Development of a Hardware in the Loop Ad-Hoc Testbed for Cooperative Vehicles Platooning

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Abstract. Cooperative Cyber-Physical Devices (Co-CPS) are reaching into the most diverse areas and pose new integration challenges. For cooperative autonomous machines, safety and reliability must be guaranteed without human presence. Among these, Cooperative Vehicular Platooning (Co-VP) applications offer an exciting promise, as they allow to improve road occupation, reduce accidents, and provide fuel savings. The high complexity and safety-critical characteristics of these applications requires them to be validated, to ensure their reliability before being applied in real scenarios, notably regarding their underlying communication transactions.
This paper presents an architecture for validating a Co-VP system via Hardware-In-the-Loop (HIL) integration of IEEE 802.11 communications and co-simulation support of a 3D simulator. We present it in a scenario of communication according to the ETSI ITS model and information exchange frequencies between the vehicles. Through these scenarios that mimic realistic conditions of Co-VP applications, we observe the impact of such variations on the number of messages received, network delay, and lateral and longitudinal platoon errors.

Keywords: Cooperative Vehicular Platooning · Vehicular Networks · Safety · Hardware in The Loop.

1 Introduction

The advance of communication technologies has expanded the ability of devices to cooperate in an unprecedented way [1, 2]. Cooperative Cyber-Physical Devices (Co-CPS) have emerged from these advances, being applied to diverse industrial [3], residential [4], logistics [5], and automotive [6] applications. Among these, one prominent application is Cooperative Vehicular Platooning (Co-VP) [7]. Co-VP enables fuel savings [8], reduced traffic flows [9], and contribute to decreasing the number of accidents [10]. In a Co-VP application, platoon members receive information from neighbors, other vehicles (V2X), or the infrastructure (V2I).

An overview of the connectivity that can enable Co-VP is illustrated in Figure 1. Co-VP is highly affected by the network conditions since the vehicle controller and platoon safety rely on information received from the environment [11].

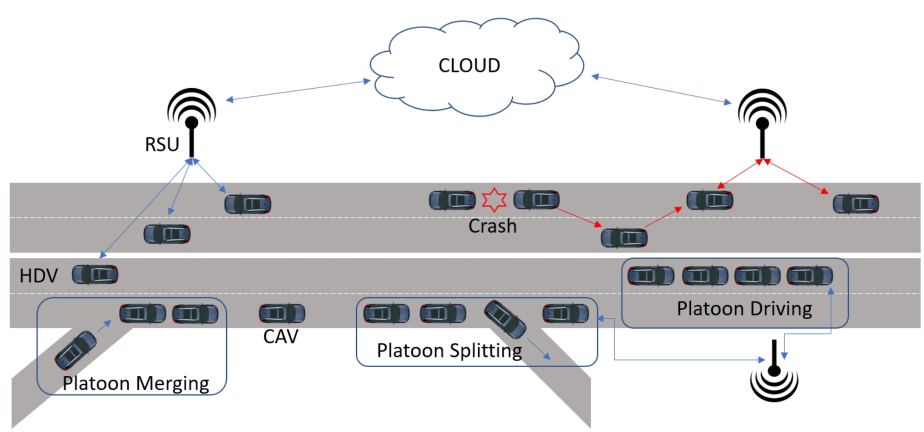

Fig. 1. Co-VP general View

Due to the variety of agents involved, the vehicle speed and the need of real-time response, system failures could result in damages and even loss of lives. Thus, they are classified as safety-critical systems [12] and thorough validation before implementing these systems is required [13]. In this context, simulators are essential to validate Co-VP systems, given their flexibility, scalability, and low-cost [14]. Nevertheless, this cannot replace system validation at the real hardware platforms, since simulators cannot encompass all real-world dynamics and the imperfections produced by process characteristics or hardware constraints [15]. However, given the cost and complexity of Co-CPS and Co-VP applications, along with the safety risks, safety limits are complex and expensive to validate in such configurations.

