a bit rate of $6Mbps$ [46]. This figure demonstrate that the throughput variation between all profiles does not reach 0.01% of the channel capacity, showing that the better performance of CSP3, CSP4, and CSP5 does not imply considerable overhead in network usage.

Discussion: As followers diverge from the leader they transmit messages at higher rates while correcting their trajectories in profiles with higher errors (BSP, BSP-P, SP1, and SP2). In profiles with a more conservative τ_{Pos}, more messages are fired, due to the values of e_i^δ. The cost of sending more messages, caused by the tighter trigger values on SP3, SP4 and SP5 is offset by the number of sent messages by other profiles. The last column of Table 8 illustrates this cost, in which the best performing profile (SP3) had 1% fewer messages than the worst performing one (BSP). Furthermore, the minor distance error profiles had the slightest trajectory corrections caused by τ_{Head}.

D. MULTI-CURVE SCENARIO - SC2

Platoon Safety: Fig. 11 shows distance error e_5^δ; as this scenario is more complex than scenario 1, the error tends to increases along the trajectory. This error is a consequence of the Euclidean distance used to calculate $d_{i,i+1}(t)$, since it is affected by the lateral deviation of the vehicles. Due to this, the distance error e_i^δ tends to increase on curves in order to reduce the e_i^θ, avoiding the *cutting-corner effect*. It demonstrates that the maximum variation of the distance error e_5^δ has a 25% reduction with SP1 in comparison with BSP and about 70% with SP3. The SP3 also outperforms the BSP-P in $\approx 15\%$. It means that the reducing τ_{Pos} has a larger influence in the distance adjustment of the platoon members than τ_{Head}, given that SP3 outperforms SP4 and SP5. In this scenario, BSP end up overestimating e_5^δ, while SP1 underestimates it. Thus, it is possible to observe that the platoon's performance is improved with SP3 since this profile presents the slightest variation (-0.5 to $0.6m$), still having the average value very close to zero. It is also interesting to notice that in the SP1 and SP2 profiles, the more restrictive value of τ_{Head}, without the reduction of τ_{Pos}, causes a slight downward shift in the average of e_5^δ, due to the corrections triggered not by position, but by the heading variation.

The Co-VP performance regarding the distance error is confirmed in the stability check, illustrated in Fig. 12. All the profiles satisfy the *local* stability criteria, and the overall distance error of SP3 for all vehicles is smaller than the other

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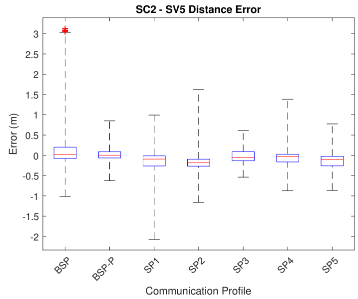

FIGURE 11. SC2 - SV_5 Distance Error (e_5^{δ})

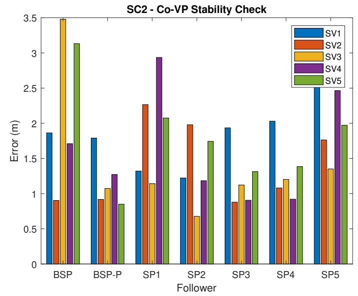

FIGURE 12. SC2 - Co-VP Stability Check

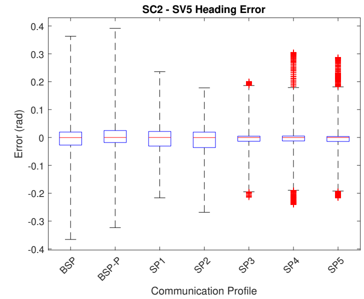

FIGURE 13. SC2 - SV_5 Heading Error (e_5^{θ})

