A Survey on Platoon-Based Vehicular Cyber-Physical Systems

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***Abstract*—Vehicles on the road with some common interests can cooperatively form a platoon-based driving pattern, in which a vehicle follows another vehicle and maintains a small and nearly constant distance to the preceding vehicle. It has been proved that, compared with driving individually, such a platoon-based driving pattern can significantly improve road capacity and energy efficiency. Moreover, with the emerging vehicular ad hoc network (VANET), the performance of a platoon in terms of road capacity, safety, energy efficiency, etc., can be further improved. On the other hand, the physical dynamics of vehicles inside the platoon can also affect the performance of a VANET. Such a complex system can be considered a platoon-based vehicular cyber-physical system (VCPS), which has attracted significant attention recently. In this paper, we present a comprehensive survey on a platoon-based VCPS. We first review the related work of a platoon-based VCPS. We then introduce two elementary techniques involved in a platoon-based VCPS, i.e., the vehicular networking architecture and standards, and traffic dynamics, respectively. We further discuss the fundamental issues in a platoon-based VCPS, including vehicle platooning/clustering, cooperative adaptive cruise control, platoon-based vehicular communications, etc., all of which are characterized by the tightly coupled relationship between traffic dynamics and VANET behaviors. Since system verification is critical to VCPS development, we also give an overview of VCPS simulation tools. Finally, we share our view on some open issues that may lead to new research directions.**

***Index Terms*—Platoon, cyber-physical system (CPS), vehicular ad-hoc network (VANET), platoon-based vehicular communications, cooperative adaptive cruise control (CACC), simulator.**

I. Introduction

WITH the development of automobile industry and urbanization, more and more vehicles are on the highway linking adjacent cities. It is estimated that currently there are more than 1 billion registered motor vehicles worldwide, and that the number will be doubled within the next 10 to 20 years. As a result, a series of critical issues are becoming more serious in modern transportation systems, such as traffic[1] congestion, traffic accidents, energy waste, and pollution. For instance, in the USA along, traffic congestion costs drivers more than \$100 billion annually due to wasted fuel and lost time [1]. Moreover, vehicle emissions caused by traffic congestion are also regarded as the key contribution to air pollution and are a major ingredient in the creation of haze in some large cities.

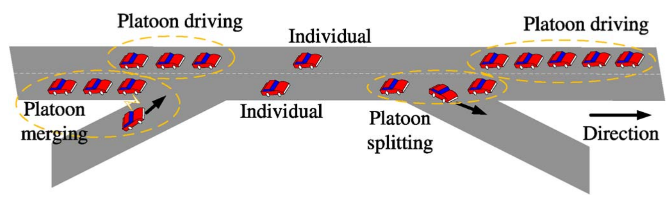

Fig. 1. Various driving patterns in highway scenario.

Although the investment on road construction can alleviate traffic congestion to some extent, it is not sustainable because of the huge construction cost and limited availability of land. To deal with these issues, an effective approach is to change the driving pattern from individual driving to a *platoon*-based driving [2]. In general, the platoon-based driving pattern is a cooperative driving pattern for a group of vehicles with common interests, in which a vehicle follows another one and maintains a small and nearly constant distance to the preceding vehicle, forming platoons as shown in Fig. 1.

In the literature [3], [4], it has been shown that the platoon-based driving pattern can bring many benefits. First, since vehicles in the same platoon are much closer to each other, the road capacity can be increased and the traffic congestion may be decreased accordingly. Second, the platoon pattern can reduce the energy consumption and exhaust emissions considerably because the streamlining of vehicles in a platoon can minimize air drag. Third, with the help of advanced technologies, driving in a platoon can be safer and more comfortable. Last but not the least, platoon-base driving pattern facilitates the potential cooperative communication applications (e.g., data sharing or dissemination) due to the relatively fixed position for the vehicles within the same platoon, which may significantly improve the performance of vehicular networking.

Clearly, a platoon is a complex physical system. As shown in Fig. 1, drivers must act cooperatively to control and manage the platoon, including formation, merging, splitting, maintenance,

Manuscript received June 27, 2014; revised January 6, 2015; accepted February 26, 2015. Date of publication March 9, 2015; date of current version January 27, 2016. This work was supported in part by the U.K. Engineering and Physical Sciences Research Council (EPSRC) under Funding Project EP/J002186/1, by the General Research Fund from Hong Kong Research Grant Council under Project 120612, by NSFC China under Project 61272462, and by the Shanghai Oriental Scholar Program.

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Digital Object Identifier 10.1109/COMST.2015.2410831

[1] In this paper, "traffic" is limited to the context of vehicle transportation.

etc. Over the past decade, many new technologies have been developed to help drivers. For instance, the adaptive cruise control (ACC) system can use sensors to detect the distance between adjacent vehicles and autonomously maintain the speed and/or distance. Meanwhile, more advanced driverless cars are being developed and several States in the USA have legalized the use of self-driven cars [5].

In addition to technologies applied individually, platoon can be facilitated by utilizing modern wireless communication technologies, which have greatly promoted the development of *intelligent transportation system* (ITS). Particularly, by integrating the wireless communication interface on board, known as *on-board unit* (OBU), a running vehicle can collect information from its neighbors or the roadside infrastructure, known as *road-side unit* (RSU), which facilitates a safer and more comfortable driving experience. In practice, vehicles with communication capability can dynamically form a mobile wireless network on a road, called *vehicular ad hoc network* (VANET), which as a promising technology can offer two types of wireless communications: *vehicle to vehicle* (V2V) communication and *vehicle to infrastructure* (V2I) communication.

Such a complex system tightly integrates computing, communication, and control technologies. Therefore, it can be considered as a platoon-based vehicular cyber-physical system (VCPS), in which all vehicles communicate via vehicular networking and are driven in a platoon-based pattern, with a closed feedback loop between the cyber process and physical process. In this article, we will present a comprehensive survey on platoon-based VCPS which covers related techniques, fundamental issues, solutions and challenges. The topics to be discussed are listed as follows:

1) We first explain the basics of platoon-based VCPS, including its applications.
2) We then briefly summarize related surveys in the literature and distinguish our survey with existing ones.
3) We provide an overview on the basic knowledge of vehicular networking architecture and standards and an overview on the basic knowledge of traffic dynamics, respectively.
4) We elaborate on the fundamental issues of platoon-based VCPS, such as platoon/cluster management, cooperative platoon-based driving, platoon-based vehicular communications, etc., all of which are highlighted by the tight coupling between vehicular networking and traffic dynamics.
5) We also review the simulation tools for VCPS verification. Specifically, we take Veins as a case study to illustrate how the coupled network simulator and mobility simulator can work interactively and evaluate the system performance more precisely.

The organization of this paper is described as follows. We first present basics of platoon-based VCPS in Section II and summarize related surveys in Section III. We then review vehicular networking architecture and standards as well as key issues about platoon dynamics in Section IV. Next, in Section V, we elaborate on fundamental issues related to platoon-based VCPSs. We then discuss VANET simulators in Section VI.

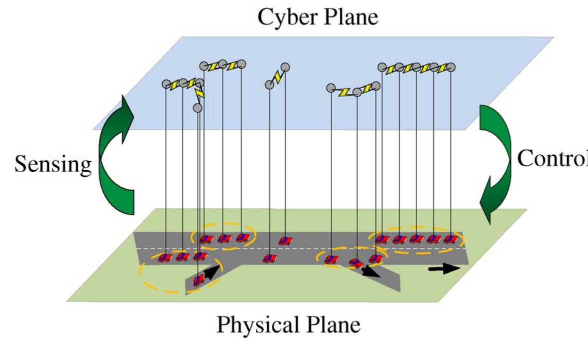

Fig. 2. An illustration of platoon-based VCPS.

Finally, we discuss the current challenges and open issues regarding the design of platoon-based VCPS in Section VII, followed by the conclusion in Section VIII.

II. Platoon-Based VCPS

In this section, we first briefly explain basics of platoon-based VCPS. We then highlight important applications of platoon-based VCPS. And finally, we describe the methodologies on platoon-based VCPS.

A. Conception

Generally, a platoon-based VCPS can be characterized by the tight coupling between vehicles' physical dynamics (mobility) and the behaviors of vehicular networks [6]. As illustrated in Fig. 2, a platoon-based VCPS consists of two planes, a physical plane and a cyber plane. The physical plane describes the platoon mobility under the constraints of traffic environment, while the cyber plane describes the behaviors of vehicular networks formed by adjacent vehicles.

Due to the tight interactions between the physical plane and the cyber plane, the impact of platoon mobility must be taken into account when analyzing the performance of vehicular networking. Meanwhile, the performance of vehicular networking, such as packet loss and transmission delay, can also significantly affect the behaviors of platoons. Therefore, tight integration of computing, communication, and control technologies is required to achieve stability, performance, reliability, robustness, and efficiency of the platoon-based VCPS.

It shall be noted that, there are in general two types of VCPS: intra-vehicle CPS and inter-vehicle CPS. For an intra-vehicle CPS, the main concern is to improve the kinetic performance of a single vehicle by combining and coordinating all of its components, such as sensors, actuators and field buses, into a tight system. For inter-vehicle CPS, the main objective is to optimize traffic performance or vehicular networking from a CPS design standpoint. In this paper, we mainly address inter-vehicle CPS, where the vehicles are considered as mobile nodes running on roads.

B. Applications

The typical platoon-based VCPSs are illustrated in Fig. 3, which can be classified into three categories from the point of

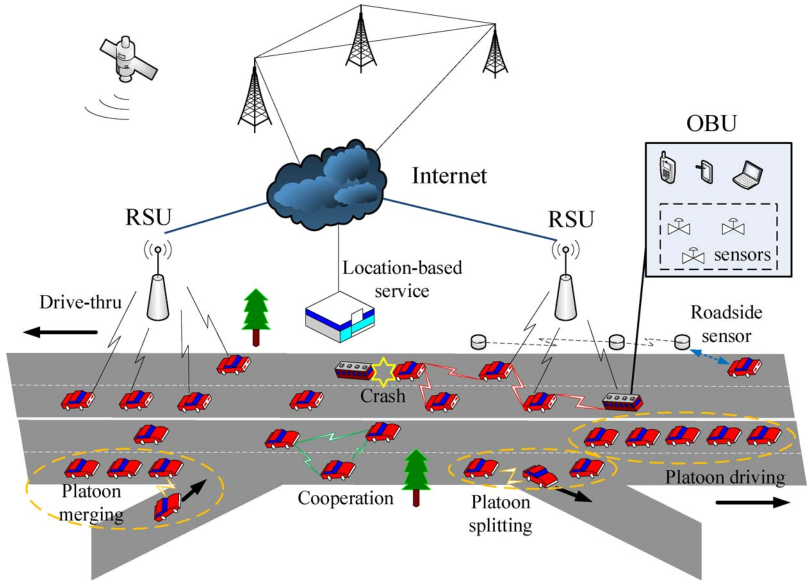

Fig. 3. A comprehensive application scenario of platoon-based VCPS.

view of application [4]: (1) traffic flow optimization, (2) traffic green and economics and (3) infotainment service.

