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Abstract

Cooperative Vehicular Platooning (Co-VP) is a paradigmatic example of a Cooperative Cyber-Physical System (Co-CPS), which holds the potential to vastly improveroad safety by partially removing humans from the driving task. However, the challenges are substantial, as the domain involves several topics, such as control theory,communications, vehicle dynamics, security, and traffic engineering, that must becoupled to describe, develop and validate these systems of systems accurately. Thiswork presents a comprehensive survey of significant and recent advances in Co-VP relevant fields. We start by overviewing the work on control strategies and underlying communication infrastructures, focusing on their interplay. We also address a fundamental concern by presenting a cyber-security overview regarding these systems. Furthermore, we present and compare the primary initiatives to test and validate those systems, including simulation tools, hardware-in-the-loop setups, and vehicular testbeds. Finally, we highlight a few open challenges in the Co-VP domain. This work aims to provide a fundamental overview of highly relevant works on Co-VP topics, particularly by exposing their inter-dependencies, facilitating a guide that will support further developments in this challenging field.

NOVEL SURVEY

Cooperative Vehicular Platooning: A Multi-Dimensional Survey Towards Enhanced Safety, Security and Validation

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ABSTRACT
Cooperative Vehicular Platooning (Co-VP) is a paradigmatic example of a Cooperative Cyber-Physical System (Co-CPS), which holds the potential to vastly improve road safety by partially removing humans from the driving task. However, the challenges are substantial, as the domain involves several topics, such as control theory, communications, vehicle dynamics, security, and traffic engineering, that must be coupled to describe, develop and validate these systems of systems accurately. This work presents a comprehensive survey of significant and recent advances in Co-VP relevant fields. We start by overviewing the work on control strategies and underlying communication infrastructures, focusing on their interplay. We also address a fundamental concern by presenting a cyber-security overview regarding these systems. Furthermore, we present and compare the primary initiatives to test and validate those systems, including simulation tools, hardware-in-the-loop setups, and vehicular testbeds. Finally, we highlight a few open challenges in the Co-VP domain. This work aims to provide a fundamental overview of highly relevant works on Co-VP topics, particularly by exposing their inter-dependencies, facilitating a guide that will support further developments in this challenging field.

KEYWORDS
Cyber-physical systems, Co-VP, Vehicular Networks, Control Models, Platooning Validation, Safety, and Security.

1. Introduction

Autonomous Vehicles (AVs) have become a reality in recent years, bringing about an impact in society that is both profound in the way it changes mobility and transportation systems as well as far-reaching in the technological evolution and challenges associated with its development process [1]. Large companies invest heavily in their autonomous platforms, seeking to enter and take hold of an emerging market of great potential [2]. According to [3,4], the global market size of autonomous driving is \$24.1B, with a growth expectation of up to \$173.15B by 2030, with Shared Mobility Services Contributing to 65.31%. However, many issues concerning cost and legal barriers must

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be addressed to achieve greater reach [5].

Under the scope of autonomous driving, Cooperative Vehicular Platooning (Co-VP) [6] emerges as a key application that will advance the safety and efficiency of autonomous driving. By having groups of vehicles traveling close together and constantly exchanging information between themselves through vehicle-to-vehicle (V2V) links or with the infrastructure through V2I links, road capacity, and fuel efficiency can be increased while accident occurrence reduces [7].

However, the development of Co-VP applications is increasingly complex due to inherent multidimensional problems. These Co-CPS impose an unprecedented integration between communication, sensing, and actuation actions, in parallel with the particular characteristics of the vehicle dynamics and the environment. Due to their interaction with the physical world, they are susceptible to malicious attacks and random faults in open environments. Their mobility and dependency on wireless communications further raise the complexity of the related issues, opening up a new set of risks. Indeed, in a cooperative platoon, messages exchanged between platoon members enable cooperative perception that contributes to improving individual situational awareness, joint maneuverability (e.g., in terms of inter-vehicle safety distance and transverse alignment of the vehicles), or overall safety through fast dissemination of emergency notifications to the other vehicles of the platoon. In turn, the communications layer must ensure strict reliability and security performance requirements. When these requirements are not fulfilled, e.g., in the presence of packet loss, transmission delay [8] or security threats [9], negative impacts can be observed in the Co-VP application. In conclusion, the cyber and physical aspects of a Co-VP system are entangled such that a compromise in the cyber system could result in physical consequences.

The study of Co-VP has advanced in several areas, such as control models for platooning [10], V2V and V2I communication [11], energy efficiency [12], interaction with other vehicles and platoons [13], among others. However, the literature presents a gap in analyzing the relationship between these related areas, needing to address the full extent of the problem adequately.

As we will present in Section 2, different facets of the Co-VP problem have been studied. However, most such works provide mostly isolated approaches spanning different domains. Such exclusive practices often result in oversimplified approximations of system components from other domains to assess performance. However, the side effects are potentially underestimated or result in over-provisioning resources. In addition, the interactions between the domains are also susceptible to unforeseeable threats, and their impacts might be silently propagated from one domain to another, leading to uncovered system failures. To ensure that the system behavior is determined with certain guarantees and no serious safety issue arises, the interplay between domains must be analyzed, validated, and verified before being integrated into the design of real vehicle components.

To assess the effectiveness of cooperative applications, it's crucial to have advanced simulation tools that can replicate road conditions, vehicle sensors and actuators, control models, and the V2X communication infrastructure. Additionally, formal verification techniques can be essential in guaranteeing the safety of these systems [14].

In addition to supporting these conditions, comprehensive toolsets are needed to analyze the interactions between all these relevant topics, as stated before. Such validation tools aim to assess the reliability and efficiency of the developed cooperative platooning solutions before real-world implementation, reducing errors, safety concerns, and costs.

Therefore, we present this work as a general review of the Co-VP body of knowl-

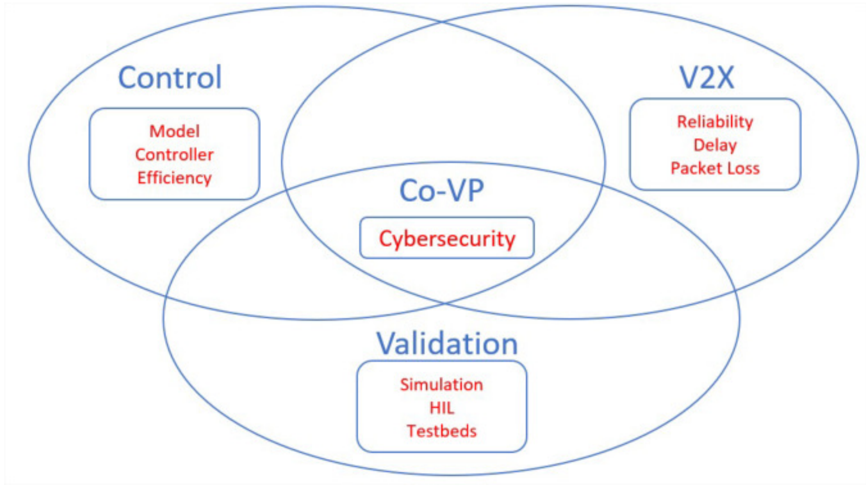

Figure 1. Survey Multidisciplinary Aspects

edge, reviewing control models, advances in communications and cooperation, leading applications, validation systems, and main challenges, whether in safety or security. We aim to provide a complete guide that supports further and solid advancements in this challenging field by exposing the interdependencies between the different domains and identifying the most recent and relevant contributions from this multi-disciplinary perspective. This perspective is illustrated in Figure 1.

The main contributions of this survey are presented below:

- We overview the fundamental surveys on Co-VP relevant topics, focusing on control, Co-VP cooperation, communications, and validation, and highlight the gaps in the literature concerning the interplay between the topics.
- We present the most recent research regarding Co-VP control strategies and detail several fundamental concepts.
- This work presents a multidimensional view of Co-VP systems, integrating the different constitutive aspects of Co-CPS. Besides the Co-VP controller models, we present recent research advancements in the underlying vehicular communication infrastructures. We highlight the importance of the interplay between Co-VP control and communications QoS by presenting the key contributions that address this issue. In addition, we consider recent advancements in cybersecurity and how the impact of Co-VP systems is evaluated and handled.
- Finally, this article presents recent advances in validation tools for Co-VP systems, categorized into *Simulation tools*, *Hardware in The Loop (HIL)* systems, and *Testbeds*. Their architectures and components are also presented.

The remainder of this paper is organized as follows. Section 2 reviews related surveys and how this work is positioned concerning them. We focus particularly on how current literature fails to consider the Co-VP problem for what it is: an instance of the Cooperative CPS paradigm. The fundamental concepts of Co-VP are presented in Section 3 as an introduction to the most relevant Co-VP control models. Advancements in the underlying communications infrastructures and Co-VP reliability against network threats and security issues are analyzed in Section 4. Next, we highlight how this multidimensional vision in Co-VP applications must be extended to multiple validation tools to aid development, including simulation, hardware in the loop (HIL), and testbeds. Finally, we highlight the current state-of-the-art of such frameworks. In Section 7, we discuss the main findings of our work and outline a set of open challenges in developing cooperative vehicular platoons. Table 1 presents the most used acronyms to enhance this work's readability.

Table 1. Acronyms List

Acronym	Meaning	Acronym	Meaning
ACC	Adaptative Cruise Control	HIL	Hardware in the loop
AV	Autonomous Vehicles	IFT	Information Flow Topology
CACC	Cooperative Adaptive Cruise Control	ITS	Intelligent Transport System
CAM	Cooperative Awareness Messages	LTE	Long-Term Evolution
CAV	Cooperative Autonomous Vehicles	MPC	Model Predictive Controllers
CBR	channel busy ratio	PID	Proportional Integral Derivative
Co-CPS	Cooperative Cyber-Physical Systems	PLS	Physical Layer Security
Co-VP	Cooperative Vehicular Platooning	PMP	Platooning Management Protocol
CSP	Constant Spacing Policy	ROS	Robot Operating System
CTHP	Constant Time-Headway Policy	SV	Subject Vehicle
DCC	Decentralized Congestion Control	V2I	Vehicle to Infrastructure
DENM	Decentralized Environmental Notification Messages	V2V	Vehicle to Vehicle
DoS	Denial of Service	V2X	Vehicle to Everthing
DSRC	Dedicated Short Range Communication	VANET	Vehicular Ad Hoc Network
ETSI	European Telecommunications Standards Institute	WAVE	Wireless Access in Vehicle Environments

2. Related Surveys

Co-VP is a complex and multi-disciplinary subject. A true example of the cooperative CPS paradigm in which the physical and cyber aspects of the system become highly integrated. To further increase the complexity, each vehicle consists of a system interacting with the remaining platoon members via different communication transactions to form Systems-of-Systems (SoS). With this in mind, we looked for surveys that addressed this complexity in both Co-VP and complementary topics. These works encompass a fundamental multi-disciplinary perspective to accurately describe, model, develop, implement, and validate these SoS's. That is the approach we follow and present in what follows.

We identified surveys covering the background of Cooperative Autonomous Vehicles (CAV), Vehicular ad-hoc networks (VANETs), Co-VP techniques and controllers, and

Table 2. Related Surveys Comparison

Topic	Ref.	Year	Address Co-VP	V2X Study	Controller Analysis	Safety Analysis	Security Threats	Validation Tools
Co-VP Arch.	[15]	2011	+	+/−	+/−	+/−	−	−
	[16]	2018	+	−	+/−	−	−	−
	[17]	2019	+	−	−	+/−	−	−
V2X Comm.	[18]	2020	+	+	−	−	+/−	−
	[19]	2019	−	−	−	−	+	
	[20]	2017	+	+	−	+/−	+/−	−
	[21]	2016	+	+	+/−	+/−	−	+/−
Controller Strategies	[22]	2017	+	−	+/−	−	−	
	[23]	2020	+	−	+	−	−	−
	[24]	2018	+	−	+/−	−	−	−
	[25]	2018	+	−	+/−	−	−	−
	[26]	2016	+	−	+/−	+/−	−	−
Validation	[27]	2019	−	+	−	+/−	+/−	+/−
	[28]	2020	+	+/−	−	−	−	+/−
Our Work		2021	+	+	+	+	+	+

vehicular validation frameworks. Table 2 summarizes the topics addressed by each work and positions our work concerning these. We cross-checked these with topics we covered in our work, such as the relationship with Co-VP applications, communication infrastructures, control systems, safety and security, and validation tools. We adopted the criterion of '−', indicating that the topic was not covered, '+/−' for incomplete coverage, and finally, '+', indicating a more complete and integrated topic coverage.