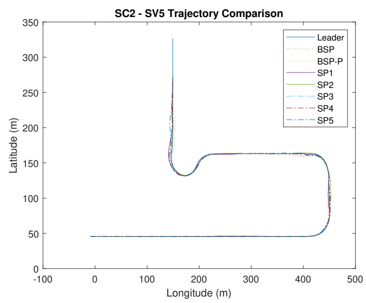

FIGURE 14. SC2 - SV_5 Trajectory Comparison

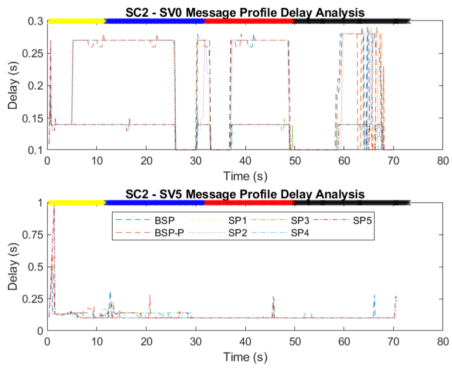

FIGURE 15. SC2 - Message Profile Delay Analysis

FIGURE 16. SC2 - Total Triggers per Profile

Profile	τ_{Head}	τ_{Pos}	τ_{Speed}	T_{max}	Total
BSP	2372	109	254	1011	3746
BSP-P	2435	95	139	1151	3820
SP1	2506	161	267	677	3611
SP2	2914	98	280	505	3797
SP3	1527	957	241	917	3642
SP4	1773	848	232	846	3699
SP5	2055	788	232	659	3734

profiles.

In scenario 2, a well-performed trajectory implies a small heading error e_i^{θ}, which indicates how well followers perform curves concerning the leader. Fig. 14 shows that the leader and vehicle SV_5 perform a similar path in all profiles, apart from minor oscillations after the first and the last curves. These oscillations can be better visualized in Fig. 13; the worst heading error of SV_5, e_5^{θ}, is near to $0.4rad$ with BSP/-P. Again, the best performance is obtained with SP3, since its application reduced the maximum value of e_5^{θ} in $\approx 50\%$, to $0.2rad$, even with complex curves, also decreasing the total variation between extreme error values.

Fig. 13 also demonstrates that exclusively reducing τ_{Head} leads to a better heading error e_5^{θ} performance, as SP1 and SP2 lowered it in $\approx 38\%$ in comparison with BSP/-P. The analysis of the maximum of e_5^{θ} in SP4 and SP5 indicates that the impact of reducing τ_{Pos} is greater than reducing τ_{Head} in the proposed profiles.

The impact in the number of transmitted messages relating to the threshold values of the heading difference τ_{Head} and position difference τ_{Pos} in SC2 can be observed in Table 16. The threshold of parameter τ_{Head} is the most activated, due to the numerous trajectory adjustments of followers in order to execute the curves of the scenario. Under SP3, the combination of a reduced τ_{Pos} with the standard τ_{Head} produces the best general Co-VP performance, reducing distance and lateral errors (e_5^{δ} and e_5^{θ}). These results confirm that reducing τ_{Pos} reduces the longitudinal and lateral errors, as observed in SC1 and SC2. Under these conditions, the SP3 reduction improves the BSP-P performance both in e_5^{δ} and e_i^{θ}, also reducing the number of sent messages. Reducing τ_{Head} also does so, although to an inferior extent.

Network Performance: The inter-message delay (IMD) is shown in Fig. 15 for SV_0 (top) and SV_5 (bottom). As SC2 is an extension of SC1, the first interval between $0 - 25s$ presents a similar behavior. However, after the first curve, at the end of the blue section and the beginning of the red section, we observe in vehicle SV_0 a few periods of high-frequency/slight inter-message delay. These high-frequency periods are caused by the path's curves and occur in all profiles. After this occurrence, the less restrictive profiles return to a lower message transmission frequency, as expected.

Nevertheless, the message delay of SV_5 presents a low IMD in all profiles, from the beginning to end of SC2, due to the vehicle's trajectories adjustments. As in scenario 1, the propagation of control information hop-by-hop, from SV_1 to SV_5, leads to SV_5 constantly requiring more abrupt adjustments, hence the increased transmission frequency. Table 16 illustrates that all profiles have transmitted a similar number of packets at the end of SC2, as in SC1.

