A Review of Connected and Automated Vehicle Platoon Merging and Splitting Operations

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Abstract-**Connected and automated vehicle (CAV) platoons have drawn much attention in the past decades, given their potential to reduce fuel consumption, elevate roadway capacity, and enhance traffic safety. As two basic platoon operations, platoon merging and splitting have been widely investigated. This study provides an overview of theoretical models and field experiments of CAV platoon merging and splitting operations. A three-step framework, including protocol design, trajectory planning, and vehicle control, is proposed to unify existing representative studies. Methodological techniques in each step are summarized and discussed. Finally, future research directions are discussed. This study contributes to the literature by providing a framework that categorizes relevant literature and guides the successful development of platoon merging and splitting operations. More importantly, it offers researchers and practitioners a rich reference for further investigations.**

Index Terms- **Platoon, merge, split, connected and automated vehicle, trajectory planning, vehicle control.**

I. INTRODUCTION

A VEHICLE platoon (sometimes referred to as a convoy or road train) is a group of vehicles operating close to each other in the same lane of a roadway segment with uniform car-following distance/time headway and speed [1]. Vehicle platooning is promising in elevating roadway capacity due to the small car-following distance and reducing fuel consumption due to the reduced aerodynamic drag, especially for heavy-duty vehicles [2]-[5].

The concept of vehicle platooning dates back to more than 60 years ago [6]-[8]. However, it is difficult to form tight and stable platoons with traditional human-driven vehicles (HVs). The emerging connected and automated vehicle (CAY) technology makes vehicle platooning easier [9], [10]. Specifically, vehicle automation eliminates human errors and enables precise vehicle trajectory control [11]. Vehicle connectivity provides efficient information sharing via vehicle-to-vehicle (V2V) and/or vehicle-to-infrastructure (V21) communication. As a result, CAVs in a platoon respond faster to changes in a complex driving environment. These features result in smoothed vehicle trajectories that improve fuel efficiency, mitigate congestion, and enhance roadway safety. These potentials have encouraged substantial interest in vehicle platooning [12], [13]. Considerable advancements have thus emerged in modeling vehicle platoon operations [2], [14]-[17].

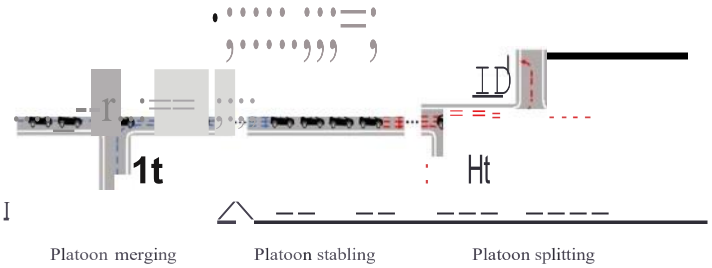

Fig. 1. Platoon operations.

Great efforts have been made to conduct field experiments on CAY platooning. Particularly, truck platooning has drawn much attention since the 1990s. Because of the substantial fuel savings, truck platoons are expected to be one of the earliest commercially available applications of roadway automation. Representative truck platoon projects include Chauffeur [16], California **PATH** [18], **KONVOI** [19], and Energy ITS [20], [21]. More recently, truck platoon tests have been taking place in Singapore [22] and Australia [23]. Besides trucks, platoon tests have also been conducted with passenger cars and small-scale robots [24]-[29].

Given such booming developments, it is timely and critical to review the state-of-the-art in CAY platoon operations and summarize the fundamental knowledge. Vehicle platooning involves three basic operations, shown in Fig. 1., including stabling, merging, and splitting. Platoon stabling investigates the problem of keeping platoons stable, i.e., maintaining the desired gap and speed. Constant distance and constant time headway are commonly used to guarantee individual vehicle stability [30]. The stability of the entire platoon (i.e., string stability) is achieved through platoon stabling strategy [30]-[32]. Many factors can lead to platoon instability, e.g., speed changes, tracking errors, and factors relevant to V2V and/or V21 communication. Particularly, communication delay and information flow topology have been found to greatly affect the internal and string stability of CAY platoons [33]-[37].

Platoon merging is the process of clustering scattered vehicles/short platoons into long platoons. Platoon splitting separates long platoons into scattered vehicles/short platoons. Like platoon stabling, platoon merging and splitting are also the building blocks for vehicle platoon applications [38]-[40].

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These two operations happen in various scenarios, for example, when ramp vehicles merge into mainlines, when long platoons pass intersections, and when vehicles exit a platoon and make lane changes [36]. Particular interest has been drawn to signalized intersections [41]. Studies have investigated how to merge vehicles into platoons to improve intersection efficiency and how to split a long platoon into shorter groups such that they pass the intersection safely during a green phrase [41]-[43]. Some studies optimize the maximum number of vehicles in a platoon considering traffic signals [44]. Platoon operations at unsignalized intersections have also been studied [45]. Most studies have focused on coordinating vehicles from different approaches to form platoons, either at arterial intersections or highway ramps [45]-[47].

Without proper management, platoon merging and splitting operations could take a considerably long time, which leads to inferior fuel efficiency and reduced roadway capacity. More importantly, operation safety raises serious concerns. However, existing review efforts on this topic have been focusing on platoon stabling [31], [48], [49]. A review of existing studies on platoon merging and splitting operations is still needed.

This paper reviews representative studies on CAV platoon merging and splitting operations to fill this gap. A synthesis of theoretical models and field experiments with reduced-scale robot cars and full-scale vehicles is presented. Existing methods for CAV platoon merging and splitting operations are unified into a three-step framework, including protocol design, trajectory planning, and vehicle control. This review paper contributes to the existing literature from the following aspects. First, this paper provides a comprehensive overview of existing literature on CAV platoon merging and splitting operations. It complements existing reviews of platoon stabling and paints a complete picture of the state-of-the-art of CAV platoon operations. Second, it presents a taxonomy based on a three-step framework to summarize studies on CAV platoon operations. Detailed methods for each step in existing studies are summarized. This not only sets up a framework to categorize relevant literature in the future but, more importantly, offers researchers and practitioners a resourceful reference for CAV platoon merging and splitting operations. Finally, challenges in existing methods are discussed. This discussion points out possible avenues for researchers and practitioners to move towards advancing the CAV platooning technology innovation and implementation.

The disposition of this paper is as follows. Section II introduces the review methodology. Section ill presents the three-step framework to unify existing studies and guide future CAV platoon merging and splitting development. Section IV reviews operation protocol design studies. Section V analyses trajectory planning studies. Section **VI** summarizes vehicle control methods employed in field experiments. Section **VII** discusses future research directions. Lastly, Section VIII concludes this paper.

II. METHODOLOGY

This review focuses on representative scientific papers investigating CAV platoon merging and splitting operations. The literature searching was conducted with queries in several databases, e.g., Google Scholar, Web of Science, and Science Direct. Searching keywords included "connected and automated vehicles", "robot car", "vehicle platoon", "merging", "platooning", "platoon formation", "splitting", "diverging", "operation protocol", "trajectory planning", "trajectory control", "vehicle control", "field experiments", "literature review" and derivations. Different combinations of these keywords were also used for searching. After initial screening, 74 representative studies were reviewed in detail. Note that the studies reviewed in this paper are by no means exhaustive. This review paper aims to survey representative studies on CAV merging and splitting, summarize key categories of methods, and identify future research directions. Readers are referred to other papers for reviews of other aspects of CAV platoons, e.g., stabling [31], [48], [49]. The following research questions were defined, and answers were acquired from the identified representative studies.