As shown, we found that none of these completely addresses these topics, and quite often, neither does their interdependence. In what follows, we highlight our findings from this analysis of the state-of-the-art.

2.1. Co-VP Architecture Surveys

One of the first surveys in vehicular platooning was presented in [15]. This survey introduces several concepts, such as string stability, and considers Co-VP as a natural development of vehicular platooning with Adaptative Cruise Control (ACC), introducing V2I and V2V communication. In addition, they gather several works in Obstacle Detection and Collision avoidance, Inter-vehicle communication, string stability, and control strategies. However, regarding inter-vehicle communication, there needs to be a reference to the current standard protocols, which greatly limits the depth ad completeness of the work.

In [16], another relevant survey, the main focus was on a control and planning architecture for CAVs, observing techniques to improve energy efficiency. First, they defined the Co-VP as one of some Real-Time motion planning techniques for CAVs and the Adaptative Cruise Control (ACC) evolution, removing the limitations of perception systems. Then, they performed a brief review of the vehicular communication protocols. In this survey, the authors defined the control analysis of the Co-VP as a one-dimensional networked dynamic system, decoupling the lateral and longitudinal Co-VP controllers. Considering the inter-vehicular distance as the primary metric of platooning, they suggested some control strategies, like Model Predictive Controllers (MPC) and Linear Consensus. Finally, the authors demonstrate that some basic level of centralized coordination is still necessary for the formation geometry and information flow network regarding platoon coordination.

A general view of the Platoon Coordination in most common car maneuvers is presented in [17]. The authors explain the maneuvers, e.g., join, merge, leave, and split. They also overview some intra-vehicle and inter-vehicle connectivity works, mainly regarding DSRC/WAVE[29] for V2V.

One of the most general surveys was presented in [21]. In this work, the authors define the Co-VP as a complex physical system integrated with modern wireless communication technologies that can be considered a CPS since they integrate computing, communication, and control technologies. This work divides the fundamental issues in Co-VP in modeling, management, stability analysis, platoon driving models, and V2X communication models. This survey also illustrates some validation methods through simulators. This work presents one of the most integrated views of Co-VP so far by establishing links between Co-VP architectures, their control methods, and network communication protocols. However, no concern for security is shown, and validation tools are covered very lightly.

2.2. V2X Communications Surveys

Architectural problems and wireless technologies that enable V2V communications are the focus of the work presented in [18]. This research also highlights these networks' security issues and discusses the usability of V2V communications enabled by vehicular fog computing. The authors reviewed several V2V trend topics, namely vehicular communication and safety applications, mainly regarding collision avoidance and security, comparing certificated and non-certificated solutions for V2V. The general V2V architecture integrates sensors that detect vehicle conditions, processors, and decision-making, responsible for coordinating actions, Global Positioning System (GPS), and the communication radio. Some V2V communication protocols are briefly introduced: DSRC, WAVE, 4G LTE, and 5G. Regarding V2V networks for platooning, the authors define the main challenges, like the formation, management, efficiency, information flow topology (IFT), and reliability in highly dense areas. However, they did not address the inter-dependencies between control and networking constraints, nor any validation strategies for Co-VP.

Regarding the security issues in vehicular networks, [19] divides this topic into three main challenges: security, privacy, and trust. With the main focus on anonymous authentication schemes, this work briefly reviews VANETs, defining system architecture, communication patterns, and V2X standards - DSRC, Wave, and IEEE 802.11p. They list the security keys as availability, confidentiality, authenticity, data integrity, and non-repudiation, explaining the services that should be provided and their corresponding threats and attacks. However, this work does not address specific cooperative vehicular applications, like Co-VP. This study is fundamental, as the cooperative nature of these SoS introduces additional security vulnerabilities which expose new risks.

Addressing Co-VP applications, the authors of [20] highlight some works about platooning in an adversarial environment, where an attacker modification of some of the control parameters can lead to string and system instabilities, reducing the platoon's safety. Hence, this work presents techniques to detect and mitigate this attack. Still, this work presents preliminary results, with few variations of attacks and

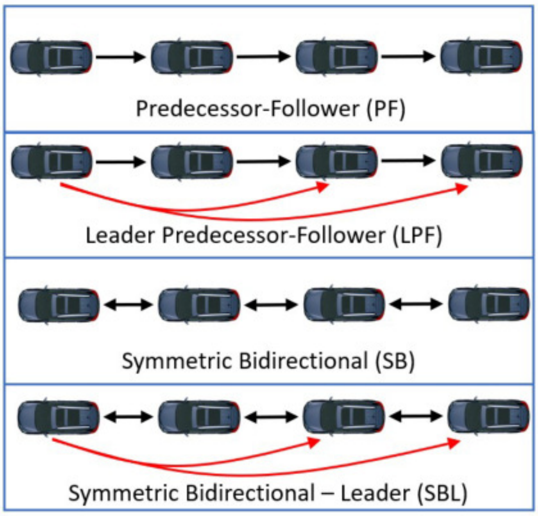

Figure 2. Co-VP Information Flow Topology (IFT)

defense mechanisms.

2.3. Co-VP Control and Efficiency Surveys

The authors of [25] primarily examine Cooperative Adaptive Cruise Control (CACC) and its architecture, which is structured around perception, planning, and actuation layers. Their work is mainly focused on longitudinal controllers that ensure string stability. They discuss MPC, Consensus, Optimal controllers, and Co-VP as key aspects of CACC technology. Meanwhile, the authors of [22] take a complementary approach, providing an overview of the performance of four distributed control models - linear consensus control, distributed robust control, distributed sliding mode control, and distributed MPC - in terms of internal stability, stability margin, string stability, and coherence behavior specifically for Co-VP.

The significance of MPC in the Co-VP literature is apparent, as evidenced by [26], which surveys the outcomes obtained using distributed MPC for Co-VP and offers a real-time MPC implementation. In contrast, [24] focuses on formation control of Co-VP and surveys various distributed and decentralized methods for vehicle formation control, highlighting the technical and implementation difficulties associated with these control methods through different topologies, which are presented in Figure 2. Another area of interest in Co-VP research is energy consumption efficiency, which is explored in [23]. The authors of this paper examine fuel economy in truck platooning and analyze contributing fuel consumption factors, such as various coordination methods and look-ahead control strategies. It is clear that the surveys on this topic do not consider the inter-dependencies with the communications topics in-depth. In most cases, there is no debate on limitations the communications infrastructures may impose over the control systems or even if current V2X communication standards can support some of the proposals. Often, the approach only considers control practices, completely neglecting that such controllers will take part in a complex SoS, and the communication interactions and their constraints must be analyzed to understand their effectiveness correctly.

2.4. Co-VP Test and Validation Surveys

Unfortunately, just a few surveys related to Co-VP cover the validation process of a Co-VP system as a central theme. Two highlighted surveys in this area are presented in [27] and [28]. In the first one, the authors reinforce the importance of the reliability and maturity of the technology that should be tested and verified. In the first survey, they summarized the testing methods for the V2X communication process using LTE-V and DSRC. This work also emphasizes the important network challenges such as latency/reliability and security. The second survey [28] is more dedicated to Co-VP Validation Strategies based on simulation, real experimentation, formal verification, and testing. However, both fail to address the fundamental topic of validating a complete SoS in all its fundamental aspects and interactions.

As seen, there is a lack of surveys that address the multi-disciplinary properties of Co-VP in a competent fashion. Most take on Co-VP from a single topic-based and thus quite limited perspective. In our survey, we consider this topic of interdependency, fundamental to all cooperative CPS, a core of our survey by overviewing the recent advances in the different relevant topics and highlighting how these overlaps are considered in the literature. In the next section, we introduce the first topic of the sour survey.

3. Co-VP Formal Model and Control

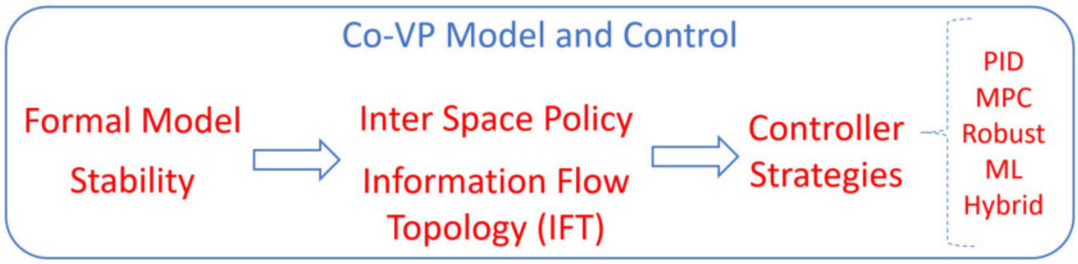

Figure 3. Section 3 general diagram

The formal definition of a Co-VP system involves the mathematical definition of its components and the relationships that define the safety of its movement in the form of functional and non-functional parameters. This section presents the basic mathematical definition of Co-VP applications, including the most used IFTs. In addition, it introduces the concepts of platooning stability based on distance measurements between vehicles. Importantly, by introducing these basic tenets of Co-VP control concepts, we ease the understanding of the control strategies. Finally, the section also presents the advances in the control models used in centralized or distributed architectures that allow the implementation of these cooperative systems. This session diagram is illustrated in Figure 3.

3.1. Co-VP Formal Model

The vehicle controller has a crucial role in the Co-VP system, given that even under perfect network communication, the received data should be analyzed and processed together with the own sensor's information in time to guarantee the platoon's safety.

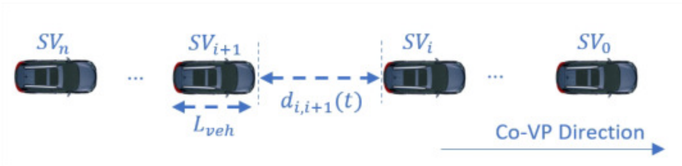

Figure 4. Basic Car-Following (B-CF) schematic

These controllers can be modeled in several ways with different approaches. For instance, models are used to emulate human behavior, describe how other drivers interact with the vehicle, and provide passengers with comfortable driving [30]. This section will introduce the central platoon characteristics, with the most used controllers, comparing their applications in several works.

Furthermore, in order to analyze the immediate interactions among vehicles in Co-VP, it is common to apply microscopic traffic models, to analyze different vehicle dynamics, including response time, the transient and steady response of a vehicle, regarding space between vehicles, velocity, acceleration, among others [21].

The car-following (CF) microscopic traffic model is one of the most used theoretical references for autonomous car-following systems [31]. It models the strong interaction between vehicles with tight space between them. Figure 4 illustrates the typical car following schematic, where identical vehicles follow each other in a single line with no overtaking. The platoon comprises $i \in \mathbb{N}$ vehicles. The full set of vehicles can be defined as $SV_i = \{i \in \mathbb{N} | 0 \leq i \leq n\}$, with a set of SVs, where SV_0 is the first vehicle and the platoon's Leader (TV). Each SV_i can be a local leader of SV_{i+1} and a follower of SV_{i-1}. The SV_i vehicle's position, speed and acceleration at time t is denoted as $x_i(t)$, $v_i(t)$ and $a_i(t)$, respectively. The distance - $\Delta d_{i+1}(t) = x_i(t) - x_{i+1}(t)$ - and the speed difference - $\Delta v_{i+1}(t) = v_i(t) - v_{i+1}(t)$ - are crucial to the CF model.