Discussion: Overall, we observe that SP3 has the best performance in the control metrics, with a saving of transmitted messages, with a reduced τ_{Pos}. This supports our claim that, by altering the message trigger thresholds (τ_{Pos} and τ_{Head})to

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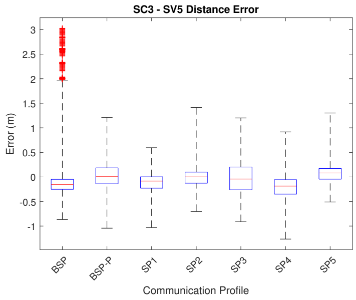

FIGURE 17. SC3 - SV_5 Distance Error (e_5^δ)

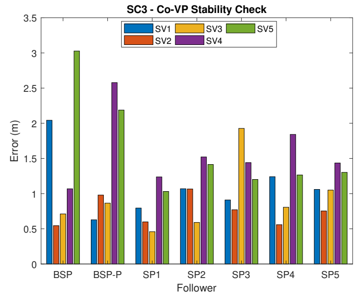

FIGURE 18. SC3 - Co-VP Stability Check

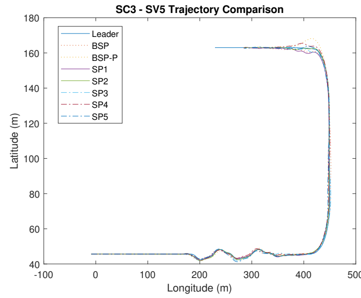

FIGURE 19. SC3 - SV_5 Trajectory Comparison

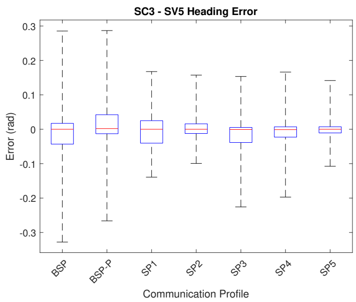

FIGURE 20. SC3 - SV_5 Heading Error (e_5^θ)

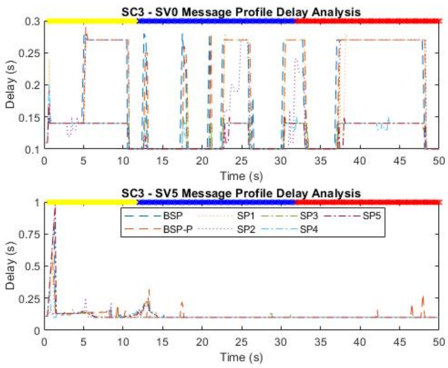

FIGURE 21. SC3 - Message Profile Delay Analysis

FIGURE 22. SC3 - Total Triggers per Profile

Profile	τ_{Head}	τ_{Pos}	τ_{Speed}	T_{max}	Total
BSP	1623	79	294	676	2672
BSP-P	1745	64	271	758	2838
SP1	1876	74	258	509	2717
SP2	2085	60	240	414	2799
SP3	1419	445	253	653	2770
SP4	1633	395	248	532	2808
SP5	1805	409	249	488	2951

s

become more sensitive, the platoon safety performance is improved without burdening the network, reducing the errors e_i^δ and e_i^θ.

E. OBSTACLE SCENARIO - SC3

Platoon Safety:

The distance error e_5^δ, presented in Fig. 17, shows that BSP has a similar performance regarding the maximum error variation as in SC2, $\approx 3.5m$, showing that the obstacles cause little or no difference in both scenarios for this profile. However, as in SC1 and SC2, the proposed profiles and the BSP-P present a better e_5^δ performance, reducing the error variation to $\approx 2.0m$, albeit at a larger error than in SC2. This result is expected since obstacles negatively impact the longitudinal platoon performance.

Even under these conditions, the platoon *local* stability is granted in all the proposed profiles, as depicted in Fig. 18, albeit with larger errors than the presented in SC1 and SC2. However, the BSP fails to provide Co-VP stability in SC3, since $\|H(s))\|_\infty > 1$.