1) How are operational management decisions made? For example, when to merge and split? What are the differences, advantages and disadvantages of different approaches?
2) How are the trajectories planned for CAVs during the platoon merging and splitting processes? What are the typical objectives, constraints, mathematical models, and solution algorithms? How do methods differ?
3) What are the methods to translate planned vehicle trajectories into actual vehicle movements in the real world? How do different methods perform?

III. THREE-STEP FRAMEWORK

Fig. 2. Three-step framework for CAY platoon merging and splitting operations.

Based on the research questions identified in Section II, this section proposes a three-step framework to unify existing literature on CAV platoon merging and splitting operations, as shown in Fig. 2.

Protocol design is the first step in designing CAV platoon merging and splitting operations. It devises the overall procedure for managing the merging and splitting operations. It also makes high-level operational management decisions (e.g., whether, when, and where a merging or splitting operation should be performed).

The next step is trajectory planning. It generates ideal trajectories that vehicles should follow during the merging/splitting operations. These trajectories are ideal because realistic disturbances (e.g., communication lags, roadway conditions, weather, and vehicle load) are not considered. The fundamental objective of trajectory planning is to assure operation safety. Other objectives such as riding comfort and energy efficiency may also be considered per application needs.

Vehicle control, the last step, specifies how the planned merging and splitting operations are implemented in the field. It directs realistic vehicle movements based on the ideal trajectories planned in the second step. Because of the complex dynamics in a realistic driving environment, vehicles may not

TABLE I

PROTOCOL DESIGN LITERATURE

Study	Management protocol		Merging position			Splitting position		
	centralized	decentralized	head	middle	tail	head	middle	tail
[50)								
[51)								
[52)								
[53)								
[54)								
[55]								
[56)								
[57)								
[58)								
[59)								
[60]								
[61)								
[62]								
[2]								
[63)								
[64)								
[65)								
[66)								
[67)								
[68)								
[69]								
[70)								
[71)								

Note: Studies are sorted based on the publication year.

accurately follow the planned trajectories. Thus, appropriate control methods are needed to minimize the trajectory tracking error.

This three-step framework summarizes the main steps in most studies on CAV merging and splitting operations. We provide a detailed discussion of each step in this framework in the following sections.

IV. PROTOCOL DESIGN

Protocol design specifies the management protocol for CAV platoon merging and splitting operations, detailing how high-level operational management decisions are made. These decisions can be made by the platoon leader if a centralized protocol is adopted or by individual vehicles if a decentralized protocol is adopted. Note that we define the centralized and decentralized protocols as two approaches for making operational management decisions instead of two communication topologies.[1] This section discusses these two protocols and related issues. Representative literature is summarized in TABLE I.

A. Centralized Protocol

In centralized protocols, a platoon leader, i.e., the first vehicle in the platoon, is typically responsible for managing the merging and splitting operations. The platoon leader periodically collects information from platoon members (i.e., other vehicles in the platoon) and makes high-level decisions for all vehicles in the platoon. Any vehicle that intends to join or leave the platoon must ask for permission from the platoon leader. The platoon merging (splitting) operation managed by the centralized protocol is illustrated in Fig. 3. This procedure can be briefly described as follows [2]:

1) The vehicle[2] that aims to merge into or split from a platoon, referred to as the merging/splitting vehicle in the following analysis, sends out a merging/splitting request to the platoon leader.
2) The platoon leader accepts or declines the request based on the current platoon configurations (e.g., size and

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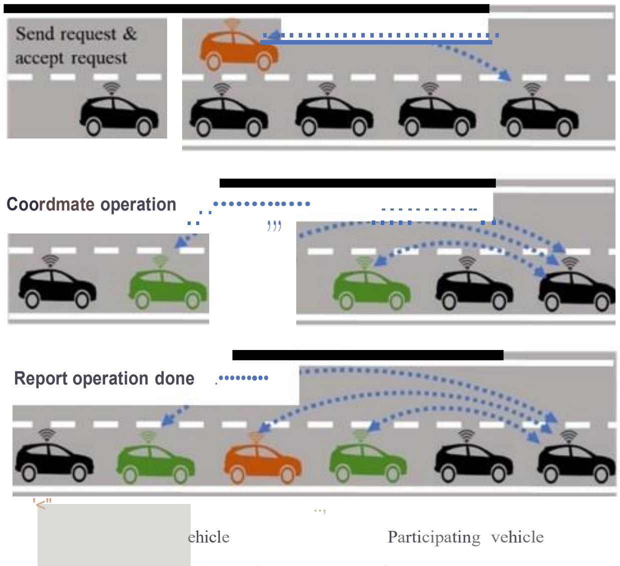
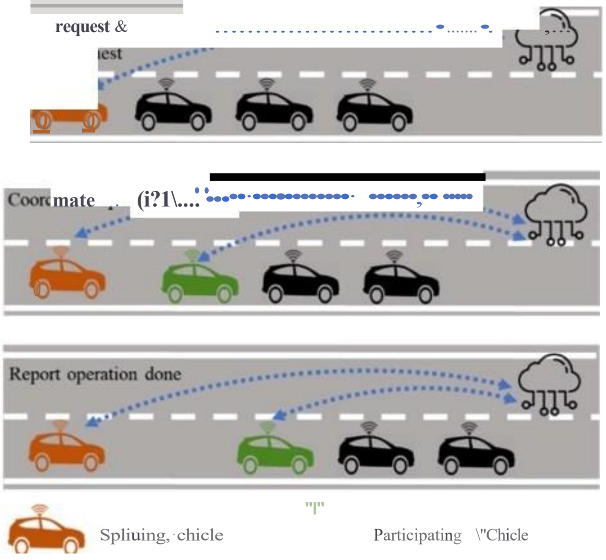
[1] Communication protocol is a critical component of successful platoon merging and splitting operations. Yet, communication is not the subject of this paper, and there are already excellent reviews on this topic. We thus refer interested readers to [119] for a survey on V2V communications, [120] for a survey on V2I communication, [121] for a survey on networking and communications for CAVs, (37] for a discussion on information flow topology, and [122] for performance evaluation of different V2V and V2I technologies.

[2] Here we discuss the case where a vehicle merges into or splits from a long platoon. The case where a short platoon merges into or splits from a long platoon follows a similar procedure. The main difference is that the leader of the short platoon will be communicating with the leader of the long platoon.



(a). Platoon merging.



(b). Platoon splitting.

Fig. 3. Centralized platoon management protocol.

vehicle type), the platoon state, and the traffic environment. A request is likely to be rejected if the platoon is engaged in another operation, the surrounding traffic is quite oscillating, the platoon is not stable, or the platoon is not in a location suitable for merging and splitting.

3) If the request is accepted, trajectories will be planned and followed for vehicles participating in the merging/splitting operation. Apart from the merging/splitting vehicle, the closest preceding vehicle and/or following vehicle usually also participate.[3] Trajectory planning can follow a centralized or decentralized structure. If trajectory planning is centralized, the platoon leader coordinates all participating vehicles to complete the requested operation. The trajectories of all participating vehicles are jointly planned to achieve better performance. The planned trajectories will be sent to the associated vehicles to guide their movements to complete the requested operation. If the trajectory planning is decentralized, each merging/splitting vehicle plans its trajectory and controls its movements to follow this planned trajectory. If any, the closest following vehicle in the platoon will adjust its movements accordingly. Detailed discussions on the trajectory planning methods and vehicle control methods are provided in Sections V and VI, respectively.
4) If the request is declined, the merging/splitting vehicle will seek another opportunity to send the request again.
5) When the requested operation is completed, the merging/splitting vehicle notifies the platoon leader. The platoon leader passes the completing notification to other participating vehicles. Upstream vehicles and downstream vehicles of the original platoon will be coordinated to reform the platoon.

