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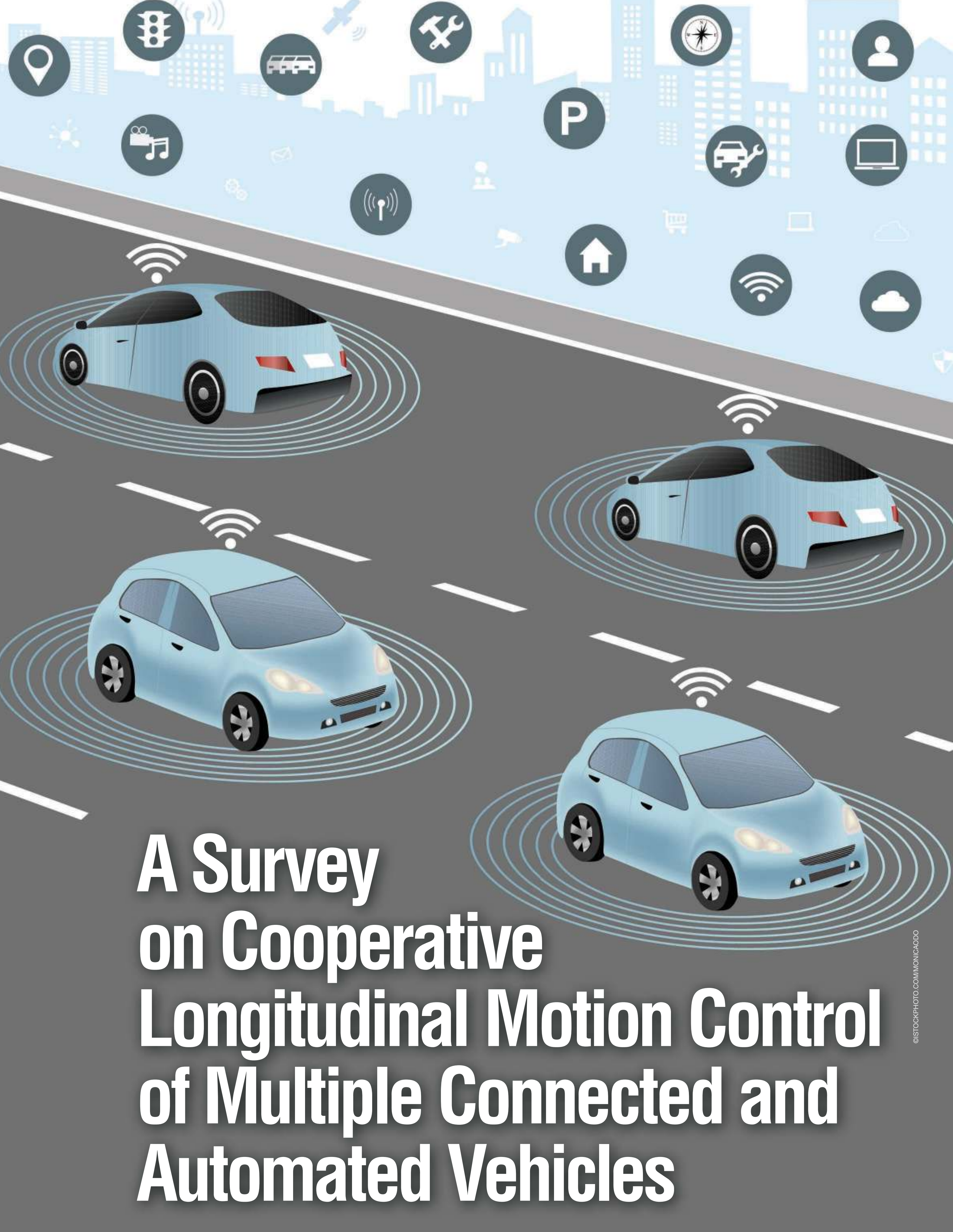
# A Survey on Cooperative Longitudinal Motion Control of Multiple Connected and Automated Vehicles



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***Abstract***—Connected and automated vehicles (CAVs) have the potential to address a number of safety, mobility, and sustainability issues of our current transportation systems. Cooperative longitudinal motion control is one of the key CAV technologies that allows vehicles to be driven in a cooperative manner to achieve system-wide benefits. In this paper, we provide a literature survey on the progress accomplished by researchers worldwide regarding cooperative longitudinal motion control systems of multiple CAVs. Specifically, the architecture of various cooperative CAV systems is reviewed to answer *how cooperative longitudinal motion control can work* with the help of multiple system modules. Next, different operational concepts of cooperative longitudinal motion control applications are reviewed to answer *where they can be implemented in today's transportation systems*. Different cooperative longitudinal motion control methodologies and their major characteristics are then described to answer *what the critical design issues are*. This paper concludes by describing an overall landscape of cooperative longitudinal motion control of CAVs, as well as pointing out opportunities and challenges in the future research and experimental implementations.

## I. Introduction

The rapid development of our transportation systems has brought a great deal of convenience in our daily life, allowing both people and goods to be transported domestically and internationally in a safe and dependable manner. It is estimated that more than one billion motor vehicles are owned by people around the globe, and it is likely that this number will doubled within one or two decades [1]. However, a number of issues related to this growth are of concern. In terms of safety, more than 30,000 people perish from roadway crashes on U.S. highways every year [2]. In terms of mobility, Americans lost an average of 97 hours a year due to traffic congestion, costing them nearly $87 billion in 2018, an average of $1,348 per driver [3]. In terms of environmental sustainability, 44.3 billion liters of fuel were wasted worldwide due to traffic congestion in 2015 [4].

To address the aforementioned issues, connected and automated vehicle (CAV) technology has undergone significant development in the last decade. The level of connectivity and automation within our vehicles has greatly increased, allowing these "equipped" vehicles to not only drive under partial or full automation using information from on-board sensors, but also behave cooperatively through vehicle-to-everything (V2X) communications. At the heart of this

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technology, cooperative longitudinal motion control has been widely studied and developed by researchers around the world during the past several decades, allowing CAVs to cooperate with each other to form or maintain certain longitudinal formations. This is accomplished by the utilization of motion control systems that rely on on-board sensors and vehicle-to-vehicle (V2V) and/or infrastructure-to-vehicle (I2V) communication. The V2V communication mainly provides real-time state information (*e.g.*, acceleration, speed, position) regarding the forward vehicle or vehicles, while the I2V communication primarily provides information about downstream traffic conditions or local speed suggestions as part of an active traffic management approach. By cooperatively controlling the longitudinal motions of multiple CAVs, some or all of the following transportation system benefits are possible: 1) Roadway capacity can be increased due to the reduction of gaps between vehicles; 2) Energy consumption and pollutant emissions can be reduced due to the reduction of unnecessary speed changes and aerodynamic drag on following vehicles; 3) Driving safety is potentially improved since the detection and actuation time is shortened compared to manually driven vehicles; further, downstream traffic information can quickly be propagated upstream; 4) Customer satisfaction can be improved since the system behavior is more responsive to traffic changes, and the shorter following gaps can deter cut-ins of other vehicles [5].

Several research efforts reported in the literature have aimed at reviewing the cooperative control strategies of CAVs from a mathematical modeling perspective, such as [6]–[8]. In contrast, this paper addresses the different aspects of CAV longitudinal motion control, not only from a theoretical point of view, but also from the perspective of experimental implementations. More generally speaking, this paper aims to answer three questions regarding cooperative longitudinal motion control: 1) *How* does it work with the utilization of multiple modules in a CAV system? 2) *Where* in the transportation systems can it be implemented? 3) *What* issues may be encountered during the design? It is important to point out that the scope of this survey paper is limited to the cooperative control of *multiple* CAVs, and does not address many existing efforts on various control methodologies for a *single* CAV (potentially with respect to the infrastructure).

The remainder of this paper is organized as follows: Section II reviews the general architecture of a CAV system, which answers the question on how cooperative longitudinal motion control works. The question of where cooperative longitudinal motion control can be implemented is addressed in Section III, which reviews the existing literature of adopted CAV technology in various traffic scenarios. Section IV answers the question of what issues will be encountered while designing the cooperative longitudinal motion control. To this end, we have categorized the major control issues described in existing literature into three types: dynamic heterogeneity, communication issues, and string stability. Finally, Section V concludes the paper and raises some open questions that need to be addressed in future research and development.