As in SC2, the Co-VP performance in SC3 regards the follower's capacity to perform the same trajectory as the leader, with smaller e_i^θ as possible. So, the SV_5 trajectory in all profiles is presented in Fig. 19, and confirms that all followers avoid the obstacles. However, the accumulated error of the SV_5 trajectory limits the ability of the platoon to perform the second curve (in the red road area) in the same trajectory of the platoon Leader. In this scenario, the BSP-P has more significant oscillation, while the SP1 suffers from the *cutting-corner* effect. As the e_i^δ tends to increase over the curves to reduce the e_i^θ, this effect explains why the SP1 has a slightly better result than the others profiles, as presented in Fig. 17.

The *slalom* maneuver performed in this scenario relies on several curves produced by the leader's trajectory. So, the τ_{Head} have a direct impact over the in Co-VP heading error (e_i^θ), as illustrated in Fig. 20, while the influence of τ_{Pos} to e_i^θ is reduced, due to the required adjustments, given curves proximity. This figure demonstrates that the SP2 and SP5, with more restricted τ_{Head} values, have the better e_5^θ performance.

Network Performance: The IMD is directly affected by the *slalom* maneuver, that triggers message transmissions at high frequency in all profiles, as visible in Fig. 21. As in SC1 and SC2, the period between $0 - 10s$ have similar behaviors, with two well-defined levels, for the BSP, BSP-P, SP1, and SP2, and others for SP3, SP4, and SP5. However, when the SV_0 starts the object avoidance algorithm, the IMD is directly affected, being reduced for the profile T_{min}. This occurrence indicates where SV_0 avoids the obstacles and when it returns to a straight trajectory, before performing the two curves and finally stops at the end of the scenario. As expected, the load on the network caused by SV_0 is slightly smaller in BSP, SP1, and SP2, while the BSP-P has the biggest number of triggered

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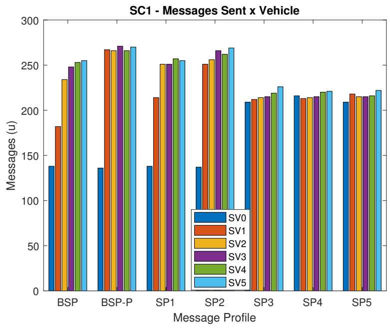

FIGURE 23. SC1 - Sent Messages per Vehicle

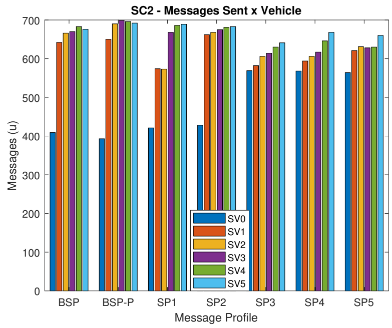

FIGURE 24. SC2 - Sent Messages per Vehicle

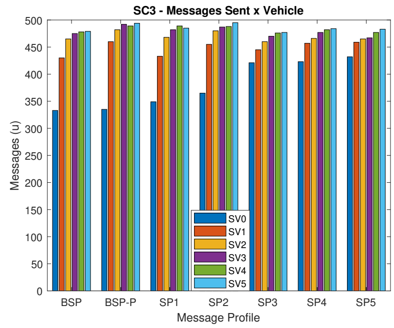

FIGURE 25. SC3 - Sent Messages per Vehicle

messages. However, as previous scenarios, this behavior does not correspond to the other platoon vehicles. The bottom figure highlight that the network load caused by SV_5 is the same for all the profiles due to the constant adjustments. However, in this scenario, the restricted τ_{Head} produces a network overhead, as presented in Fig. 10 and confirmed in Table 16. Thus, SP5 implies a 10% overhead over sent messages and about 0.005% over the network capacity.

Discussion In this scenario, the impact of the τ_{Head} restriction becomes more evident since the leader's *slalom* to avoid obstacles forces the other vehicles to make quick turns to correct their route. While the standard profiles in ETSI ITS G5 present a performance similar to that obtained in scenarios 1 and 2, the proposed profiles still produce better performance, with lower distance and heading errors. Even in the reduction of T_{max} in BSP-P does not reduces the e_i^{θ} as the proposed profiles. However, this scenario presents an overhead of profiles with a more restricted τ_{Head}, affecting a more crowded network scenario.