An intermediate model between full simulation and the real system is the Hardware in the Loop (HIL) [16]. Typically used in automotive environments, HIL provides a well-defined condition for the Device Under Test (DUT), commonly used to test complex physical systems and processes. Compared to field testing, it is a cheaper solution and presents results that are easier to replicate [17]. In addition, the HIL-based approach allows experimentation and analysis of a specific component in the Co-VP study, such as On Board Units (OBUs) and Road Side Units (RSUs). These tests can be realized over additional safety-critical scenarios, enabling the analysis of the vehicle response while ensuring a risk-free environment.

In this paper, we present an implementation of HIL aimed at validating the communication infrastructure of Co-VP systems, using as a base the CopaDrive model shown in [14]. So, we integrated the CopaDrive and Wi-Fi communication

Table 1. Acronyms Table

Acronym	Meaning	Acronym	Meaning
BSP	Basic Service Profile	OBU	On Board unit
CAM	Cooperative Awareness Messages	PF	Predecessor-Follower
Co-CPS	Cooperative CPS	ROS	Robot Operating System
Co-VP	Cooperative Vehicular Platooning	RSU	Road Side Unit
CPS	Cyber-Physical Systems	TRC	Transmission Rate Control
DUT	Device Under Test	V2I	Vehicle to Infrastructure
ETSI	European Telecommunications Standards Institute	V2V	Vehicle to Vehicle
HIL	Hardware in The Loop	VANET	Vehicular Ad Hoc Network
IFT	Information Flow Topology	WAVE	Wireless Access in Vehicular Environment

devices (IEEE 802.11), using the Robot Operating System (ROS) as an interface. The contributions of this work can be divided into three aspects:

- To present a HIL architecture integrating a 3D simulator and a real communications model to validate the communications infrastructure and its impact on the vehicles' platooning performance.
- Present a hybrid communications model between the application layer of ETSI ITS-G5 [18] and the physical layers of IEEE 802.11. We validate this communication model and the delays between messages using control boards used in real vehicles.
- Analysis of the Co-VP use case using different maximum communication frequencies and the message triggers defined in ITS-G5, analyzing the lateral and longitudinal platooning errors.

The organization of the rest of this paper is as follows. In Section 2, we present related work describing HIL implementations. The architecture of the developed HIL is explained in Section 3, including the equipment and technologies used. Next, we present the proposed scenarios and the evaluation tests. Final remarks are drawn Section 5. An acronyms list is presented in Table 1 to the reader's convenience.

2 Background

The flexibility of HIL in enabling the interaction between physical test vehicles and virtual vehicles from traffic simulation models has been studied before [19], showing it increases validation scalability and reduces costs. Another advantage of HIL is to evaluate safety-critical systems and resources that usually operate in highly variable environments in a controlled and limited environment. It also allows for parallel development of different system components on the fly [20]. The general HIL architecture for Co-VP scenarios is presented in Figure 2, where a bidirectional information flow between the Cyber-Physical physical and virtual subsystems is shown.

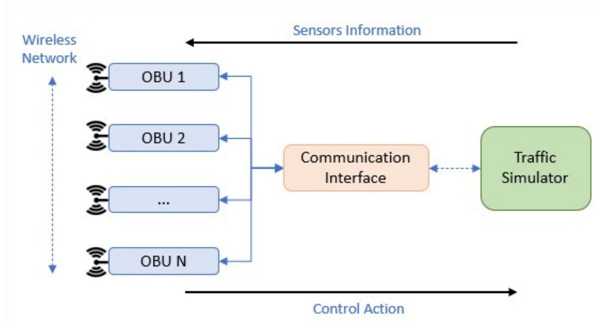

Fig. 2. HIL General Architecture

Just a few works address the HIL application in Co-VP environments. For instance, the work presented in [21] enables Co-VP performance evaluation based on stability and collision risk analysis. Furthermore, extensive simulation using real-world vehicle parameters can examine longitudinal controller specifications and network characteristics, observing platooning performance limits caused by network constraints and control system settings. Extending the network constraint analyses, the impact of Transmission Rate Control (TRC) on a Co-VP scenario based on industrial V2X nodes operating on ETSI ITS-G5 channels is the main focus of [22]. It evaluates the longitudinal distance of simulated vehicles in congested scenarios by changing the message frequency based on a simulation of four vehicle OBUs with data logging over Matlab Software.