## II. Architecture of CAV Systems

Although this paper focuses on the "control" aspect of CAV systems, the control system cannot work without involvements of other modules. In general, we will consider a communication module, perception module, localization module, and planning module as shown in Fig. 1. In this section, we summarize the system architecture of CAV systems based on existing literature, aiming to answer how cooperative longitudinal motion control works within an integrated environment of subsystem

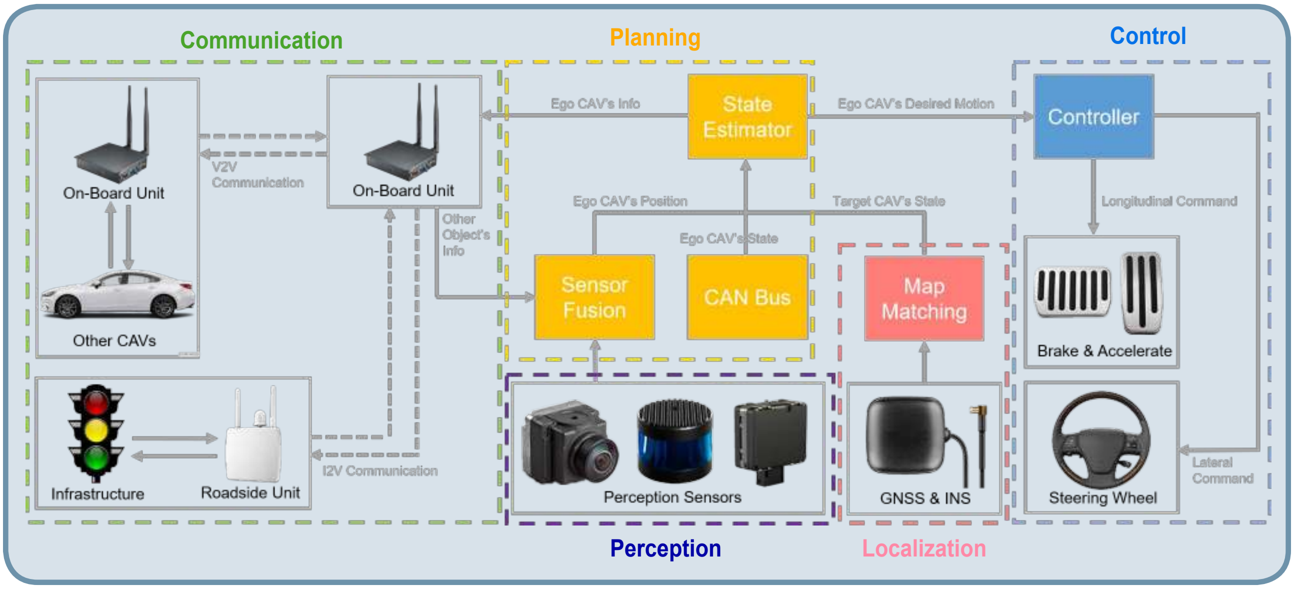

**FIG 1** General architecture of a CAV system with five modules: Communication, localization, perception, planning, and control.

modules. Both hardware and software are being developed to realize the cooperative automation functionality, where CAV systems are always installed as a set of distinct additional components in factory-standard production vehicles. While designing the architecture for CAV systems, two major engineering requirements are usually considered: 1) Each function in the system architecture should be a self-contained unit that does not depend on other same-hierarchical-level functions, except for receiving its inputs; 2) The developed system architecture should be minimally intrusive in the existing vehicle architecture [9].

Applications based on intensive international research on cooperative automation of CAVs have been developed and implemented through numerous demonstrations. We have reviewed several existing CAV designs and implementations for cooperative automation purposes, such as those from the Grand Cooperative Driving Challenge (GCDC) [9]–[12], the University of California at Berkeley's PATH Program [13], and the Federal Highway Administration (FHWA)'s CARMA platform [14]. Based on this review, we summarize the general architecture of a CAV system as illustrated in Fig. 1.

### *A. Perception Module*

Perception sensors equipped on a CAV system, such as cameras, radar and/or LIDAR, are the primary sources of information regarding surrounding vehicles and the road environment. This sensor information is typically integrated and then provided to the planning module.

The perception sensors also play a crucial fallback role in terms of acquiring information about the driving environment, when information about other CAVs or the infrastructure from V2V/I2V wireless communication is impeded by wireless dropouts or channel congestion. Note that the scope of this paper is limited to longitudinal motion control of CAVs, where most existing related implementations are realized as SAE Level 1 automation [15]. Lateral control maneuvers like lane keeping and lane changing are considered to be conducted by human drivers. Therefore, the perception sensors of such CAV systems need to focus primarily on providing the preceding vehicles' information and/or traffic signals' information, such as the speed of the preceding vehicles, the clearance with respect to the immediately preceding vehicle, and the Signal Phase and Timing (SPaT) information.

### *B. Communication Module*

The communication module of a CAV system facilitates real-time and reliable wireless V2V/I2V communication. As can be seen from the communication module in Fig. 1, hardware communication devices installed on the ego-CAV receive information from other CAVs, while simultaneously sending its own state information to others through V2V communication. Additionally, it can also exchange information with the roadside infrastructure through I2V communication. The communication module of a CAV system can provide additional information that cannot be readily detected by perception sensors, and can generally provide information more quickly than through sensor detection and processing. This includes:

- Information from other vehicles that are beyond sensor ranges or that are occluded from view by intermediate vehicles, or due to horizontal/vertical road curvatures.
- Vehicle status information from other vehicles that cannot be sensed by remote sensors (wheel speeds, fault status, performance capabilities, etc.).
- Immediate notification of speed change or steering commands as soon as they have been issued to another vehicle's actuators, even before the vehicle's motion has begun to change.
- Negotiations between cooperative vehicles regarding desired maneuvers (merging, lane changing), so that these can be done more safely and efficiently.

The information flow topology defines the origins and destinations of information transmission among CAVs and the infrastructure, thus playing a very important role in information exchange and sharing [16]. Some of the representative information flow topologies of CAVs are illustrated in Fig. 2. The first four are V2V-only information flow topologies, where no roadway infrastructure element gets involved in the information flow. The latter three are V2V/I2V-hybrid information flow topologies, where the roadway infrastructure element (*e.g.*, traffic signal, variable speed limit, etc.) either sends its information to the leader of a vehicle platoon, or broadcasts it to all vehicles in the platoon. Red color vehicles in those topologies denote CAVs that are in the "broadcast" mode, which not only directly send their own parameters to their immediate followers, but also share to some other following vehicles in the platoon. It should be noted that different information flow topologies may introduce various issues with respect to communication and string stability, which are reviewed and discussed in Section IV.

### *C. Localization Module*

The localization module of a CAV system typically consists of two different hardware components: GNSS & INS (*i.e.*, global navigation satellite system and inertial navigation system) and the coupled map matching component.

The GNSS & INS component serves as a combined satellite & inertial-based navigation system, which can be optionally augmented by terrestrial reference stations [10]. This component can provide precise position, movement, and posture measurements for the self-localization and attitude determination of CAVs by differential correction. It should be noted that the relative positioning accuracy between the ego CAV and other equipped objects (*i.e.*, other CAVs and/or infrastructure features) is not solely determined by the GNSS update frequency. It is also based on the accuracy of the GNSS position measurements, and communication delay. Considering the aforementioned factors, a GNSS update rate of 10 Hz is sufficient for general cooperative automation applications, and a faster sampling rate based on GNSS & INS integrated measurements will reduce positioning errors at higher vehicle speeds [17].

Map matching is important to a CAV system, especially for some of the applications where the ego CAV needs to adjust its longitudinal speed to merge with other CAVs coming from another lane at an intersection or a highway ramp. The correct assignment of CAVs to lanes is important, as well as their relative longitudinal gaps. Therefore, a map of the implementation environment can be built *a priori*, and match with the vehicle coordinates (*i.e.*, longitude, latitude, heading) received from the GNSS & INS component. To compute distances between the ego vehicle and other vehicles, traffic signals, merging points or other objects, those objects need to be adjusted to their closest lanes by retrieving the nearest neighbor GNSS track vertex [10]. Each object's coordinates can then be matched onto the associated lane to obtain its projection point, and then the relative longitudinal distance between two objects can be derived by summing the segment lengths falling in between those projection points on the same GNSS track (if they are on the same lane), or by calculating the difference of distances to the merging point of two GNSS tracks.

### D. Planning Module

The planning module processes data received from the communication module, the localization module, as well as the perception module, and sends motion commands (of the ego vehicle) to the control module. The planning module of a CAV system usually includes the following components: sensor fusion, a vehicle controller area network (CAN bus), and a state estimator.

The sensor fusion component processes all sensing data received from the perception sensors and the communication module of the CAV system, and sends it to the state estimator component. Unlike more highly automated vehicle (AV) systems that require the entire surrounding environment to