It is possible to represent the vehicle response in a time-continuous model using the acceleration a_{i+1} in terms of $\Delta d_{i+1}(t)$ and $\Delta v_{i+1}(t)$ to SV_i and v_{i+1} and a set of ordinary differential equations (ODEs) [32]:

$$\dot{x}_{i+1}(t) = v_{i+1}(t) \tag{1}$$

$$\dot{v}_{i+1}(t) = f(d_{i+1}(t), v_{i+1}(t), \Delta v_{i+1}(t)) \tag{2}$$

In this model, the current state of SV_i defines the mobility of SV_{i+1}. It is crucial to notice that the B-CF model does not address the vehicle's lateral controller, considering only the longitudinal aspects of the Co-VP.

3.2. Co-VP Stability Analysis

The CF model's instability is usually responsible for traffic congestion, stop/slow-and-go oscillations, and even accidents with CAVs. Moreover, the increase of perturbation, with oscillations in speed and distance between the vehicles, causes instability and decreases the Co-VP safety. Considering the Co-VP longitudinal controller, the stability analysis studies how the perturbation of SV_i evolves [33].

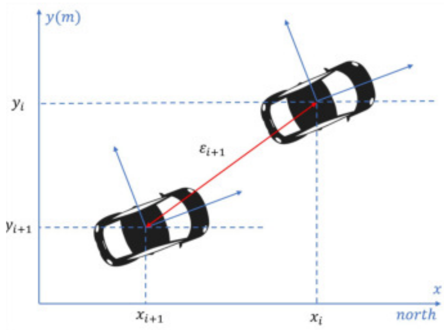

Figure 5. Distance Error

The linear stability analysis concerns minor disruptions' impact on Co-VP. As Co-VP applications are designed for road traffic, this model suits Co-VP studies involving vehicles with nearly constant speed. In [34], the authors discuss various stability analysis models, such as local and asymptotic stability, and provide mathematical definitions for them. Lyapunov stability, which falls under the category of local stability, ensures that any initial disturbance remains small enough, while asymptotic stability guarantees that a sufficiently small perturbation will decrease to zero over time. Regarding traffic flow, the authors define local stability as the stability of an individual vehicle under slight disturbance, while asymptotic stability refers to Co-VP stability, also known as string stability.

In this work, we will introduce and use the string stability concept definition from [35–38], which is based on the spacing error between the real and the desired inter-distance between SV_i and SV_{i+1} [39]. The string stability requires that the disturbance strictly attenuates between each leader-follower pair as it propagates away from the SV_0. The spacing error for the $SV_{i+1}th$ vehicle can be determined using:

$$\varepsilon_{i+1}(t) = SV_i(t) - SV_{i+1}(t) + d_{des}, \tag{3}$$

were d_{des} is the desired intra-platoon distance, as illustrated in Figure 5. The steady-state error transfer function is defined by:

$$H_i(s) = \frac{\varepsilon_{i+1}}{\varepsilon_i}, \tag{4}$$

where the platoon string stability is guaranteed if $\|H_i(s)\|_\infty \leq 1$ and $h(t) > 0$, where $h(t)$ is the impulse response corresponding to $H(s)$. The string stability definition uses the $\mathcal{L}_2$ norms, where $\|H_i(s)\|_\infty = max_t|\varepsilon_i(t)|$ is the maximum magnitude of the perturbation within infinite time. This metric characterizes the Co-VP string stability worst-case performance, using the maximum frequency response of the transfer function from the perturbation to ε_{i+1}. The authors of [40] propose a more flexible stability analysis, defining the string stability as $\mathcal{L}_\infty$, guaranteeing the absence of overshoot for a signal while it propagates throughout the platoon. In this approach, it is possible to guarantee the Co-VP local stability in a string with n vehicles if:

$$H(s) = \frac{\varepsilon_n}{\varepsilon_1} < 1. \quad (5)$$

Several factors have a direct influence over the Co-VP stability. Namely, the *vehicle parameters*, which include delays in response time, maximum heading and speed, the *spacing policy*, that refers to the distance between SV_i and SV_{i+1}, the *control model* and the *communication structure*.

The main challenge with vehicle parameters is the uncertainty associated with the model. In [41], the authors address this issue by proposing a solution using centralized Co-VP control and an MPC strategy, where vehicle accelerations are determined based on worst-case scenarios for each vehicle. Using a stochastic approach to predict vehicle behavior, platoon stability can be maintained flexibly, even when human-driven vehicles are mixed with autonomous ones. Following a Leader-Follower approach, the platoon leader receives data from all followers, determines the strategy, and then sends it back to the followers. In [42], the authors suggest a new delayed feedback MPC scheme for sensors with limited measurement range and actuator time delay. They also introduce controllers that adapt their parameters online by solving a receding horizon optimal control problem.

The work presented in [43] deals with a Co-VP consisting of a non-linear CAVs model with parametric uncertainty and unknown external disturbance. To address these issues, the authors propose an adaptive backstepping control scheme with an online estimator based on V2V communication. To prevent spacing error growth, the scheme uses asymmetric time-varying constraints. In contrast, the authors of [44] adopt a different approach by categorizing and dealing with the disturbances differently. Specifically, they use a feedforward controller for large yet infrequent perturbations and a feedback controller for small yet frequent perturbations. They show that their approach outperforms the standard MPC implementation.

3.3. Co-VP Inter-Space Policy

The majority of Co-VP adopt one of two common inter vehicles space methodologies: *constant spacing policy* (CSP), which is independent of the speed of the controlled vehicle [45]; and *constant time-headway policy* (CTHP), that uses the current speed of the vehicle to define the safety distance [46]. The CTHP is usually recognized as a safe practice for human drivers. The objective range (d_{ref}) in this policy is $d_{ref}(t) = SD + t_h v_{i+1}(t)$, where $SD > 0$ is the safety distance and t_h is the defined time headway, generally between 0.5 and 2 seconds.

While using CTHP is common in Co-VP, [47] propose a new method that improves on this approach by using a non-linear range policy. This policy decouples t_h from the time constant of the vehicle's mechanical control loop and is obtained through an optimization procedure with traffic flow and stability constraints. Tests show that this method achieves stable traffic flow up to a significantly higher traffic density, even with different vehicle models. In a different study, [48] examine inter-platoon stability by extending the CTHP approach to study the flow of many platoons, considering the whole traffic flow as the interaction between cooperative platoons. Platoon leaders receive information from other platoon leaders via the V2I communication strategy, and a virtual leader is used for the entire platoon.

Other variations have also been explored in different studies. For instance, in [49], vehicles use onboard sensors to maintain distance between them and receive a_i from the local leader via V2V communication. In [50], a flexible, safe distance constraint ensures safe distance and communication connectivity in the platoon. This method allows a CAV to meet with the platoon within any preset time without being bound to initial requirements or system parameters.

3.4. Co-VP Information Flow Topology

The communication structure has a significant role in platoon stability, as explained in [24]. Message size, information type to be transmitted, and the message distribution's topology all matter in the stability control. The most common strategies are the *predecessor-follower* (PF) method [14] and the *symmetric bidirectional communication* (SB) [51]. In the first approach, the SV_i sends messages to SV_{i+1} and receives no messages from them. In the *bidirectional* communication, the messages are also sent from SV_{i+1} to SV_i. The PF communication also has different implementations, like in [52], where the authors investigate a merging algorithm for the vehicles to join a platoon. In this work, the vehicle receives data from the previous two vehicles in the platoon to perform a *consensus* algorithm, defining a *predecessor to 2 followers*, or P2F. The authors of [53] proposed a granulated *predecessor leader-follower* to create a scalable platoon. The leader transmits messages to the following two vehicles in this work. Then, the last one becomes a *G-leader* and reproduces the leader information to the following two vehicles and the next *G-leader*. As a result, the authors could keep the stability of 8 vehicles platooning in several conditions.

Based on several studies, it is possible to improve platoon stability using some methods: broadcast the information of the leader to all the vehicles [45]; using CTHP instead of CSP [46]; non-linear spacing policies and non-identical controllers [54]; sending messages in both ways - from previous cars to following cars and in the opposite direction [55]. However, broadcasting information to all vehicles and providing bidirectional communication between vehicles is a strategy that decreases its benefits as the platooning size increases [56]. Table 3 summarizes the works presented in this section regarding control strategy, controller type, issues, spacing policy, and IFT.

3.5. Co-VP Controller Strategies

Several control models can be applied in Co-VP, ranging from simplified controllers to very complex ones. Such models directly influence the response time of the platooning applications and are also responsible for guaranteeing the platoon's stability in different situations.

3.5.1. Co-VP PID Controllers:

Although considered simple, the Proportional Integral Derivative (PID) controller is a solution widely used in Co-VP applications. For instance, in [14,57], two PID controllers are integrated to perform lateral and longitudinal control of a platooning. A maximum vehicle number was determined to guarantee the platoon's safety in both works.

In [58], a modified version of the PID control is implemented. The authors use an adaptive Proportional Derivative (PD) controller to ensure platoon stability. In addition, they propose a dynamic information exchange mechanism between vehicles

Table 3. Summary of Control Models for Co-VP

Controller Strategy	Cite	Year	Description	Model Applied Issues	Space Policy	IFT
Linear	[49]	2020	Distributed	-	CHTP	PF
	[50]	2019	Distributed	-	CSP	PF
	[51]	2017	Distributed	Degraded Communication	CSP	PF
	[52]	2016	Distributed Consensus	Communication Delay	CSP	PF
	[53]	2019	Distributed	-	CSP	-
	[45]	2017	Distributed	Actuator Lag	CHTP	PF
	[46]	2015	Distributed Consensus	Communication Delay	CHTP	LF
	[54]	2004	Distributed	-	CSP	PF
	[55]	2013	Distributed	-	CSP	SBF
	[56]	2013	Distributed Non Linear	-	CHTP	SBF
PID	[14]	2017	Distributed	Degraded Communication	CSP	PF
	[57]	2020	Distributed	Actuator Delay	CHTP	PF
	[58]	2018	Distributed	Degraded mode with compensation	CHTP	P2F
MPC	[41]	2018	Centralized	Actuator Lag	CSP	FL
	[42]	2018	Centralized and Delayed	Lag Sensors	CSP	LF
	[59]	2018	Distributed	-	CSP and CHTP	SBF
	[60]	2018	Centralized	-	CHTP	FL
	[61]	2017	Distributed	-	CHTP	PF
	[62]	2020	Distributed	-	CSP	PF
	[44]	2020	Distributed Feedforward and Feedback	Unmodeled Dynamics and Initial Tracking Error	CTHP	PF
Robust	[43]	2020	Distributed Adaptive Backstepping	Parametric uncertainty and disturbance	CTHP	PF
	[63]	2017	Distributed H_∞	Degraded Communication	CHTP	PF
	[64]	2014	Distributed H_∞	Real vehicles with ETSI-G5	CHTP	P2F
ML DRL	[65]	2020	Centralized	PID parameter tuning	CTHP	PF
	[66]	2023	Distributed	Dynamic Programming	CSP	PF
	[67]	2022	Distributed	V2V Communication	CHTP	PF

based on a predecessor-follower mode. Under this scheme, the information about the previous vehicle is transmitted to the next two vehicles in the platoon. Furthermore, the sensors detect the distance and position of the preceding vehicle. Thus, when communication is lost, the controller does not immediately switch to a degraded mode but rather attempts to compensate for the communication failures.

3.5.2. Co-VP MPC Controllers:

Another usual controller for Co-VP applications is the MPC and its variations. For example, the authors of [59] compare the PID with the MPC to maintain inter-vehicular distance and headway time between the vehicles. They used the VISSIM simulator combining CSP and CHTP for safety analysis. The authors showed that MPC improves the platoon's control performance in this case. However, in this work, the communication prerogative is that all the vehicles can share their data with the surrounding vehicles without data loss. Therefore, the authors also conclude that a well-tuned PID can maintain platoon stability with less computational power, but the tuning can be very empirical and inefficient. Otherwise, the parameters adjusted in MPC are more comfortable and can also help with lost packets in communications.

In [60], an MPC is used to allow the platoon interaction with an HDV, *joining* and/or *spliting* from a Co-VP, using CHTP as a safety condition. This approach uses a centralized node (an RSU or another vehicle) to publish to all vehicles on the road. This work does not consider the communication range, allowing the centralized node to receive data from all the platoon vehicles.