The above procedure considers the first vehicle in a platoon to be the leader managing the platoon. This is the assumption in most existing studies using a centralized management protocol, probably because of its flexibility, simplicity, and promise to be implemented at the early stage of CAY deployments. As the technology evolves, it is possible to manage platoons in a corridor/network with a centralized operational center (e.g., a roadside unit, a remote operational center), as Fig. 3 (b) shows. This centralized operational center monitors the operations of individual platoons and coordinates vehicles among platoons [59]. For example, the operational center can find the best platoon for a vehicle to join. A centralized operational center is expected to be equipped with high-performance computers to handle extensive computation tasks of multiple platoons.

B. Decentralized Protocol

In decentralized protocols, there is not a platoon leader. High-level operational decisions are locally distributed among vehicles that can communicate with other vehicles directly [51], [57], [58], [62], [72]. A vehicle that intends to join or leave the platoon needs to ask for permission from the closest following vehicle, which makes space for the requested operation. This is the procedure that most existing studies use in decentralized protocols. Permissions from other vehicles are not necessary for successfully implementing the requested operation. However, the merging/splitting vehicle may also notify other vehicles so that they can facilitate the requested operation. For example, the closest preceding vehicle can adjust its movement to create a gap together with the closest following vehicle [56]. The platoon merging and splitting procedures managed by decentralized protocols, as Fig. 4 shows, can be described as follows.

1) The merging/splitting vehicle sends the merging/splitting request to the closest following vehicles in the platoon. The operation intention may also be sent to other vehicles in the platoon to ask for assistance.
2) The closest following vehicle accepts or declines the request. Other vehicles choose to help or not.

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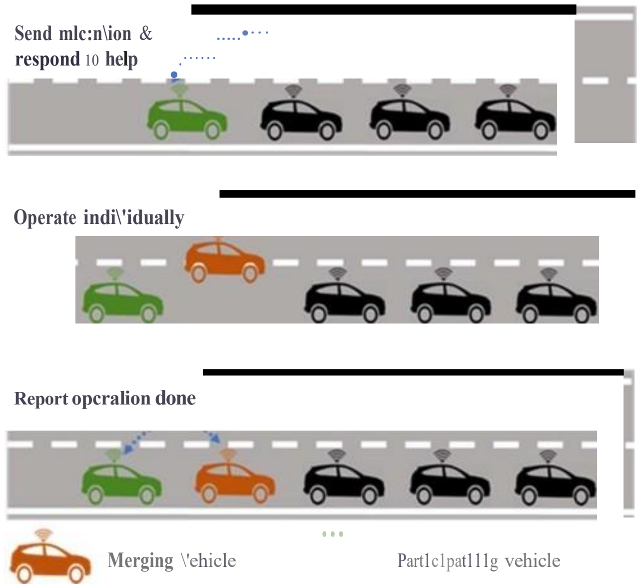
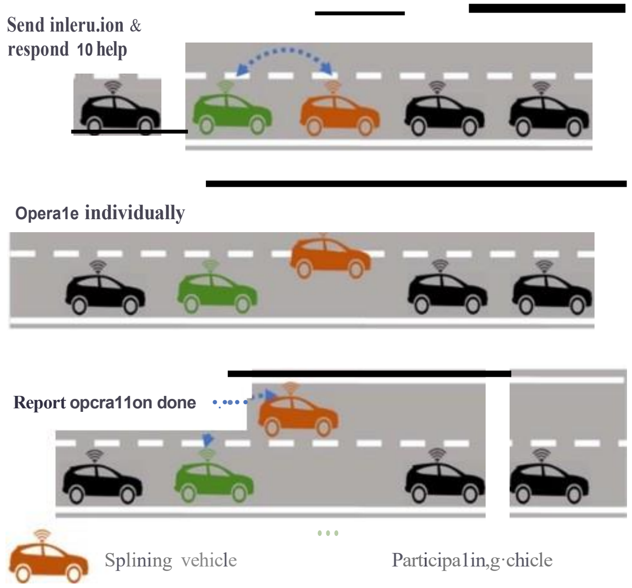
[3] The number of participating vehicles in the merging/platooning operation varies. Sometimes, the entire platoon may be coordinated to facilitate the ?peration especiallr when the plat_oon is relatively short. Theoretically speaking, the more vehicles are coordinated, the more efficient the operation is. However, the increase in the number of participating vehicles also increases the computational burden of trajectory planning.



(a). Platoon merging.



(b). Platoon splitting.

Fig. 4. Decentralized platoon management protocol.

The conditions considered in the centralized protocol are also considered here.

3) If the request is accepted, the next step is trajectory planning. Since the high-level decisions are decentralized, the trajectory planning process must also adopt a decentralized structure. Thus, each participating vehicle (i.e., the requesting vehicle, the closest following vehicle, and other vehicles that choose to assist) will plan its trajectory based on its perceptions of the environment and control its movement to follow the planned trajectory. Detailed trajectory planning and vehicle control methods are discussed in Sections V and VI, respectively.

4) If the request is declined, the merging/splitting vehicle will seek another opportunity to request the desired operation.

5) The merging/splitting vehicle notifies the participating vehicles when the requested operation is finished. If any, upstream vehicles of the original platoon will catch up with downstream vehicles to reform the platoon.

C. Position to Merge/Split

The position to merge/split is one of the high-level decisions to be made in protocol design, and it varies for both operation protocols. Here we offer a discussion of the position to merge/split and how this decision affects the merging/splitting operations.

In most existing studies, the merging/splitting vehicle can merge in and split from the tail of the platoon [60]. In this case, the original platoon remains intact, i.e., the original platoon will not be separated into subgroups during the merging/splitting operation, as illustrated in Fig. 3 (b). This saves communication efforts and is beneficial to fuel efficiency. If the management protocol is centralized, this approach also ensures that the same vehicle remains the platoon leader. This is valuable since it saves the information exchange between the original and new leaders. The merging/splitting vehicle can also merge/split in the middle of the platoon [61], as illustrated in Fig. 3 (a) and Fig 4. This approach is more flexible than merging/splitting in the tail. It allows vehicles traveling to the same destination to stay together in the platoon. This configuration also avoids changing the platoon leader in centralized merging/splitting protocols. Sometimes, for the highest level of operation flexibility, the merging and splitting operations can happen at the head of the platoon [55]. The merging vehicle or the closest following vehicle of the splitting vehicle becomes the new platoon leader after the merging or splitting operation is completed.

For the merging operation, the position to merge can be selected based on the application needs. In centralized management protocols, the platoon leader may allow vehicles to merge at the tail if it aims to reduce the information exchange and the impacts on the existing vehicles in the platoon as much as possible. To increase the operation flexibility while keeping the platoon leader unchanged, merging in the middle can be allowed. The platoon leader may select the position for the merging vehicle to join for optimal performance (e.g., in terms of fuel economy and operation efficiency) based on vehicles' schedules and destinations [73]. Yet, for the splitting operation, the position of the splitting vehicle cannot be selected; it is determined by vehicle routes, i.e., vehicles need to split once they reach a certain distance from their destinations. If the management protocol allows for splitting at any position (i.e., head, middle, and tail), the splitting vehicle can exit with only one splitting operation. Otherwise, the splitting operation may need to be conducted multiple times. Fig. 5 illustrates splitting a vehicle in the middle of the original platoon when splitting is only allowed to happen in the tail.