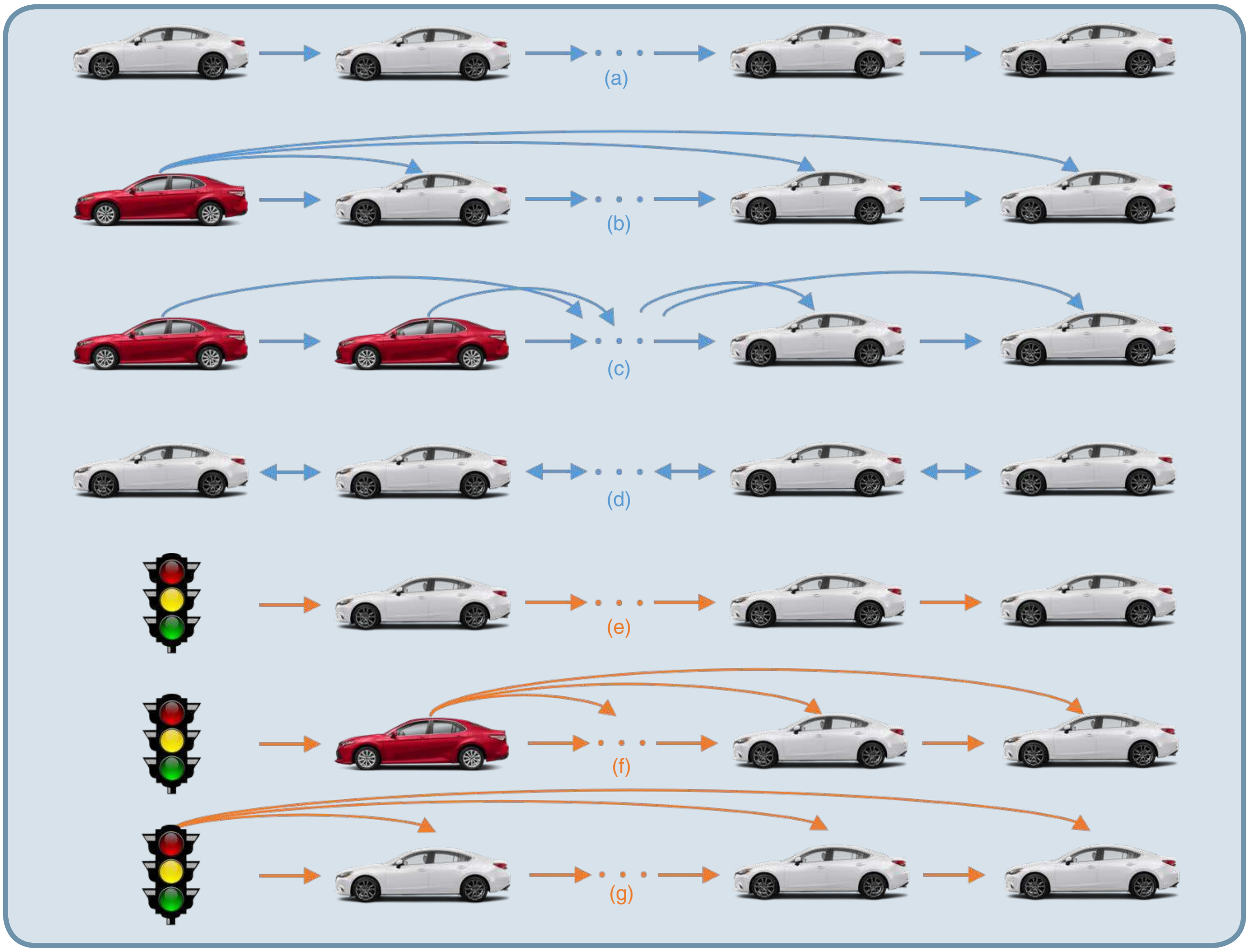

**FIG 2** Typical information flow topologies: (a) predecessor-following (PF), (b) predecessor-leader-following (PLF), (c) multiple-predecessor-following (MPF), (d) bidirectional (BD), (e) PF with the infrastructure sending information to the leader, (f) PLF with the infrastructure sending information to the leader, and (g) PF with the infrastructure broadcasting information.

be precisely measured by multiple perception sensors, cooperative longitudinal motion control discussed in this paper requires less information regarding the surrounding environment, and therefore less data is fused in the sensor fusion component. However, this component is crucial in harnessing the complementary nature of the vehicle's sensors and communication systems, based on the following issues that Kianfar *et al.* encountered during the development of their CAV system [11]: 1) When the ego-CAV is under tunnels or bridges, information from GNSS will be unreliable. Therefore, in addition to the INS, the position of the CAV can also be improved by using the sensing data measured by the perception sensors if it can be associated with a reference map; 2) When the V2V communications are impaired, the data measured by perception sensors will still be available to estimate the relative position, speed, and acceleration of the immediately preceding vehicle.

Although the GNSS & INS component is able to provide the speed of the ego-CAV, its measurement is highly affected by the GNSS connection and precision. For example, if the ego-CAV is traveling through a tunnel, speed information will not be available from GNSS. More accurate and timely speed measurements should be obtained from the wheel-speed sensors that are an integral element of production anti-lock braking and traction control systems. Therefore, wheel speed measured from the ABS system on the CAN bus is much more accurate and reliable. The CAN bus also allows the planning module of the CAV system to get access to many other vehicle sensors and states.

The state estimator component receives data from the sensor fusion, CAN bus, as well as map matching, processes the data with preset filters, and then computes a desired motion of the ego-CAV for the control module to realize. Motion planning has been developed in various ways for high-level AVs, including graph search-based planners, sampling-based planners, interpolating curve planners, and numerical optimization approaches [18]. However, since we only focus on the longitudinal motion of CAVs in this paper, the planning process in the state estimator component becomes much easier: To simply choose when and by how much to accelerate or decelerate, or else to keep the current longitudinal speed. As mentioned in the CAV system developed by Martensson *et al.* [9], the accuracy of the state estimation highly depends on the quality of the available data (*e.g.*, the accuracy, latency or the outage duration of the GNSS measurements or V2V communication, and the performance of the perception sensors under the existing environmental conditions), and also the quality of the process estimation models.

### *E. Control Module*

The control module of CAV systems consists of a software part and a hardware part: A controller component that integrates the motion control algorithms of the CAV, and the physical actuators of the CAV that actuate the longitudinal and/or lateral commands generated by the controller component. Although lateral control is not within the scope of this paper, it is still illustrated in Fig. 1 to make the CAV system architecture complete.

The controller component in this control module receives the ego-CAV's desired motion from the planning module, which includes information such as the reference trajectory or desired path of the CAV [19], the decision whether to join or leave a vehicle platoon [9], the desired position of the ego CAV in the vehicle platoon [11], or the desired arrival time at a specific location (*e.g.*, traffic signal stop bar or ramp merging point) [20]. The cooperative longitudinal motion control, which is the major topic of this paper, will be developed and implemented in this controller component to determine the reference acceleration or speed at each time step. This reference value will then be converted into longitudinal commands for the accelerate/brake pedal of the CAV, thereby allowing it to achieve the desired motion determined by the planning module [13].

## III. Cooperative Longitudinal Motion Control Applications

The cooperative automation of CAVs can introduce benefits to current transportation systems with respect to safety, mobility, and environmental sustainability [21]. As one of its major tasks, cooperative longitudinal motion control of multiple vehicles has been widely studied. Many researchers have been focusing on the mathematical modeling and software simulation of cooperative longitudinal motion control under different cases in transportation systems, while others have been contributing a good deal of effort to the test of such systems on full-scale vehicles to verify their effectiveness in realistic traffic conditions. In this section, relevant studies are categorized into five different operational concepts: 1) cooperative adaptive cruise control (CACC) and platooning, 2) cooperative merging at highway on-ramps, 3) speed harmonization on highways, 4) cooperative eco-driving at signalized intersections, and 5) automated coordination at non-signalized intersections. In this survey paper, we consider both simulation-based theoretical work and experimental work.

As shown in the performance matrix (see TABLE I), upon finishing this survey, we qualitatively evaluated these five operational concepts based on five different criteria: 1) The extent of theoretical research reported to date; 2) The extent of experimental research reported to date; 3) The potential transportation safety benefits; 4) The potential mobility benefits; and 5) The potential environmental benefits. The first two criteria are independent from the latter three criteria, so we differentiate them by different markings in the performance matrix.

### *A. Cooperative Adaptive Cruise Control (CACC) and Platooning*

#### 1) Overview of the Operational Concept

Cooperative adaptive cruise control and platooning are terms that have been adopted and utilized relatively loosely during recent years, such that different researchers visualize different functions and capabilities when discussing CACC or platoon-based systems. At the heart of the concept is the merging of adaptive cruise control (ACC), a subset of the broader class of automated longitudinal speed control systems, with a cooperative module enabled with V2V communication and/or I2V communication [5]. In this subsection, only V2V communication-based CACC and "platoon" studies are discussed, while some I2V communication-based CACC studies are covered in some of the latter subsections.

By applying cooperative longitudinal motion control algorithms, CACC and platooning allow CAVs to form vehicle strings or platoons with shorter inter-vehicle distances, leading to increases of roadway capacity, decreases of energy consumption due to the mitigation of aerodynamic drag and unnecessary speed fluctuations, and also possibly in the long-term labor cost savings due to the elimination of human drivers in the following CAVs. A significant amount of work has been conducted so far to study cooperative longitudinal motion control in CACC and platooning, both theoretically and experimentally. Some researchers have also looked into the extreme operational case of CACC and platooning, when multiple CAVs conduct coordinated active brake control to avoid longitudinal collisions, and meanwhile mitigate the relative kinetic energy density between any pair of CAVs in the platoon [22]–[24].

The differences between CACC and platooning should be clarified to minimize confusion. CACC is a simple extension of ACC, based on the addition of information communicated among vehicles and/or between vehicles and the roadway infrastructure. Drivers may choose to enter and leave strings of CACC vehicles at will, and there are no special responsibilities for the driver or the control system of the first vehicle in the string. Platoons are more formally organized sequences of vehicles using cooperative longitudinal motion control, in which joining and leaving the platoon are managed by the control system or the driver of the first vehicle. The car following control discipline (*i.e.*, spacing policy) of CACC systems is generally based on maintaining a constant time gap, while the discipline for platoons is more likely to be based on a constant clearance distance, which makes it more challenging to achieve string stability [5].

### 2) Theoretical Research and Simulations

Extensive research has been conducted in the field of CACC, where the literature reviews conducted by Dey *et al.* and Wang *et al.* covered several different aspects of this operational concept of CAVs [25, 26]. Specifically, cooperative longitudinal motion control is considered as the core of a CACC system, since it keeps the string stability of a CACC string and avoids rear-end collisions of multiple CAVs.