1) Traffic Flow Optimization: The primary objective for vehicle platooning is to reduce traffic congestion and improve traffic flow throughput. To this end, many platoon related projects have been implemented in the past decades. The most famous one is the *California Partners for Advanced Transit and Highways* (PATH) project [7] which commenced in 1986 and aimed to improve traffic throughput by deploying platoons in highway. Another project is the *Grand Cooperative Driving Challenge* (GCDC) [8] where multiple teams tested their *Cooperative adaptive cruise control* (CACC) vehicles and benchmarked them to the CACC vehicles of other competitors. The aim of the GCDC is to promote the development, integration, and deployment of cooperative driving systems based on the combination of vehicular communication and the state-of-the-art of sensor fusion and control.

The recently emerging vehicular networking technologies facilitate vehicles platooning on roads [8] and promote smoothness of traffic flow [83]. The E.U.-sponsored SARTRE program [9] ran from 2009 to 2012 and deployed a platoon on highway with a lead vehicle (typically truck) followed by a series of cars driven autonomously in close formation. The experiments showed that the platoon can drive at speeds of up to 90 km/h with a gap between the vehicles of no more than 6 m.

2) Traffic Green and Economics: Another critical issue for platoon-based VCPS is to improve traffic efficiency and promote greener traffic environments, such as saving traveling time, cutting down fuel consumption and reducing exhaust emissions. The representative project called Energy ITS [10] in Japan aimed at the CO2 emission reduction from automobiles, which includes two themes: an implementation of automated truck platooning system and an evaluation method of effects of ITS-related systems and technologies on the CO2 emission reduction. In [11], decentralized platoon lane assignment was proposed to decrease travel time and enhance traffic capacity. Robust H_∞ control method [12] was introduced to design platoon velocity profile, taking into consideration fuel consumption, road inclinations, emissions and traveling time. Zhang *et al.* [13] discussed longitudinal control of heavy trucks for the purpose of reducing fuel consumption.

3) Infotainment Service: Wireless communications also boost various infotainment applications in vehicular networking, such as vehicle-platoon-aware data delivery among vehicles [14], platoon-based drive-thru internet access [15], cooperative local service [16], etc.

C. Methodologies

Clearly, common knowledge regarding VCPS is the cornerstone to support platoon-based VCPS, which mainly involves two general aspects in term of the taxonomy, as shown in Fig. 2: (1) networking related issues that mainly include vehicular networking standards and architecture to support V2V and V2I communication, and (2) traffic dynamics that include traffic flow distribution and vehicle mobility models. We will illustrate these preliminaries in Section IV.

To meet the requirements of platoon-based VCPS implementation, there are several specific issues. On the one hand, in a platoon-based VCPS, vehicles are supposed to guarantee the platoon-based driving pattern. To achieve this goal, some fundamental issues, such as platoon management (i.e., how to regulate the actions of platoon formation, maintenance and splitting), platoon attributes (e.g., stability) analysis and cooperative platoon driving, need to be addressed. In addition, it is critical to design suitable protocols or algorithms to facilitate data delivery within the platooning system. On the other hand, the platoon-based driving pattern reshapes the whole traffic flow distribution into intra-platoon and inter-platoons, compared to individual driving pattern, which can significantly affect the vehicular networking and communication in the VCPSs. Therefore, it is essential to re-evaluate the communication performance (e.g., connectivity of V2V and V2I) of vehicular

TABLE I
A COMPARISON OF RELATED SURVEYS IN THE LITERATURE

Reference	Vehicular networking issues (the cyber perspective)	Traffic dynamics issues (the physical perspective)	Coupled issues (the CPS perspective)	Comments
[17], 2009	Inter-vehicle communications and applications	N/A	N/A	From the communication perspective
[18], 2009	N/A	vehicle mobility model; mobility simulation	N/A	From the vehicle physical perspective
[19], 2010	Intra-vehicle communication; inter-vehicle communication, standards and protocols	N/A	N/A	From the communication perspective
[20], 2011	VANET application and ITS projects; VANET architecture, standards, protocols and security; VANET QoS	N/A	N/A	From the communication perspective
[21], 2011	VANET architecture; on-the-road infotainment and safety service; network management and deployment	N/A	N/A	From the communication perspective, based on service requirement
[22], 2011	Handoff management	N/A	N/A	From the communication perspective
[23], 2011	Internet access and protocols; information routing	N/A	N/A	From the communication perspective, focusing on infotainment service
[4], 2011	Inter-vehicle communication	Mobility model; platoon stability;	Cooperative platoon driving	Platoon related issues from the control perspective
[24], 2013	Communication standards and protocols; routing	Mobility model	N/A	Communication issues from the green environment perspective
[25], 2014	N/A	traffic control systems	N/A	cooperative driving issues from the control perspective
[26], 2014	VANET physical layer modeling and networking layer implementation in simulator	Mobility model and simulation	Integrated simulator	Simulator, from the system verification perspective
Our work	Networking architecture, standards and protocols	Traffic flow distribution and mobility model; platoon stability	Platoon management; VANET connectivity; beacon dissemination; drive-thru system; cooperative platoon driving; system verification	View both networking and traffic issues from the CPS perspective; platoon-based

networking under the specific platoon-based driving pattern. These fundamental issues will be addressed in Section V.

III. RELATED SURVEYS

In this section, we first briefly summarize the surveys regarding vehicular networking, traffic optimization, etc., in the literature, then highlight our work in this paper.

In the past few years, several comprehensive surveys have been conducted on vehicular networking, covering various issues including applications, architecture, protocols, and security [17], [19]–[23], most of which are reviewed from the communication (i.e., cyber) perspective. In [17], various inter-vehicle communication protocols were extensively reviewed from application perspective. Qu *et al.* [19] introduced the concept of intelligent transportation spaces (ITSp) and analyzed possible communication technology candidates for ITSp. A comprehensive survey related to vehicular networking was conducted in [20], which provided an overview of vehicular networking applications and associated requirements, along with challenges and their proposed solutions. Cheng *et al.* [21] summarized the infotainment application requirements as well as the network management and deployment from the user and system viewpoint, respectively. A specific issue of mobility and handoff management in VANETs was discussed in [22], in which the authors identified the challenges of vehicular communication caused by high mobility and illustrated the related countermeasures from both host-based and network-based aspects, respectively.

Some other surveys, on the other hand, focused on traffic flow optimization from the control perspective [4], [25]. In [4], many technique issues regarding vehicle platooning were discussed, such as obstacle detection and collision avoidance techniques, lateral and longitudinal control strategies, trajectory planning methods, etc. In [25], Li *et al.* focused on traffic efficiency with the help of vehicular networking. They compared designing schemes of traffic control systems under different information topologies.

Some other reviews were stated from the special aspects: such as communication protocols for green environment [24], mobility models in VANET [18], and simulators development [26].

To highlight the major contributions of different existing surveys, we present a comparison of various surveys in Table I. Here we note that most existing studies review mainly from the perspective of a single discipline. In this paper, we try to review the related issues from the VCPS perspective, taking into account the tight interaction between the vehicular networking behaviors and traffic dynamics. Specifically, we will focus on platoon-based VCPS, providing a comprehensive overview of fundamental issues, solutions as well as the implementation verification.

TABLE II
APPLICATION REQUIREMENTS FOR INFORMATION DISSEMINATION

Message Type	Use cases	Latency constraint	Dissemination mode
State Monitor	road condition, kinetics information	100ms–1second	periodic, broadcast
Control	Cooperative driving	100ms	periodic, multicast
Infotainment	news, media	second level	event, unicast
Warning	lane-change, overtaking, collision	100ms	event, broadcast

IV. BASICS AND PRELIMINARIES OF PLATOON-BASED VCPS

In this section, we review the basic knowledge of platoon-based VCPS from two aspects: vehicular networking standards as well as architecture and traffic dynamics description.

A. Vehicular Networking Standards and Architecture

The primary objective for vehicular networking is to support data dissemination via V2V or V2I communication for various vehicular applications. The typical information can be classified into four types: state monitoring information, control packets, infotainment data, and warning message, as summarized in Table II.

We can observe that the latency constraints may range from milliseconds to seconds under different dissemination modes to meet the application's requirement. Additionally, the information can be periodically created or event triggered with different communication modes: broadcast/multicast/unicast. Next, we first introduce existing VANET protocols, then review vehicular networking architectures and discuss how they can meet the requirements of VCPS applications.

1) VANET Protocols: To enable VANET, many organizations and institutes have been devoting to the standardization of vehicular communication in recent years, such as CEN TC278, ISO TC204, ETSI TC ITS, IEEE 1609 and IETF. Meanwhile, the US Department of Transportation (DOT) is crafting a proposal enforcing all new vehicles to embed dedicated short-range communications (DSRC) based V2V radio interfaces by early 2017 [27].

In the following, we introduce two typical protocol families: IEEE Wireless Access in Vehicular Environment (WAVE) family and IETF Mobility extensions for IP family.

WAVE is the de-factor protocol family which is based on DSRC technology and defines the architecture and services necessary for multi-channel DSRC/WAVE devices to communicate in a mobile vehicular environment. WAVE combines IEEE 802.11p and the IEEE 1609 protocol suite [28], covering from the physical layer (bottom) to the application/service layer (top), as illustrated in Fig. 4.

On the physical layer, IEEE 802.11p utilizes 75 MHz of bandwidth on the 5 GHz spectrum (specified by DSRC standard of the United States), which is partitioned into one *Control Channel* (CCH) and six *Service Channels* (SCHs). On the MAC layer, IEEE 802.11p extends the *basic service set* (BSS) standardized in IEEE 802.11, and it also adopts the *Enhanced Distributed Channel Access* (EDCA) mechanism introduced in IEEE 802.11e, which classifies different data flows into different *access categories* (ACs).

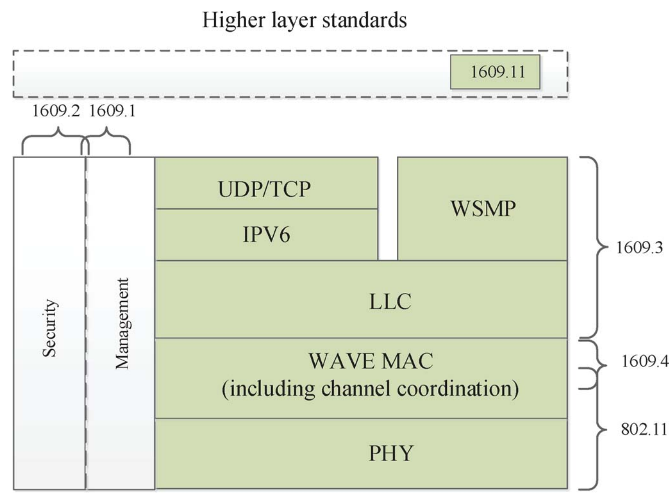

Fig. 4. Protocol stack of WAVE.

Besides IEEE 802.11p, IEEE 1609 protocol family provides more functions. For instance, the MAC sublayer of IEEE 1609.4 (Multi-channel Operation) specifies channel timing and switching among CCH and SCHs, which supports both safety and non-safety applications simultaneously running on the vehicle with single radio interface. On top of IEEE 1609.4, IEEE 1609.3 (Networking Services) defines addressing and data delivery services within a WAVE system, supporting both generic Internet Protocol version 6 (IPv6) and specialized *WAVE Short Message Protocol* (WSMP). For the application layer, IEEE 1609.11 (Electronic Payment) specifies the inter-operable payment protocol referencing to ISO standards. Specifications for other industrial fields are still underway.