However, in [61], centralized MPC is considered challenging to implement in real Co-VP applications, given the system's dynamics. This work proposes a Distributed MPC (DMPC), where the algorithm in each car does not need the leader's information but only from its neighbors. There is an optimal local solution for each vehicle that does not need to *a priori* know the entire platoon's desired set point. In this case, they consider that only the followers directly communicating with the leader know the desired path. Then, they introduce a constraint in the follower's position based on the neighbor's information. The authors address their tests in different unidirectional topologies, like predecessor-following, predecessor-leader following, two-predecessor following, and two-predecessor-leader following.

In [62], the authors conducted numerical simulations to compare the fuel efficiency of a new distributed EMPC strategy with a commonly used distributed target-tracking MPC strategy. The proposed strategy aims to enhance fuel efficiency while ensuring the platoon's stability and string stability. To achieve this, they utilized the fuel consumption functions of the vehicles as the objective cost of the distributed MPC.

3.5.3. Co-VP Robust Controllers:

The authors of [63] propose a decentralized control approach to address platoon stability by formulating a multi-objective H_∞ control. The objective of this control is to guarantee string stability of a vehicle platoon in ACC and CACC while allowing tradeoffs between vehicle following performance, system robustness, and string stability. Two scenarios are considered in this work: one with ACC using only local sensors and another with CACC using vehicle communications. In case of communication failure, the vehicle operates as an ACC. Similarly, [64] also employs H_∞ control to support multiple-vehicle look-ahead CACC design, considering linear platooning. This work uses a novel definition of $\mathcal{L}_2$ string stability. The communication approach uses a predecessor-follower and two-predecessor follower to analyze how communication complexity impacts the system's performance.

3.5.4. Co-VP Controller design with Machine Learning:

The use of machine learning (ML) models in Co-VP applications is still restricted, but some studies have explored their use as an alternative to control parameters. For example, a study presented in [68] aimed to reduce fuel consumption by using an IFT-PF to transmit the state of the agents globally and a specific channel to establish rewards of the DRL model. The proposed approach considers the multi-agent variation inherent in platooning, including vehicle inputs and outputs. Additionally, [69] introduced a path planning scheme that utilizes DRL on the network edge node for improving the driving efficiency of autonomous vehicular platoons in terms of fuel consumption. The proposed approach considers a joint optimization problem that factors in the task deadline and fuel consumption of each vehicle in the platoon.

The authors of [65] focused on the longitudinal controller and proposed the use of a longitudinal PID controller for platooning. The optimal parameter tuning was performed as a goal of a deep reinforcement learning (DRL) model. The authors claimed a reduction in stability time and distance error using a Hardware-in-the-Loop (HIL) as a validation tool. Similarly, [66] proposed an integrated approach that combines DRL and dynamic programming (DP) to develop efficient vehicle tracking policies in Co-VP scenarios. The proposed system, FH-DDPG-SS, uses three key ideas to improve efficiency: transferring network weights backward in time, approximating stationary policies, and scanning through reduced state space. However, this paper did not compare its results with other scenarios.

Furthermore, the work presented in [67] investigates the impact of V2X communications on platoon control performance using DRL. The study explores the tradeoff between the gain of including exogenous information in the system state for reducing uncertainty and the performance erosion due to the curse of dimensionality. The study determines the most appropriate state space for platoon control under different information topologies and quantifies the value of each piece of information to establish the most optimal policy. Additionally, [70] proposes a model-based DRL algorithm for the CACC of connected vehicles, including a platoon of both human-driven and connected AVs via V2V and vehicle-to-cloud communication. However, these implementations are theoretically validated, and their effectiveness in real-world scenarios needs further investigation.

3.6. Co-VP Controllers Conclusion:

The choice of controller model for Co-VP applications greatly influences the system's performance and safety. Responsible for ensuring the platoon's stability, its complexity can directly affect its applicability in the real world, considering communication errors, processing time, and these algorithms' response. Thus, the choice depends heavily on the mechanical systems' responsiveness and the vehicular network's communication capacity. Table 3 summarizes the works presented in this section, comprehensively comparing the controller strategies while addressing several issues. We also conclude there are limitations regarding the Co-VP application of these controllers. Some are just proved theoretically correct and never deployed, and those which are subject to some kind of different validation strategy are usually deployed in very limited scenarios. One of the biggest challenges of these applications lies precisely in the variety of

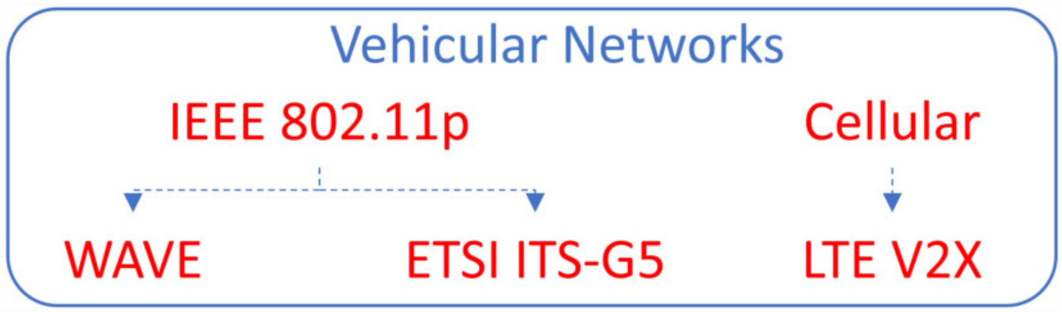

Figure 6. Vehicluar Networks

deployment possibilities, hence the importance of flexible validation tools that can mimic such possibilities. This is still a fundamental problem that must be addressed to understand these proposals' limits better.

4. Co-VP Communications

Co-VP applications face several challenges due to the interference caused by communication systems, including Packet Loss Ratio (PLR) and delay. The quality of wireless communication significantly impacts the performance and safety of platoon control and, thus the stability of the platooning conditions. However, although many studies analyze vehicular networks' performance, few address these networks' impacts on Co-VP controllers and their consequences for system reliability. This section presents recent and relevant studies about Co-VP reliability based on network communication threats such as PLR, inter-message delay, Transmission Rate Control (TRC), and the solutions designed to mitigate their influence on the platoon. These works are summarized in Table 4. Figure 6 presents the most commonly used vehicular networks.

4.1. Communication Threats

One of the first Co-VP network performance analyses was presented in [71], with a study about the impact of PLR on Co-VP's string stability performance within a CSP model. V2V communication was established based on the IEEE 802.11p standard with a fixed-time message. The authors concluded that the beacon sending frequency and PLR influence the Co-VP application's performance since the string stability decreases while the messages' frequency decreases. The same network threats were observed in [72], where the authors evaluated the impacts of network properties and controller system specifications on platoon stability. Using a simple communication model and different controller parameters, they evaluated the distance error between the platoon vehicles and concluded that the platoon stability decreases while the average PLR increases.

The authors investigate the effect of PLR and time delay on Co-VP lateral and longitudinal PID controllers in [73]. Two communication models, DSRC and LTE-V, were analyzed, and a packet loss model based on the Bernoulli distribution and a fixed time delay were used. The study found that both the time delay and packet loss lead to an increase in longitudinal and lateral errors. However, the experiments were conducted under either time delay or packet loss, but not both simultaneously. The authors conducted a field test with two vehicles and LTE-V communication, which had fixed time delays.

Table 4. Summary of Co-VP Network Analysis

Network Model	Cite	Year	Controller Model	Model Issues
Generical	[74]	2020	Feed Forward loop with PID controllers	Packet Loss and Time Delay
	[75]	2020	H_∞	random single packet drop
	[72]	2018	PD	Packet Loss, Time Delay and TRC
	[76]	2020	PID	Time Delay and Sensor Faults
	[77]	2019	Linear Controller	Packet Loss
	[78]	2018	Linear Controller	-
WAVE	[79]	2019	Linear Controller	Packet Loss
	[80]	2020	Linear Controller	Packet Loss and Time Delay
	[71]	2011	Linear Controller	Packet Loss
	[8]	2018	MPC	Packet Loss and Channel Crowding
ETSI ITS-G5	[81]	2017	Linear Controller	Time Delay
	[82]	2018	Linear Controller	Packet Loss, Time Delay
	[83]	2019	Linear Controller	Packet Loss, Time Delay
	[84]	2015	PID	Time Delay
	[12]	2016	Linear Controller	Packet Loss, Time Delay and TRC
	[85]	2015	Linear Controller	Time Delay and TRC
	[86]	2019	Longitudinal Vehicle Dynamic Model	TRC
	[87]	2018	Linear Controller	Packet Loss and Time Delay
LTE V2X	[73]	2018	PID	Packet Loss and Time Delay
	[88]	2018	Linear Controller	Time Delay and Throughput
	[89]	2018	Linear Controller	Time Delay

The authors of [8] analyzed a 14-vehicle Co-VP application using the WAVE communication protocol with a fixed time delay between the messages. A deliberate communication failure was introduced in one vehicle in this work, and the Co-VP performance was observed after this error. They also evaluated the channel crowding, changing the default message time and demonstrating that the PDR decreases while the CBR increases.

In the study presented in [74], the authors conducted a numerical simulation and a hardware-in-the-loop (HIL) implementation to evaluate the performance of the Co-VP controller under a stochastic packet loss model and a constant message delay. They proposed a feedforward controller integrated with two PID controllers to address model uncertainties and determined the system's string stability parameters. The simulation results indicated that the dropout rate negatively impacts string stability and following accuracy, but only up to a certain limit. However, the HIL implementation did not encounter any packet dropouts since there were only two on-board units (OBUs). A similar approach was taken in [75], where the Co-VP stability was assessed against random single packet drop and external disturbances. The authors proposed a robust LMI-based distributed H_∞ controller to ensure the vehicles' longitudinal safety distance within two different IFTs, namely, the bidirectional predecessor-follower and a hybrid solution bidirectional predecessor-follower with leader-followers. They evaluated the Co-VP performance with different packet drop rates (ranging from 0% to 30%) and a varying number of follower vehicles.

The authors of [80] analyzed the time-varying performance of IEEE 802.11p Co-VP communication under disturbance in the leader's behavior, considering the impact of packet loss and message delay. They derived the time-dependent estate of each follower and concluded that IEEE 802.11p can maintain string stability under disturbance. However, this study only considered the leader-followers' IFT communication topology, which reduced the number of sent messages. A similar evaluation was presented in [82], but using the ETSI ITS-G5 standard and the leader predecessor-followers IFT. This work identified the phenomena that reduce communication performance based on message synchronization after sequential disturbances.

A Co-VP driving system that integrated network and control perspectives is proposed in [77]. They established the upper bounds on the acceptable error due to packet losses and optimized the real inter-vehicle gap to ensure platoon string stability. They adopted a symmetric bidirectional IFT where the subject vehicle received data from the predecessor and the next one. The authors concluded that a flexible inter-vehicle distance associated with safety bounds could mitigate the issues due to packet losses in Co-VP applications. In [90], the authors defined a worst-case boundary for the latency of DENM in ITS-G5 scenarios to alert vehicles about emergency brakes.

4.2. Communications Parameters Tuning

The communication performance of Cooperative Vehicle-Platoon (Co-VP) systems is affected by various factors that need to be studied and optimized. Several works in the literature have analyzed the impact of communication parameters on Co-VP performance. For example, the authors of [12] studied the effect of Transmission Rate Control (TRC) on fuel consumption, and the authors of [86,87] demonstrated the impact of TRC on the string stability controller performance. Moreover, the emergency brake in Co-VP applications was analyzed in [83,85], and a feasible region of communication delays was proposed in [83].

The performance of Co-VP networks also depends on the message trigger strategies. The literature has two standard models: the time-triggered and the event-triggered strategies. The ETSI ITS-G5 standard defines the event-triggered strategy as a standard, but many implementations use fixed time messages [74,83,85]. The event-triggered strategy increases platoon safety using a high message frequency ratio, but it can also increase packet collision due to a crowded network [81]. The authors of [76] and [78] proposed flexible event-triggering strategies, but their conclusions are not based on ITS communication standards.