Otherwise, the authors of [23] implemented a HIL test platform using the Carsim/Simulink vehicle simulator integrated with real DSRC modems. This HIL allowed a realistic evaluation of the parameter selection method of a Co-VP model based on a feedforward controller within a stable column boundary. In addition, this platform also evaluates the impact of dropout and communication delay on the longitudinal column stability of the Co-VP. Finally, an LTE C-V2X[24] HIL implementation was presented in [25]. Although this work is still under development, the authors have already presented an interesting platform based on the CARLA simulator, integrated with Simulation of Urban MObility (SUMO) and direct communication between the simulated vehicles via C-V2X Mode 4 modules. This platform implements a Software-Defined-Radio (SDR) based on three radio devices that mimic three real vehicles. In future HIL implementation developments, various Co-VP controller models can be evaluated based on the SUMO simulator.

2.1 Cooperative Vehicular Platooning

The interest in platooning applications is increasing in industrial and academic environments due to its advantages for traffic and drivers. Co-VP applications increase road efficiency in traffic, reducing vehicle distances, lowering energy

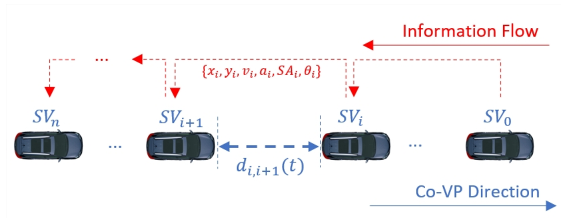

Fig. 3. Co-VP Predecessor-Follower Information Flow Topology (PF-IFT)[31]

consumption, and reducing CO_2 emissions. On drivers side, it reduces the travels time and a reduction in travel time due to reduced traffic congestion [26, 27].

In this work, we assume a platoon of $n + 1$ vehicles under a V2X communication environment using a Predecessor-Follower Information Flow Topology (PF-IFT) [28], as presented in Figure 3. Each vehicle has sensors to measure its global position, speed, acceleration, and heading. The vehicles in the platoon are referred to as car_i (where $i \in \{0 \leq i \leq n, i \in \mathbb{N}\}$), with car_1 being the platoon leader. Each car_i can be both a local leader of car_{i+1} and a follower of car_{i-1}. Each follower decides their behavior based solely on the messages received from the local leader, transmitted upon activation of kinematic triggers based on the ETSI ITS-G5 standard. Each car_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 platoon members control model is based on the integrated lateral and longitudinal Look Ahead Controller, as presented in [29, 30].

2.2 Vehicular Communications

Communication between vehicles and infrastructure is increasingly necessary, thus opening up the possibility of creating effective C-ITS, allowing road users and traffic managers to share information and use it to coordinate and co-decide on their actions. This information flow is built upon an IEEE 802.11n network on a Vehicular AdHoc Network (VANET). So a VANET is a subclass of a mobile AdHoc network, which does not depend on fixed infrastructure, allowing the network nodes (mostly vehicles) to move freely. The VANET has two main goals: continuous connectivity for mobile users while on the road and efficient wireless connection between vehicles without access to any fixed infrastructure [32].

Regarding vehicle communications, several studies have been performed in VANETs, including comparisons between different technologies [33]. Among the most studied and promising ones are IEEE 802.16e [34], LTE C-V2X [35], and IEEE 802.11p [32]. Despite the great discussion of which will prevail in the future, an in-depth comparison of each of them will not be analyzed within this project's scope. It is a fact that the IEEE 802.11p is the most used, tested, and accepted nowadays for vehicular communications [36], [37]. As a complement, 5G with all its features [38] network slicing, a greater number of connected devices, lower latency, and greater speed in transmissions that can be up to ten times faster than 4G [39] become all communications faster and more secure.