Another similar standard family is the ITS communications specified by ETSI, which shares some DSRC technologies with IEEE WAVE but diverges in multichannel management [29].

Although supporting both V2V and V2I communication, WAVE only offers intermittent and short-lived V2V/V2I connectivity due to the fast moving vehicles and dynamically changing VANET topologies on roads. To improve information dissemination for IP-based vehicles, many emerging mobile IP protocols can be applied, which are specified under Internet Engineering Task Force (IETF). In particular, IETF has extended MIPv6 to support *networking mobility* (NEMO), named as the NEMO basic support protocol [30], where mobile network nodes (MNNs) can only be accessed through mobile router (MR). To implement NEMO in vehicular networking, two approaches were proposed in [31]: MANET-centric and NEMO-centric, depending on the location of NEMO in the protocol stack.

Clearly, besides the basic functionality, there still exist many challenges for Mobile IP and NEMO, especially in highly dynamic traffic scenarios [32], such as end-to-end transmission delay due to tunneling burden between *home agent* (HA) and MR, appropriate location for the HA, etc. To address these challenges, some schemes for route optimization have been proposed [33]–[35]. In [33], the proposed VARON protocol aims to improve the bandwidth and delay for inter-vehicle communications by combining an infrastructure network (e.g., a 3G network that offers Internet access) and a VANET (used for a multi-hop communication). Chen *et al.* [35] proposed a novel NEMO management scheme wherein some adjacent vehicles with similar moving pattern are regarded as a *virtual bus* (similar to platoon) and all MRs can connect to each other. In this way, the front MR can perform the pre-handoff procedure to reduce the handoff delay of the rear MR. A similar scheme also was introduced in [34], in which vehicles are grouped into clusters and the cluster head is selected as an MR to maintain the IP mobility for other vehicles.

Different from the aforementioned schemes, which are based on a generic IEEE 802.11 network for V2I, a recent study in [36] proposed a Vehicular IP in WAVE (VIP-WAVE) framework that defines the IP configuration for extended and non-extended IP services, and a mobility management scheme supported by Proxy Mobile IPv6 over WAVE. With this framework, it has been shown that the QoS of WAVE/IEEE 802.11p can also be improved by the signaling and movement detection mechanisms.

2) Vehicular Networking Architecture: Due to vehicular mobilities and limited transmission ranges of IEEE 802.11p, the VANET connectivity may be intermittent and it may be difficult to achieve a sufficiently small handoff latency. To solve these problems, one effective solution is to build a hybrid vehicular networking architecture integrating VANET with the cellular network [37]. According to the guidelines of *Communications Access for Land Mobile* (CALM) [20], the envisioned vehicular communication infrastructure combines both distributed VANETs and centralized cellular networks, which can benefit from a large coverage area and high networking throughput.

A VANET-UMTS integrated network architecture was demonstrated in [37], where RSUs are connected to the UMTS interface and vehicles are dynamically clustered by taken three related metrics into account: UMTS *Received Signal Strength* (RSS), vehicle movement, and inter-vehicular distance. Among these clusters, a minimum number of optimal mobile gateway equipped with both IEEE 802.11p and UTRAN interfaces are select to link VANET to 3G networks upon multi-metric selection mechanism. To migrate the current serving gateway to more optimal new gateway, a handover mechanism is employed. Meanwhile, gateway advertisement and discovery operation is launched to inform VANET nodes of the newly selected gateway.

With the pervasive deployment of cellular networks and the increasing applications of smartphones nowadays, some recent work recommends utilizing smartphones to execute VANET applications, which is considered as an economic communication alternative compared to VANET. [38] showed that smartphones enriched with Long Term Evolution (LTE) capabilities are feasible for V2I communication as the 4G network penetrates market rapidly. Some typical use cases include [39] road travel times estimation by the aid of mobile phones and the traffic accident detection [40] by leveraging accelerometers and acoustic data on mobile phones.

As an important complement to vehicular networking, wireless sensor networks (WSNs) also have been deployed along the roadside to enhance traffic safety and efficiency [41]–[43]. Nevertheless, due to some strict constraints to WSNs, like scarce energy, limited memory, and smaller transmission range, it is still challenging to design a reliable and energy efficient hybrid sensors and vehicular Networks.

Since vehicular network is essentially a network of machines that are communicating without human intervention, the process can also be described as Machine-to-Machine (M2M) communications [44]. Specifically, the recent evolving LTE-Advanced standards support machine-type communications (MTC) which allows large-scale devices autonomously exchanging information. Consequently, MTC enabled LTE-A may potentially facilitate many vehicular applications, like floating car data (FCD), vehicle diagnosis and fleet management [45]. In [46], a use case of dynamic traffic forecast was investigated which uses on-board sensors as an information source. To reduce the impact of MTC traffic on the QoS of human-to-human communications, this paper presented a channel-aware transmission strategy wherein vehicles probabilistically transmit FCD based on the measured signal-to-noise ratio.

In addition to the networks discussed above, which are mainly focusing on the wireless domain, vehicle networking can be improved by the emerging mobile cloud computing as well as context-aware technologies [47], [48]. In [49], a V-Cloud architecture was introduced that combines the concepts of VANET, CPS and Cloud Computing to provide safety and comfortability for driver and improve environmental conditions as well. The proposed architecture included three layers: in-car vehicular CPS, V2V and V2I network layers. Similar work was done in [50], wherein cloud computing was integrated into vehicular networks such that the vehicles can share computation resources, storage resources, and bandwidth resources.

B. Modeling Traffic Dynamics

Traffic dynamics describe the spatiotemporal behaviors of the collective vehicles on road, which normally can be characterized in two ways: the traffic flow distribution from the *stochastic* perspective and traffic mobility models from the *fluid dynamics* perspective.

1) Traffic Flow Distribution: From the stochastic perspective, traffic dynamics can be characterized by certain traffic flow distribution with several parameters. Among these parameters, statistics of *time headway* is regarded as the most fundamental one that is defined as the time between two consecutive vehicles passing the same point and traveling on the same direction. Alternatively, the headway can also be described by the distance of two consecutive vehicles. In general, time headways are assumed to be independent and identically distributed random variables.

Since the 1960s, many time headway distribution models have been proposed, among which the typical representatives include exponential distribution, normal distribution, gamma distribution, and log-normal distribution [51], [52]. In [53], the statistical distribution for inter platoon gaps, intra-platoon headways and platoon size were modeled by using the field data from highway bottlenecks. In [54], three types of probabilistic models were proposed for traffic distribution: the single model, the combined model and the mixed model. Experimental results showed that the *Shifted Hyper Log-normal Model* (HyperLNM) fits well in many real scenarios.

In [55], Chen *et al.* employed a unified car-following model integrated with Markov process description to simulate different driving scenarios. Time headway is verified to be log-normally distributed by NGSIM Trajectory Data. Based on the stochastic model of time variation of distance headway, Abboud *et al.* [56] further proposed a discrete-time lumped Markov chain to model the time variation of the distance between two neighboring cluster heads. Accordingly, they derived the probability distributions of single-hop cluster-overlapping time, which can essentially measure the stability of VANETs clustering algorithms.

In general, stochastic models describe the statistic behaviors of vehicle and characterize the steady state of traffic flow. However, these models cannot exhibit the instantaneous interactions among vehicles especially in dense traffic condition.

2) Traffic Mobility Models: From the fluid dynamics perspective, traffic mobility can be typically classified into the macroscopic and microscopic models.

The macroscopic fluid model describes the *gross* characteristics of a traffic flow, including three primary traffic flow parameters in a small road segment $[x, x + \Delta x]$: traffic density $\rho(x, t)$ (cars per meter), velocity $v(x, t)$ (meters per second) and flow rate $q(x, t)$ (cars per second). Two fundamental equations in the fluid model are given as follows:

$$q(x, t) = \rho(x, t)v(x, t) \tag{1}$$

$$\frac{\partial \rho(x, t)}{\partial t} + \frac{q(x, t)}{\partial x} = 0 \tag{2}$$

where the first equation illustrates the relationship between the three parameters, the second one is the conservation of vehicles equation which describes that the number of vehicles in x increases according to the balance of inflow at $[x, x + dx]$.

The most well-known macroscopic model is the *Lighthill-Whitham-Richard (LWR) models* [57], which assumes the velocity as a function of the density, i.e., velocity is always in local equilibrium with respect to the actual density. Microscopic traffic model provides the fine-grained description of individual vehicle dynamics, in particular the transient and steady responses of a vehicle such as spacing, velocity and acceleration track, etc. Some typical microscopic models include the car-following model, the cellular automata model, and the spring dynamics model.

The car-following model is probably the most popular microscopic traffic mobility model that can effectively describe the strong interaction among adjacent vehicles with close spacing. The general diagram of a car-following model is illustrated in Fig. 5, which describes how the following vehicle mobility is regulated by a set of control rules based on the current state of the preceding vehicle.

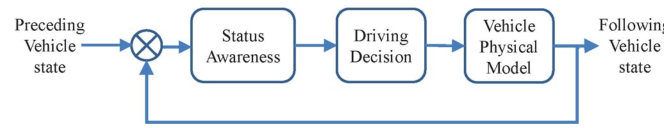

Fig. 5. General scheme for car-following models.

Mathematically, the car-following model [58] can be expressed by:

$$\frac{dv_j(t)}{dt} = \dot{v}_j(t) = f\left(S_j(t), v_j(t), \Delta v_j(t)\right). \tag{3}$$

where the acceleration of vehicle j, denoted as $\dot{v}_j(t)$, depends on its velocity $v_j(t)$, the inter-vehicle spacing to the preceding one $S_j(t)$, and the velocity difference $\Delta v_j(t) := v_j(t) - v_{j-1}(t)$.

One typical car-following model is the *Intelligent Driver Model* (IDM) [59], a time-continuous car-following model based on the stimulus-response approach. The instantaneous acceleration consists of a free acceleration on the road where no other vehicles are ahead and an interaction deceleration with respect to its preceding vehicle. It is verified that IDM can also accurately model the dynamics of a platoon that consists of ACC-equipped vehicles [60]. Some other major car-following models include the Gipps model [61], the Krauss model [62], etc.

The cellular automata model is another class of mobility model with discretization in space and time, therefore it reduces the computational complexity and is usually applied in transportation planning for large area. The cellular automata model describes a road system as a grid of equal-size cells occupied by a vehicle or being vacant. Each vehicle can be synchronously controlled moving from cell to cell by the specified rules in discrete time steps. One of the most popular cellular automata is the Nagel and Schreckenberg (N-SCHR) model [63].

The spring dynamics model was demonstrated in [64], wherein the following vehicles are linked together upon leader's navigation in one platoon. The critically damped spring is defined to identify the oscillations of inter-vehicle spacing.

In summary, traffic mobility models can demonstrate the kinematic changes of traffic flow at different granularity levels. However, the statistic characteristics of the traffic flow at the steady state are not explicitly explored.