The comparison between the SPs standardized by ETSI and those presented here takes into account not only the reduction of e_i^{δ} and e_i^{θ}, but also their impact on the network. The analysis of the SC1, SC2, and SC3 results shows that SP1-5 reduces errors compared to BSP in all scenarios and also outperforms BSP-P to a lesser extent in reducing e_i^{δ} and with great advantage in reducing e_5^{θ}. The comparison of the cost of the higher constraint triggers can be seen in the tables 8, 16, and 22, and also reinforced with the Figs. 23, 24, and 25, which illustrate the amount of messages sent by each vehicle in each scenario in each profile tested. These figures show that the evaluated profiles do not increase the number of messages sent by each car and show that BSP, even in simpler scenarios, tends to send more messages to obtain a performance inferior to SP3, for example.

F. NETWORK PERFORMANCE - SC4

The results on network performance presented for Scenarios 1, 2 and 3 showed that proposed SPs have residual impact on the number of transmitted messages in comparison with ETSI profiles. In Scenario 4, we extend SC3, the best performing SP, by increasing the number of communicating vehicles, to simulate conditions of a high density vehicle occupation and, accordingly, high occupation of the wireless medium. For simplicity, additional 'virtual' vehicles were simulated as if they were in same position as the leader. This setup, while very pessimistic, allows us to study performance in almost worst-case conditions: when the leader fires a message, the 'virtual' vehicles also sent it, inducing a very large medium usage at that instant. Tests were run with 10, 20, 40, 60, 80, and 100 cars. In SC4, our analysis is limited to Packet Delivery Rate (PDR) related to the increasing number of vehicles.

Fig. 26 shows PDR for each proposed profile as the number of vehicles increases. In this scenario, we assume that a better PDR leads to better Co-VP performance since more messages are being delivered to the followers. However, in this paper, we will not address the PDR decreasing impact over the platooning performance, but just the analysis about how the PDR decreases with the rising number of vehicles in each profile.

Beginning with 10 vehicles, PDR is close to 100% in all profiles, from BSP to SP5, meaning that we can believe that the performance obtained in SC1, SC2, and SC3 should be maintained. Meanwhile, for 20 cars, the variation between the best and the worst PDR is 4%. Thus, under these conditions, the SP5 PDR is $\approx 99\%$ while the BSP PDR is nearly 95%. SP1, SP2, and SP3 PDRs remain around 97%, and SP4 and BSP-P deal with 96%. Therefore, the decreasing PDR should not have a high impact on the Co-VP performance in these conditions. This analysis also shows that the more significant restriction of τ_{Head} and τ_{Pos} does not severely impact the increase in the number of packets since the drop in the PDR is directly related to the increase in collisions.

The best PDR response decays to 94% in SP5 while increasing the number of vehicles to 40. On the other hand, the worst PDR response is obtained from the SP1, with 94%. SP3 and SP4 have a similar PDR response as SP5, while BSP, BSP-P, and SP2 have a PDR near 87%.

As expected, when the number of vehicles increases up to 60, the PDR response decreases in all the profiles. However, the best PDR response is obtained in SP2, with 82%, while SP5 decays to 80%. BSP, BSP-P, and SP4 have a PDR of 75%. The SP3 and SP1 have the worst PDR result, close to 69%. Finally, raising the car quantity to 80 and 100

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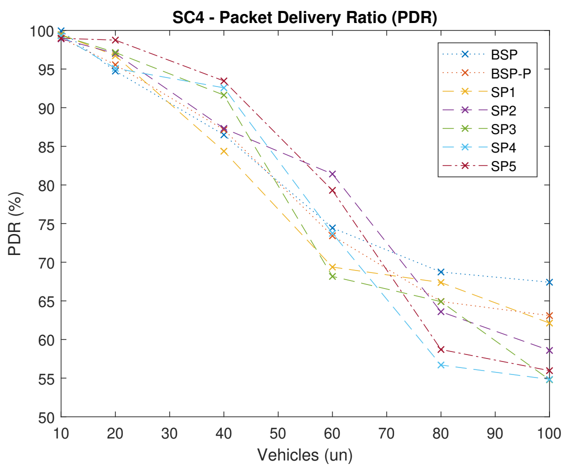

FIGURE 26. SC4 - Packet Deliver Ratio

leads the PDR response for under 70% in all the profiles, which indicates a communication link that may cause safety concerns [49].