The performance evaluation of time delay between messages in Co-VP applications was studied in [84]. The authors compared the CAM time delay using ETSI specifications and fixed frequency of $10Hz$ and concluded that the Co-VP performance with the fixed frequency outperforms the ITS-G5 standard, especially at higher speeds.

The IEEE 802.11p MAC standard, used in Co-VP networks, is based on the CSMA/CA approach. However, this policy will likely lead to collisions and degraded performance as network load increases [79]. The authors proposed an overlay TDMA-

Table 5. Security Requirements and Attacks

Security Requirement	Attack
Availability	Blackhole and Greyhole; Flooding; Denial of Service (DoS); Jamming; Coalition [94]; Malware; Tampering; Greedy Behaviour; Spamming;
Integrity	Falsification; Replay; Spoofing;
Confidentiality	Eavesdropping; Location Tracking;
Autenticity	Certificate replication; Sybil ; Masquerading; Tunneling; Free-Riding [19];

based MAC that synchronizes messages between vehicles, reducing collisions. The performance of two TDMA algorithms and IEEE 802.11p MAC CSMA/CA implementation in Co-VP networks was compared, varying platoon sizes.

The performance comparison of IEEE 802.11p and LTE-V2V regarding high-density truck-Co-VP scenario conditions was studied in [89]. The authors presented the CAM message latency and reception rate as performance metrics and concluded that long platoons could benefit from LTE-V2V due to better link budget. However, this conclusion was contradicted by the works in [88,91]. The authors of [88] demonstrated that the LTE-V2V system could not support Co-VP applications under congested scenarios. Similarly, [91] demonstrated that ITS-G5 outperforms LTE-V2V in cases where the LTE-V2V has concurrent data with the V2X communication.

These various works we highlighted prove that Co-VP systems are highly influenced by variations caused by the network QoS. Thus, the controllers of Co-VP systems must be prepared to deal with these variations to guarantee the system's safety. However, this influence from different vehicular network models still needs to be better studied in more relevant and realistic scenarios. Hence, such proposals must be validated closer to the real scenario as possible, as we will introduce in Section 6.

5. Security Analysis of Co-VP applications

In addition to the problems inherent to communications, such as delays and packet losses, the Co-VP networks are subject to interference from other agents, often ill-intended, affecting their operation, destabilizing the platooning [92,93]. Such attacks can be divided into categories: information availability, integrity, authenticity, or confidentiality [94]. Some security requirements and concepts for specific Co-VP scenarios are presented in [95] and summarized in Tab. 5. This section presents several Co-VP cybersecurity research works summarized in Tab. 6. These works highlight the impact of security threats on the Co-VP application and propose strategies to mitigate them.

5.1. Vehicular Network Vulnerabilities

Several works focus on physical layer security (PLS) regarding the confidentiality of shared information. For instance, in [96], the performance of the PLS is studied over fading channels regarding data secrecy. Furthermore, the authors of [97] establish

Table 6. Co-VP Cybersecurity Research

Network Model	Cite	Year	Simulation	Attack Model	Attack Type	Solution
Non Co-VP	[96]	2020	Numeric	Confidentiality	Physical Layer Attack	-
	[97]	2019	Numeric	Confidentiality	Physical Layer Attack	-
	[98]	2019	Numeric	Confidentiality	Physical Layer Attack	Reconfigurable Intelligent Surfaces
	[99]	2019	-	Confidentiality, Authenticity	Falsification	SerIOT Extension
	[100]	2018	Numeric	Confidentiality	-	Public Key
	[94]	2019	-	Availability, Integrity, Confidentiality, Authenticity	Several	-
Generic Co-VP Network	[92]	2018	Numeric	Authenticity	Falsification	Gain Limit
	[95]	2019	-	Confidentiality, Authenticity	Key distribution	
	[101]	2020	Numeric	Authenticity	DoS; Replay; Falsification;	Distributed attack detection, -
	[102]	2020	Numeric	Availability	DoS	-
Zigbee	[103]	2020	ROS + Testbed	Authenticity	Falsification	Monitoring Sensors
	[104]	2019	ROS + Testbed	Authenticity	Falsification	Monitoring Sensors
DSRC/ WAVE	[93]	2018	VENTOS	Availability, Confidentiality Authenticity	Falsification; Replay; DoS; Man in the Middle	Voting, -
	[105]	2015	VENTOS	Availability, Authenticity	Falsification; Jamming;	Voting
	[106]	2020	Numeric	Availability	DoS	Distributed Nonlinear MPC
	[107]	2016	VENTOS	Availability, Authenticity	Falsification; Replay;	Two Network Models
	[108]	2018	Plexe	Authenticity	Falsification	Proof of Location Scheme
	[109]	2018	Plexe	Availability, Confidentiality Authenticity	Spoofing; DoS Falsification; Burst Transmission;	Collaborative control strategy
LTE C-V2V	[110]	2020	Plexe	Availability, Confidentiality Authenticity	Falsification; DoS Man in the Middle	-

a series of challenges for PLS in vehicular communications, proposing a case study based on the coexistence of hybrid technologies. Finally, [98] applies a reconfigurable intelligent surface (RIS) in the PLS, proving that the PLS secrecy is affected by the number of RIS cells and their location. However, none of these works analyze the specific case of platooning and the consequences or applications of these techniques to Co-VP systems.

Considering that the most accepted standards for vehicular communication are based on IEEE 802.11p and LTE-V2X, the authors of [94,100,110] carry out an analysis of the vulnerabilities of these technologies to cyber-attacks. Still, only the work presented in [110] analyzes the use case of Co-VP applications using the LTE-V2X standard. Furthermore, this scenario analyzes attacks from an RSU, a vehicle, and two agents simultaneously. Thus, the impacts caused by PDR, inter-vehicle distance, and speed change during attacks are studied.

An improvement for RSU's security, based on the Internet of Things project called SerIOT, is proposed in [99]. This solution implements a monitor for RSU, connecting them to the SerIOT Software Defined Network (SDN). In this way, as the outgoing information for the RSU is monitored, any anomalies can be detected. Furthermore, this solution also implements a honeypot to detect malicious vehicles. However, this work does not evaluate this solution's impacts and actual gain in a Co-VP-relevant scenario.

5.2. Co-VP Stability under Security Attacks

A quantitative analysis of the platooning stability under security attack is performed in [9]. The authors investigate the risks of a cyber-attack on the stability of platooning, also analyzing countermeasures and their weaknesses. Finally, the authors proposed a system to detect attacks such as message falsification and jamming, through observation of previous values or voting, based on information provided by various vehicles. In jamming detection, the procedure adopted is similar to that seen in detecting a degraded network with platooning output.

A Denial of Service (DoS) attack provided by jamming is studied in [106]. In this case, a restricted attack between two consecutive vehicles is performed, and a secure distributed nonlinear MPC algorithm detects and mitigates the attack using local sensors and previous information, keeping the platooning stable. An alternative solution for the attack problem in Co-VP systems is proposed in [107], using the IEEE 802.11p and the Visible Light Communication (VLC) solution. Furthermore, the authors compare the speed error in the platooning over a packet falsification and a replay attack in a scenario with just the DSRC communication and another with both communication models. Although both situations present errors, the one with both communication modules suffers less oscillation within the attacks.

In [104], a Bias injection Attack is used to cause a slowly time-varying attack signal in a predecessor-follower platoon and on a bidirectional platooning. The authors proposed an attacker-detector game based on a centralized detector that defines the best vehicles to add a sensor and detect the attack. In this scenario, the bidirectional data in the Co-VP application increase the system's security. This work is extended in [103] with a scalable number of vehicles. The authors of [108] propose several reactions to mitigate a position falsification attack using a proof location scheme. This work also demonstrates a solution to avoid collisions by detecting false messages.

The authors of [101] presented a distributed attack detection mechanism, where each vehicle has its detection system, estimating the local leader position and evaluating the received information. They also propose two recovery methods based on the state estimation of the system. The distributed Co-VP controller is also evaluated over an adversarial environment with the DoS attack [102], where the delay limits are estimated to determine the platooning safety.

In a more general scenario, the authors of [109] propose a distributed collaborative strategy to avoid longitudinal instability in the platoon formation under an adversarial environment. This strategy is evaluated using Plexe against Spoofing, Message Falsification, DoS, and Burst Transmission. In addition, this algorithm uses a Vote Strategy based on other vehicles' information to detect and mitigate an anomaly.

One tool commonly used for security issues in communications is blockchain. However, its application in Co-VP systems is still in its early stages, with few implementations. For example, the work in [111,112] presents an overview of blockchain-based cybersecurity mechanisms and their performance. These works show applications related to vehicular communications but not applied to a specific model, such as Co-VP. Thus, they present a guide for future applications, but mostly without immediate application.

Blockchain is viewed as a significant tool for accrediting platoon members. The research described in [113] employs a pre-established blockchain to establish the platoon, ensuring the application's security but necessitating prior knowledge between the vehicles. In [114], the authors suggest utilizing a PoW-based blockchain between RSUs and a previously defined blockchain network between vehicles. The former handles vehicle trust, reputation management, and ITS-related services, while the latter is used for collaborative decision-making and leader election. Although an experimental analysis is provided in this second scenario, it is not conducted using practical simulators.

All of the works cited allow us to observe the safety impacts of Co-VP applications under a cyber-security attack scenario. However, there is still much space to explore since the types of attacks can vary, and the control conditions can also be the most diverse. Also, it is possible to observe that no testbeds are focused on this type of validation, which means that it is difficult to evaluate the impacts of some of the proposed solutions in a CO-VP system, particularly considering the imposed constraints, and thoroughly assess their benefits. Therefore, validation tools are critical to carrying out this kind of evaluation, mainly if they support a more accurate representation of the Co-VP scenario in all its inter-dependencies.

6. Validation Tools

The complexity of Co-CPS implies the need for extensive validation support tools to test the most diverse conditions to which the devices may be subjected during their operation to synthesize the real world. Such tools make it possible to understand the safety limits of these devices and their applications, reducing costs, development time, and risks of carrying out immature tests in the real world. Therefore, Co-VP tests should be performed to analyze possible failures in specification, design, and implementation over the several project components [115]. The authors of [27] enunciate several V2X testing methods and describe their main focus and a few standards. For instance, the latency and reliability of V2X should be tested with function, performance, and communication conformance testing. In addition, application vulnerabilities and security risks can be mitigated with security penetration and accelerated testing. Finally, after the V2X validation with *in-lab* testing, the field tests should evaluate the

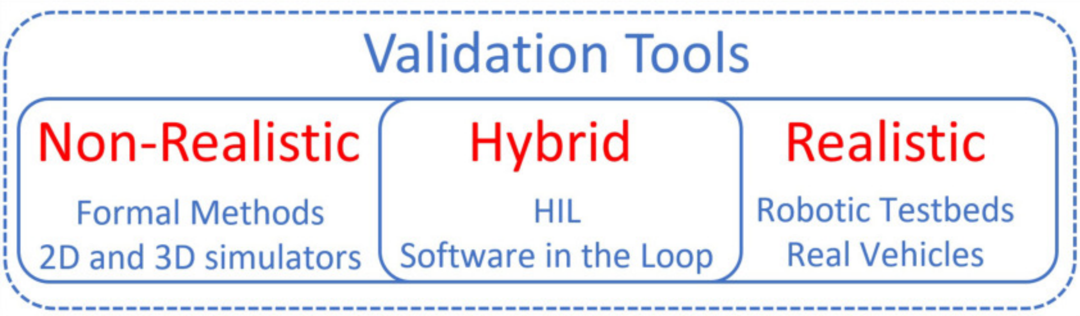

Figure 7. validation tools general view

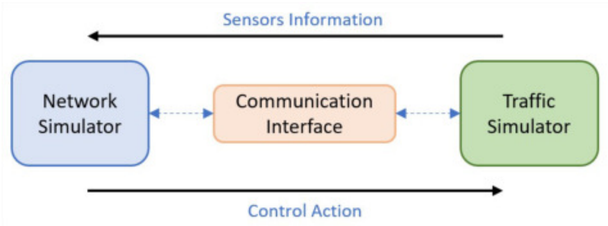

Figure 8. Simulation General Architecture

V2X application's performance and function requirements in a real environment.