V. Fundamental Issues in Platoon-Based VCPS

In this section, we first discuss the architecture of platoon-based VCPSs, then review some fundamental issues of platoon-based VCPSs from the perspectives of both traffic optimization and vehicular networking optimization, respectively. These issues mainly include platoon/cluster management, cooperative platoon-based driving, platoon-based vehicular communications, etc., all of which are highlighted by the tight coupling between vehicular networking and traffic dynamics.

A. Modeling Platoon-Based VCPSs

Platoon-based VCPS is considered as a complex networked control system, and one primary issue is to comprehensively understand the coupled relationship between vehicular networking and traffic dynamics.

Nekoui *et al.* [65] studied the relationship of three fundamental issues within a simple transportation system: traffic flow, safety and communications capacity. They initiated a comprehensive study combining transportation with communication fields and sought to address their mutual dependencies. The experimental results and analysis showed that wireless communication among vehicles helps to increase traffic flow throughput because it reduces the driver's perception-reaction time and hence allows high speed compact platoons. Moreover, for a fixed amount of traffic flow, VANET communication can help significantly increasing the safety between two adjacent vehicles.

C. Lei *et al.* [66] investigated the platoon stability of a CACC system in the presence of imperfect communication. They conducted the simulation by coupling traffic simulator with networking simulator. Experimental results indicated that beacon sending frequency and packet loss ratio have significant influence on the performance of the evaluated CACC controller. Lower beacon sending frequency and higher packet loss ratio of V2V communication may impair the CACC controller performance on platoon stability.

Consequently, the traditional method for such VCPSs design is not applicable, in which each component (computing, communication, physical process) is modeled and designed separately under the assumption of other components being in fixed deterministic behavior. To tackle this issue, a case study is illustrated in [6], where the cooperative vehicle safety (CVS) is designed by a systematic CPS approach. The general CVS consists of two subcomponents with significant interaction: a communication subcomponent (networking process) for safety messages transmission, and a computing subcomponent for tracking neighboring vehicles (estimation process), safety messages transmission control and collision alarm. By characterizing the effect of physical process dynamics and communication subcomponent on the computing subcomponent, an adaptive algorithm was designed which controls the rate and range of transmission based on the perceived tracking error and the measured channel occupancy, respectively.

A platoon-based VCPS is supposed to describe vehicular applications, such as safety applications or infotainment services, in a VANET environment from the CPS perspective, where each vehicle drives in a platoon-based pattern. Jia *et al.* [67] jointly considered VANET operation and platoon dynamics, and proposed architecture for platoon-based VCPSs. Based on this work, a general platoon-based VCPSs architecture can be illustrated in Fig. 6. The unity of vehicle is composed of two parts: the platoon-based mobility/control model which regulates the vehicle dynamics under a platoon-based driving pattern, and the networking/communication model that generalizes the networking request of VANET applications of a vehicle, such as the communication topology, networking layer specification, etc. The two main processes of the system are the networking/communication process and the platoon mobility process.

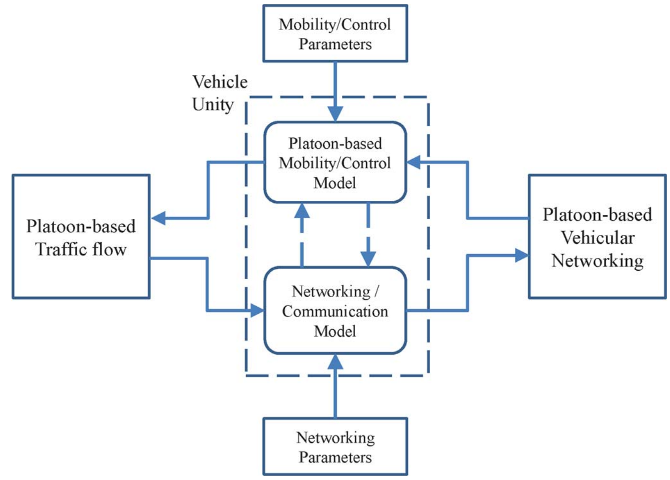

Fig. 6. Architecture for platoon-based VCPSs.

The platoon mobility process can be presented as platoon driving actions regulated by certain mobility/control model with the help of vehicular communication. Some typical actions include platoon forming, maintenance, merging and splitting. Platoon parameters as the reference input of the control model describe the expected platoon profile, such as platoon size, intra-platoon spacing and inter-platoon spacing. Here we consider the case of CACC system to exemplify the platoon mobility process. Typically, the control objective of CACC is to maintain a desired inter-vehicle or inter-platoon distance (i.e., expected platoon profile). With the help of inter-vehicle communication, the CACC system can be modeled as a networked control system wherein feedback loop design couples both VANET and platoon mobility. Some uncertainties of practical VANET, such as packet loss and probabilistic transmission delay, have negative impact on the control performance, as referred to [66].

On the other hand, networking process mainly supports data dissemination on the request of platoon-based VCPS application, which may exhibit different VANET performance under various platoon-based traffic flow scenarios. In a collision risk warning application, for example, each vehicle is supposed to periodically broadcast its kinematic status to neighbors. Clearly, if the platoon size is small and the inter-platoon spacing is large, packet delay and loss seldom happen within a single platoon even at high rate of message generation; In case of large platoon size and small inter-platoon distance, packet delay and loss would be significantly larger given the same message generation frequency. Networking parameters as the reference input of the networking/communication model such as the message generating rate, transmission power, etc., can be adaptively adjusted according to the current traffic dynamics.

In summary, the performance of a platoon-based VCPS is jointly determined by both networking process and control process, which closely combines communication, computation and control together.

As shown in Fig. 6, the fundamental technical issues in platoon-based VCPSs can also be generalized into two sides

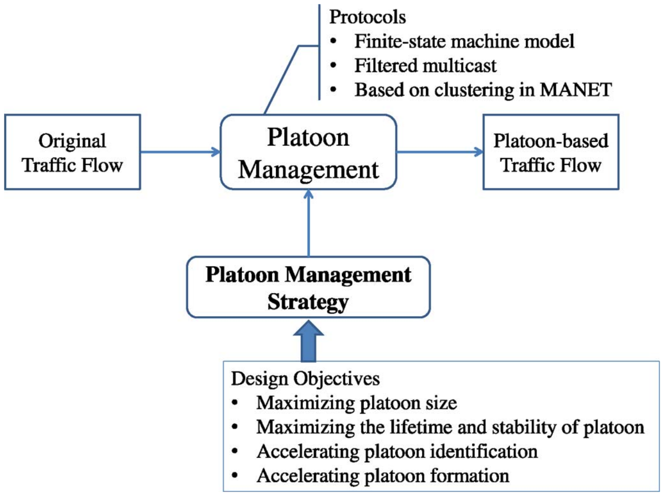

Fig. 7. The platoon management system in existing studies.

from the perspective of system optimization objective. One side is to optimize the traffic flow with the help of vehicular networking, the corresponding technical issues mainly include platoon management, platoon-based cooperative driving and the stability of platooning system. The other side is to analyze and optimize vehicular networking performance by the aid of platoon-based traffic flow. Two typical issues involve platoon-based V2V communication and platoon-based V2I communications. In the remainder of this section, we will elaborate on these fundamental issues.

B. Platoon/Cluster Management

Platoon management is a fundamental function for platoon-based VCPSs, which involves platoon formation, merging and splitting, etc. Based on the existing efforts, we illustrate the platoon management system in Fig. 7 [68].

As shown in this figure, existing studies are classified according to the platoon management protocol and the platoon management strategy. The platoon management protocol enables vehicles to manage platoon with common interests, while the platoon management strategy determines the structure of a platoon based on various design objectives.

In terms of platoon management protocol, a filter-multicast protocol was proposed in [69] to realize dynamic platoon-ID allocation, platoon dynamic formation and management. A finite-state machine model was developed in [14] to describe the operating process of the platooning protocol. In [70], an application level protocol is designed for the join maneuver of the platooning system. Specifically, the authors considered the coexistence of automated vehicles and manual vehicles on the same road, and utilized state machines mechanism to handle all possible cases in the process of a car joining the platoon.

In a more general sense, many existing protocols for clustering in mobile ad hoc networks (MANETs) can be customized and applied to support platoon management. For example, Tarik Taleb *et al.* presented a dynamic clustering mechanism to form clusters with a cooperative collision-avoidance (CCA) scheme [71]. For more details, please refer to [72] which reviewed recent works on clustering algorithms from the information exchanging perspective. Nevertheless, it is still challenging to form the stable cluster or platoon especially in heterogeneous and drastic changing traffic scenarios. A comprehensive description of traffic mobility and local networks (here local networks denote the neighborhood lists of vehicles) is crucial for better platooning or clustering algorithm. For example, entropy is selected as the indicator of the cluster stability in [73], which achieves better performance than other schemes only using partial metrics such as velocity, direction, connectivity.

In terms of platoon management strategy, in [2], the objectives included (1) maximizing the platoon size and (2) maximizing the life time of platoon. To reach these goals, Hall *et al.* designed a scheme to group vehicles based on their destination at the entrance ramp. Different from [2], a distributed control strategy was proposed to implement platoon assignment and lane selection by virtue of V2V communication [11]. Platoons are only grouped at the start of segment, faster lanes are assigned to platoons with longer origin-to-destination distances. In [69], vehicles are categorized into three roles, master, member and normal vehicle, according to their relative positions and communication range, and then are formed into a platoon based on the their roles. In [14], the main objective is to quickly identify the platoon, where a prediction scheme was designed to accelerate platoon formation when some vehicles are moving towards a different direction (i.e., platoon splitting). To mitigate the negative impact of traffic disturbance on platoon management, a novel disturbance-adaptive platoon architecture was proposed in [68], where the desirable intra-platoon spacing and platoon size are derived under traffic disturbance and VANET constraints.

In summary, to form and maintain a stable platoon, both traffic dynamics and VANET behaviors are supposed to be taken into account.

C. Platoon Stability Analysis

Platoon stability exhibits the essential feature of intra-platoon dynamics from the control theory perspective. Intuitively, platoon stability is defined as the spacing error between the desired and actual inter-vehicle spacing not amplifying to the upstream of the platoon [74], which can be mathematically expressed in time-domain or frequency-domain forms.

The spacing error for the ith vehicle is defined as:

$$\varepsilon_j = x_j - x_{j-1} + L_{des} \tag{4}$$

where L_{des} is the desired intra-platoon distance specified in the spacing policy. Accordingly, the steady state error transfer function is defined as:

$$H(s) = \frac{\varepsilon_j}{\varepsilon_{j-1}}. \tag{5}$$

Theoretically, platoon stability is guaranteed if the following two conditions are satisfied:

1) $\|H(s)\|_\infty \leq 1$
2) $h(t) > 0$

where $h(t)$ is the impulse response corresponding to $H(s)$.