Linear feedback control has been widely adopted as the key cooperative methodology for much previous CACC work. Van Arem *et al.* developed a feedback control algorithm to compute the reference acceleration, so it can be further converted to a position of accelerate/brake pedal by the vehicle model and control the motion of the CAV [27]. This proposed methodology was simulated in the microscopic traffic simulation model MIXIC to examine the impact of CACC on the traffic flow. Double-integrator consensus algorithms have been adopted widely for cooperative longitudinal motion control of CACC vehicle strings. Similar to van Arem *et al.*, many other double-integrator consensus algorithms also compute a reference acceleration based on the speed and position of the ego-CAV and its predecessor [28]–[30]. Wang *et al.* further proposed a lookup table-based approach to select the damping gain of the double-integrator consensus algorithm, satisfying different constraints of CACC strings [31].

Optimal control has been considered as another major approach for the longitudinal cooperation in a CACC string by many research studies. In general, the design of an optimal controller can be equivalently formulated as a structured convex optimization problem with multiple objectives (*e.g.*, minimizing energy consumption) and system constraints. Unlike most linear feedback control approaches that only consider vehicle speed and position as inputs, optimal control approaches often take nonlinearity and constraints into account, such as powertrain characteristics and

Table I. Performance matrix of different cooperative longitudinal motion control operational concepts.

| | Extent of Work Using CAVs | | Potential Benefit to Transportation Systems | | |
|---|---|---|---|---|---|
| | Theoretical Work | Experimental Work | Safety Benefit | Mobility Benefit | Environment Benefit |
| A. Cooperative adaptive cruise control and platooning | ✦✦✦ | ✦✦ | ★ | ★★★ | ★★ |
| B. Cooperative merging at highway on-ramps | ✦✦ | ✦ | ★★ | ★★★ | ★ |
| C. Speed harmonization on highways | ✦✦ | ✦ | ★★ | ★½ | ★ |
| D. Cooperative eco-driving at signalized intersections | ✦ | ½ | ★ | ★★ | ★★½ |
| E. Automated coordination at non-signalized intersections | ✦½ | | | ★★ | ★ |

vehicle aerodynamics. Van de Hoef *et al.* formulated a convex optimization problem with vehicle dynamics constraints for a group consisting of a coordination leader and its coordination followers, aiming to maximize the fuel savings [32]. Wang *et al.* proposed a platoon-wide Eco-CACC system, aiming to minimize the platoon-wide energy consumption and pollutant emissions with vehicle dynamics constraints at different stages of the CACC operation [33]. A further study about the intra-platoon vehicle sequence was conducted by optimization methodology [34]. Turri *et al.* studied the cooperative look-ahead control of a heavy-duty CACC system, where the fuel calculation of vehicles is formulated as an optimal control problem to find the optimal engine speed to minimize fuel consumption with traffic safety and mobility constraints [35].

It should be noted that, besides the aforementioned two primary cooperative longitudinal motion control methodologies, there are many other control approaches of CACC and platooning, including model predictive control (MPC) [11], [110]–[113], $\mathcal{H}_\infty$ control [114]–[118], sliding mode control (SMC) [119], and other methodologies [120]–[125]. Their advantages and disadvantages will be analyzed in Section IV, categorized by separate control issues.

#### 3) Experimental Implementation

The earlier research on cooperative longitudinal motion control emphasized closely-coupled platooning with higher levels of automation, including the automatic steering control designed by University of California at Berkeley's PATH Program at San Diego, California, in 1997 [36], [37]. More recent research has come from the opposite direction, building on production ACC systems that only automate vehicle following, while the drivers perform the other functions. PATH prototyped the first such cooperative ACC system in the early 2000s [38] and used it for a series of experiments with drivers from the general public to determine their preferences for use of the available time gaps between 0.6 s and 1.1 s in public freeway traffic [39]. A second-generation CACC system was prototyped by PATH and Nissan on four Infiniti M56 vehicles and was tested under a variety of conditions to ensure string stability of the multiple-vehicle string [13]. Research on these vehicles also showed the stability enhancements and performance improvements of the CACC system compared to conventional ACC and to an ACC controller based on the popular IDM+ vehicle following model. The car-following dynamic responses of these ACC and CACC systems were used to derive simplified car-following models for incorporation into traffic microsimulations [40], and those models have been applied to several studies showing the potential for CACC to dramatically improve traffic flow at higher market penetrations and traffic volumes [41]–[43]. Besides the related work conducted by the PATH program, a good deal of pioneering work has also been accomplished by researchers from the Netherlands. The Netherlands Organization for Applied Scientific Research (TNO) equipped several Toyota Prius with CACC functions to conduct highway vehicle platooning [44]. Advanced vehicle platooning projects were completed in the GCDC held in the Netherlands in 2011 [45]. This challenge aimed to support and accelerate the introduction of CAVs in everyday traffic, and competitions like this provide public visibility about the practical case of vehicle platooning based on theoretical studies.

Note that a large portion of cooperative control work on CACC has been developed for heavy-duty trucks, which are likely to have the best business case for early adoption of the technology. These are typically referred to as "truck platooning" experiments, where an illustration of the truck platooning on highways is shown as Fig. 3. In the U.S., the PATH Program has developed three generations of proof-of-concept prototype truck platooning systems, including the first two based on Freightliner Century model tractors, and the third based on Volvo tractors [46]. Different cooperative operational concepts were developed and tested, including string formation, steady-state cruising, string split maneuvers, and managing faults or abnormal operating conditions [47]. Peloton Technology has focused on two-truck platooning product development since the company's founding in 2011, where its system has reported a 4.5% energy savings for the lead truck and 10% for the following truck [48]. In Japan, the Energy ITS project led to the development of an automated truck platooning system, which achieved a 14% energy saving when the trucks are empty-loaded and the gap is 10 m, and a 15% energy saving when the trucks are ordinarily loaded and the gap is 4 m [49]. In Europe, similar work was conducted by RWTH Aachen University's "KONVOI" project, where the field test was conducted on German highways with one leading human-driven truck and three following trucks using CACC speed control and automatic steering [50].

Truck platooning mainly aims at reducing air drag and thereby energy consumption, which is slightly different from passenger vehicle platooning which primarily aims at improving traffic flow efficiency. In the longer term, truck platooning system developers are aiming to achieve higher level automation of the following trucks so that they can be operated without drivers, which will lead to major labor cost savings and some relief from the current shortage of truck drivers.

**FIG 3** CACC for heavy-duty trucks: "Truck platooning".

## B. Cooperative Merging at Highway On-Ramps

### 1) Overview of the Operational Concept

Traffic merging at highway on-ramps is a major conflict that generates safety and mobility concerns. The difficulty arises for the driver along the on-ramp where he/she has to discern whether to accelerate or decelerate to enter the main line safely and may not have a clear line of sight to the mainline traffic.

Meanwhile, the drivers on the mainline highway may have to modify their speeds to permit the entrance of merging vehicles, thus affecting the traffic flow [51]. To address these issues, cooperative automation of CAVs has been studied and applied to the highway on-ramp merging case, where different control algorithms have been proposed and implemented to allow CAVs to merge with each other in a cooperative manner. Existing related work was reviewed by Rios-Torres *et al.* [7], Scarinci *et al.* [52], and Zhao *et al.* [53], respectively. Two points need to be noted for the merging case:

- The "merging" maneuver usually denotes a lane change behavior, which involves the lateral motion control of CAVs. However, within the scope of this survey, we are interested in longitudinal control that adopts V2V and/or I2V communication to regulate vehicle longitudinal gaps before they conduct the lane change rather than focusing on the lateral motion maneuver.
- The majority of the literature in this survey focuses on cooperative longitudinal motion control of CAVs. However, a few of them also considered the planning process, which formulated the cooperative merging into a scheduling problem. Only if all upcoming CAVs are strategically scheduled into certain merging sequences, their developed cooperative longitudinal motion controllers can be applied to control CAVs before they reach the conflict zone.

### 2) Theoretical Research and Simulation

The concept of utilizing virtual vehicles of a CACC system in the highway on-ramps cooperative merging case was originated from Uno *et al.* [54]. The proposed approach maps a virtual vehicle onto the highway main line before the actual merging happens, allowing vehicles to perform safer and smoother merging maneuver. Lu *et al.* applied a similar idea in their system, where they first formulated the merging problem differently with respect to two different geometric layouts of the road (*i.e.*, either with or without a parallel acceleration lane), and then proposed a speed based closed-loop adaptive control method to control the longitudinal speed of merging CAVs [55]. Chou *et al.* further investigated the virtual vehicle method in cooperative merging using a high-fidelity traffic microscopic model, where its effects were simulated for a baseline case with conventional manual merging as well as cases with 50%, 60%, 75% and 100% market penetration of CAVs [56].

Wang *et al.* proposed a distributed cooperative highway on-ramp merging system using both V2V communication and I2V communication, where two vehicle strings are formed on the main line and on-ramp, respectively [57]. As shown in Fig. 4, CAVs will be assigned with sequence IDs based on their arrival times at the merging point through I2V communication, and will cooperate with their neighboring vehicles (either real ones on the same lane or virtual ones on the other lane) through V2V communication. The distributed consensus algorithm was proposed to control the longitudinal motion of CAVs in this proposed system. In addition to that, agent-based modeling and simulation of the proposed on-ramp merging system were further conducted in the game engine Unity [58].