Discussion The analysis of the PDR chart in Fig. 26 confirms that the profiles proposed with the restriction of $\tau_{\mathrm{P}os}$ and $\tau_{\mathrm{H}ead}$ do not cause more network congestion than the ETSI profiles. Furthermore, although their PDR also declines with the increase in network congestion, their performance in SC1, SC2, and SC3 scenarios proves that this is an option that tends to increase the safety of the platoon by reducing errors e_i^δ and e_i^θ.

Considering the proposed scenarios and the results presented, we reinforce the thesis that a greater restriction of the ITS-G5 $\tau_{\mathrm{P}os}$ and $\tau_{\mathrm{H}ead}$ triggers positively impacts platooning performance without causing overhead on the communications network. Thus, in adverse conditions, such as obstacles and curves, the SP1-5 profiles present better performance than the profiles established by ETSI. Moreover, among the profiles presented, it was possible to observe that the SP3 profile represents the best cost-benefit, as it reduces the errors e_5^δ and e_5^θ in all scenarios, without providing overhead concerning the profiles proposed by ETSI. The PDR response of SP3 also indicates this profile's applicability regarding the proposed conditions, with reduced errors and similar network performance, compared with other profiles. So, for an up-limited scenario of 40 vehicles, the 94% PDR suits as an acceptable compromise for a Co-VP application, but further investigation is necessary to evaluate the platoon safety condition under more congested scenarios.

Thus, based on the results obtained, we propose the implementation of the Platoon Service Profile (PSP), based on SP3, with a more restricted $\tau_{\mathrm{P}os}$, aiming to increase the platoon's performance, reducing longitudinal and lateral errors. This profile showed an improvement in e_5^δ of 74% on SC2 and 44% on SC3 compared to BSP/-P. Also, improved e_5^θ by 42% on SC2 and 50% on SC3 over the same profiles, without increasing overhead. As the scenario proposed in SC3 can be considered extreme, due to the presence of the "slalom", this profile would successfully meet the needs of Co-VP systems in a diversity of scenarios not covered by the ETSI BSP/-P.

VI. CONCLUSIONS AND FUTURE WORKS

This work presented five new Service Profiles, using different message threshold values over triggers $\tau_{\mathrm{H}ead}$ and $\tau_{\mathrm{P}os}$, that were compared the BSP and BSP-P profiles proposed in the ETSI specifications. The performance observed on the studied scenarios shows that the proposed adjustments in $\tau_{\mathrm{H}ead}$ and $\tau_{\mathrm{P}os}$ positively impact the Co-VP safety performance, reducing both longitudinal and lateral errors.

In SC1 and SC2, SP3 presented the best results, with $\tau_{\mathrm{P}os}$ adjusted, while in SC3, the best lateral error was achieved with the $\tau_{\mathrm{H}ead}$ adjustment. Thus, the integrated analysis of all scenarios showed that the joint reduction of the triggers $\tau_{\mathrm{H}ead}$ and $\tau_{\mathrm{P}os}$ did not necessarily show the best result in all scenarios in lateral and longitudinal terms. The different results are affected by triggering conditions that cause different adjustments and corrections in the platoon, often increasing longitudinal errors to correct lateral errors.

Furthermore, the need for corrections arising from errors accumulated throughout the platoon and the activated triggers also implied an increase in network load. Thus, it was observed that the use of more restricted triggers did not significantly increase the load on the network since these triggers implied fewer corrections and, consequently, fewer messages sent. Such observation is extended to a scenario of an increase in the number of vehicles, where less restricted triggers do not represent a significant gain in terms of network performance, burdening it in a very similar way in all profiles.

We conclude that reducing the value of $\tau_{\mathrm{P}os}$ proposed by the ETSI ITS standard can increase safety conditions of the platoon in complex scenarios, involving curves and even with the presence of obstacles. So, we propose a Platoon Sevice Profile (PSP) based on the $\tau_{\mathrm{P}os}$ reduction from $4m$ to $2m$. Furthermore, it should also be noted that the reduction of $\tau_{\mathrm{H}ead}$ in very close obstacle scenarios also improves the lateral error, ensuring system safety.