D. Comparing Centralized and Decentralized Protocols

In centralized protocols, platoon operations are completed more efficiently due to the coordination among vehicles. This is extremely valuable in improving traffic mobility for

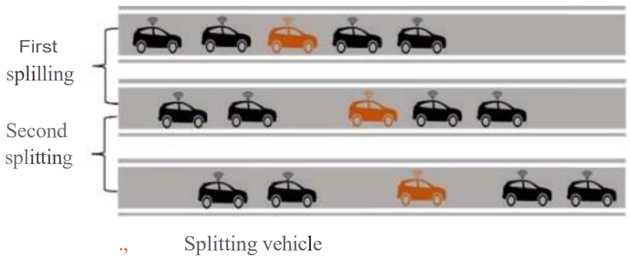


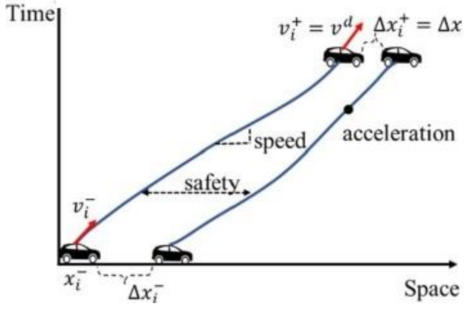
Fig. 5. Illustration of consecutive splitting operations.

both the subject platoon and the surrounding traffic, and probably why most existing studies chose centralized protocols. However, centralized protocols require advanced V2V and/or V2I communications, which could be challenging in engineering implementations, especially at the early stage of CAV development. They also face a greater computation burden since decisions of all vehicles have to be made by the platoon leader. Further, centralized protocols suffer from lower system robustness because once the leader fails (e.g., due to hardware or software issues), the whole platoon fails. For example, the whole platoon is at risk once the leader is faced with cyber attacks. On the bright side, only the platoon leader has the information about all vehicles in the platoon. This lowers privacy risks because other vehicles cannot access such information.

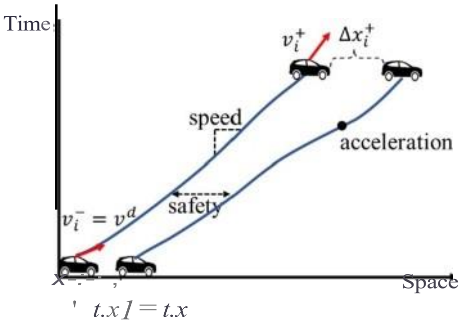
Decentralized protocols overcome the limitations of centralized protocols. Vehicles only percept the environment via sensors and/or short-distance communication technologies and adjust their movements based on the perceived information. This decentralized structure imposes less communication and computation burden, thus requiring fewer resources on the software (e.g., high-performance computing units) and hardware (i.e. long-distance communication devices). Decentralized protocols also yield higher system robustness by distributing the communication and computation among vehicles. However, the operation efficiency of decentralized protocols is inferior without centralized vehicle coordination, i.e., it takes more time to complete the operation. Further, any vehicle may have access to other vehicles' information, rendering higher privacy risks.

V. TRAJECTORY PLANNING

Trajectory planning is to generate vehicle trajectories, i.e., the location/speed//acceleration of vehicles over time, to guide the platoon operations. As illustrated in Fig. 6 (a), the initial state of the merging operation is a group of scattered vehicles indexed as *i* E *I* := {1, 2, • •• , /}, where *I* is the set of vehicles and *I* is number of vehicles. Vehicles have different speeds *v;,* locations *X;-,* and car-following gaps *fix;--* The ending state is a platoon with identical speed *vt* = *vd* and identical gap *tut* = *fix.*Ontheopposite, as Fig. 6 (b) shows, the initial state of the splitting operation is a platoon with an identical initial speed *vi* = *vd,* initial location *X;-,* and identical car-following gap *fix;-* = *fix.* Theending state is a group of scattered vehicles *i* E *I* := {1, 2, ••• , /}, each



(a) Merging



(b) Splitting

Fig. 6. Trajectory planning.

with speed *vt* and gap *fix(-* Both the merging and splitting operations are subject to kinematic and safety constraints. The speed of a vehicle is bounded by a minimum speed and a maximum speed *V.* The vehicle acceleration is restricted to an interval [, *a],* where and *a* are the minimum and maximum acceleration, respectively. The car-following gap between two consecutive vehicles is no less than the minimum gap *so* plus the distance a vehicle needs to travel during reaction time r. This is needed to ensure consecutive vehicles do not collide during the operation.

The goal of trajectory planning is to devise trajectories that guide the vehicles transitioning from the initial state to the ending state during a given time horizon *T* := [O, *T],* where *T* is the length of the time horizon. The resulting trajectory is typically a time series of the vehicle location *x;(t),* speed *v;(t),* or acceleration *a;(t).* Both centralized and decentralized methods have been proposed to plan trajectories of platoon merging/splitting operations. Note that a centralized management protocol can use a centralized or decentralized trajectory planning method, but a decentralized management protocol must use decentralized trajectory planning methods. This section summarizes both centralized and decentralized trajectory planning methods.

A. Centralized Trajectory Planning

In centralized trajectory planning, vehicle motions are coordinated by the platoon leader or the operational center. Various strategies have been proposed to devise platoon operation trajectories in a centralized manner, summarized in TABLE II. One set of studies considers merging two vehicle groups (a group can be a vehicle or a short platoon) into a platoon

TABLE II

CENTRALIZED TRAJECTORY PLANNING LITERATURE

Study	Merging	Splitting	Two-group	Multiple-group	Solver	Heuristic
[14]						
[15]						
[79]						
[74]						
[43]						
[78]						
[65]						
[76]						
[75]						
[77]						
[46]						
[80]						
[81]						
[82]						

Note: Studies are sorted based on the publication year.

or splitting a platoon into two groups. For example, [74] investigated trajectory planning when a mainline platoon needs to split and make space for merging vehicles (i.e., merging in the middle as described in Section IV). [43] solved the splitting trajectory for a platoon that is too long to pass the intersection in a green phase. While the operation of two groups is computationally simple, the trajectory planning must be repeated multiple times if the operation involves multiple groups. This could be computationally inefficient, and the resulting trajectories are not system optimal. Thus, other studies propose strategies to operate multiple vehicle groups simultaneously. [15], [75], [76], and (65] investigated trajectory planning for merging a set of vehicles into a platoon on a single-lane highway. Reference (77] studied a similar problem but considered multilane platoons. References [78] and [65] explored how to generate optimal trajectories for multiple vehicles during the splitting operations.

Despite the number of groups involved in the operation, most centralized trajectory planning strategies formulate the trajectory planning problem, or at least part of the problem, into optimization models. The decision variable can be vehicle position, speed, acceleration, and jerk. Details of the optimization models vary according to the problem being investigated. However, similar components exist in terms of the objective functions, constraints, and solution methods.