Other than the virtual vehicle concept, many other approaches were also proposed to realize the cooperative merging case. Specifically, Dao *et al.* proposed a distributed control protocol to assign vehicles into vehicle strings in the merging scenario [59]. Rios-Torres *et al.* presented an optimization framework and an analytical closed-form solution that allowed online coordination of CAVs at on-ramp merging zones [60]. In addition, Liu *et al.* investigated the impact of CACC vehicle string operation on the on-ramp merging areas [42]. Their study revealed that the highway capacity increases greatly as

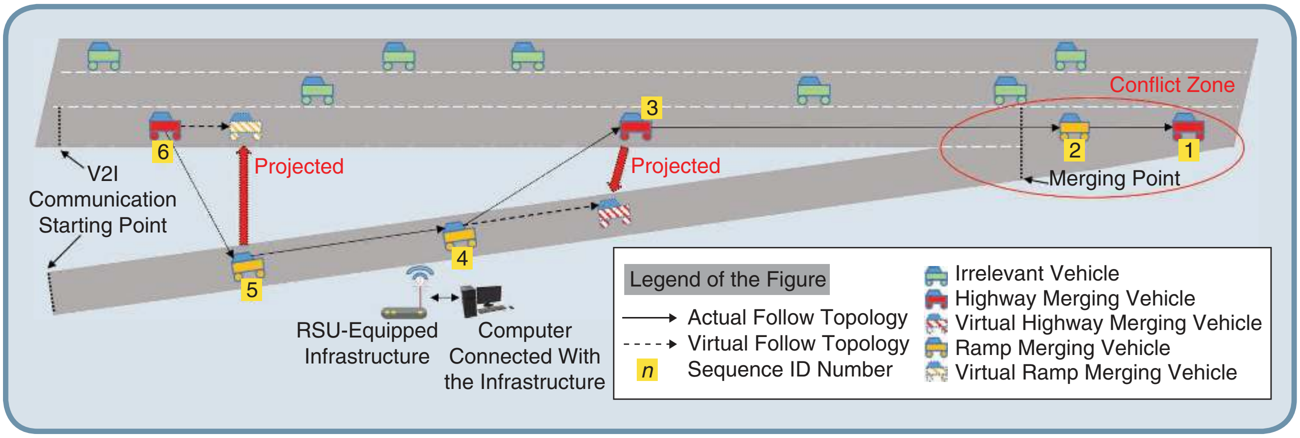

**FIG 4** V2X-based distributed cooperative on-ramp merging system [57].

the CACC market penetration rate increases, with a maximum value of 3080 veh/hr/lane at a 100% market penetration.

### 3) Experimental Implementation

While the aforementioned simulations are encouraging, their transition to experimental implementations are far from straightforward. Experiments need to be conducted on closed test courses with suitable road geometry (merging on-ramps and merge transition lanes of suitable length) and the experiments pose significant safety challenges because faulty control of vehicle speed or lane changing can lead to serious crashes. Therefore, much less experimental implementations of cooperative merging have been conducted by researchers worldwide.

Researchers from the PATH program conducted experimental tests on their cooperative automated merging systems both on their RFS test track and on the Crows Landing test track [61]. The proposed general real-time algorithm was successfully implemented on their CAVs using V2V communications to negotiate the maneuvers and coordinate the speed control of the vehicles. Milanes *et al.* proposed a fuzzy logic-based controller to act on the CAV's longitudinal motion control actuators (*i.e.,* engine and brake controls), following the references set by a decision algorithm [51]. A local control station (LCS) was developed to serve as an infrastructure, which receives information from the CAVs in its domain, analyzes this information to determine when a potentially risky situation may arise, and notifies the CAVs of suggested maneuvers through I2V communication. Their experimental implementation emulated a congested traffic situation by allowing a Citroen to use ACC to follow another one at a low speed. Another Citroen came from the ramp and merged between these two vehicles, which was decided by LCS. This work was part of the AUTOPIA program, which aimed to develop highly AVs using production vehicles and tested them in the real-world traffic [62].

Recently, FHWA conducted an experimental implementation of a connected and automated lane change maneuver using two CAVs and a manually driven lead vehicle [63]. A simplified PID controller was developed to coordinate the longitudinal distance and speed of different vehicles, and the results from their test at the Federal Law Enforcement Training Center in Cheltenham, MD showed its effectiveness in cut-in, front-join and back-join scenarios, respectively. Researchers from University of Minnesota [64], as well as East Tennessee State University [65], [66] also conducted similar experimental implementations on highway on-ramp merging scenarios using V2V communication.

## *C. Speed Harmonization on Highways*

### 1) Overview of the Operational Concept

Speed harmonization is the shorthand term often applied to the group of highway traffic management strategies that aims to reduce temporal and spatial variations of traffic speed, so as to increase safety and mobility of the transportation systems, meanwhile reducing negative impacts on the environment [67]. Within the scope of this survey, we review cooperative longitudinal motion control applications that seek to automatically adjust vehicle speeds on highways.

### 2) Theoretical Research and Simulation

Most of the foundational research efforts in this topic area (*e.g.*, [68], [69]) focused on displaying mandatory speeds on infrastructure-mounted variable speed limit (VSL) signs (which are legally equivalent to fixed speed limit signs), or sharing speed harmonization information with connected vehicles (CVs) and allowing their drivers to respond to that information. Within the scope of this survey, we also review the speed harmonization cases where the longitudinal motions of multiple CAVs are controlled by cooperative longitudinal motion control methods. Taking advantage of CAV technology, Ghiasi *et al.* proposed a speed harmonization algorithm that smooths the speed trajectories of vehicles to improve traffic mobility and reduce energy consumption [70]. Their proposed algorithm is also applicable to mixed-traffic environments where only a portion of vehicles are CAVs. Malikopoulos *et al.* developed an optimal control-based speed harmonization for CAVs, and the proposed method was estimated to reduce 19–22% fuel consumption for each vehicle compared to the baseline scenario, in which human-driven vehicles were considered [71].

As one of the traffic control approaches of speed harmonization on highways, VSL can be applied based on a variety of strategies that seek to modify different aspects of traffic flow. Some researchers combined VSL with some other cooperative longitudinal motion control design to achieve a better system performance. Wang *et al.* developed a VSL based longitudinal motion control algorithm for CAVs using I2V communication, predicting that this speed harmonization

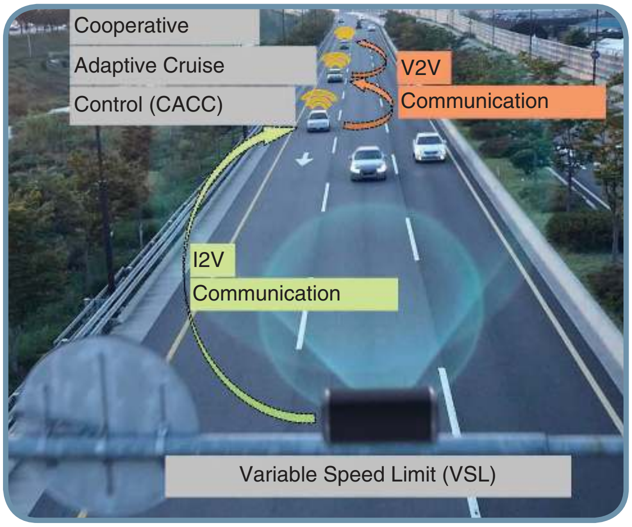

**FIG 5** Conceptual illustration of a CACC-enabled VSL system.

approach reduces total travel time and average energy consumption [72]. Kondaker *et al.* established an I2V-based VSL system, where CAVs with CACC functions can receive downstream information much in advance [73]. The sensitivity analysis predicted that the developed approach will outperform the uncontrolled scenario by 20% in travel time reductions, 6–11% in safety improvements, and 5–16% in energy consumption reductions, respectively.

#### 3) Experimental Implementation

Although there were quite a few practices and field tests of speed harmonization cases worldwide during the past decade, such as the ones conducted in the U.S., Germany [74], France [75], Sweden [76], and Greece [67], none of these used CAV technology. More recently, there were only a very few experimental implementations of CAV-based speed harmonization cases. FHWA conducted a speed harmonization implementation on I-66 near Washington, DC with three CAVs that were equipped with I2V communication, and three more probe vehicles [67]. A simplified speed harmonization algorithm was proposed to control the longitudinal motion of the CAVs, where those three CAVs were positioned next to each other to regulate the upstream traffic speed along the highway. The impacts of this speed harmonization implementation were measured by those three probe vehicles and roadside traffic speed detectors, showing that the traffic stream trajectories after this speed harmonization approach reduced oscillatory behavior as characterized using the power spectral densities of the measurements.

### *D. Cooperative Eco-Driving at Signalized Intersections*

#### 1) Overview of the Operational Concept

Cooperative eco-driving at signalized intersections using I2V communication has been a research interest for multiple research organizations globally, including “Eco-Approach and Departure” application proposed in the U.S. [77], and “GLOSA” application proposed in the U.K. [78]. In their applications, the SPaT information is sent to the approaching CAV, so itself can plan its longitudinal speed trajectory to avoid unnecessary speed changes or full stops in order to reduce energy use and emissions.