TABLE III
A SUMMARY OF EXISTING STUDIES ON PLATOON STABILITY ANALYSIS

Reference	Vehicle parameter	Spacing policy	Communication structure	Control law
[75], 2011	Parasitic time delays and lags of the actuators and sensors	CTH	Predecessor-following; spacing and velocity	Sliding-mode
[76], 2008	Reaction time, update time, and adaptation time.	CTH	Predecessor-following; spacing and velocity	IDM model
[74], 2004	Actuator lag	Constant spacing	Predecessor-following, predecessor and leader following; spacing	PID
[77], 1998	Actuator lag	Constant spacing	Leader-following; spacing, velocity and acceleration	Sliding-mode
[79], 2005	Actuator lag	CTH; quadratic range	Predecessor-following; spacing and velocity	Sliding-mode
[80], 2009	Actuator lag	Safety Spacing Policy; quadratic range	Predecessor-following; spacing and velocity	Sliding-mode
[81], 2007	Heterogeneous actuator lag	Constant spacing	Leader-following; predecessor-following; spacing and velocity	PID
[82], 2011	actuator lag	Constant deceleration; CTH	Predecessor-following; spacing and velocity	Range (R) vs. Range-rate diagram; PD

In the literature, it has been shown that many factors may influence platoon stability. In view of the platoon control system structure, we can classify these factors into four aspects:

- **Vehicle parameter**: Vehicle parameters physically reflect the inherent characteristics of the vehicle stemming from manufactory, such as the parasitic time delays and lags in the engine and actuators.
- **Spacing policy**: In general, there are two types of intra-platoon spacing policies: the constant spacing and variable spacing. The former one indicates the separating distance being independent of the speed of the controlled vehicle, while the latter one denotes that the intra-platoon spacing is related to the vehicle's speed. The typical representatives of these two policies are the constant spacing and the *constant time-headway* (CTH) spacing.
- **Communication structure**: The communication structure describes the topology and information that connects and exchanges among vehicles.
- **Control law**: The control law defines control algorithms on the vehicle.

Some existing studies regarding platoon stability are summarized in Table III.

Regarding the impact of vehicle parameters on platoon stability, the parasitic time delays and lags of the actuators and sensors have been considered in [75] when modeling the practical ACC-equipped vehicle longitudinal dynamics for both homogeneous and heterogeneous platoons. By employing the sliding-mode controller and CTH spacing policy, it is shown that the parasitic time delays take the larger negative effect on the string stability than the parasitic time lags.

In [76], Kesting *et al.* summarized three characteristic time impacting on the traffic flow stability by microscopic modeling approach: reaction time, update time, and adaptation time. The reaction time and the update time have similar dynamic effects because both introduce instabilities via "short-wavelength mechanisms" that can be both local or collective in nature, while the velocity adaptation time triggers instabilities exclusively via collective "long-wavelength mechanisms."

Reference [81] investigated the stability of a heterogeneous platoon with arbitrary length and arbitrary vehicle type ordering, where the heterogeneous platoon is defined to be stable if the propagating errors are limited and uniformly bounded.

Apart from the constant spacing and CTH spacing, some other spacing polices were proposed in the literature. In [79], the quadratic spacing policy was proposed to both maximize the traffic capacity and balance between traffic flow stability, string stability and sensitivity by using the constrained optimization procedure. The analysis and simulation results showed that the quadratic spacing policy can achieve a higher critical density and a lower maximum sensitivity compared to the CTH policy. A safety spacing policy (SSP) was proposed in [80] which enables safe driving and improves traffic flow throughput in the meantime. SSP is a nonlinear function of the vehicle velocity and takes the vehicle's braking capacity into account to adapt the desired safe inter-vehicle spacing. Mathematical analysis and simulation results showed that SSP ensures both the platoon stability and the traffic flow stability as well as obtains a higher traffic capacity.

Communication structure is another key factor for stabilizing platoon. Seiler *et al.* [74] analyzed disturbance propagation in a platoon and showed error amplification of intra-platoon spacing under a *predecessor-following* control strategy with constant spacing policy, in which each vehicle only has the relative position to its preceding one. To maintain a constant intra-platoon spacing, a *predecessor-leader* control strategy [77] was proposed wherein each vehicle is supposed to get information from both its preceding vehicle and the platoon leader. In [78], platoon stability was investigated under both predecessor-following and *symmetric bidirectional* communication structures with linear and nonlinear controllers, respectively. The results showed that although the peak value of the position tracking error in bidirectional structure is much smaller than that in the predecessor-following structure, the bidirectional structure suffers from high sensitivity to the platoon size.

Normally a vehicle has two operational modes: spacing control mode and speed control mode. To achieve a better traffic flow performance, it is critical for the vehicle to design a suitable switching logic that decides when to switch between

TABLE IV
A SUMMARY OF EXISTING STUDIES ON PLATOON-BASED COOPERATIVE DRIVING

Reference	Control objective	VANET topology	VANET factors	Control strategy
[84], 2014	platoon safety	sensor and communication; position, speed, and braking action	Communication delay	braking feedback control;
[85], 2010	CTH	Predecessor-following	Communication delay	PD controller; feedforward controller
[86], 2012	Stable acceleration	Predecessor-following	Sensor fusion delay	Model predictive control and frequency domain linear control.
[12], 2012	Multi-criteria optimization	Intra-platoon	Transmission delay	Velocity tracking controller and $H\infty$
[68], 2014	Minimize acceleration noise	Preceding platoon	Inter-platoon	Spacing control and speed control
[89], 2011	CTH	Predecessor-following	Sampling frequency, zero-order-hold and constant network delays	PD controller; feedforward controller
[87], 2012	CTH	Predecessor-leader	Communication delay	Sliding-mode
[90], 2013	CTH	Predecessor-following	Packet loss	PD controller; feedforward controller
[88], 2012	Constant platoon length	Two preceding vehicle	Information noise	Consensus control

the two operational modes. In [82], a switching strategy was proposed for the ACC-equipped vehicles in a platoon, in which a constant-deceleration spacing control model was designed by way of the Range vs. Range-rate diagram. The PD controller for headway control mode was designed to guarantee the platoon stability.

In summary, various factors may affect platoon stability. Specifically, the emerging VANET technology is integrated into the platooning system design and essentially changes the communication structure of the platoon-based VCPS.

D. Cooperative Platoon Driving

Platoon control with the help of vehicular communication significantly improves traffic safety and efficiency [83]. As a typical application of platoon-based VCPSs, the cooperative platoon driving with vehicular communications has attracted increasing concerns in recent years [68], [85]–[88], which are summarized in Table IV.

In [84], Xu *et al.* quantified the impact of communication information structures and contents on platoon safety. They designed the platoon safety control system and compared the system performance under different information structures (i.e., front sensors, rear sensors, and wireless communication channels) and different information contents (such as distances, speeds, and drivers action) settings. The results showed that communications outperform distance sensors in the effective enhancement of platoon safety. Moreover, event data (e.g., drivers' braking events) may contain more effective information for platoon management than some traditional information such as distance and vehicle speed.

One general design of CACC system was proposed in [85], which adopted the CTH policy in a decentralized control framework. The system considered a feasible communication structure, i.e., the vehicle only communicates with its directly preceding one, taking communication delay and heterogeneity of the traffic into account. The control structure of the CACC system is composed of a standard ACC system with a PD controller and a feedforward controller using the preceding vehicle data via V2V communication. Based on a frequency-domain-based approach, a minimum time-headway can be derived to ensure the platoon stability. Theoretical and experimental results showed that V2V communications enable the vehicles driving at smaller inter-vehicle distances while the platoon stability is guaranteed.

Moreover, a practical CACC architecture was implemented on a Volvo S60 in the GCDC competition [86]. Global Positioning System (GPS) and the sensing module as the complement of the communication structure help the vehicle get information of the preceding one in case of 802.11p-based V2V communication error. Two approaches were designed for controlling the vehicle longitudinal motion: the model predictive control (MPC) and the frequency domain linear control.

Some specific control objectives are also discussed in the literature. For instance, to eliminate longitudinal collision without the need to break up the platoon, some constraints such as fuel consumption, road inclinations, emissions and traveling time are considered in the design of vehicle velocity [12]. In the proposed velocity control scheme, the leader velocity is determined by all vehicles reference velocities in the same platoon. In [68], Jia *et al.* specially aimed to improve the comfortability and reduce the fuel consumption in disturbance scenarios. To this end, they proposed a novel driving strategy for the platoon leader, in which the preceding platoon's information as reference is utilized to derive the desired acceleration for the leader. Simulation results showed that the proposed driving strategy can effectively improve the traffic flow smoothness.

Some limitations and uncertainties in practical vehicular networking, such as transmission range, packet loss, and probabilistic transmission delay, may have negative impacts on the platoon control system performance [66]. Consequently, it is critical to clarify how these communication constraints and uncertainties affect the platooning system and how to implement the vehicle platooning under such communication uncertainties.

In [91], a limited range of forward and backward vehicular communication was considered for a linear time-invariant platoon control system. The analysis and simulation results showed that although extra forward communication range can significantly reduce the rate of disturbance amplification, it does not avoid platoon stability problems in a qualitative sense. In addition, bidirectional communication appears to facilitate platoon stability but simultaneously cost very long transients as platoon length grows.

In [89], Sinan *et al.* investigated the impact of imperfect wireless communication on the platoon stability in a CACC system, including some factors such as the sampling frequency, zero-order-hold and constant network delays. They adopted the same control structure for the CACC system from [85] and modeled it as a networked control system wherein a feedback loop design couples both VANET and the platoon mobility. Discrete-time frequency response analysis showed the tradeoffs among the vehicle following controller, network performance and string stability performance criteria.

To tackle the packet loss in impaired V2V communication, Ploeg *et al.* [90] utilized onboard sensors to estimate the preceding vehicles acceleration which should be originally obtained via V2V communication. Based on the estimated acceleration, the proposed control strategy of graceful degradation of one-vehicle look-ahead CACC can achieve a noticeable improvement of string stability characteristics.

In [92], the negative impact of the tracking lag parameter was taken into account in a platoon control system. A hierarchical platoon controller design framework is established, comprising a feedback linearization controller at the first layer and a decentralized bidirectional PD controller at the second layer.

The aforementioned literatures normally assume fixed communication structure in the platoon-based VCPS, such as predecessor-leader, predecessor-following, symmetric bidirection, etc. However, practically, the topology of vehicular networks is time-varying and complicated, accompanied by heterogeneous uncertainties like communication delays, packet loss, and transmission errors. Therefore, it is crucial to explore more generic communication structures suitable for VANETs. The initial work was reported in [93], in which dynamical systems as the paradigm are used to model information exchange within a platoon, and vehicle platooning is formulated as a typical consensus problem.

A consensus-based platoon controller was proposed in [88], where vehicles are deployed to converge the weighted intra-platoon spacing to a constant. To tackle observation noises, Wang *et al.* proposed a two-stage stochastic approximation algorithm with post-iterate averaging. Simulation showed the effectiveness of V2V communication in vehicles deployment compared to the sensor-based communication.

In [94], Bernardo *et al.* considered vehicle platooning in presence of the time-varying heterogeneous communication delays. They adopted the leader-follower control topology and formulated vehicle platooning into a consensus problem. By using Lyapunov-Razumikhin theorem, the upper bound delay can be calculated to guarantee the stability of the platooning system.

In summary, the platoon-based cooperative driving heavily depends on the network structure and control strategies, which closely integrates communication, computation and physical processes together. To achieve better system performance, tightly coupled and feedback method is recommended, in which each component of the system is modeled based on other controllable and measurable components, and the control strategies on each component are implemented from the perspective of the overall system performance.

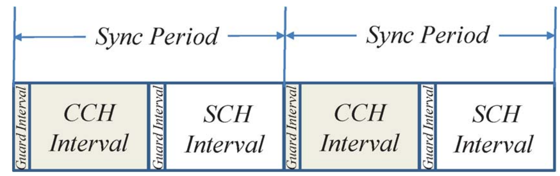

Fig. 8. Division of time into CCH intervals and SCH intervals in WAVE.