1) Objective Function: An objective function is simply a function representing the cost/benefit to be optimized during the platoon merging or splitting operations. Let $K_j \subset I$ be the subset of vehicles considered in trajectory planning. For example, K_j consists of the merging vehicle and the nearest preceding vehicle if a "two-group" strategy is considered. With this, the objective function can be generally formulated as

$$\min_{[\cdot]} \sum_{i \in K_j} \int_0^T f_i(t)dt, \qquad (1)$$

where $f_i(t)$ denotes the cost/benefit of vehicle i at time t and its specific functional form depends on the objective being considered. Different objectives have been considered per application needs. The simplest objective is to make sure that the operations are safe. For example, [75] minimized the weighted sum of the speed deviation from the maximum speed and the yaw rate deviation from the maximum yaw rate. Other popular objectives are the fuel consumption (14], (43], (65], (76], [78], driving comfort [76], [78], traffic throughput (74], and traffic mobility [46], [76]. Depending on how the objective function is formulated mathematically, existing centralized trajectory planning methods can be summarized into four categories as follows.

a) Linear programming (LP): In an **LP** model, the objective function is formulated as a linear function of the continuous decision variables. For example, mobility can be measured as the time to traverse a given distance. In the case of platoon merging and splitting, the more quickly the operation is completed, the higher the mobility [76], (78]. Let t_j be the time when the operation is completed. Then, $f_i(t)$ can be written as a linear function as follows

$$f_i(t)=t_j. \qquad (2)$$

Plugging the above equation into (1) yields a nonlinear function with an integral term. Thus, the time horizon T is discretized to enable a linear formulation. The LP method is attractive in terms of computation efficiency. However, many objectives (e.g., driving comfort) are not easy to formulate as a linear function, which hinders the application of the LP method.

b) Quadratic programming (QP): Many objective functions of interest in the trajectory planning literature are quadratic. For example, in [75], the speed deviation from the maximum speed can be formulated as

$$f_i(t) = (v_i(t) - v)^2. \qquad (3)$$

Besides, fuel consumption and driving comfort can be represented by squared acceleration. As a result, in studies that aim to minimize fuel consumption or maximize driving comfort (e.g., [76]-[78]), the objective function can be written as

Ji (t) = at (t). (4)

With a quadratic objective function, methods from QP are needed to approach the trajectory planning problem.

c) Mixed-integer linear programming (MILP): A MILP is different from an LP by introducing integer decision variables in the model. A MILP is needed when decisions apart from trajectories are considered (e.g., merging order) or the decisions relevant to trajectories are discretized (e.g., speed only changes by a pre-defined amount each time). For example, [46] optimized the merging order with the merging time and speed. To formulate the merging order decision, a binary variable *bij* was introduced, which equals 1 if vehicle *j* follows vehicle *i*. This results in a MILP model.

d) Multi-objective optimization (MOO): MOO is used when multiple objectives need to be optimized. For example, [43] proposed a bi-objective optimization model. In this model, the first objective minimizes the platoon operation time, i.e.,

$$\min_{f_i(t)} \sum_{i\in\mathcal{K}} \int_0^T t_i dt. \tag{5}$$

The second objective minimizes fuel consumption, i.e.,

min L (7 at (t)dt. (6)
f;(t). IE JCJ0

Note that MOO is different from optimizing the weighted sum of multiple objectives. The purpose of MOO is to solve a set of Pareto solutions (known as the Pareto frontier) where one objective cannot be improved without deteriorating the performance of another.

2) Constraints: The platoon merging and splitting operations are typically subject to vehicle kinematic and safety constraints. These constraints can be formulated as the following linear inequalities:

Q.:::v;; (t) :::: V, Vi E JC, t ET, speed limit;
f! :::: a; (t) :::: ii, Vi E JC, t E T, acceleration limit;
x; (t) - x;+1 (t) so+ v;+1 (t) -r, Vi E JC, t E T, safety.

Another category of constraints that need to be considered is the boundary conditions. Initial boundary constraints specify the vehicle states (e.g., speed) at the beginning of the time horizon. Ending boundary constraints describe vehicle states upon the completion of platoon operations. These constraints can be written as linear equations as follows

x; (0) = x;, initial boundary on location;
v; (0) = v;, Vi E JC, initial boundary on speed;
x; (T)-x;+1(T) = t:ut, Vi E JC, final boundary on gap;
v; (T) = v;, Vi E JC, final boundary on speed.

The initial boundary constraints are usually the same across existing studies for platoon merging and splitting operations. The final boundary conditions are also the same for almost all platoon merging studies, i.e., vehicles are cruising at the same speed *vd* and every two consecutive vehicles keep the same car following gap /'u. Yet, for platoon splitting studies, the final boundary conditions vary. Some studies only require that consecutive vehicles are separated by a certain distance such that other vehicles can merge into the current platoon or certain vehicles in the current platoon can exit [83]. Other studies may also impose speed regulations. For example, when a long platoon needs to be separated into two shorter ones to pass a signalized intersection, the second part of the platoon should stop (*v*+ = 0) at the stoping bar by the end of the splitting operation [43].

3) Solution Methods: Commerical solvers exist for solving optimization models. To solve LP and MLP, CPLEX and Gurobi are two popular options. Gurobi is also widely used to solve QP, among many other nonlinear programming solvers, e.g., SNOPT. Yet, the solution efficiency of commercial solvers quickly degrades as the problem size grows and may not satisfy the needs of real-time implementation, that requires sub-second level computation time for vehicle control. To address this issue, efficient heuristics have been proposed, e.g., genetic algorithm [75], iterative procedure [74], and trajectory dimension reduction [76], [78].

A genetic algorithm is a stochastic global search method. Only trajectories that score better objective values and satisfy constraints are saved for the next generation of solution searching. An iterative procedure separates the optimization problem into steps (e.g., splitting the optimization time) and solves the problem step by step. Trajectory dimension reduction reduces the number of decision variables in the optimization problem by assuming that vehicles maintain a constant acceleration/jerk within a short period of time.

These heuristics are carefully designed with problem-specific properties. As a result, they solve the optimization problem to the optima or near-optima with a significantly expedited solution time, which is rather appealing to real-world implementations. On the other hand, customized heuristics are usually not general enough to produce satisfying results when applied to differently formulated problems.

B. Decentralized Trajectory Planning

In decentralized trajectory planning, vehicle movements are not coordinated. Most decentralized trajectory planning studies assume that each vehicle adjusts its movements based on its current perceptions of the environment (e.g., the state of the preceding vehicle). Decentralized trajectory planning is usually one-step, i.e., determining the trajectory of the next time step with information of the current time step. Such a decentralized structure has drawn much attention in recent years. Representative studies are summarized in TABLE **III.**

Most of the studies plan vehicle merging/split trajectories using the information of the closest preceding vehicle and the merging/splitting vehicle [38], [57], [58], [60], [84]-[89]. Information about the closest preceding vehicle can be easily acquired with onboard sensors, e.g., LIDAR and RADAR. Therefore, only considering the information of the closest preceding vehicle is easy to implement. However, it is possible

TABLE ill

DECENTRALIZED TRAJECTORY PLANNING LITERATURE

Study	**Merging**	**Splitting**	**Preceding vehicle information**	**Multiple vehicle information**	**Liner rule**	**Nonlinear rule**
[90)						
[84)						
[89)						
[53)						
[91)						
[38)						
[57)						
[58)						
[93)						
[94)						
[95)						
[83)						
[60)						
[85)						
[86)						
[64)						
[39)						
[87)						
[92)						
[96)						
[97)						
[88)						
[98)						
[99)						
[100)						
[69)						

Note: Studies are sorted based on the publication year.

to further improve the operation performance by considering the information of multiple surrounding vehicles via the V2V or V21 communication technologies. But only limited studies have considered this possibility. For example, [90] proposed a platoon control[4] concept using information from the lead, preceding, following, and merging/splitting vehicles. References [34] and [60] designed the accelerations of the merging/splitting vehicle and the following vehicle in the platoon using the information of the preceding and leading vehicles. Reference [92] developed a distributed longitudinal controller to form connected vehicle platoons by considering the information of multiple preceding vehicles and car-following interaction between vehicles.