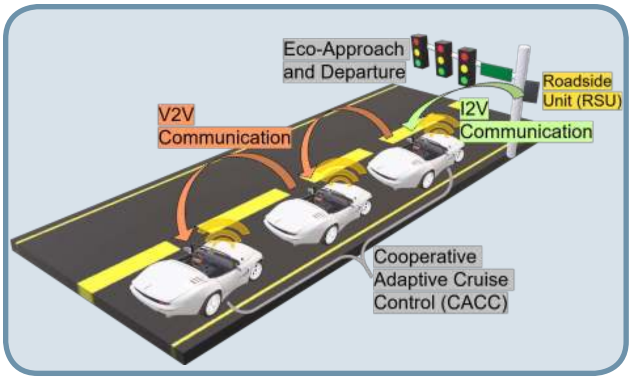

**FIG 6** CACC-enabled cooperative eco-driving at signalized corridors [83].

Based on the original single-vehicle eco-driving application, some researchers proposed to also add V2V communication in the loop, aiming to increase the system-wide benefits. As illustrated in Fig. 6, the leader of a CACC vehicle string can receive SPaT information from the roadside equipment unit, and share it with its following CAVs while traveling along signalized corridors [79]. A typical scenario of this case will be that, when the leading CAV decides to decelerate and slowly approach the intersection to avoid a full stop at the intersection during the red phase, upstream CAVs can also follow its maneuver through V2V communication based on their cooperative longitudinal motion controllers to save energy.

#### 2) Theoretical Research and Simulation

Yang *et al.* developed a cooperative longitudinal motion control algorithm for CAVs traveling through isolated signalized intersections, where the optimal longitudinal speed trajectory was computed to minimize the energy consumption, ensuring that each approaching CAV arrives at the intersection as soon as the last CAV in the queue is discharged [80]. Microscopic traffic simulation showed that the proposed system can produce vehicle energy savings up to 40% when the CAV market penetration rate is 100%. Wang *et al.* proposed a novel cluster-wise cooperative system to reduce energy consumption of CAVs traveling along signalized corridors [81]. All CAVs approaching a particular intersection are grouped into different clusters with deterministic sequences based on their estimated time-to-arrival at the intersection. Each vehicle cluster consists of several CACC platoons in different lanes, and different CACC platoons are coupled by the coordination among platoon leaders. The longitudinal speeds of all CAVs in this system were controlled by separate cooperative longitudinal motion controllers. The numerical simulation showed that the proposed cluster-wise system can reduce the energy consumption by 11%, and reduce the pollutant emissions by 18%, respectively, compared to the baseline scenario with 100% conventional vehicles in the system.

In addition to the aforementioned literature, some researchers also put their efforts into this case by considering the mixed traffic environment, *i.e.*, the penetration rate of CAVs is not 100%. Zhao *et al.* developed a cooperative eco-driving longitudinal motion control scheme for a group of vehicles with mixed CAVs and conventional vehicles [82]. A complicated interaction scheme was developed by them to allow CAVs and conventional vehicles to cooperate with each other, and the numerical simulations with different penetration rates showed the overall energy consumption continues to drop as the penetration rate of CAVs increases. Wang *et al.* proposed a cooperative eco-driving system whose idea can be simply illustrated by Fig. 6 [83]. Microscopic simulation was conducted using real-world traffic data (traffic count and SPaT), and the results showed that under a certain penetration rate of CAVs in the traffic environment, the proposed cooperative eco-driving application may even introduce negative energy impact on the traffic environment, due to the conservative driving behavior of CAVs and the lack of cooperation between a CAV and a conventional vehicle.

Another scenario at signalized intersections in which cooperative longitudinal motion control can make a significant difference is likely to be the coordinated start of CAVs. Shladover *et al.* specified in their work that, even if the I2V communication is not adopted in this scenario, the first CAV stopped at a signal in a queue can broadcast its state information so that any following CAVs can accelerate in a synchronized fashion [5]. It was expected that cooperative longitudinal motion control of multiple CAVs in the string will enable a much quicker clearance of the queue at the signal, increasing the intersection throughput or facilitating the selection of shorter signal cycles without sacrificing throughput.

A higher dimension of CAVs conducting cooperative eco-driving at signalized intersections is the joint optimization of SPaT information and vehicle trajectories to find the global optimum for the combined traffic and vehicle control problem [84]–[87]. In those studies, different numerical and microscopic traffic simulation results showed that greater environmental benefit and/or mobility benefit of the signalized intersections can be gained than from the aforementioned approaches, where only cooperation among multiple CAVs is considered. However, such studies may not be applicable to our current traffic environment, since many of them made the assumption that all vehicles in the system are CAVs [88], or all traffic signals have fixed cycle lengths [89].

#### 3) Experimental Implementation

A pioneering work of eco-driving at signalized intersections was jointly conducted by University of California, Riverside, BMW Group and PATH in FHWA's exploratory advanced research (EAR) program in 2012 [90]. It was focused on providing advice to the driver about the recommended speed to approach the signalized intersection in a smoother way, and hence to reduce fuel consumption. This basic concept was then extended to the AERIS Project's Eco-Signal Operations scenario [91], [92], and some recent eco-driving projects as well [93]. The Multi-Modal Intelligent Traffic Signal System (MMITSS) project developed a family of intersection signal control applications for CAVs, with goals of eco-driving and improving efficiency and throughput of the transportation systems [94]. When CAVs reach a high market penetration and cooperative longitudinal motion control can be applied, the general intelligent traffic signal control (ISIG) can ensure that CACC strings are not broken by signal phase changes, allowing all CAVs in the string to travel through the intersection within the same green phase.

Although there were several projects focused on the cooperative control of a single CAV with respect to traffic signals, to this stage, there is no published experimental implementation about the cooperative control of multiple CAVs and traffic signals. However, including the AERIS, MMITSS, the U.S. Department of Energy's SMART Mobility project [95], and the FHWA's TOSCo project [96], there are several ongoing projects in the U.S. that are looking into testing this use case with realistic CAVs. It can be expected that more experimental implementations on cooperative eco-driving at signalized intersections will be conducted by public agencies and research organizations worldwide in the coming years.

### E. Automated Coordination at Non-Signalized Intersections

#### 1) Overview of the Operational Concept

The cooperative automation of CAVs at non-signalized intersections has been another popular topic in the research field of intelligent transportation systems for a long time. Since intersections are one of the most common traffic conflict situations, much work has been conducted to increase traffic safety and improve traffic flow by applying V2V communication and/or I2V communication. Specifically, approaching CAVs can be assigned specific sequences by the proposed planning/scheduling algorithms, and their motions will be controlled by the proposed cooperative longitudinal motion controllers once the planning/scheduling is finished.

Although the concept has been appealing for researchers, who have produced many simulation studies, there are serious impediments to practical realization of the concept: It ignores the needs of pedestrians and cyclists; It requires a 100% market penetration of highly automated vehicles; It is severely fault intolerant, since even minor errors in the motion of a vehicle are likely to cause severe crossing-path crashes with vehicles traveling in the orthogonal direction.

#### 2) Theoretical Research and Simulation

Pioneering work of automated coordination of multiple CAVs at non-signalized intersections were conducted by researchers in University of Texas at Austin. Dresner *et al.* proposed a multi-agent automated intersection system, where the reservation-based approach was shown to outperform current intersection with either traffic lights or stop signs in a simulation study [97]. On top of that, Fajardo *et al.* developed a first-come-first-served reservation system for CAVs traveling through the intersection, and a comprehensive microscopic traffic simulation showed that it would significantly outperform a traditional traffic signal in minimizing delay [98].

In 2004, Neuendorf *et al.* adopted the virtual platoon concept to propose a decentralized cooperative longitudinal motion controller for CAVs at automated intersections, where the general idea can be illustrated by Fig. 7 [99]. Medina *et al.* further developed an automated intersection system for CAVs using a similar approach, which consists of a bi-level architecture: a supervisory level with subsystems target vehicle assignment and control reconfiguration; and an execution level with cooperative vehicle motion control design [100]. Xu *et al.* also adopted the virtual platoon methodology to project vehicles approaching from different directions of an intersection into a virtual lane [101]. Jin *et al.* proposed a multi-agent motion management protocol for CAVs to form virtual platoons based on V2V communication before approaching the non-signalized intersection [102]. Compared to the conventional traffic signal control system, the proposed system was predicted to shorten the average travel time by 30% and to reduce the energy consumption by 23%.

### 3) Experimental Implementation

For the use case of automated coordination at non-signalized intersections, there were a few experimental implementations conducted by European research organizations, such as the Cybercars and Cybercars-2 projects in France [103], [104]. However, including the aforementioned two projects, most test projects put their research focus on the motion planning of CAVs, *i.e.*, how to plan the trajectories of CAVs so they will not collide with each other while travelling through the intersection. Very limited literature can be found that discussed the motion control of CAVs in their implementations of automated coordination at non-signalized intersections, since it is a relatively easier task compared to the scheduling and coordination of multiple CAVs.

## IV. Control Issues

In the aforementioned case studies, multiple CAVs need to be coordinated to maintain safe inter-vehicle distances while accomplishing specific cooperative driving tasks, such as speed regulation, car following, lane changing, and overtaking. In these tasks, cooperative longitudinal motion control plays a significant role to improve system performance and ensure vehicle safety. This topic has been heavily studied in a variety of research, in which not only control performance (*e.g.*, internal stability, string stability, scalability, and robustness), but also operational performance (*e.g.*, safety, fuel economy, and riding comfort) was considered.