The increasing interest in vehicular cooperative applications induced the definition of standards over different VANET models to define conditions and use cases for technology development. So, some organizations have worked in this direction, creating the Wireless Access in Vehicular Environments (WAVE) [40] in the U.S.A and the European Telecommunications Standards Institute (ETSI) ITS-G5 [41] in Europe, being both supported by IEEE 802.11p.

In an embedded scenario, the V2V communication is ensured by the OBU, present in each vehicle. This module will be responsible for transmitting messages between vehicles and sending and receiving data from the neighbors. Looking forward to speeding up message transmissions, the general V2V communication model defines a broadcast message containing the vehicle information to be used by neighbors. In addition, the ETSI ITS-G5 standard and WAVE define the transmission of basic messages, called Cooperative Awareness Messages (CAM) and Basic Safety Messages (BSM), respectively, enabling collective perception. The CAMs can be transmitted periodically, at a pre-defined time interval, or event-triggered when a kinematic threshold is crossed, e.g., when speed or heading angle strikes a given value [31].

3 HIL Simulation Architecture

An HIL architecture allows to simulate a complex scenario (e.g., vehicular platooning) while integrating real-world components for validation within the architecture. Conceptually, the single entity *vehicle* is actually composed of two subsystems: the communication subsystem, in the form of On-board Units (OBU) that provide ad-hoc communication between vehicles, and the physical vehicle itself. In the presented HIL architecture, the first subsystem is accurately replicated by actual OBUs (one per each vehicle in the scenario), whereas the vehicles and the world in which they exist are simulated using ROS nodes and Gazebo, a simulator of vehicle dynamics and control. The HIL architecture and implementation presented in this paper is based on the version of Copadrive described in [14]; a more detailed representation of it can be found in Figure 4.

3.1 Platooning Application

We consider three vehicles in which the first, Car_1, is the global leader of the Co-VP application, acting autonomously to follow a line in the track. The followers are respectively Car_2 and Car_3, but this configuration can easily be extended to more vehicles. The vehicle speed and position controller model is based on the integrated system presented in [29]. Thus, it is possible to validate the lateral and longitudinal errors between the vehicles during their movement. This controller is based on a double PID controller, responsible for the vehicle's speed and steering angle.

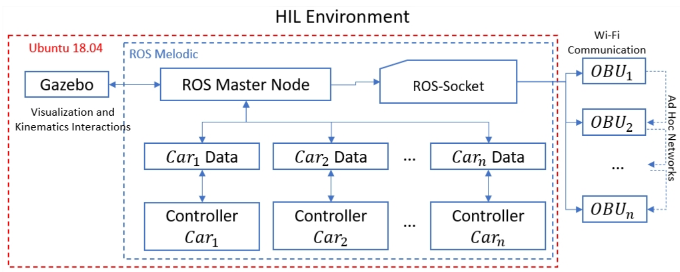

Fig. 4. HIL implementation View

3.2 Communication via Wireless Media

In this implementation, we are using Jetsons TX2 [42] equipped with Wi-fi interfaces as OBUs. The wireless link is meant to provided solely communication between the local leader and its follower. To share data between OBUs, each Jetson contains two processes, a ROS Server and ROS Client, shown in Figure 5. The ROS Server provides vehicle information (received from the ROS Master) to the ROS Clients present at other OBUs through the wireless medium. Upon reception of a message, the ROS Clients transmit that information to its respective ROS Server.

3.3 OBU-Simulation Connection

Each Jetson has access to all necessary ROS topics through a Master-Slave connection setup between the Master (deployed at the machine running the simulation) and each Slave (the Jetsons). This connection model allows a ROS full-duplex communication, so each Jetson can publish and subscribe to the necessary topics. To this end, we set up a socket connection in stream mode using TCP/IP.

The ROS Server at each vehicle has access to the vehicle information by subscribing to the topic $car_i/carINFO$ published, after which it builds messages in CAM format. Whenever required, the data is serialized [43] and sent to the bonded clients. On the ROS Client side, the data has to be deserialized to reconstruct the CAM, which is immediately published in the topic $car_i/RXNetwork\_wi\_fi$, where the leader vehicle subscribes to the $car_1/carINFO$ topic and forward the data to the other two vehicles, which will respectively publish in the $car2/RXNetwork\_wi\_fi$ and $car3/RXNetwork\_wi\_fi$ topics.