Unlike centralized trajectory planning strategies that pursue system-level optimal trajectories, decentralized strategies focus more on computation efficiency. Thus, instead of using complex optimization models, decentralized trajectory planning strategies usually formulate mathematical equations to represent the relationship between system inputs (i.e., the information stated in the last paragraph) and response variables (i.e., vehicle trajectories, e.g., position, velocity, or acceleration).[5] These equations describe vehicle kinematics and inter-vehicle interactions to ensure that the merging/splitting operations can be completed safely. These equations define a set of rules to determine the response variables; thus, most decentralized trajectory planning strategies are rule-based approaches.

Based on how the mathematical equations are formulated, decentralized trajectory planning rules are generally divided into linear and nonlinear.

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[4] The word "control" sometimes is used in trajectory planning studies. It differs from the actual control problem in field experiments where vehicle movements (e.g., throttle/brake) are controlled in the presence of real-world disturbances. It still refers to devising ideal trajectories, e.g., generating speed/acceleration instructions.

[5] Some studies have constructed decentralized optimization models to devise the following vehicle's future trajectory after predicting the preceding vehicle's trajectory when passing signalized intersections [I 04]. However, this technique has not been used in CAY platoon merging and splitting operations.

1) Linear Rules: As the name reveals, linear rules describe the response variable (i.e., vehicle trajectory) as a linear function of the system inputs. With a slight abuse of the notation, here we define $K,$ as the set of vehicles whose information can be acquired. With this, the linear trajectory planning rule can be generally formulated as follows:

$$0; = L_{jEK,} (a.;i\ 11X;j + /J;i\ 11v;i + 'Yii\ !1a;i), \qquad (7)$$

where $0;$ is the trajectory planning output (or response variable) for vehicle i (e.g., vehicle speed or acceleration), $11X;j,$ $11v;j,$ and $!1a;j$ is the location difference, speed difference, and acceleration difference between the merging/splitting vehicle and the jth vehicle in set $K,$ respectively; $a.;i,$ $/J;i,$ and $'Yii$ are the corresponding coefficient, respectively. Note that here we omit time index t in relevant variables (e.g., $0;,$ $11X;j)$ for the convenience of the notation unless stated otherwise. Due to their simplicity, these rules have been widely adopted in the literature.

a) General physics laws of motion: General physics laws of motion were used to develop a merging operation strategy in [89]. The authors assumed the merging vehicle accelerates at a user-specified acceleration rate to a user-specified speed. Next, the merging vehicle decelerates at a deceleration rate specified by the user to reach the same speed as the preceding vehicle at a distance specified by the user. This process can be modeled by general physics laws of motion. Solving the equations yielded two linear rules to maintain fixed spacing and fixed time headway between the merging vehicle and the closest preceding vehicle. For example, to maintain a fixed spacing, the acceleration over time is formulated as

$$a; (t) = \frac{2\ [(so - x; (t)) + (v;\_J\ (0) - v; (0))\ t + ½a;\_1\ (t)\ t^2]}{t2}, \qquad (8)$$

where $v;\_J(t)$ and $a;\_J(t)$ are the speed and acceleration of the preceding vehicle, respectively. Following this study, [38] and [90] linearized a third-order vehicle dynamic model to devise platoon merging trajectories.

b) Adaptive cruise control (ACC): ACC is a technology that automatically adjusts a vehicle's speed to keep a safe distance from a preceding vehicle. Reference [96] utilized linear ACC to generate inter-vehicle gaps during the merging operation. An ACC controller is typically formulated as follows

$$a; = a.;11X;(i-1) + f.Jl1v;(i-1)\cdot \qquad (9)$$

[64] designed an ACC-based time gap controller by also taking into account the acceleration differences as follows

$$a_i = \alpha_i \Delta x_{i(i-1)} + \beta \Delta v_{i(i-1)} + \Delta a_{i(i-1)}. \qquad (10)$$

Besides, [83] planned the trajectory for the merging/splitting vehicle with a set of piecewise linear equations describing the desired acceleration and speed using the information from the preceding vehicle to assure safety.

c) Cooperative adaptive cruise control (CACC): CACC is an extension of the ACC by allowing inter-vehicle cooperation. This is possible due to vehicle connectivity. Recent studies have shown increasing interest in designing CACC methods for trajectory planning. For example, [87] designed a cooperative platoon-based gap opening controller for CAY merging operations. Reference [94] proposed a linear CACC system to guide platoon merging maneuvers. Reference [60] proposed a CACC model to regulate the trajectories of the merging/splitting vehicle, where the acceleration is jointly determined by two equations to avoid collisions. In free-flow traffic, a vehicle will try to maintain a desired speed $v*$ with acceleration

$$a1; = /J; (v* - v;). \qquad (11)$$

In the car-following scenario, the vehicle's acceleration is

$$a2; = a.;11X;(i-t) + /J; (v* - v;) + y;a;\_J, \qquad (12)$$

where $a;\_J$ is the acceleration of the preceding vehicle. The acceleration of vehicle i is then

$$a_i = \min\{a_{1i}, a_{2i}\}. \qquad (13)$$

d) Spring-mass-damper system: The spring-mass-damper system is a physics concept widely adopted to model how objects reduce oscillations with the spring constant, the damping coefficient, and the mass. A handful of studies (e.g., [38], [85], [86]) have proposed trajectory planning methods for CAY merging and splitting operations using the spring-mass-damper system concept. With vehicle $i's$ mass $m;,$ these methods define the spring force, shock absorber force, and friction force as a set of linear equations as follows

$F_{5;} = a.; (11x; - l;),$ spring force;
$Fai = /J;11v;,$ shock absorber force;
$Fi; = y;v;,$ friction force;

where $l;$ denotes the spring's non-stretched length (which can be computed as $so + v;+i\ (t)$ r in a CAY platooning system); $a.;,$ $/J;,$ and $y;$ are parameters. Early studies using this concept assumed that $a.;,$ $/J;,$ and $y;$ are fixed parameters (e.g., [38]). Recent studies (e.g., [86]) found that vehicles moved differently as the parameters changed. Applying the above equations to Newton's second law, we obtain the acceleration of vehicle i as follows

$$a_i = (F_{si} + F_{ai} + F_{fi})/m_i. \qquad (14)$$

Some studies (e.g., [86]) omit the friction force to simplify the analysis.

2) Nonlinear Rules: While linear rules are simple, they may result in inferior trajectory quality (e.g., less smoothed because of the speed jumps) and platoon instability. Thus, nonlinear rules have been proposed. Reference [84] established two speed boundary curves for the merging/splitting vehicle, one for safety and the other for time efficiency. Both curves incorporate a square root term to capture the nonlinear relationship between the velocity and the system inputs. Reference [57] used the Newtonian force model to design the trajectories of the merging/splitting vehicle, where the spacing between the merging/splitting vehicle and the closest preceding is captured

TABLE IV
PLATOON OPERATIONFIELD EXPERIMENT LITERATURE

Studies	**Merging**	**Splitting**	**Robots**	**Vehicles**	**Longitudinal Control**	**Lateral Control**
[91]						
[53]						
[58]						
[93]						
[94]						
[83]						
[l03]						
[79]						
[15]						
[64]						
[87]						
[96]						
[88]						

Note: Studies are sorted based on the publication year.

in a third-order term. Reference [58] merged and split platoons by using polynomial equations. Reference [97] utilized the bezier curve to generate the merging vehicle trajectory between lanes. Reference [88] used a proportional-integral-derivative **(PID)** speed controller to generate a gap in the platoon for the merging vehicle, which is proportional to the square of the velocity of the merging vehicle. These nonlinear rules are highly diverse. Extracting a general formulation is not feasible. Interested readers are referred to the studies above for detailed formulas.