As previously stated in Section 2, Co-VP validation strategies can be divided into *simulation*, *real experimentation*, *formal verification*, and *testing*, as illustrated in Figure 7. Such validation strategies allow for analyzing a system or algorithm's behavior in several situations under defined performance criteria. This section will focus primarily on *simulation* and *real experimentation* validation tools, with a very brief description of the other methods.

The formal foundation, used in *Formal verification*, is an essential tool to check the system's correctness using an accurate model description. Formal validation can be divided into model checking, theorem proving, and handwritten proofs. This validation method provides a way to avoid errors and evaluate the system behavior at design time, long before the implementation, by specifying the system properties to be analyzed with an agnostic approach to the scenarios and checking their correctness. The *Testing* validation process consists of executing a system model to detect errors that can cause software failure [28].

6.1. Simulation

Simulative verification is a widely adopted validation approach for Co-VP applications due to the challenges and expenses involved in implementing a real large-scale environment with CAVs and supporting communication infrastructures. This approach involves the creation of a simulated environment that closely mimics the system's behavior and external conditions. Simulated scenarios offer a controlled and replicable environment that provides extensive testing fields. However, the increasing costs, complexity, and safety risks associated with actual vehicle deployments necessitate even more realistic simulation-based verification tools. These tools must help bridge the gap between development and real-world deployment. Specifically, they must accu-

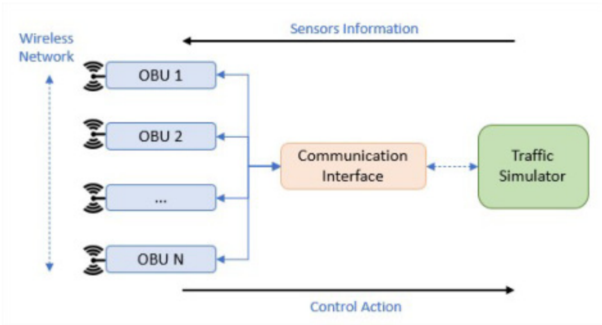

Figure 9. HIL General Architecture

rately mimic real-life scenarios from both the autonomous driving or control and communications perspective, as both perspectives are highly interdependent. Therefore, comprehensive simulation tools must integrate traffic mobility and control simulators with network simulators. Ideally, they should support direct validation of developed modules.

6.1.1. Traffic and Network Simulators

Traffic mobility simulators can be classified into macroscopic or microscopic simulation models, considering the traffic flow granularity and the vehicle's properties. An extensive review of these simulators is presented in [116], where the most famous ones are Gazebo [117], a time-driven robotic simulator that provides support for multiple physics engines with ROS (Robot Operating System) integration, Carla [118], also a time-driven simulator specifically designed for autonomous driving research based on Unreal Engine, and SUMO [119], an event-driven platform for traffic simulation with support for a large number of vehicles and with a powerful integrating interface called TraCi. Network simulators model and test the network performance with different protocols, from the physical to the application layer. Regarding their V2X model support, the most popular ones are the discrete-event simulators NS-3 and OMNET++. The first has an 802.11p MAC entity and IEEE 1609 standards implemented, while the second one has an ITS-G5 implementation based on Artery project [120].

At present, various simulation frameworks aim to facilitate the integration of traffic mobility simulators and network simulators for assessing ITS. However, the accuracy of Co-VP simulation heavily relies on the seamless integration of simulators. Figure 8 provides an overview of this architecture, and Table 7 summarizes all the frameworks mentioned in this context. We categorized the simulators into 2D and 3D simulators. Although 3D simulators offer a more precise and realistic representation of sensors, vehicles, environment, and Co-VP conditions, including better visualization, 2D simulators are more lightweight regarding computing resources, facilitating greater simulation analysis scalability.

6.1.2. 2D Co-VP Frameworks:

2D traffic simulators are the most common basis for vehicular simulations and, by extension, for Co-VP frameworks. Such systems tend to simplify the interactions between objects, generally neglecting some physical aspects, usually referring to the lateral movements of the vehicles. However, they are simulators capable of representing

Table 7. Summary of Simulation Frameworks for Co-VP

Simulator Type	Cite	Year	Framework	Traffic Simulator	Network Simulator	Network Model
2D Co-VP Framework	[121]	2019	VTI's	SUMO	OMNET++	DSRC/WAVE
	[120]	2015	Artery	SUMO	OMNET++	ITS-G5, LTE-V2V
	[122]	2019	Artery	SUMO	OMNET++	LTE-V2V
	[123]	2019	Artery	SUMO	OMNET++	ITS-G5
	[124]	2013	iTetris	SUMO	NS-3	-
	[125]	2014	Plexe	SUMO	OMNET++	DSRC/WAVE
	[126]	2016	Plexe	SUMO	OMNET++	DSRC/WAVE
	[87]	2018	Plexe	SUMO	OMNET++	ITS-G5
	[127]	2019	Plexe	SUMO	OMNET++	ITS-G5
	[119]	2018	SUMO	SUMO	-	IEEE 802.11p
	[88]	2018	SUMO + NS-3	SUMO	NS-3	LTE-V2V
	[128]	2019	Veins	SUMO	OMNET++	DSRC/WAVE
	[105]	2015	Ventos	SUMO	OMNET++	DSRC/WAVE
	[129]	2017	VSimRti	SUMO	NS-3	DSRC/WAVE
	[130]	2011	VSimRti	SUMO; PHABMACS	NS-3; OMNET++	DSRC/WAVE
3D Co-VP Framework	[118]	2017	-	Carla	-	IEEE 802.11p
	[131]	2019	-	Carla	-	IEEE 802.11p
	[132]	2020	-	Carla	-	IEEE 802.11p
	[133]	2021	Copadrive	Gazebo	Artery and OMNET++	ITS-G5
	[134]	2017	-	Webots	NS-3	DSRC/WAVE
	[14]	2017	-	Webots	-	ITS-G5
	[135]	2017	-	Webots	-	ITS-G5
Co-VP Potential Framework	[136]	2020	-	Webots and SUMO	OMNET++	DSRC/WAVE; LTE-V
	[137]	2016	Acceleration Framework	Acceleration Model	NS-3	DSRC/WAVE
	[138]	2019	QoS-CITS	-	-	TCP/UDP
	[139]	2019	Matlab	Simulink	Matlab	DSRC/WAVE

large-scale systems with lower computational costs without great graphic demands. Some examples include iTETRIS [124], which integrates SUMO and NS-3, but, despite the project potential, it is no longer active, and there is no available support for new developments.

The VSimRTI [130] uses an ambassador concept to support the integration of virtually any simulator. Different traffic and network simulators have already been integrated, such as SUMO, PHABMACS, NS-3, and OMNeT++. The authors of [129] present a Platooning Management Protocol (PMP) using VSimRT with Sumo and NS-3. This work tested the required maneuvers and proper communication behaviors with NS-3 configuration similar to ITS-G5 standards based on IEEE 802.11p.

Veins is an open-source CAV framework [128] that combines SUMO and Omnet++ in a bi-directional coupling, allowing for online simulations. Veins extends OMNeT++ by incorporating a communication stack based on IEEE 802.11p, creating a network node in OMNET++ for all the vehicular nodes in SUMO. The traffic and network simulation frameworks are connected through the TraCI interface. Furthermore, Plexe [125] is a Co-VP extension of Veins that supports platooning applications and CACC with various cruise control models. The longitudinal controller uses a linear acceleration control method, while a simplified transversal control method (i.e., steering) is utilized to switch lanes and execute Co-VP dynamics correctly. In [126], the authors used Plexe with a consensus-based controller for the Co-VP application, which focuses on the effects of poor vehicular communication. The IEEE 802.11p stack with beaconing distribution, similar to WAVE 1609.4, was used in this study. Additionally, [87] demonstrates how even minor changes in the configuration of ITS-G5 communications can impact safety performance and time-critical C-ITS applications. The authors implemented ETSI standards regarding the CAM messages with 3 DCC configurations. Finally, [127] compares DCC-3 against STB (no congestion control mechanism), DynB, LIMERIC, and DCC-7 using Plexe. This study benchmarks these models regarding CBR, Inter-Reception Time (IRT), Fairness, and Safe Time Ratio.

The integration of Plexe with the VTI driving simulation software is described in [121], resulting in a VTI driving simulator with various CACC use cases, including platooning and human drivers. This work identifies several challenges for the Plexe simulation, such as the difficulty of adding an HDV and the inability to switch from cooperative to autonomous driving mode. The lateral controller in SUMO is also a limitation, as it does not represent real-world scenarios due to instantaneous lane changes.

Ventos is another simulation framework that couples Sumo and OMNET++. Its primary purpose is to analyze vehicular traffic flow and develop new control logic, such as self-driving and collaborative driving while supporting V2V and V2I communication using DSRC. In [105], VENTOS was used to test a PMP algorithm by merging V2V communication with radar measurements, with WSMP carrying beacon and micro-command messages based on IEEE 1609.4. The framework has also been utilized in studies on connected vehicle security [107] and dynamic traffic routing [140].

Given the NS-3 high flexibility, the authors of [88] developed an integrated platform that combines SUMO and a modified version of NS-3 with the V2V transmission capability, according to LTE-V2V specification. They compared several platooning systems using network metrics, like end-to-end throughput and delay profiles. This work adjusted the frame structure, channel modeling, and performance evaluation to reproduce LTE-V2V standards.

Artery [120], integrates Veins and the Vanetza ITS-G5 [141] implementation. The Vanetza provides generic ITS-G5 networking features, operating as an Application Layer to Veins. In this way, the Artery extends Veins, incorporating ETSI ITS-G5 standard protocol stack. This framework also integrates SUMO and OMNET++, but with the possibility to analyze the behavior of vehicles with different capabilities, like different sets of VANET applications. The Artery's core works on top of Vanetza with a configurable set of VANET applications. The current Artery version [122] has released a new model that does not extends Veins. In this model, the physical and MAC layers are provided by INET instead of Veins. This modification opened a new set of variations that allows the implementation of different stacks, like LTE-V2X, as presented in [122].

6.1.3. 3D Co-VP Frameworks:

The need to better mimic reality in a simulated environment of CO-VP systems has been rising, given the necessity of closing the gap between the validation and actual implementation. In this context, 3D frameworks have gained ground in vehicle simulations, which naturally expanded their horizons for Co-VP applications. These simulators allow analyzing the details of the systems in a microscopic view, including the differences in heights, weight, and even interaction between objects and sensors. In this way, the simulations become more realistic, better representing the application scenario.

For instance, a novel Co-VP simulator framework was presented in [133], where the authors integrated Gazebo with OMNeT++ by extending Artery. They joined the Gazebo support for multiple physics engines with OMNET++ capabilities and Artery ITS-G5 basis to implement a microscopic simulator to represent realistic Co-VP scenarios. For instance, unlike other frameworks, this one allows the analysis of the lateral controller of the vehicles regarding heading and steering angles. Furthermore, the integration between Gazebo and OMNET is provided by Robot Operating System (ROS) through a publish/subscribe method using topics.

Other robot simulators, like Carla, are available to support this kind of simulation. Although the Carla simulator has a high engine power and ROS integration possibility, to the best of our knowledge, there is no literature about this traffic simulator as a part of a Co-VP framework integrated with a network simulator. In [131], and [132], the Carla simulator was used to study, respectively, the Co-VP overtaking behavior in a two-lane highway and to implement a decentralized novel model-free controller for platooning. However, the communication was not simulated in both works using a realistic network protocol.

Another prominent robot simulator is Webots [142]. Webots was originally designed as a research tool to investigate mobile robots' control algorithms, and since 2018, it has become an open-source project. Several microscopic vehicular models and possible integration tools have been used within a large physical background. This simulator has been used in some Co-VP frameworks, allowing multiple studies. For instance, in [134], the authors integrated Webots and NS-3 to demonstrate the capabilities of the simulation tool, using an ideal and realistic communication channel but with no proper stack model. In [135], and [14], the Co-VP performance was evaluated under several conditions, revealing its weakness in real scenarios, like normal and degraded network models, speed changing, and full brake. Given the vehicular model, the Webots allows the analysis of longitudinal and lateral controller models. Nevertheless, there is no integration with a network simulator in those works.