As all OBUs can monitor ROS topics, all vehicles have access to their neighbor's information. However, by design, the follower only uses local leader information.

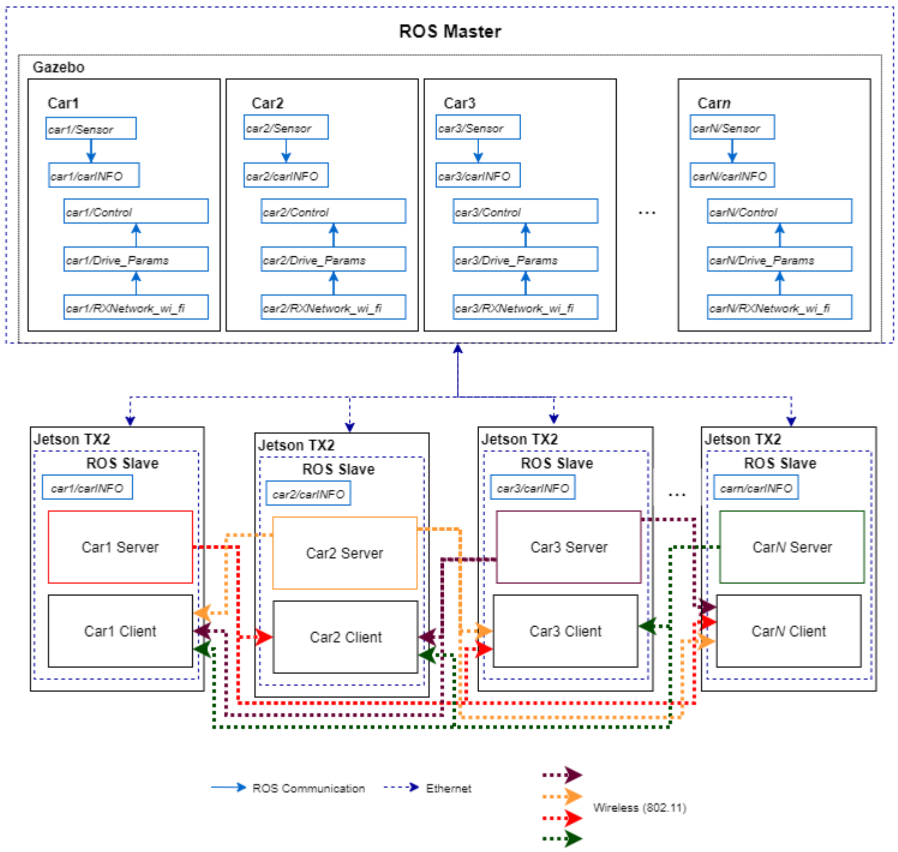

Fig. 5. System Architecture

4 System Evaluation

To evaluate the capability of the proposed HIL system, we define a realistic scenario that allows the comparison between different messaging profiles. The ETSI ITS-G5 [41] standard presents a set of rules for triggering CAM messages, defined in [31] as Basic Service Profile (BSP), based on the variation of speed, distance, and heading of the vehicle between two measurements, presented as follows:

- Maximum time (T_{max}) interval between CAM generations: $1s$;
- Minimum time (T_{min}) interval between CAM generations: $0.1s$;
- Heading difference: the absolute difference between the current and last heading provided in a CAM; a CAM is triggered if heading difference $> 4°$;
- Position difference: a CAM is triggered if position difference $> 4m$;