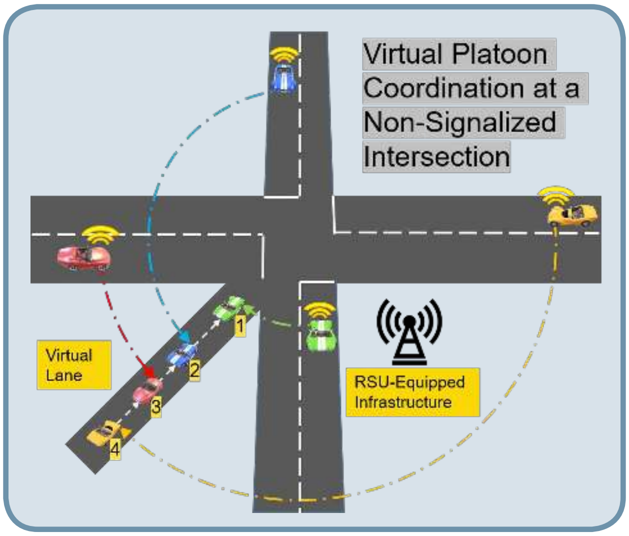

**FIG 7** Virtual platoon coordination at a non-signalized intersection.

In cooperative longitudinal motion control of multiple CAVs, some problems still need to be addressed. In terms of vehicle dynamics, due to the existence of nonlinear components (*e.g.*, engine, transmission, tire resistance, and aerodynamic drag), longitudinal vehicle dynamics are inherently nonlinear and heterogeneous. In terms of wireless communication networks, due to the uncertain reliability of wireless communication links, communication time delays and packet losses are unavoidable in the information sharing process among vehicles. With these time-delayed and partially missing measurements of system states, the controllers of CAV systems need to be carefully designed to reduce the adverse impact of vulnerable feedback channels on system performance. Moreover, CAV systems are expected to not only improve their own performance but also help smooth the entire traffic flow. In a CACC string (or a vehicular platoon), a typical application of cooperative longitudinal motion control of CAVs, it is required that the car-following errors should not be amplified when propagating upstream, which is called string stability.

To address the issues mentioned above, different types of control methods have been proposed, *e.g.*, distributed consensus control [27]–[30], [44], [105]–[109] distributed optimal control [33], [34], distributed model predictive control (DMPC) [11], [110]–[113], distributed $\mathcal{H}_\infty$ control [114]–[118], distributed sliding mode control (DSMC) [119], and some other approaches [120]–[125]. Since some of the existing literature already reviews different control methods used in cooperative longitudinal motion control, *e.g.*, [1], [6], [25], [26], [126], in this paper, we mainly focus on the solutions for three typical control issues, *i.e.*, dynamics heterogeneity, communication issues, and string stability.

### *A. Dynamics Heterogeneity*

To simplify the problem of cooperative longitudinal motion control, many studies assume that the dynamics of multiple CAVs are homogeneous, which facilitates the modeling and analysis of CAV systems. For example, in [16], a CAV system was treated as a homogeneous multi-agent system so that it can be decomposed into $N$ (the number of vehicles) subsystems with the same dimension as a vehicle's dynamics model. This method was also used in [118], [127] to synthesize robust $\mathcal{H}_\infty$ platoon controllers. However, the assumption of homogeneity is not realistic in practice due to the diversity of vehicle models and types and the individual differences in powertrain components. Therefore, dynamics heterogeneity should be considered in the control design process.

For CAV systems with heterogeneous vehicle dynamics, a simple information flow topology will facilitate the system modeling and analysis. For example, [128], [129] consider CACC systems with the predecessor-following (PF) topology. In this case, the CAV system naturally has a cascade structure, so that we only need to consider two consecutive vehicles, which can be taken as the basic element of a CACC system. However, when it comes to complex information flow topologies, these cascade structures may no longer exist. In this case, the effects of heterogeneous dynamics are coupled by the complex information flow topologies, which need to be properly addressed.

In the literature, one typical approach to address dynamics heterogeneity is to treat it as a type of heterogeneous model uncertainties imposed on nominal homogeneous systems. By doing so, the main task is reduced to controller design with robustness to these heterogeneous model uncertainties. For example, in [114], vehicles' dynamics heterogeneity was treated as a type of additive uncertainties $\Sigma(\Delta A_i, \Delta B_i)$ imposed on linear vehicle dynamics $\Sigma(A, B)$, then the heterogeneous dynamics model becomes $\Sigma(A_i, B_i) = \Sigma(A, B) + \Sigma(\Delta A_i, \Delta B_i)$. In contrast to this, vehicles' dynamics heterogeneity was modeled as productive uncertainties in [115]–[117], where the transfer function from control input $u_i(s)$ to vehicle acceleration $a_i(s)$ was modeled as $G_i(s) = a_i(s)/u_i(s) = P(s)(1 + \Omega(s)\Delta_i)$ with nominal model $P(s)$ and model perturbation $\Omega(s)\Delta_i$. Based on these models, distributed $\mathcal{H}_\infty$ control method can be used for system stabilization as well as to minimize the impact of heterogeneous uncertainties on nominal systems. In particular, as suggested by [117], the eigenvalue decomposition and linear transformation method can be used to address the coupling of controllers induced by complex information flow topologies, thus the design of distributed controllers does not rely on the scale of CAV systems.

Another approach to address dynamics heterogeneity is to drive the heterogeneous dynamics to a homogeneous reference model with guaranteed control performance. By doing so, the closed-loop behaviors of heterogeneous vehicles will converge to the homogeneous reference models, for which control methods for homogeneous CAV systems can be applied. For example, [130] applied model reference adaptive control (MRAC) to CAV systems subject to parametric uncertainties so that vehicles' heterogeneous dynamics converge to string stable reference dynamics. Adaptive sliding mode control was used in [131] to drive vehicle acceleration to a given homogeneous sliding surface so that vehicles behave homogeneously when sliding variables converge to zero. Similar techniques were also used in [132] to address heterogeneous parameter mismatches in nonlinear vehicle dynamics.

In essence, the aforementioned two approaches are both *implicit* methods, which means dynamics heterogeneity is not directly addressed but viewed as equivalent uncertainties or disturbances on homogeneous systems. Actually, they are both based on the assumption of limited deviations from homogeneous systems. In detail, robust control methods try to stabilize nominal homogeneous systems as well as to minimize the impact of bounded dynamics heterogeneity, while adaptive control methods try to drive a heterogeneous system to a homogeneous reference model. In contrast to these implicit methods, there are also *explicit* methods that address dynamics heterogeneity directly. One typical method is DMPC, or distributed receding horizon control (DRHC). For example, in [110], DRHC was applied to CACC systems with continuous-time vehicle dynamics and the PF topology. This study was further extended to the case of discrete-time vehicle dynamics and general unidirectional topology in [112]. In these studies, the formulation of closed-loop dynamics was not required in stability analysis, and dynamics heterogeneity can be directly considered in the design of local optimization problems. Moreover, for some specific information flow topology, linear controllers can also be used to address dynamics heterogeneity explicitly. For example, the stability criteria of CACC systems with heterogeneous vehicle dynamics were analytically derived in [132], where a lower triangular structure due to the directed acyclic graphs (DAGs) enables the decomposition of the heterogeneous system. In [133], [134], CACC systems with heterogeneous dynamics and time headways were studied for the multiple-predecessor-following (MPF) topology, which can be regarded as a special case of DAGs. Note that the PF topology is also a special case of the MPF topology, so dynamics heterogeneity can be easily addressed under the PF topology.

It is argued that the aforementioned approaches all have their own advantages and disadvantages. In detail, the first two implicit methods provide guaranteed robustness or adaptability to dynamics heterogeneity, but inevitably bring conservatism in control design since the controller depends on the largest deviation of all the vehicles' heterogeneous dynamics from the nominal homogeneous one. The explicit methods reduce this conservatism but have specific requirements on information flow topologies or only apply to some limited cases.

### B. Communication Issues

As described earlier, vehicles rely on on-board sensors, such as cameras and radar, to measure neighboring vehicles' states. With the introduction of V2V communication and I2V communication, CAVs are able to obtain the states of those beyond their direct measurement ranges and to obtain information that cannot be detected by remote sensors (such as the issuance of internal control commands on-board other vehicles). This helps enhance the sensing range of CAVs, and may further benefit the whole CAV systems. However, this will also bring about various communication issues to CAV systems. Fortunately, because the communicated information is supplementary to the information obtained from on-board sensor systems, it is possible for the CAV systems to continue operating as AV systems with reduced performance when communication problems occur. The extent of the performance reduction depends on the severity of the communication fault, and the specifics of the CAV application, and how heavily it depends on the information that cannot be obtained from onboard remote sensors.

Firstly, due to the introduction of wireless communication, different information flow topologies can be employed in CAV systems, which may pose challenges to system design and analysis, while expanding the range of design choices. As suggested by [16], [135], information flow topology can be modeled with the algebraic graph theory, with which the main property of a type of information flow topology can be characterized by its corresponding Laplacian matrix. Therefore, the effects of topology Laplacian matrices, especially their eigenvalues, on CAV systems were discussed in detail in most of the literature. For example, to avoid a case-by-case study on specific information flow topology, [16] studied general information flow topology with real eigenvalues, while [127] focused on topology with complex eigenvalues. For these two cases, the Jordan canonical form and modal canonical form were respectively utilized for system decomposition and stability analysis. Similar methods were also used in [115], [117]. Moreover, unknown but eigenvalue-bounded topology was considered in [116], [131] to account for system robustness under a more realistic communication environment.