6.1.4. Generic Simulators

In addition to the frameworks presented so far, other validation frameworks featuring vehicle control integrated with communication systems have great potential for validating Co-VP systems. In this subsection, we analyze some of these applications that may be modified, adding functionality to validating Co-VP scenarios.

In [136], the authors designed a framework that integrates Webots, SUMO, and OMNET++ using a client/server model. In this application, the SUMO is the Server, providing traffic demand and representing a 2D system. The Webots allow a 3D visualization and provide the CAVs control, while the OMNET++ provides the V2X structure - using 802.11p or LTE-V communication. This implementation introduces multiple human driving simulators in the CAVs scenario.

The authors of [137] developed a potential Co-VP simulator called *Acceleration Framework* that consists of a self-built microscopic traffic simulator integrated with NS-3. This traffic simulator contains an *acceleration model* that recognizes different approaches for regular, connected, and autonomous vehicles and a *Lane-Changing Model* that captures the effects of additional information on lane-changing behavior in a connected driving environment, using a game-theoretical approach. In addition, this simulator allows for V2I and V2V analysis. However, this framework has not yet been addressing Co-VP-specific applications.

The framework developed in [138], called *QoS-CITS*, is oriented to Quality of Service (QoS) analysis in CAVs, by looking into throughput, safety, and fuel consumption. This simulator also analyzes aspects such as how long one vehicle is delayed when it travels along its planned trajectory and how the neighboring vehicles could impact the desired path plan. The CAVs communication is provided by the X2X Sim module, which simulates TCP/UDP protocols, simulating wireless communication. Although this framework can potentially be used in Co-VP validation, it does not implement V2X standard communication.

The Matlab/Simulink also powers up several Co-VP analyses and simulators. For example, in [139], the authors designed a bit-accurate simulation environment for vehicular networks using the MATLAB discrete event system (DES). The authors use an *integrated simulator* containing traffic and network simulators. The developed network simulator contains a DSRC/WAVE implementation with a precise representation of the PHY layer compared to the NS-3 implementation. The authors have a better computational cost within this simulator regarding events and show a more realistic packet success rate (PSR) than NS-3. However, this simulator has not been tested in Co-VP applications, and its vehicle movement model is still restricted.

6.2. Experimentation Tools

Simulator frameworks are essential in validating Co-VP systems, given their flexibility, scalability, and reduced cost. However, testing on real platforms is the most important step in development since simulators cannot encompass all the real-world dynamics, imperfections, and constraints, no matter how accurate they are. Nevertheless, given the costs and complexity of Co-CPS and Co-VP applications, their large-scale implementation over accurate models is quite complicated. In this way, such validations can often be divided into two stages to reduce costs and allow the analysis of each system component in a modular way. These two steps are defined as Hardware in the loop (HIL) simulations and experimental Testbeds. This section will introduce these tools, dividing HILs into those that have or do not have Co-VP implementations, while the Testbeds are separated into more generic examples and Co-VP implementations with non-standard vehicular network communication and the ones with some ITS network. All the quoted HIL implementations are summarized in Tab. 8, while the Robotic Testbeds are presented in Tab. 9.

6.2.1. HIL Generic Implementations

HIL testing is frequently used in car manufacturing, as it provides a well-defined environment for the device under test (DUT) typically used for testing complex physical systems and processes. Compared to real field tests, it is less expensive, and the results are much easier to replicate [143]. The HIL approach also allows the experimentation and analysis of a specific component in the Co-VP analysis, like the OBUs, RSUs, or the real-time vehicle response. Figure 9 presents the general HIL architecture for Co-VP scenarios, encompassing bidirectional information flow between the physical and virtual subsystems. In this architecture, HIL flexibility allows physical test vehicles to interact with virtual vehicles from traffic simulation models, increasing validation scalability and reducing costs [144]. Another advantage of HIL testing is evaluating safety-critical systems and features that generally operate in highly variable environ-

Table 8. Summary of CACC HIL Platforms

Co-VP	Cite	Year	Framework	Controller Model	Network Standard	Objective
No	[147]	2017	-	-	ITS-G5	DCC models
	[146]	2017	PaTAVTT	Longitudinal and Lateral	802.11ac	U-Turn
	[143]	2018	OMNET++ Artery	-	ITS-G5	Network Performance
	[144]	2018	CACC HIL	Simple Mobility	DSRC	Traffic Simulator
	[148]	2018	-	Stop-and-go Re-routing Process	ITS-G5	V2V and V2I test
	[149]	2019	VENTOS-HIL	Longitudinal	DSRC	Emergency Electronic Brake
	[150]	2019	Vissim	Longitudinal	DSRC	Fuel consumption and emissions control
Yes	[151]	2014	LabView	Longitudinal Platoon Maneuvres	3G cellular network	Co-VP Controller
	[72]	2018	-	Longitudinal	Abstract network model	Longitudinal String stability
	[86]	2019	PCA Framework	Longitudinal	ITS-G5	TRC impact
	[74]	2020	OSU-ADL -CAV HIL	Longitudinal	DSRC	Distributed Co-VP Controller
	[152]	2020	Carla	Longitudinal	LTE V2X	parallel communication framework
	[133,153]	2019	Copadrive	Longitudinal and Lateral	ITS-G5	RTM and CLW evaluation

ments in a controlled and limited environment. It also allows the parallel development of different system components on time [145].

For instance, the PaTAVTT is a HIL testing platform that performs trajectory tracking of CAVs [146]. In this work, the authors validated the algorithm model and control strategies in Carsim/Simulink and then migrated it to the HIL platform. In the HIL platform, the vehicles communicate with the central network node using the 802.11ac (Wi-Fi) standard and evaluate the performance of several *U-turn* movements. This platform allows the implementation of Co-VP applications, like following, lane changing, and overtaking, but none of them is presented in this work. The Wi-Fi communication network limits the comparison with other Co-VP scenarios, given the differences with IEEE 802.11p.

In [150], a HIL testbed is described, which enables the evaluation of CAV performance with about 1% error in fuel consumption, emulating an actual vehicle using the VISSIM simulator. The testbed involves V2V and V2I communication using the DSRC/WAVE stack and Cellular Network. A similar configuration using VISSIM and simulated DSRC/WAVE communication in conjunction with a physical vehicle was used in [144]. This HIL testbed allows for the testing of vehicle connectivity and automation functions under different virtual conditions and the evaluation of critical hardware and software components in CAV platforms. Additionally, the simulation incorporates DSRC latency and packet loss to estimate real-time communication.

The VENTOS framework is extended in [149] with HIL support (VENTOS-HIL). In this implementation, real OBUs/RSUs are connected to VENTOS, and for each physical device, there is a corresponding virtual OBU or RSU, allowing all the actions on the physical devices to reflect on the simulation itself and vice versa. The adopted network standard is the DSRC/WAVE. The HIL capabilities were analyzed using an emergency brake scenario, showing the extended simulator capabilities.

In [148], a HIL Simulation Framework for evaluation and fast prototype of CAV's applications was developed using SUMO as the traffic simulator. The authors claim that the implemented HIL structure is cost-efficient and easily configurable to allow several CAV tests. In this work, an *Orchestrator* was designed to be a systems manager, integrating the SUMO with the attached real HW-based OBU/RSU devices. Each one of these devices has an *gpsfake* instance, producing essential location data required by the HW/SW V2X protocol stack. The Orchestrator and the remaining modules use TCP sockets, while the V2X communication uses the ITS-G5 standard. In this HIL implementation, the user can create several scenarios but is limited to SUMO and TraCI capabilities. The HIL capabilities were evaluated in a scenario where V2X communication should support dynamic re-routing of a vehicle in a congested traffic area.

The HIL approach can also evaluate specific network conditions or components. For instance, in [147], experimental validation of ETSI DCC models was proposed. This work studied the unfairness and oscillation issues of DCC implementation and analyzed the process stability of the DCC mechanism under different network conditions and CAM parameters. However, although an actual OBU device was used, there where no mobility in the simulation. In [143], a reactive HIL simulation was implemented with a simulated scenario using OMNeT++ and the real-time 802.11p Over the Air (OTA) proxy. The V2V evaluation tests perform the communication analysis of one simulated *physical twin*, representing the vehicle able to distribute the received messages to/from surrounding simulated vehicles.

6.2.2. Co-VP HIL Implementations

The HIL flexibility allows different Co-VP evaluation analyses. For instance, the authors of [151] presented a Co-VP PMP strategy validation using HIL, built over a decentralized controller model, where each vehicle in the simulation has an OBU, collects the primary data, and forwards them to a central manager that stores and reorganizes the vehicles. These OBUs communicate through the 3G cellular network, suffering from several delays caused by the centralized communication strategy.

The work presented in [72] enables the Co-VP evaluation performance based on stability and risk-of-collision analysis. Extensive simulation using real-world vehicle parameters can examine longitudinal controllers' specifications and network characteristics, allowing the observation of platooning performance boundaries caused by network constraints and control system definitions. However, the network communication model was assumed as abstract and straightforward, with no communication protocol stack, using the IEEE 802.15.4 standard in the 2.4 GHz band, while the vehicle dynamics are simulated with Matlab. Extending the network constraints analyses, the impact of Transmission Rate Control (TRC) over a Co-VP scenario based on industrial V2X nodes operating in the ITS-G5 channels is the main focus of [86]. It evaluates simulated vehicles' longitudinal distance in congested scenarios, changing the message's frequency, based on a four OBUs vehicle simulation with data logging over the Matlab Software.

The authors of [74] implemented a HIL test platform using the Carsim/Simulink vehicle simulator integrated with real DSRC modems. This HIL enabled a realistic evaluation of a Co-VP model's parameter selection method based on a feedforward controller within a stable string boundary. Furthermore, this platform also evaluates the impact of dropout and communication time delay in the Co-VP longitudinal string stability.

An LTE C-V2X[154] HIL implementation was presented in [152]. Although this work is still under development, the authors already presented an exciting platform, based on the CARLA simulator, integrated with SUMO and direct communication between the simulated vehicles through C-V2X Mode 4 modules. This platform implements a Software-Defined-Radio (SDR) based on three radio devices that mimic three real vehicles. Several Co-VP controller models can be evaluated in future HIL implementation developments based on SUMO implementation.

An extension of the Copadrive simulator to a HIL platform was presented in [153]. In this work, the authors integrate the Gazebo with ITS-G5 OBUs to evaluate the impact of several message frequencies in the Co-VP controller. This HIL implementation also introduces critical safety tools evaluations, using a Run Time monitor (RTM) and a Control Loss Warning (CLW) to increase the Co-VP safety. Finally, this implementation allows the lateral vehicle controller evaluation and longitudinal analysis.

6.2.3. Generic Robotic Testbeds

The importance of HIL implementation cannot be denied, as it can aid in developing a considerable portion of the system. However, certain restrictions exist, such as the inability to evaluate vehicle components. To bridge the gap between simulation-based approaches and full vehicle deployments, robotic testbeds emerge as a promising solution. These testbeds can integrate with various platforms to be deployed in real vehicles and can also be used in controlled environments, providing a partial replication of a realistic scenario at a fraction of the cost of an actual vehicle, as discussed in [155].

Several testbeds have been developed to evaluate autonomous vehicles, but they have limitations regarding Co-VP analysis. For example, the authors of [156] developed a low-cost testbed that can be implemented in different vehicle models to test different control algorithms for autonomous trajectory following. However, this testbed lacks V2X communications support and uses onboard sensors for platooning testing. Two other testbeds for platooning that do not support V2V communication are presented in [158] and [157]. The latter uses the HoTDeC hovercraft, which provides greater flexibility but has significantly different vehicle dynamics from a traditional car.