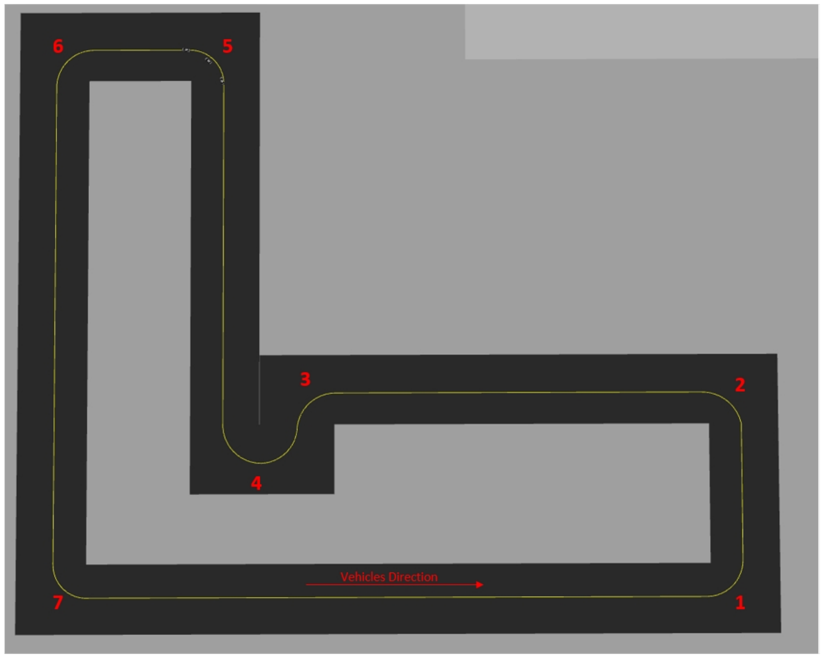

Fig. 6. HIL's evaluation circuit scenario

- Speed difference: a CAM is triggered
  if speed difference $> 0.5m/s$;

The circuit used during the validation intends to imitate a possible city scenario with five 90° turns and a 180°, as presented in Figure 6. In each scenario, the maximum message firing frequency was changed between $10Hz$, $7.5Hz$, $5Hz$, $2Hz$, and $1Hz$. Under these conditions, the kinematic triggers of message sending and the proposed time limit were evaluated. We also compare the HIL results in each scenario with the one presented in a fully simulated scenario, with no message delays. Thus, it can be observed how the different communication conditions affect the control of the vehicles in the proposed scenario.

Regarding the actual OBU equipment, whereas in [14] commercial ETSI ITS-compliant OBUs were used, in the present implementation these have been replaced by Jetsons TX2 [42] equipped with WiFi communication. This does not affect, however, the validity of the proposed HIL approach.

4.1 Scenario Results

Figure 7 demonstrates the trajectory traveled by the platoon leader and vehicles 2 and 3 in each simulation in scenario A. The analysis of the trajectory traveled by the vehicles using the BSP shows that the profiles with lower maximum messaging frequency have a more significant discrepancy between the trajectory of the leader and that of the follower vehicles. It can be observed in curves 1, 2,