VI. VEHICLE CONTROL

Vehicle control is the last step for CAY platoon merging and splitting operations. It is needed to translate theoretical trajectories into vehicle movements in the real world in the presence of disturbance. The goal is to control vehicles to follow the planned trajectories as much as possible. To test the performance of different vehicle control methods, small-scale robots (robots for short) and full-scale vehicles (vehicles for short) can be used as test objects. The same control logic applies. Some detailed control components may vary because of different technical configurations. For example, the direct control variable for vehicles is throttle/brake but most likely motor rotation per minute for robots. When resources are limited, robots are effective alternatives to vehicles in field experiments. Besides, robots can be completely controlled and do not pose any safety concerns while testing. Yet, outcomes from using robots usually do not directly apply to vehicles. To achieve the ultimate goal of operating vehicles on roads, extra efforts are needed, e.g., model parameter tunning. This section summarizes existing vehicle control methods and associated field experiments for testing their performance. **TABLE IV** presents a summary of platoon operation field experiments.

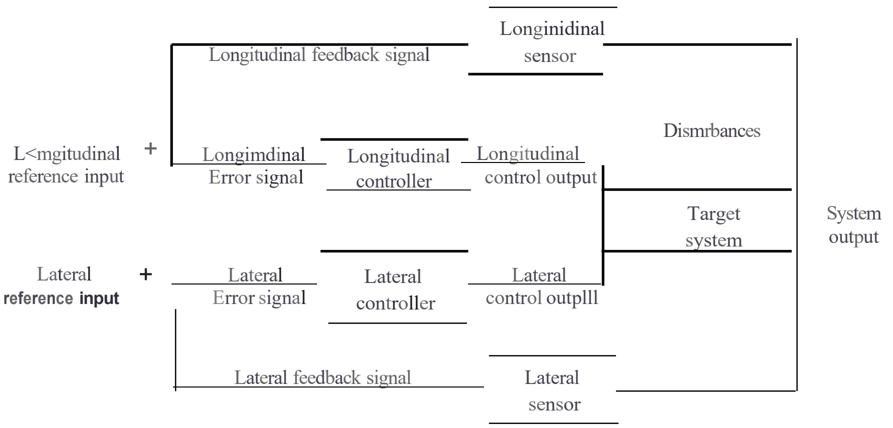
Most of the existing field experiments adopted feedback control to regulate vehicle/robot movements, given its simplicity and strong capability to compensate for model inaccuracies, control errors, and unmeasured disturbances [101]. Longitudinal control regulates vehicles/robots to follow designated longitudinal motions to finish the corresponding operations. Different longitudinal control strategies have been proposed with different control inputs and outputs. Some of them take speed errors as inputs [93], and some use distance/position errors [64], [83], [87], [91], [96]. For the control output, some of these strategies yield adjusted acceleration [15], [53], [83], [91] and some generate adjusted speed [58], [64], [87], [88], [93], [96].

The general vehicle longitudinal control model is formulated as follows

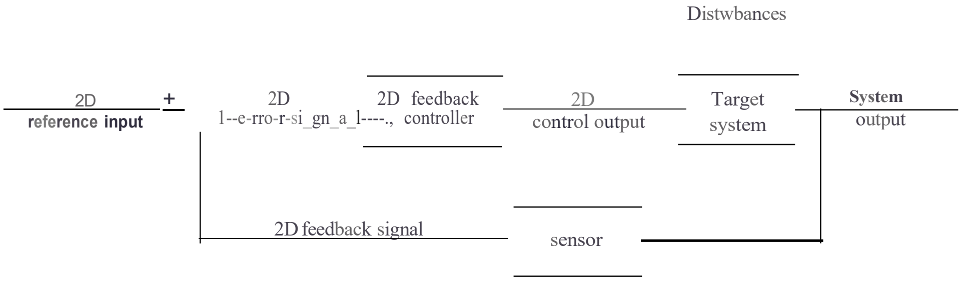
$$\varphi = f^x\left(\epsilon^x\right) + f^v\left(\epsilon^v\right) + g(v,a), \tag{15}$$

where rp is the vehicle control output, e.g., adjusted vehicle speed/acceleration, r(Ex) is the location control error, J° (E^0) is the speed control error, and $g(v,a)$ is the function with respect to vehicles' speed and acceleration. The specific forms of these functions are highly diverse. Interested readers are referred to the studies in TABLE IV.

Lateral control is also needed to ensure vehicles/robots operate on the track while finishing the operation in real-world implementations. [15] utilized pure pursuit to control robots running on an oval test track. Reference [53] proposed a look-ahead lane-keeping method to control the vehicle's lateral movements. Reference [64] developed a lateral controller to guide vehicle lateral movements while merging and splitting. Reference [96] used a path controller to ensure the robot sticks to a straight test track. Generally, the vehicle lateral control model is described as $oJ = f^0$ (E^0), where oJ is the ajdusted turning angle and f° (E^0) is the vehicle orientation error.



(a) Separated feedback controllers



(b) 2D feedback controller

Fig. 7. Vehicle control.

Most existing studies separated longitudinal control and lateral control by using two controllers [102], as shown in Fig. 7 (a). A few studies controlled both directions simultaneously using one integrated controller [58], [103], as shown in Fig. 7 (b). For these studies, the desired trajectories of the operations are time-specific 2D curves.

Existing studies mostly use single-input and single-output (SISO) controllers (e.g., PIO) to regulate vehicle movements. SISO controllers use a single value (e.g., current speed error) as the input and outputa single value. In comparison, multiple-input and multiple-output (MIMO) controllers (e.g., model predictive control, MPC) require a time series of reference inputs, e.g., vehicle speed/acceleration in a short time window, and generate a time series of outputs. MIMO controllers plan for multiple time steps in the future and thus are expected to produce higher control accuracy. Yet, the MIMO controllers have not been paid much attention in vehicle platoon experiments [79]. This is probably due to the unavailability of future vehicle trajectories. Specifically, a target vehicle trajectory for the future must be used as the control input in a MIMO controller. Given that most existing studies plan vehicle trajectories step by step with rule-based approaches, future trajectories are not available. Thus, SISO control has been dominantly utilized.

VII. RESEARCH DIRECTIONS

This section discusses future research directions. We first discuss two directions for CAV platoon merging and splitting studies overall, followed by specific research directions for each step in the proposed framework.

A. Overall Directions

Most existing studies have focused on platoon operations in a pure CAY environment without considering HVs [104]. To handle mixed traffic, including HVs, methods in each step may need to be modified. While most operation protocols remain the same, the CAV platoon gap shall be set as a small value such that HVs cannot easily cut in. If HVs do successfully cut in, the original CAY platoon can be separated into two sub-platoons for better management. In the presence of HVs, decentralized CAY platoon trajectory planning may remain the same because the following vehicle adjusts its movement step by step based on its perception regardless of the preceding vehicle type. Yet, centralized CAY trajectory planning is challenged by human driving stochasticity because it devises vehicle trajectories for multiple future time steps. In this case, HY trajectory prediction is required [105]. Precise trajectory prediction is challenging because of the HY stochasticity, and sometimes a small error could lead to serious consequences, e.g., collisions. Therefore, more advancements are needed in developing effective HY trajectory prediction models. After platoon operation trajectories are planned, vehicle trajectory control is just to control vehicle movements to follow the planned trajectories as much as possible. Since HY randomness has been taken care of in the planning stage, control techniques proposed in the pure CAV environment should still apply to mixed traffic.