E. Platoon-Based V2V Communication

To facilitate various platoon-based applications, such as vehicle platooning and infotainment service, an effective design for vehicular communication is a must in platoon-based VCPSs. For a typical platoon-based traffic scenario, some basic issues regarding vehicular communication are: (1) How to efficiently disseminate message within the intra-platoon and inter-platoons. (2) How to improve communication performance between the platoon/vehicle and RSU. In this part, we first address the former issue and review the related work on the analysis and optimization for intra-platoon communication and inter-platoon connectivity, respectively.

1) Intra-Platoon Communications: To support vehicle platooning, each vehicle in the same platoon is supposed to periodically disseminate its current kinematic status (including position, velocity, acceleration, etc.) to the neighboring vehicles, namely *beacon message dissemination*. Such a beacon dissemination process is supported in both IEEE 1609.4 standard and ETSI ITS-G5 architecture.

In IEEE 1609.4, the channel access time is divided into synchronized intervals (SI). Each SI contains a guard interval and an alternating fixed-length interval, including the CCH interval (CCHI) and the SCH interval (SCHI), as shown in Fig. 8. The default specification of IEEE 1609.4 allows one vehicle to send the beacon message, i.e., basic safety message (BSM), during CCHI and infotainment information during SCHI on a single-radio interface. To tackle the inefficiency of channel switching, U.S. DOT adopted the dedicated CH172, the always-on safety channel, for exchanging BSMs with full performance, as designated by Federal Communication Commission (FCC) [95].

In the ETSI architecture, cooperative awareness messages (CAMs), similar to BSMs, are also normally transmitted on a CCH. A decentralized congestion control (DCC) function is adopted to alleviate channel congestion by adjusting transmission parameters according to the channel load, such as the transmit power, the minimum packet interval, the data rate and the sensitivity of the radio.

However, media access congestion on CCH may introduce adverse effects, such as the lower beacon reception rate in dense traffic conditions and the risk of starvation for non-safety bulky data in sparse traffic flow [29]. To improve the scalability of beacon dissemination, many schemes have been proposed which can be classified into the contention-free based and the contention-based. The main idea for typical contention-free solutions is that vehicles are grouped into a cluster in which the cluster head is responsible for allocating *time division multiple access* (TDMA) slot to other cluster members [96], [97]. As for typical contention-based solutions, the networking parameters, such as the beacon frequency, beacon dwelling time, transmit power and contention window size, are adjusted adaptively in accordance with the changing traffic conditions to achieve better system performance [98]–[108].

Song *et al.* [98] investigated the case that all safety messages generated during SCHI are rush to access as soon as the CCHI starts, which causes the flash crowd problem for the safety applications. To alleviate the adverse effect, a distributed periodic access scheme is proposed by using a hashing function to distribute the access time of the safety messages into CCHI instead of SCHI.

In [100], an application-level messaging frequency estimation scheme, called frequency adjustment with random epochs (FARE), was proposed to maximize the number of beacon messages that are successfully delivered to neighbors. The main idea is that beacon frequency can be adaptively regulated based on the neighboring vehicular density estimated by the FARE algorithm. In case of strict messaging frequency requirements for safety applications, in [101], the authors proposed a novel approach to reduce collisions among beacons and improve the delivery probability. The beacon application can create its own notion of timing slots and dynamically change the beacon transmission timing slot based on the observed use of the slots by other vehicles.

An insight to the tradeoff between control channel reliability and service channel bandwidth was investigated in [103], which indicated the effectiveness of dynamic adjustment of CCH. An adaptive MAC mechanism was proposed in [99], where the ratio of dwelling time in CCH and SCH can be adjusted adaptively according to the current traffic density. However, the method for density estimation has not been mentioned in this paper. Similarly, Wang *et al.* [104] proposed a variable CCHI to enhance the saturation throughput of IEEE 1609.4 in VANETs. Moreover, a coordination mechanism was adopted to provide contention-free SCHs by the channel reservation on CCH.

Beacon congestion problem was investigated in [105] from the distributed control theory perspective. Proactive and reactive controllers can be integrated into the beacon congestion control system, where the former estimates the desired transmission parameters via the accurate system model according to current neighboring information (e.g., number of nodes), while the latter adapts the feedback mechanism to achieve the control robustness.

Stanica *et al.* [106] investigated the impact of the minimum contention window on V2V communication. They proposed a dynamic adjustment of the minimum contention window to improve the performance of the IEEE 802.11 protocol based on the local node density.

In [107], Bansal *et al.* designed a linear message congestion control mechanism where the packet injection rate is controlled based on continuous feedback (beaconing rate in use) from the local neighbors. However, convergence is only guaranteed when all the vehicles are in range, which may lead to unfairness in multi-hop scenarios.

Some cross-layer design approaches are also introduced for beacon optimization. For example, a joint approach was proposed in [108] which combines the adaptive transmission power at the physical layer with the QoS parameters at the MAC layer. Based on the estimated local vehicle density, the transmission range is dynamically changed by adjusting the transmission power. Moreover, the contention window size can be adapted according to the instantaneous collision rate to enable service differentiation.

It shall be noted that most proposed congestion control methods regulate the BSM transmission rate to not exceed a certain channel utilization threshold. However, this distributed control methodology may lead to the divergence of individual rate settings among even closely neighboring vehicles [109]. The main reason lies in the microscopic adjustment of the channel utilization being frequently classified differently by neighboring vehicles. To mitigate the unfairness of beacon rate allocation, a mean-checked rate control was proposed wherein the congestion control is not only distributed but also coordinated by the average BSM rate of the neighborhood.

Most of aforementioned literatures aimed to improve the overall benefit instead of dedicating to the specific applications like vehicle platooning. Indeed, as we stated previously, some vehicle platooning control systems require different communication structures such as "predecessor-leader" and "Predecessor-following," which may be taken into account when designing the beacon dissemination policy. As such, some recent studies proposed the called *application-aware* solutions, i.e., coupled design of beacon dissemination with the characteristics of platooning application [87], [110], [111].

In [87], a "predecessor-leader" control strategy was adopted to maintain the constant intra-platoon spacing. Towards this, five information-updating schemes were proposed to exchange data between vehicles, all of which subject to an upper bound delay to ensure a stable platoon. To cope with the heavy communication load among intra-platoon and possible data collisions between adjacent inter-platoons, one CCHI is divided into several time-slots which are allocated to the vehicles based on their respective positions in the platoon.

In [110], Segata *et al.* proposed an intra-platoon communication strategy dedicated for the leader-following based CACC system. Transmit power control is used to let leader send beacon to all vehicles within the platoon while other vehicle just connect to its closest one. Moreover, beacons are disseminated in a TDMA-fashion way: the leader sends its beacon first, then followed by others.

To improve the reliability for the delay-sensitive platooning application, in [111], the master vehicle was identified in one platoon to coordinate the whole beacon disseminations in a collision-free way and enlarge transmission coverage as well. Moreover, retransmission scheme was designed in transport layer to alleviate the expired packets over a specific service channel dedicated to inter-platoon communication.

In summary, it is very challenging to design effective beacon dissemination scheme for vehicle platooning, which requires not only stable beacon reception ratio but also quick response

TABLE V
A SUMMARY OF EXISTING STUDIES ON VANET CONNECTIVITY

Reference	Connectivity scenario	PHY layer	Traffic dynamics	System metrics
[113], 2008	V2V	Unit disk	Independent individual; Poisson distribution	connected vehicle number; connectivity distance
[114], 2012	V2V	Rayleigh and Rician fading; Doppler spread	Independent individual; Poisson distribution	Minimum transmit power; the maximum number of hops
[115], 2011	V2V	Two-ray model	Log-normal distribution	Link duration
[116], 2010	V2V, store-carry-forward	Unit disk	Independent individual; Poisson distribution; two-lane with opposite direction	Transmission delay
[117], 2012	V2V, store-carry-forward	Unit disk	Independent individual; Poisson distribution; two-lane with opposite direction	Message propagation speed
[67], 2014	V2V, store-carry-forward	Unit disk	Platoon-based; log-normal distribution; two-lane with opposite direction	Message transmission delay
[119], 2011	V2V, relayed by RSUs	Unit disk	Independent individual; Poisson distribution; two-lane with opposite direction	Rehealing delay, the number of rehealing hops
[120], 2014	V2V, V2I	Unit disk	Platoon-based; Poisson distribution; one-lane	connectivity probability
[121], 2011	V2I	Unit disk; log-normal shadowing	Independent individual; Poisson distribution; uniform distribution for RSUs	Access probability; connectivity probability
[122], 2011	V2I, relayed via V2V communication	Free space fading	Independent individual; Poisson distribution;	Packet delivery delay
[123], 2012	V2I, relayed via V2V communication	Unit disk; log-normal shadowing	Independent individual; Poisson distribution;	Uplink and downlink connectivity

to the changing traffic conditions. In addition, most of work assumed platooning messages would be transmitted on the same channel as safety channel (e.g., channel 172 in US). As verified in [112], however, vehicle platooning with the dedicated service channel can outperform that with CCH. The dilemma lies in the tradeoff between performance of platooning application and efficiency of channel utilization.

2) Inter-Platoon Communications: Inter-platoon communications mainly involve the issue of VANET connectivity, which is a fundamental measurement to the linking quality of vehicular communication. In this part, we focus on VANET connectivity and data forwarding especially in platoon-based traffic flow consisting platoons and ordinary vehicles that are not involved in any platoon.

The existing related studies are summarized in Table V.

One typical work on VANET connectivity was [113], where Yousefi *et al.* investigated connectivity between vehicles in a typical highway scenario. The number of vehicles passing the observer point is assumed subject to Poisson process, and speeds are independent identically distributed and independent of the inter-arrival times. Analytical expressions were derived for the average connectivity distance and cluster size, referred to as connectivity metrics, with a queuing theoretic approach. It was shown that increasing the traffic flow and the vehicles transmission range may enhance the connectivity metrics. Moreover, for the traffic flow with normally distributed speeds and fixed average value, enlarging the variance of the speed distribution can also improve the VANET connectivity. However, the analytical results are only applicable under condition of sparse traffic wherein vehicles drive in free state, regardless of the strong interaction among vehicles in dense traffic flow.

Different from the conventional graph-theoretic approach, [114] investigated network connectivity under a physical layer-based QoS constraint, i.e., the average BER meeting a target requirement. To simulate the realistic VANET environment, the impact of Doppler spread and radio propagation (with Rayleigh and Rician fading models) are considered when estimating the minimum transmit power to ensure the network connectivity. Link duration is another important metrics of VANET connectivity. Yan *et al.* [115] derived the probability distribution of the lifetime of individual links between two vehicles in a VANET. Analytical results showed that link duration is subject to log-normal distribution.