The aforementioned studies all assumed a fixed information flow topology. In practice, the information flow topology of CAV systems is generally time-variant or switching due to the loss and recovery of communication links or the joining and leaving maneuvers of vehicles. In the literature, topology switching can be classified into two types, *i.e.*, restricted switching and arbitrary switching. If a topology can be switched to another only when a specific condition is satisfied, *e.g.*, the topology has been maintained for a period of time (dwell time), this type of switching is called restricted switching; otherwise, it is called arbitrary switching. For these two types of topology switching, different methods were proposed for system stabilization. For example, [29] studied switching networks with finite dwell times and derived a sufficient condition on the pinning gain with respect to the leading vehicle. [130] designed an adaptive switched controller and used the mode-based average dwell time to address the network switching. [136] also considered switching topology with finite dwell times but applied finite-time stabilization theory to CACC systems. Different from these studies, [137] considered CACC systems subject to arbitrary topology switching. Since the CACC system in consideration was stable under each topology, a common Lyapunov function can be designed for stability analysis.

Beyond the switching of information flow topology, time delays in communication will also affect the performance of cooperative longitudinal motion control of CAV systems. To address this issue, two typical methods for delayed system, *i.e.*, the Razumikhin-based method and Krasovskii-based method, were both studied in the literature. For example, uniform and constant time delays were considered in [114], where a Razumikhin-based method was applied to synthesize an $\mathcal{H}_\infty$ controller. In addition to uniform and constant time delays, [138] considered multiple time-varying delays and used adaptive feedback gains to compensate for the errors arising from outdated information. Linear matrix inequality (LMI) based stability conditions were examined and the upper bound of time delays was estimated. [28] designed a consensus-based CACC controller by using the concept of aggregate delay, and a Razumikhin-based method was applied to stability analysis. Such analysis was further extended to the case of heterogeneous time delays in [29], [139]. To compare the Razumikhin-based and Krasovskii-based methods, [137] further designed a consensus-based controller and demonstrated the less conservatism of the latter method in the sense of a greater upper bound of time delays.

As for packet losses in wireless communication, one feasible solution is to achieve smooth transition to remove the reliance on V2V communication. For example, [140] designed an acceleration estimation algorithm using onboard sensors in the case of communication failures so as to achieve seamless transition from CACC to ACC. [130] designed an adaptive switched controller for the transition from CACC to ACC to address the network switching due to communication failures.

### C. String Stability

As a specific example of cooperative longitudinal motion control of CAVs, CACC is a representative spatiotemporal system, which should be not only internally stable, *i.e.*, to maintain desired formations, but also string stable, *i.e.*, to attenuate the propagation of disturbances/errors in the upstream direction. Note that internal stability of a CACC system does not necessarily lead to string stability, since error signals may be amplified upstream even if the closed-loop system is internally stable. This will eventually result in collisions of consecutive vehicles. Therefore, string stability is a basic requirement for a cooperative automation system that involves more than two vehicles, and deserves careful consideration.

For example, early research on the string stability of inter-connected systems includes [141]–[143]. Afterwards, numerous studies have been focused on the string stability of CACC systems, *e.g.*, [7], [52], [59], [110], [128], [144]–[153]. In these studies, the definition of string stability in terms of the norms that were used can be classified into several types, *e.g.*, $\mathcal{L}_2$ string stability [128, 154], $\mathcal{L}_p$ string stability [129], string stability [143], $\mathcal{L}_\infty$ string stability [155], and head-to-tail string stability [156]–[158]. The interested readers may refer to [155] for more details.

In the majority of the existing literature, string stability is mainly studied case-by-case in terms of the information flow topology. The most widely discussed topologies have been PF, predecessor-leader-following (PLF), and bidirectional (BD). Recent studies on string stability for general information flow topology are focused on the MPF topology, which can cover a large set of topologies since the number of predecessors is not fixed. For example, [159] proved that the constant spacing policy cannot guarantee string stability for CACC systems with the MPF topology. In order to relax the rigid formations, the constant time headway policies were extended to the MPF topology. For example, in [160], the desired distance between vehicle $i$ and $i-l$ $(1 \leq l \leq i)$ was defined as $d_{i,i-l} = \Sigma_{k=i-1}^{i-1} h_k v_0 + l \times d$, where $h_k$ is the headway of vehicle $k$, $v_0$ is the speed of vehicle 0, and $d$ is the homogeneous standstill gap. In [153], [154], it is defined that $d_{i,i-l} = l \times (hv_i + d)$, where $h$ is the homogeneous time headway, and $v_i$ is the speed of vehicle $i$, in order to remove the requirement of the leading vehicle's speed. In [133], [134], it is defined that $d_{i,i-l} = \Sigma_{k=i}^{i-l+1} h_k v_k + d_k$, where $d_k$ is the heterogeneous standstill gap of vehicle $k$, in order to achieve consistent desired inter-vehicle distances, *i.e.*, to satisfy that $d_{i,k} = d_{i,j} + d_{j,k}$ when $v_j \neq v_k$. The minimum employable time headways were derived in [134], [155], [156], to guarantee string stability under the MPF topology.

As suggested by [142], the following conclusions can be drawn on the string stability of CACC systems: 1) If the constant spacing policy is adopted, a PF information flow topology cannot guarantee string stability. Broadcasting the leader's information to the following vehicles in the string through V2V communication can extend the information flow, thus ensuring string stability. 2) Instead of adopting a constant spacing policy, the constant time headway policy can be used to ensure string stability, where the inter-vehicle distance relies on the relative speed of vehicles, and therefore relaxes the formation rigidity of the system. 3) Asymmetry control under the BD topology is also an effective approach to achieve string stability.

## V. Discussion and Conclusions

This paper presented a literature survey on cooperative longitudinal motion control of multiple CAVs from three different perspectives:

a) *It demonstrated how cooperative longitudinal motion control works in CAV systems from a high-level architecture point of view.* The system architecture of CAV systems was reviewed by disaggregating them into subsystems and their hardware/software components.

b) *It described examples of cooperative longitudinal motion control, explaining where it can be implemented in the transportation systems.* Upon demonstrating how cooperative longitudinal motion control works, we were also interested in where it can work. Therefore, five different transportation applications that take advantage of cooperative longitudinal motion control of multiple CAVs were introduced, with each of them bringing one or more benefits to the transportation systems. Specifically, literature was categorized by theoretical research and simulation, and experimental implementation for each application.

c) *It elaborated on the major control issues of cooperative longitudinal motion control of multiple CAVs, pointing out what factors should be considered while designing cooperative longitudinal motion controllers.* Rather than listing different cooperative longitudinal motion control methodologies of existing CAV systems, we identified major control issues of cooperative longitudinal motion control and categorized them into three types: dynamics heterogeneity, communication issues, and string stability. Many related literature sources were reviewed under each control issue.

Although many positive results have been reviewed and analyzed in this survey, there are still some open questions that need to be addressed in future work related to cooperative longitudinal motion control of multiple CAVs. Three specific questions can be asked on top of the aforementioned three conclusions of this survey:

a) *How can we build a more reliable architecture for CAV systems?* Unlike most theoretically proposed CAV systems that assume a static setting, a more realistic traffic network will introduce a highly dynamic environment. For example, cooperative longitudinal motion control of multiple CAVs is heavily based on V2V communication, which is vulnerable to communication impairments such as time delays and packet losses. Also, cyberattacks such as jamming, V2X data injection, and vehicle sensor manipulation can also impair the performance of CAV systems. In the future development of cooperative longitudinal motion control of multiple CAVs, the resilience against system impairments or attacks should be considered and studied. How to conduct fault detection and isolation regarding communication impairments or cyberattacks, how to temporarily but smoothly switch to degraded modes of control that are less dependent on the communicated data, and how to maintain string stability under those situations can be some interesting topics to study and test.

b) *How can we identify and close the gap between theoretical research and experimental implementation?* It is true that many advanced methodologies have been proposed and analyzed in theory, however, the gap between theoretically functional and practically functional needs to be identified and closed. For example, the theoretical studies of string stability in most cases ignored the destabilizing effect of communication delays. CAV systems that will appear to be stable based on theoretical analyses are not always stable in practical implementations due to unavoidable delays in communications. Therefore, stability analyses need to include realistic quantifications of communication delays in order to compensate for this gap between theory and practice. Theoretical research results need to be tested under various realistic conditions to identify this gap, but that can be both labor-intensive and time-consuming.

c) *How can we develop more ready-to-market cooperative control methodologies within a mixed traffic environment?*

Most of the literature reviewed in this survey made strong assumptions that all involved vehicles are CAVs, however, it is obvious that we will endure a long period during which the traffic environment is mixed with different types of vehicles: CAVs, CVs, AVs, and conventional vehicles. Cooperative longitudinal motion controllers that work for a pure CAV environment do not necessarily work for a mixed traffic environment, given the uncertainties introduced by other vehicle types in the environment. In order to facilitate more ready-to-market CAV applications, the future development of cooperative control methodologies may take advantage of advanced sensing and communication technology to deal with a mixed traffic environment.

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