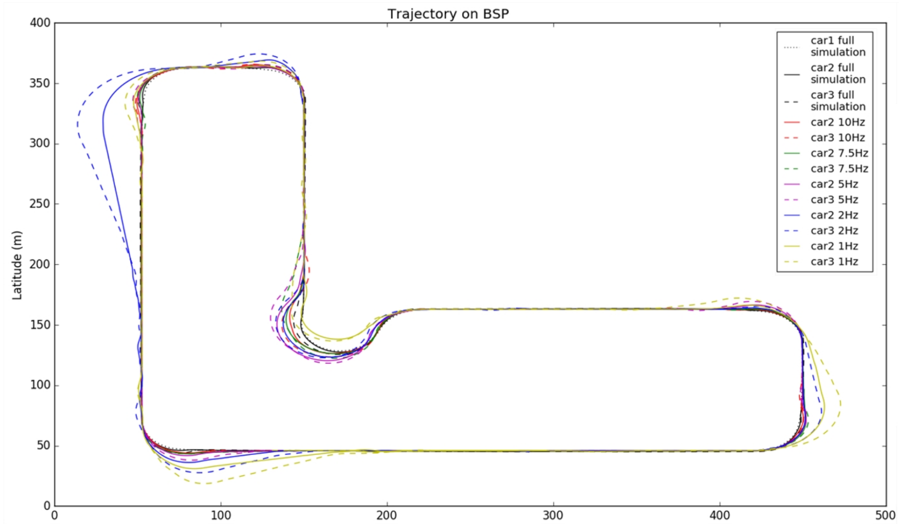

Fig. 7. Performed Trajectory on BSP

and 7 and curves 5, 6, and 7, respectively, at a maximum frequency of $1Hz$ and $2Hz$. The analysis of Figure 7 further illustrates that the trajectory error of car_3 is greater than that of car_2 at almost all frequency variations. However, as the communication frequency increases, this difference is reduced and inexists for frequencies beyond $7.5Hz$. In other words, even motion triggers are not enough to guarantee that the trajectory is the same among all vehicles since increasing the sending frequency improves this adjustment.

Finally, the joint analysis of the tests demonstrates the impact of the delay between messages on the vehicle control system. This impact is illustrated by comparing the simulated follower's trajectory, with near zero inter-message delays, and in the HIL implemented models. In the entire simulation scenario, the followers can perform the same trajectory as the leader, while this capacity is reduced as we reduce the communication frequency.

The conclusions obtained from the vehicle's trajectory are corroborated by analyzing the error of the longitudinal distance between them during the trip. The desired distance between the vehicles is defined in [29] as a constant time-headway policy (CTHP) that uses the vehicle's current speed to define the safety distance. Thus, the distance error is calculated as the difference between the current and the desired distance. This error is presented in Figure 8 as the error of the longitudinal PID controller. This figure illustrates how the maximum values of the longitudinal error increase with decreasing maximum messaging frequency. The distance error varies along the route, being corrected on the straight lines, but suffers a high impact with the circuit curves.

Another analysis of the performance of the Co-VP system is performed concerning the follower's lateral error compared to the leader. As observed in Figure 7, the curves performed by the followers that move over a lower messaging frequency exhibit a higher error. This observation is reinforced in Figure 9, which

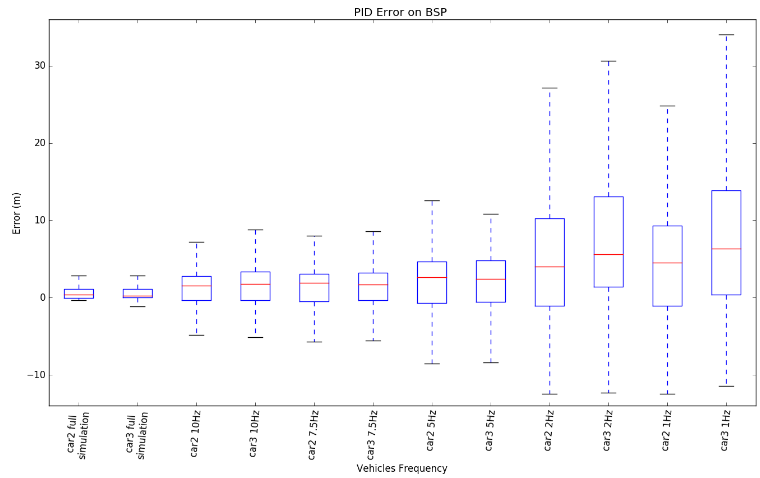

Fig. 8. PID Error on BSP

indicates the fit of the heading of the leader and the followers at different frequencies for curve 7. This figure illustrates that the HIL simulations with higher sending frequencies present less oscillation and quick stabilization, returning to the correct trajectory. However, this oscillation is more significant in the lower frequency cases and prevents the system from stabilizing quickly.

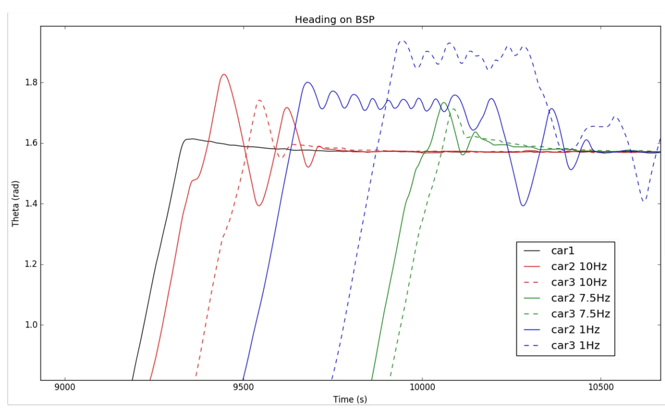

Fig. 9. BSP Heading Comparison

Using the HIL model for the various frequencies pointed out still makes it possible to observe the number of messages each local leader sends to its follower. As the position and heading errors propagate from the leader to the end of the platoon, the table 2 shows that the number of messages sent from car_2 to car_3 is higher than from car_1 to car_2.