To effectively transmit safety message in VANETs, a store-carry-forward scheme has been proposed which exploits opportunistic connectivity between vehicles moving on opposing directions to achieve greedy data forwarding [67], [116]–[118]. Kesting *et al.* [116] proposed a transversal message hopping strategy to transfer message between consecutive vehicles. They derived analytical probability distributions for message transmission times under the assumption of Poissonian distance distribution between adjacent vehicles. In [117], Baccelli *et al.* analyzed the information propagation speed in a bi-directional highway. The conclusion shows that under a certain threshold of vehicle density, information propagates on average at the vehicle speed. While vehicle density exceeds this threshold, information propagates may increase quasi-exponentially with respect to vehicle density. Agarwal *et al.* studied message propagation [118] in a 1-D VANET where vehicles are Poisson distributed and move at the same speed but on either direction on a bi-directional roadway. They identified the upper and lower bounds for the average message propagation speed, which revealed the impact of vehicle density on the message propagation.

Different from most studies focusing on individual vehicle, in [67], the authors considered the dense traffic scenario of vehicle driving in platoon-based pattern. They investigated

VANET connectivity in such platoon-based traffic flow in which the interaction between vehicles has been taken into account. Both the analytical and simulation results showed that traffic dynamics have significant impact on VANET connectivity. In [120], V2V connectivity was investigated in platoon-based VANETs where vehicles are Poisson distributed with different traffic densities. The analysis showed that compared to VANETs without platoons, the platoon-based VANETs can significantly improve networking connectivity both in the V2V communication scenario and in the V2I communication scenario.

To further enhance V2V connectivity in VANET, RSUs sometimes can be exploited to forward information between disconnected vehicles [119]. In a typical straight highway with two-lane in opposite directions, a new safety message routing flow mechanism was proposed which utilizes RSUs or forwarder vehicles to forward message among successive cluster. The simulations showed that by deploying only a limited number of RSUs, VANET performance such as the network connectivity and the message penetration rate can be significantly improved.

Another important issue is V2I connectivity for infrastructure-based vehicular relay networks. Ng *et al.* [121] analyzed two basic metrics related to V2I connectivity and derived the access probability and connectivity probability with closed forms, i.e., the probability that an arbitrary vehicle can access its nearby BSs and the probability that all vehicles can access at least one BS, for a given subnetwork bounded by two adjacent base stations and vehicle communicating with a base station in at most two hops. Two different types of radio propagation models are considered, including the unit disk model and the log-normal shadowing model.

Abdrabou *et al.* investigated the packet delivery delay for V2I communication via multi-hops of V2V communication in low density VANETs [122]. Based on the analysis, the required minimum number of RSUs for a straight road is derived under the constraint of the transmission delay. A complementary work was conducted in [123], in which Zhang *et al.* concerned the uplink and downlink connectivity performance between vehicle and RSUs in multi-hop scenarios. Some trade-offs between the key performance metrics and the important system parameters were fully investigated, such as the inter-RSUs distance and the traffic density, the radio coverage and the maximum number of hops.

In summary, there are many studies focusing on VANET connectivity under various scenarios. However, most of them assume vehicles drive freely in sparse traffic condition, i.e., each vehicle runs randomly and independently with little interaction among them, which is unrealistic for dense traffic condition. Furthermore, the effect of large-scale deployment of autonomous vehicles on vehicular communication is still unclear.

F. Platoon-Based V2I Communications

V2I communication, also called Drive-thru Internet access, is a primary application for platoon-based VCPSs, where all vehicles have opportunities to access Internet service from a RSU when they enter into the transmission coverage of the RSU. However, there are some typical communication deficiencies in the drive-thru scenario, such as the limited connection time [129], high transmission errors [15], unfairness in service time [124], etc. Moreover, IEEE 802.11p utilizes the well-known *carrier sense multiple access with collision avoidance* (CSMA/CA) mechanism, which may exhibit poor performance with significantly increased packet loss and average delay [125] in a dense traffic scenario. The relevant system analysis and optimization works on these issues are summarized as follows [15], [124], [126]–[133].

Data communication performance was evaluated in [126], wherein the analytical model was derived to quantify the impacts of the traffic density, the vehicle velocity, AP's transmission range and bit rates on the data downloading performance of drive-thru Internet. Luan *et al.* [127] investigated the impact of vehicle mobility on the achievable drive-thru throughput and proposed a 3-D Markov-chain-based model to represent the status of the moving node in the drive-thru process, in which the spatial zone of the node is taken into account. Different from Bianchi's model, which represents the transition between back-off counter values and stages from the microscopic perspective, Zhuang *et al.* [128] modeled the packet transmission in drive-thru Internet as a renewal reward process from the macroscopic perspective.

To overcome the poor link quality in the limited drive-thru Internet region, a V2V relay scheme [129] was proposed aiming to extend the service range of roadside APs and maintain high throughput within the extended range. By exploiting the platoon-based mobility mode, a reliable proxy was selected to help data forwarding. A cooperative MAC scheme was proposed in [130], which utilized the broadcast nature of wireless media to maximize the system throughput for data downloading scenarios. Helper nodes are selected to rebroadcast the frames when some vehicles encounter frames loss from an RSU. A joint multi-flow scheduling and cooperative downloading approach was proposed in [131] to improve the download throughput of drive-thru Internet systems. The multi-flow scheduling scheme selects the vehicle nearest the RSU with the highest rate to download information, while cooperation between vehicles can further increase the system throughput.

In [132], spectrum allocation was performed to meet the QoS requirements of vehicular applications. The vehicles can form clusters, wherein shared-use channels are used for inter-cluster communication and exclusive-use channel is used for intra-cluster communications, respectively. A hierarchical optimization model was formulated with the aim to maximize the utility of the vehicular nodes in a cluster and minimize the cost of reserving an exclusive-use channel, subject to the constraints of QoS data transmission and collision threshold with licensed users.

In [15], Jia *et al.* investigated the uplink performance of drive-thru Internet in error-prone environments. By jointly considering traffic mobility and wireless communication, they proposed a novel platoon-based cooperative retransmission scheme in which a vehicle helps to retransmit the data for its neighbors in case of failed transmission. Moreover, a 4-D Markov chain was formulated to model the cooperative retransmission behavior in the proposed scheme.

Heterogeneous velocities among vehicles lead to different sojourn time for each vehicle within the coverage of RSU. To solve this unfairness in accessing to drive-thru Internet, Harigovindan *et al.* [124] adapted the minimum contention window size based on the vehicle velocity to achieve the optimal fairness, i.e., all vehicles with different velocities have the same chance to access drive-thru Internet during their sojourn time within the coverage of RSU.

A new VANET performance optimization problem was elaborated in [133], in which the position control strategies are applied for those vehicles with controllable mobility to maximize the weighted average data rate of the bottleneck link in a VANET. This problem can be solved by two different control methods: one is the optimization theoretic approach, in which the issue is formulated as a non-convex optimization problem in a central way. However, this approach required information of the entire network. Another approach is the game theoretic approach in which each vehicle finds its position in a distributed manner, only the vehicle's neighboring information is required.

In summary, traffic dynamics have significant impact on drive-thru Internet system. To improve the system performance, an efficient solution is to cooperatively access to RSU among vehicles by exploiting the characteristic of traffic dynamics, for example, the platoon-based driving pattern or controllable vehicle position distribution.

VI. System Verification and Validation

Simulation is considered as an effective tool for VCPSs verification as practical VCPSs implementation and deployment require high cost and intensive labor. In this section, we first briefly review traffic mobility simulators and networks simulators, respectively, then we indicate the requirement for coupling the two types of simulators to evaluate the system performance. In particular, we take Veins as a case study to illustrate how the coupled simulator works interactively.

A. Traffic Mobility Simulators and Network Simulators

The major function of a traffic mobility simulator is to provide an accurate mobility model of each vehicle as well as interactions between them in virtual traffic environment, so that relatively realistic traffic information can be obtained from the simulator. This process may be essentially regarded as the description of the physical process of the VCPSs. On the other hand, a network simulator mainly evaluates the networking performance of each vehicle in a VANET, which corresponds to the computing and communication process of VCPSs.

1) Traffic Mobility Simulators: Traffic mobility can be classified into the macroscopic and microscopic model in view of the traffic flow granularity. Some related overviews have been given on traffic mobility simulators [26]. Since we focus on the interaction between the traffic mobility and VANET, we only consider the microscopic traffic mobility simulators.

Generally, a traffic mobility simulator consists of three major components: (1) motion constraints, such as road topology, intersection policies, speed limitations, multi-lane features and so on. (2) traffic generator which mainly includes trip generation, mobility pattern and lane changing behavior. (3) simulator interface, such as vehicle traces, visualization tools, program platform, interface with other software, etc.

Some typical traffic mobility simulators include VISSIM [134], VanetMobiSim [135] and SUMO [136].

VISSIM is a microscopic interval-based traffic flow simulation software developed by PTV AG. It has the ability to achieve multi-modal simulation with different types of traffic such as vehicles, public transport, cyclists, pedestrians, etc., all of these types can interact mutually. VISSIM supports 3D visualizations for real-time traffic status. Moreover, VISSIM provides the dedicated user interface by which external signal control systems and user-defined signal control logic can access the simulator.

VanetMobiSim is an agent-based vehicular traffic simulator which can support realistic automotive motion models at both macroscopic and microscopic levels. At the microscopic level, it provides mobility models such as IDM with Intersection Management (IDM/IM), IDM with Lane Changing (IDM/LC) and an overtaking model (MOBIL), which realistically describes interactions among inter-vehicle and vehicle-to-infrastructure.

Simulation of Urban MObility (SUMO) is an open source, purely microscopic, multi-modal traffic simulator. It implements the simulation based on space-continuous and time-discrete vehicle movement, allows defining different vehicle types and supports different car-following models such as IDM, Krauss model and PWagner model. SUMO can also read networks from other traffic simulators, for example, VISUM, VISSIM, or MATsim. Specifically, SUMO allows an external application to connect to and interacts with a simulation via a general traffic control interface, which could make it possible to bi-directionally couple traffic simulators and network simulators.

2) Network Simulators: They are commonly used to model and test the performance of networking protocols, which may cover from the physical layer to the application layer. In the following, we briefly introduce two popular open-source tools: NS-3 [137] and OMNeT++ [138], which are all based on a discrete-event simulation core.

NS-3 is a discrete-event network simulator written in C++. As the new successor of NS-2, NS-3 supports both wired and wireless networks, and in particular has imported more features suitable for VANETs, like the enhancements in device and channel models or an implementation of vehicular mobility models. Furthermore, 802.11p MAC entity and IEEE 1609 standards have been implemented by a Google Summer of Code project that finalized in September 2013 [26].

OMNeT++ is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators. It is free for academic and non-profit use, being widely used in the global scientific community. OMNeT++ supports many domain-specific functional networks and mobility models independently developed by other model frameworks. For example, MiXiM is an OMNeT++ modeling framework created for mobile and fixed wireless networks

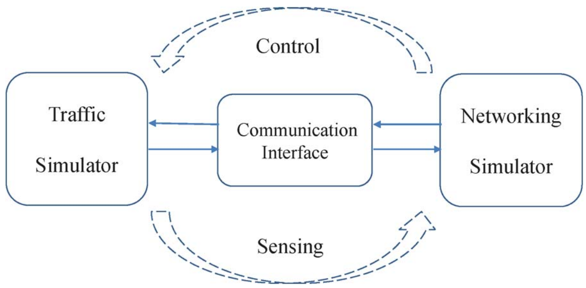

Fig. 9. Federal architecture of the integrated simulators.