As future work, we will investigate the impact of the drop in PDR with the increase of vehicles on the safety conditions of the platoon. This scenario also suggests the possibility of validating a flexible trigger profile based on road conditions.

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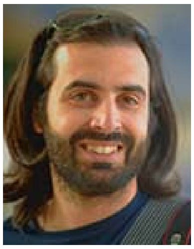

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APPENDIX A: TRIGGERS ACTIVATION LIST

FIGURE 27. Triggers Profile per Vehicle

-	-	SV0				SV1				SV2				SV3				SV4				SV5			
Scen.	SP	τ_{Head}	τ_{Pos}	τ_{Speed}	T_{max}	τ_{Head}	τ_{Pos}	τ_{Speed}	T_{max}	τ_{Head}	τ_{Pos}	τ_{Speed}	T_{max}	τ_{Head}	τ_{Pos}	τ_{Speed}	T_{max}	τ_{Head}	τ_{Pos}	τ_{Speed}	T_{max}	τ_{Head}	τ_{Pos}	τ_{Speed}	T_{max}
	BSP	1	42	42	53	37	24	44	77	91	6	49	89	108	2	46	93	96	2	55	101	102	3	56	95
	BSP-P	1	37	33	65	122	2	35	108	130	2	41	93	128	0	42	101	136	4	44	82	135	2	44	89
	SP1	1	41	42	54	82	15	43	74	134	5	45	68	132	2	53	65	145	1	48	64	127	0	54	75
SC1	SP2	1	43	40	55	124	9	42	89	147	4	43	68	162	3	44	68	163	0	51	51	178	1	50	51
	SP3	1	107	39	62	1	111	40	60	1	108	40	66	0	109	41	66	4	109	43	64	9	95	50	72
	SP4	5	108	41	65	1	111	40	62	1	112	40	62	0	104	42	70	7	102	40	72	1	107	50	64
	SP5	1	105	39	65	6	112	40	64	1	108	41	66	0	109	40	67	1	112	41	63	10	104	44	66
	BSP	168	82	38	121	400	13	40	189	419	7	41	199	449	5	42	174	467	0	45	171	469	2	48	157
	BSP-P	154	76	16	147	414	17	14	205	455	2	23	210	472	0	23	204	470	0	28	198	470	0	35	187
	SP1	184	81	40	116	371	39	39	125	390	38	43	102	501	3	50	114	517	0	50	119	543	0	45	101
SC2	SP2	196	79	38	115	524	9	40	89	538	5	47	78	545	3	51	76	552	2	51	76	559	0	53	71
	SP3	171	225	39	134	212	203	39	128	246	159	39	162	263	145	39	167	306	125	41	158	329	100	44	168
	SP4	174	225	38	131	249	183	39	123	265	159	39	143	304	139	39	135	362	98	37	149	419	44	40	165
	SP5	181	221	37	125	336	133	38	114	357	125	37	112	371	115	38	104	372	122	35	101	438	72	47	103
	BSP	159	50	41	85	254	17	43	118	287	7	45	128	310	1	56	110	307	3	55	115	306	1	54	120
	BSP-P	167	41	38	102	290	12	35	136	312	5	46	134	324	1	53	129	321	3	52	128	331	2	47	129
	SP1	184	46	42	79	284	19	42	90	329	7	43	90	362	2	32	87	351	0	49	91	366	0	50	72
SC3	SP2	208	38	39	87	340	13	39	67	377	5	41	66	391	1	36	60	382	1	45	64	387	2	40	70
	SP3	161	129	40	95	210	95	37	107	230	75	41	118	256	53	42	122	280	46	42	111	282	47	51	100
	SP4	171	122	40	92	256	76	39	90	270	58	38	102	301	44	41	93	321	49	45	72	314	46	45	83
	SP5	210	115	40	88	296	75	39	82	301	70	38	95	310	61	41	78	339	46	43	71	349	42	48	74