6.2.4. Co-VP Robotic Testbeds with General Network Communication

There are different equipment combinations for implementing a testbed aimed at Co-VP applications. Thus, some use communications do not follow a commonly used vehicular pattern, often focusing on control issues or validating specific algorithms. For instance, the testbed developed in [159] allows the Co-VP analysis using vehicles on a scale of 1:10 for passenger cars and 1:14 for trucks. This testbed allows implementing of different control strategies for several autonomous driving applications and even platooning. In addition, a CACC controller with a predecessor-follower IFT was implemented in the Co-VP experiment, using UDP messages over a WiFi standard. This testbed allows longitudinal and lateral platoon control.

The Arizona State University researchers presented the VC-bots testbed [160], designed to create an open platform for research experiments and education services on

Table 9. Summary of Platooning Robotic Testbeds

Co-VP Implementation	Cite	Year	Framework	Implementation	Network Standard
Potential Application	[156]	2018	Autonomous Car	Lidar System	-
	[157]	2017	HoTDeC Hovercrafts	Vision System	-
	[158]	2019	Cheap Controller Unitis	Lidar System	-
Generic Networks	[159]	2019	Small scale vehicles	CACC with PF	
	[160]	2016	VC-Bots	PF model with platoon maneuvres	WIFi
	[161]	2017	VC-Bots	PF model with platoon maneuvres	WIFi
	[162]	2018	Zynq/SoC	FPGA Based with Cooperative Sensing and Information Interaction	Zigbee modules
	[163]	2020	WiFiBot ARV	PF	IEEE 812.15.4
	[164]	2020	Remotely Accessible Cars	PF with variable controller models	Centralized WiFi
	[165]	2017	Autonomous Car	ACC	5G emulation
ITS Networks	[166]	2020	Low cost testbed	LF, PF and LPF	Simplified DSRC
	[167]	2020	Carma	Cooperative Driving Automation (CDA) with ROS Topics	DSRC
	[168]	2019	Drive-by-Wire electric vehicle	Linear feedforward longitudinal controller and MPC lateral controller	DSRC
	[81]	2017	Toyota Prius III Executive	Event triggered	ETSI ITS-G5
	[133,155]	2020	RoboCoPlat	PF with PID	ETSI ITS-G5

VANET, vehicular cloud computing infrastructures, and future intelligent vehicle applications. The VC-bots testbed consists of robotic platforms configured to simulate various car models, providing a flexible platform for developing different cooperative platooning strategies [161]. However, the V2V communication in the testbed relies on WiFi networking, and the control systems are separated for the longitudinal and lateral control. The longitudinal controller uses V2V communication, while the lateral controller employs a camera vision algorithm.

Some testbeds rely on exceptional communication standards to implement Co-VP applications. For example, in [162], a Zigbee communication module is implemented in each vehicle to provide V2V communication. This testbed uses an FPGA as the vehicle's mainboard and applies cooperative sensing and information interaction between the vehicles to control the platoon's stability. In addition, the ZigBee module on the leader vehicle works as a coordinator node to supervise the whole network.

Co-CPS cybersecurity can also be analyzed through Co-VP testbeds, as presented in [163]. A platooning testbed was built with WIFIBOT autonomous robotic vehicles in this work, using the IEEE 812.15.4 standard for V2V communication. This work introduces a cooperative secret key agreement called CoopKey, a scheme for encrypting/decrypting the control messages. The algorithm's efficiency is evaluated regarding the longitudinal distance of the platooning members.

A cyber-physical testbed for wireless networked control systems is presented in [164]. The author proposes a testbed composed of *Remotely Accessible Cars (RAC)* that uses a Wireless LAN as a communication link. Each vehicle has several sensors to detect a line in the track and send it to a central node. This node analyses the vehicle's data, like position and speed, and sends back the vehicles' commands to guarantee Co-VP stability. In this testbed, three controllers are evaluated with a predecessor-follower IFT: PID, Linear Quadratic, and MPC. However, the centralized approach does not attend to the requisites for a high-demand Co-VP network application with a high delay.

The authors of [165] created a system that uses 5G ultra-reliable and low-latency communications (uRLLC) emulation to implement vehicular cooperative demands. The primary aim of this project was to develop a V2X communication platform with a small frame structure, quick real-time processing, and flexible synchronization. The system was tested in an autonomous vehicle to evaluate cooperative driving scenarios such as semi-simultaneous emergency brakes. However, it is important to note that this testbed focuses on the communication platform and does not consider the potential effects on a cooperative controller.

6.2.5. Co-VP Robotic Testbeds with ITS Network Communication:

A low-cost robotic testbed is presented in [166]. This testbed presents a flexible IFT to evaluate a Co-VP emergency brake situation under communication losses. The Co-VP analysis can be performed with a Leader-Follower, Predecessor-Follower, and Leader Predecessor-Follower IFTs and different communication loss parameters, using TDMA communication over a simplified DSRC standard. Furthermore, as the vehicles have a low cost, the testbed can quickly escalate, respecting the radios' communication ranges for different IFT conditions.

An important robot testbed for testing Co-VP applications has been developed in the CARMA [167] project. The CARMA project is an initiative led by the Federal Highway Administration (FHWA) to enable Cooperative Driving Automation (CDA) research and development. This initiative includes cloud-based transportation systems and a vehicle-based platform for automated vehicles to share data and intent with other vehicles and infrastructure to enable cooperative actions. The CARMA evaluation tools include an open-source simulation environment built on CARMA and SUMO and the development of a scaled testbed with hardware for autonomous driving. The CARMA controller model uses the ROS as the main publish and subscribe method to integrate most project components, with the DSRC standard as the communication protocol. The Co-VP implementation, with string stability and platoon maneuvers, was planned for October 2021.

The longitudinal and lateral control separation was also used in the testbed control implemented in [168]. In this testbed, the Co-VP controller does not rely on a high-accuracy positioning system or V2I information. Nevertheless, the Co-VP controller uses V2V communication and a low-cost onboard millimeter-wave radar sensor. The preceding vehicle's information, like acceleration, heading, and yaw rate, is sent to the following vehicle through wireless communication while the radar calculates the inter-vehicle distance and velocity difference. A drive-by-wire electric vehicle was the testbed model, using OBUs with DSRC standards to implement V2V communication.

Just a few testbeds in the literature have already implemented the ITS-G5 standard. For instance, the testbed presented in [81] includes a three vehicles platoon to validate an event-triggered control scheme and communication strategy experimentally to guarantee an L2 Co-VP string-stability. The Toyota Prius III Executive is the testbed vehicle model with ETSI ITS-G5 OBUs for V2V communication. However, as this testbed uses real vehicles, the scalability is significantly compromised, restricting the possible tests and reducing the system's flexibility. In addition, the authors only investigate the system's time response for vehicles' longitudinal speed and acceleration in this work, avoiding the vehicle lateral controller analysis. To increase the scalability, the work presented in [155] introduced a 1:10 testbed called RoboCoplat. This testbed is an extension of CopaDrive, allowing the analysis of the simulated Co-VP algorithms in a realistic platform, using embedded OBUs to communicate through ITS-G5.

Given the advantages and limitations of each validation platform for Co-VP systems, there is no one-size-fits-all solution for their development, testing, and validation. Hence, the best approach is to employ multiple testing and validation tools that cater to each stage of the development process and incorporate different technologies. However, the absence of integration among various validation platforms can significantly prolong the development time of Co-CPS systems. Additionally, it is undesirable to expend effort repeatedly integrating system components with validation platforms that are ultimately discarded due to significant differences between test environments and the prototype system.

In this line, efforts such as [133] tried to bridge this gap by providing Co-VP development and validation frameworks that rely on fixed and flexible middleware architectures such as ROS. In this work, the authors used ROS as an enabler and integrator to support the development and validation of Co-VP continuously, covering 3D simulation, e.g., via the COPADRIVE framework, HiL, and small-scale robotic testbeds to ease this process. The objective was to reuse software components as much as possible while enabling their validation throughout development.

7. Conclusions and Open Challenges

This survey has led to various conclusions and potential research avenues, which we summarize in this section. We aimed to achieve a multidisciplinary perspective to provide a comprehensive understanding and development of Co-VP applications. Therefore, we have identified several challenges for each topic, which are briefly summarized in the following paragraphs. These challenges highlight the complexities and limitations of Co-VP systems and emphasize the need for further research and development to ensure their safety and reliability.

Control The methods of control for Co-VP systems are varied, although there is a tendency towards simplified PIDs, different versions of the MPC system, and robust control applications. However, the selection of a controller directly impacts the system's complexity of implementation and the potential for errors, particularly with time constraints. Additionally, some theoretical solutions do not account for handling errors arising from actual control processes, including network delays or the inherent uncertainties of mechanical systems, significantly limiting their use in practice.

Another challenge facing Co-VP controller methods is managing mixed traffic, which includes HDV, ACC, and Co-VP. Additionally, ensuring safe interaction with the environment and various agents is crucial in a practical Co-VP implementation. This interaction directly affects Co-VP controller models that must strike a balance between responsiveness and complexity while ensuring the system's safety.

Co-VP Communications The configuration of network parameters has a significant impact on the safe execution of planned activities in Co-VP systems. However, testing the limits of these communication models while considering the implemented controller systems is a challenging task, as traditional validation tools may not be realistic enough. Additionally, the scalability of these analyses is also a major challenge for real-world implementation, given the large number of critical scenarios and possible failures. Therefore, it is essential to analyze these scenarios thoroughly to minimize the risk to the agents.

On the bright side, the increasing computational capacity of embedded systems creates new opportunities for implementing more advanced techniques and models. For instance, with the latest devices, it is now feasible to implement more complex control techniques or even artificial intelligence models that can reduce errors and potentially prove more reliable under critical scenarios.

Cybersecurity in Co-VP The amount of work on cybersecurity for Co-VP systems is still short, as most of the research in the areas refers specifically to cybersecurity problems in vehicular systems, not addressing this SoS. Thus, analyzing the impacts of security threats on the performance of Co-VP systems is still a field with much room to be addressed. As important as analyzing the impacts, the challenge is still posed by implementing cooperative countermeasures against possible cyberattacks. Since such attacks can generate catastrophic effects, response systems must be as efficient and quick to act, preserving the system's safety. Again, the difficulty in adopting a single communication network standard does not help settle security concerns and enable trustworthy security-certified communication stacks. Thus, such implementations produce large security openings, entailing the possibility of cyber-attacks and the consequent need for quick cyber-security detection and countermeasures.

Validation Tools To ensure the safety of Co-VP systems, it's essential to validate them in realistic settings. Simulations are useful for exploring the system's limits, especially if Hardware in the Loop testing is involved. However, the final validation of the system should be conducted in real-world conditions to evaluate the responsiveness of communication and mechanical systems. To reduce the time and cost of validation, comprehensive validation frameworks covering all stages from development to simulation, robotic testbeds, and final deployment should be used. The integration of various validation stages through open robotic development frameworks like ROS could enhance the system's modularity, enable component reuse, and support continuous integration and validation.

New tools have been developed that simulate Co-VP applications with greater realism, which helps them assess actual problems more accurately. However, the difficulty in integrating these simulators with different communication standards and the high computational cost of such frameworks can decrease their effectiveness in validating more complicated scenarios.

Final Remarks The interest in implementing Co-VP systems has brought great investment to this area in academia and the automotive industry since they can enable interesting solutions to reduce traffic, energy consumption, and road accidents. Several aspects of these systems have been studied from different perspectives and by different communities, however most often partially and incompletely, either from a control, communications, or mere traffic engineering perspective. In this work, we seek to synthesize the most recent advances in Co-VP by pushing for a multi-disciplinary perspective which is crucial, given the way these topics overlap and how they are tightly interconnected with themselves and with the overall system reliability and trustworthiness. This is in line and interwoven with the nature of the cooperative CPS paradigm, of which Co-VP is a promising application. Herefore, such analysis of the current research state-of-the-art we are enabling through this document is fundamental and will pave the way in facilitating the development of this SoS by accurately addressing the topics involved. Moreover, from this analysis, we provide a list of fundamental challenges the community must address if these applications become a reality.

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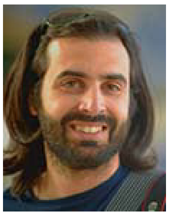

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