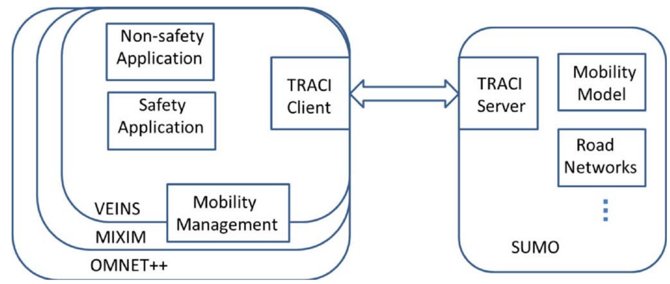

Fig. 10. Veins architecture.

including VANET. It offers detailed models of radio wave propagation, interference estimation, radio transceiver power consumption and wireless MAC protocols.

B. Integrated Simulators and Veins

As stated previously, vehicle platooning under VANET environment is envisioned as a typical VCPS tightly coupling both vehicular networking and platoon mobility. To precisely simulate such a platoon-based VCPS, a federated simulation architecture is required which combines the well-developed traffic simulator and network simulator through general traffic control interfaces, as illustrated in Fig. 9 [18].

When a simulation task starts, the traffic simulator periodically disseminates the real-time tracking information of each vehicle to the network simulator via the communication interface. On the other hand, in the network simulator, if one vehicle receives the alerted message from another one which demands mobility pattern changing to avoid collision, it will instantly send the corresponding command via the communication interface to the traffic simulator. The traffic simulator then will change the vehicle's mobility based on the command message. Consequently, in this way the two primary processes in platoon-based VCPS, communication process and mobility process, can be simultaneously simulated and coupled together.

Some typical integrated simulators include TraNS [139], iTETRIS [140] and Veins [141], etc. TraNS federates a traffic simulator SUMO and a networking simulator NS-2, while iTETRIS integrates SUMO and NS-3, and Veins couples SUMO with OMNET++. All the three integrated simulators utilize the "Traffic Control Interface" (TraCI) as the communication interface which adopts a very similar command-response approach and a TCP connection.

Veins is an open source Inter-Vehicular Communication (IVC) simulation framework which is composed of network simulator OMNeT++/MiXiM and the road traffic simulator SUMO. The architecture of Veins is shown in Fig. 10. To perform VCPSs evaluations, both simulators run in parallel and connect to each other via TraCI, with OMNeT++/MiXiM acting as the TraCI client and SUMO acting as the TraCI server. This implementation allows bidirectionally-coupled simulation of road traffic and network behavior. Aside from modules to model and to influence road traffic, Veins offers a comprehensive suite of IVC-specific models that can serve as a modular framework for developing user own applications.

Veins has already been utilized to design various VCPSs applications, such as infotainment service [142] and vehicle platooning system [70]. Next, We will illustrate how to simulate a CACC system by way of Veins.

A typical CACC simulation model in each vehicle consists of three elements: communication, vehicle mobility behavior and control strategy. Veins simulates the communication networking behavior, while SUMO simulates the mobility behavior of vehicles. To implement the control strategy for CACC, we normally utilize Matlab/Simulink as an effective tools to design an appropriate controller in advance, then implement the controller in C++ source codes and integrate it into SUMO. The simulation sequence is presented as follows.

1) At each simulation time step, a node (vehicle) in Veins first sends the related traffic information received from its neighbors (which depends on the networking topology designed by CACC) to SUMO.
2) For each vehicle in SUMO, the received reference information from Veins is used as the input of the controller to evaluate a desired acceleration and velocity.
3) SUMO is then implemented at the next time step to simulate the movement of vehicle.
4) After moving the vehicle, SUMO will send the vehicle trace back to Veins. Then Veins updates the corresponding movement of communication node (vehicle) in the networking graph according to the vehicle position information from SUMO.

VII. Challenges and Open Issues

In this section, based on the existing studies on the fundamental issues in platoon-based VCPSs, we discuss some open issues for future research.

A. Deployment of Platoon-Based Driving Pattern

Although vehicle platooning has been widely accepted as the future promising driving pattern, it is still challenging to be autonomously implemented in highways.

Many factors may affect the incentive to form platoon for the individual vehicle, such as different destinations for each vehicle, heterogeneous vehicle types, or even the driver's distrust of the platoon-based driving pattern.

Technically, the current platoon-based cooperative driving is vulnerable to unreliable vehicular communications. In view of the cyber process of VCPSs, the status of vehicular networking is dynamic, i.e., the performance metrics such as the packet reception ratio and the transmission delay are changing within a certain range. Thus one critical issue is how to adaptively control the platoon-based cooperative driving system in such a dynamics vehicular networking. For example, most of presented control systems assumed that to achieve the control performance, a constant minimum sampling frequency is desired. However, a variable sampling frequency seems more suitable for occasional disturbance in traffic flow: lower sampling frequency is adopted for stable traffic flow and higher sampling frequency is required when traffic disturbance occurs.

The local situation awareness is considered as a prerequisite for most of decentralized platoon-based VCPSs design. However, the practical imperfect communication channel with packet loss and transmission delay impairs the accuracy of the local situation estimation and accordingly has a negative impact on the system performance. Therefore, it is still a challenge to accurately and timely estimate the local traffic condition under imperfect vehicular networking environment.

In addition, platoons are normally assumed to have unified system parameters, such as the same inter-vehicle distance within the platoon and the same model parameters (acceleration, actuator parasitic delay, etc.) for all vehicles. The further work is expected to pay attention to the heterogeneous platoon-based cooperative driving, which is more closing to the practice.

It shall be noted that the accuracy of the relative position parameters are very critical for vehicle platooning implementation, especially for the communicated-GPS-only platoon system [143]. Many related studies have been focusing on improve the GPS precision. However, the information from GPS is unavailable under some conditions, e.g., when vehicles running under tunnels or bridges. To achieve the accurate position parameters in such cases, the integrated GPS with on-board sensors (such as radars or infra sensors) as well as the sensor data fusion should be taken into account.

Multi-metrics optimization on the platoon-based driving is also an open issue, in which not only the platoon stability is regarded as the primary control objective, but also the traffic efficiency such as travel time and energy saving is involved.

B. Communication for Vehicular Platooning

As we stated previously, the current IEEE 802.11p-based vehicular communications meet many challenges, e.g., the lower packet reception rate especially in case of a highly mobile and dense deployment. Although various solutions have been proposed in the past few years, the future DSRC evolutions are expected to further improve the performance of vehicular communications. Some potential enhancements [144] may include: adopting more advanced PHY technologies such as multiple-input-Cmultiple-output (MIMO) support (IEEE 802.11n) [145] and multiple stream support (IEEE 802.11ac) [146], more flexibility in channelization and better MAC congestion control protocols. In addition, the extended vehicle to pedestrian communications could enhance safety to pedestrians and cyclists.

Moreover, vehicular communication protocols dedicated for platooning application need to be further investigated. For example, under the platoon-based driving pattern, traditional V2V and V2I communications are transferred to intra/inter-platoon and platoon to RSU communications. In this case, it is important to develop more effective protocols for data dissemination. To facilitate individual vehicles forming into platoon, the standardization for platooning application is also essential. The envisioned protocols should specify cooperative platoon behaviors among vehicles, such as platoon merging and splitting.

Another critical issue is cyber security, which has attracted more concerns with the large-scale deployment of vehicular networks. Specifically, the cooperative platoon-based driving pattern is more vulnerable to vicious attacks which may lead to traffic chaos even car crash on road. In such a platoon-based VCPS, one vehicle may suffer the potential attacks from infrastructures or other vehicles. The typical attacks include the fake message (e.g., BSM) and the poisoning of map database locally stored on vehicles. The mitigation techniques mainly require the setup of an authentication system and a misbehavior detection system [147].

C. Exploring Platoon-Based Traffic Flow and Vehicular Networking

Vehicle platooning has been regarded as the promising technology to deal with transportation challenges, e.g., to mitigate traffic congestion and to reduce vehicle emissions. However, it is not yet clear how and to what extent the current traffic flow is influenced by this type of cooperative driving pattern. In other words, can the platoon-based traffic flow be characterized or modeled? In addition, due to the increasing market penetration rate of autonomous car, both platoon-based driving and individual driving could coexist on road for a period of time. It is also crucial to investigate how this coexistence has impacts on road safety, traffic flow efficiency, road capacity and fuel economy.

Some recent work has started to investigate on these issues. For example, a platoon-based macroscopic model was proposed in [148] which verified that platoon-based driving behavior of intelligent vehicles enhances the stability of traffic flow with respect to a small perturbation. However, the research on this issue is expected to go further.

Likewise, vehicular communication may also be affected by the platoon-based driving pattern. However, due to limited number of vehicles experiments implemented on road, it is not yet clear what is the network performance under large-scale deployment of V2V communication, such as network connectivity and throughput. Towards this, the first large-scale field trials on V2V communication, e.g., the Ann Arbour Safety Pilot [149] in the US and the simTD project [150] in Germany, are in progress.

In addition, a more realistic highway traffic simulator is needed through which these platoon-based driving scenarios can be run to evaluate the actual effects on traffic flow and VANET performance.

D. Coexistence of Hybrid Applications

With the rapidly growing cloud computing services, future VCPSs demand more applications being simultaneously deployed in single vehicle. One big challenge is how to optimize the shared radio resource allocation and schedule among the various applications. Specifically, the jointly considering the

QoS of both the periodic and event-triggered communication tasks has not been fully addressed.

A top-down approach is commonly utilized to design VCPSs in which the application requirements are transformed and vertically implemented at one or more networking layers. However, when multiple applications coexist, different design objectives may conflict at the same layer. In this case, the tradeoff design for whole VCPSs is demanded.

Moreover, previous studies have not fully addressed the tight relationship between traffic dynamics and networking performance, which could be utilized to optimize the QoS of the heterogeneous vehicular networks. For instance, in case of high dense traffic condition, vehicle dynamics follow the car-following model, which can be utilized to implement cooperative communication among the adjacent vehicles with similar driving pattern.

In addition, since vehicles form a platoon-based pattern, it is critical to design a hybrid vehicular communication system which not only offer high throughput and low delay for data transmission, but also guarantee the timely and reliable control information dissemination among vehicles.

Clearly, platoon-based VCPS is envisioned as an interdisciplinary subject which tightly couples computation, communication with control. However, due to the nature gap among these disciplines, a cross-disciplinary methodology for modeling and designing such a complex system is still ongoing.

VIII. Conclusion

Vehicle platooning is a promising driving pattern and has become the future trend in the modern transportation system. In this paper, we have provided a comprehensive survey on platoon-based vehicular cyber-physical systems. We first demonstrate two basic aspects of platoon-based VCPSs: 1) the vehicular networking architecture and standards; and 2) the platoon dynamics which involve mobility model and control strategy for the platoon. We then comprehensively elaborate some fundamental issues in platoon-based VCPSs, including platoon/cluster management, cooperative platoon driving, platoon-based vehicular communications, etc. The corresponding simulators as the effective tools for system verification are also discussed. Finally, we have presented the challenges and open issues regarding platoon based VCPSs. We hope this survey will provide better understanding the existing developments and the future trend of platoon-based VCPSs.

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