Additionally, despite the fruitful advancements in platoon merging and splitting operations, efforts have rarely been made to compare the advantages and disadvantages of different methods. This limits real-world implementations and thus impedes platoon technology innovation. Future efforts can be devoted to a comparison study, which would be important for establishing technical standards for CAY platoon merging and splitting operations.

B. Protocol Design

Existing models for CAY merging and splitting operations have adopted centralized or decentralized management protocols. Both protocols have merits and drawbacks. These protocols are essentially two extremes in a continuous spectrum in terms of the "degree of centralization":the centralized protocol has the highest degree of centralization with all vehicles being coordinated by one vehicle; in contrast, the decentralized protocol has the lowest degree of centralization with each vehicle making decisions for itself. Ideally, the degree of centralization ranges from one to the maximum number of vehicles a platoon can accommodate. Thus, future studies could design management protocols beyond the two extreme conditions. For example, a platoon can be divided into sub-platoons. The leader in each sub-platoon makes decisions for all vehicles in this sub-platoon. Such a design likely combines the advantages of the two extreme cases.

Existing studies lack investigation on important decision-making details that affect the performance of the platoon merging and splitting operations. For example, in what circumstances should the merging/splitting request be accepted? How far away from the destination should a vehicle request a split operation? When admitting a new vehicle into the platoon, how to decide on the best platoon merging position? If more than one vehicle or sub-platoon needs to perform operations, should they operate simultaneously or sequentially? What would be the best operation order if the operations were conducted sequentially? Further, as vehicle connectivity technology evolves, multiple platoons may be managed by a centralized operational center. This case opens up the question of which is the best platoon to join for a merging vehicle. These decisions are non-trivial and likely have substantial impacts on the performance of the merging/splitting operations.

C. *Trajectory Planning*

Most studies have used decentralized trajectory planning because of the model's simplicity and computation efficiency. Decentralized models are typically dedicated to solving feasible trajectories in terms of safety. In contrast, centralized models solve the optimal trajectories for a given objective function. Searching for the optimal trajectory usually requires a (much) longer solution time because of the model complexity. Worse still, the solution time increases substantially as the problem size grows, e.g., the solution time can be in minutes [106]. This could pose serious issues for real-time applications that require computation time at the sub-second level. The lack of centralized models does not mean that methodological endeavors to build such models are trivial. Instead, if centralized models can be solved efficiently, CAY operators are expected to yield better performance. Thus, efforts should be made to develop efficient solution approaches for centralized models. The optimality gap between centralized models and decentralized models should also be investigated.

Recent studies show the great potential of reinforcement learning methods in planning vehicle trajectories [107], [108]. The reinforcement learning methods learn the optimal trajectory by training agents to interact with the environment. These methods are data-driven and can capture complex dynamics in a traffic system. Once the agent is well-trained, it is expected to yield (near-)optimal trajectories in almost no time. Despite their great potential, reinforcement learning methods have not been applied to plan platoon merging/splitting trajectories. A big hurdle in developing reinforcement-learning-based trajectory planning models is agent training. It usually takes a while before the agent produces reasonable results. Physics models can be incorporated to guide the agent and expedite the training process. However, the combination of physics models and learning-based methods is still a relatively new topic. More advancements are expected in the near future.

Finally, sometimes platoon merging and splitting operations are accompanied by lane changes. Yet, existing studies on platoon operations have mainly focused on planning longitudinal trajectories (i.e., car-following), assuming that vehicle lane changes are finished instantaneously. Very limited studies have integrated longitudinal and lateral trajectory planning [109]. More advancements are needed in this direction and yield better overall trajectory quality.

D. Vehicle Control and Field Experiments

In contrast with abundant theoretical platoon operation studies, field experiments are lacking. Most of these proposed operation strategies are tested by simulations, and thus their real-world applicability remains unanswered. An important factor that simulation studies cannot capture is communication delay. Vehicle control would be erroneous when the delay is longer than the control time step. Thus, vehicle trajectory tracking methods have been extended to incorporate communication delays in general vehicle control studies [110]-[112]. Existing field experiments about platoon merging and splitting operations are relatively small-scale. The corresponding communication delays can be ignored. As a result, their vehicle control strategies did not account for communication delays explicitly. However, when it comes to large-scale implementations where communication delays cannot be ignored, state-of-the-art delay mitigation strategies should be incorporated. Information flow topology is another critical factor affecting the performance of CAV platoon operations. It is found that the communication topology has substantial impacts on internal and string stability [113], scalability [113], safety [114], robustness [115], and fuel costs [116]. Recent studies have proposed CAY control strategies with different information flow topologies (e.g., [117]).To improve vehiclecontrol for the CAV merging and splitting process, future efforts are needed in this direction.

The existing field tests are usually conducted on public roads or test tracks in a controlled environment. Most of them only investigated subject vehicles without considering surrounding traffic. The generalizability of the proposed strategies to large-scale applications subject vehicles interact with surrounding traffic is uncertain. This could raise serious issues, especially when the surrounding traffic is human-driven vehicles that operate stochastically. CAV movement control can be easily interrupted, and thus the operation performance would significantly degrade. It is desired to incorporate surrounding traffic into field tests to verify the model's generalizability. In terms of vehicle controllers, most existing studies use SISO controllers to regulate vehicle movements. SISO controllers are computationally efficient. Yet, their performance cannot be guaranteed because they only focus on the current time step without planning for the future. The utilization of MIMO controllers in regulating vehicle motions to follow optimization-based multiple-step platoon operation trajectories has not been paid much attention. More efforts are needed in this direction to enhance the vehicle control performance and consequently harvest the benefits of CAV trajectory optimization in the real world.

Further, the longitudinal controllers proposed by existing studies in field experiments usually output speed and acceleration, which cannot be directly applied to vehicles and robots. The direct control variables are throttle/break for vehicles and motor rotation for robots. However, how the controller outputs are converted into vehicle/robot control variables remains unclear in most existing studies. Reference [53] calculated the throttle/brake angle using a sliding surface controller. Reference [93] calibrated a static lookup table to indicate the relationship between the pedal and the control error. The above controller parameters and the lookup table need to be adjusted based on the driving environment, which is characterized by various factors, e.g., weather, roadway condition, and vehicle load. Thus, it is demanded to develop an adaptive conversion to save resources and improve vehicle control performance. Reinforcement learning is one of the promising methods to achieve this goal [118]. The adaptive conversion between the controller outputs and the vehicle/robot control variables can be built and updated as the learning agent explores the environment. Finally, integrating trajectory planning and vehicle control in real-world applications is also an interesting future research direction.

VIII. CONCLUSION

CAV platoons have shown great potential in improving fuel efficiency, increasing roadway capacity, and enhancing traffic safety. Platoon merging and splitting are two fundamental operations and have drawn much attention in the past decades. This study provides an overview of CAV platoon merging and split operations. A synthesis of theoretical models and field experiments is presented. The existing methods for CAY platoon merging and splitting operations are unified into a three-step framework, including protocol design, trajectory planning, and vehicle control. Detailed methods for each step in existing studies are summarized and discussed. Finally, future research directions are discussed in light of the review results. This study not only proposes a framework to categorize relevant literature and guide the successful development of CAV operations in the future but, more importantly, offers researchers and practitioners a rich reference for further investigation on CAV platoon merging and splitting operations.

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