Finally, we also evaluate the delay between messages sent from car_1 to car_2 and from car_2 to car_3 at each given frequency. This analysis studies the time

Table 2. Sent Messages

Sender	Frequency	$10Hz$	$7.5Hz$	$5Hz$	$2Hz$	$1Hz$
car_1	Time Trigger	1296	762	620	34	0
	Kinematic Trigger	0	170	210	702	728
	Total	1296	932	830	736	728
car_2	Time Trigger	1303	734	561	805	0
	Kinematic Trigger	0	222	396	53	804
	Total	1303	956	957	858	804

between messages sent by the ROS server allocated respectively on cars 1 and 2 to the client version of ROS on cars 2 and 3. As this HIL implementation includes OBUs using Wi-Fi as the communication medium, capturing this information is essential for different studies and modeling Co-VP systems. This delay is shown in Figure 10. This figure illustrates that above the frequency of $5Hz$, the difference between the delays is minimal. This difference is reflected in the car's movements on the track and their trajectory. At lower frequencies, this delay increases, implying larger trajectory, distance, and heading errors.

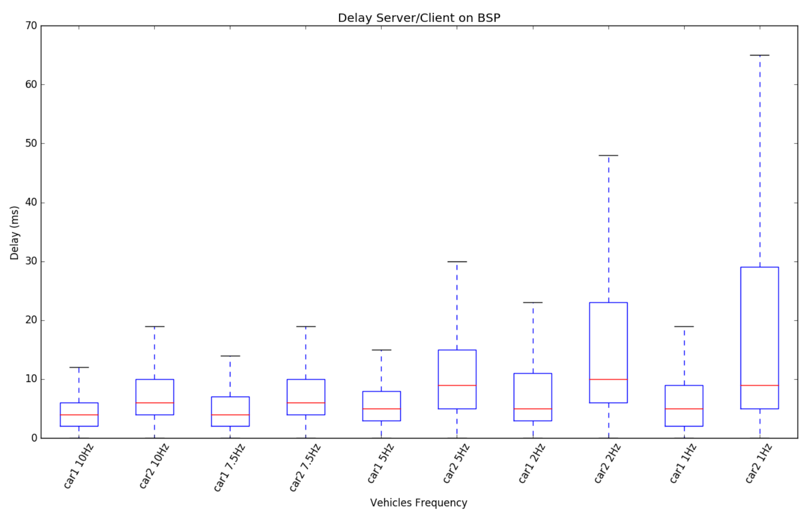

Fig. 10. Delay During the BSP Tests

5 Conclusion and Future Works

This paper presents a HIL architecture for the evaluation of Co-VP systems. The architecture brings together actual radio equipment – 802.11 (WiFi)-capable On-Board Units – and a software simulation of the physical dynamics and control of vehicles – based on ROS and Gazebo. This allows us to analyze the impacts of communication in the performance of Co-VP applications in a realistic fashion, as message exchanges are carried out by actual hardware. To showcase the presented HIL implementation, we deployed a simulated platoon using control algorithms already experimentally validated in realistic circuit, and quantified application performance (lateral and longitudinal errors) and communication performance (delays between messages) while varying the message-sending frequencies and triggers across the ranges defined in ETSI ITS standards family. Thus, we firmly believe this tool can contribute to different studies on Co-VP systems, both in the control and communications areas, due to the implemented client-server structure for communication between the devices.

We hope to scale the system to more vehicles and study the impact of other communication models on the platoon, ensuring its safety conditions and minimizing the errors found.

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