Received May 31, 2021, accepted June 10, 2021, date of publication June 15, 2021, date of current version June 25, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3089615

Platoon Transitional Maneuver Control System: A Review

SAREH BADNAVA[1], NADER MESKIN[1], (Senior Member, IEEE), ADEL GASTLI[1], (Senior Member, IEEE), MOHAMMED A. AL-HITMI[1], (Member, IEEE), JAWHAR GHOMMAM[2], MOSTEFA MESBAH[2], (Member, IEEE), AND FAIÇAL MNIF[2], (Senior Member, IEEE)

[1]Electrical Engineering Department, College of Engineering, Qatar University, Doha, Qatar
[2]Department of Electrical and Computer Engineering, College of Engineering, Sultan Qaboos University, Muscat 123, Oman

Corresponding author: Nader Meskin (nader.meskin@qu.edu.qa)

This publication was made possible by International Research Collaboration Co-Fund [IRCC2020-15] from Qatar University. The open-access publication of this article was funded by Qatar National Library.

ABSTRACT Connectivity and autonomy are considered two of the most promising technologies to improve mobility, fuel consumption, travel time, and traffic safety in the automated transportation industry. These benefits can be realized through vehicle platooning. A vehicle platoon is composed of a group of connected automated vehicles (CAVs) traveling together at consensual speed, following the leading vehicle (leader) while maintaining a prespecified inter-vehicle distance. This paper reviews the different existing control techniques associated with the transitional platoon maneuvers such as merge/split and lane change. Different longitudinal and lateral vehicle dynamics that are mainly used in the transitional platoon maneuvers are discussed. The most used control algorithms for both longitudinal and lateral control used for transitional platoon maneuvers are reviewed and the advantages and limitations of each control strategy are discussed. The most recent articles on platoon control maneuvers have been analyzed based on the proposed control algorithm, homogeneously or heterogeneously of platoon members, type of platoon maneuver, the aim of control problem, type of implementation, and used simulation tools. This paper also discusses different trajectory planning techniques used in lateral motion control and studies the most recent research related to trajectory planning for automated vehicles and summarizes them based on the used trajectory planning technique, platoon or/and lane change, the type of traffic, and the cost functions. Finally, this paper explores the open issues and directions for future research.

INDEX TERMS Platoon maneuver control, split, join, lane change, longitudinal control, lateral control, trajectory planning.

I. INTRODUCTION

Current transportation systems are being challenged with the constant increase in traffic capacity, fuel consumption, and environmental pollution. Vehicle platooning is an Intelligent Transport System (ITS) application that has arisen as a promising solution for these traffic issues [1].

The primary purpose of vehicle platooning (see Fig. 1) is to group interconnected vehicles traveling in the same direction with short inter-vehicle distances to improve traffic management, increase traffic capacity, reduce travel time, and enhance passengers' comfort by eliminating extreme accelerations and decelerations. This is achieved by adjusting the vehicles' speeds using onboard longitudinal motion controllers and inter-vehicle communication.

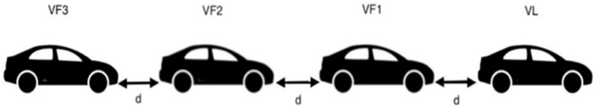


FIGURE 1. Vehicular platooning system. VL and VF stand for vehicle leader and vehicle follower respectively.

Besides longitudinal motion, vehicle control in a platoon needs to deal with transitional maneuvers such as lane change and splitting from and joining the platoon [2]. Some of the main challenges in vehicle platooning are joining the platoon

The associate editor coordinating the review of this manuscript and approving it for publication was Shihong Ding.

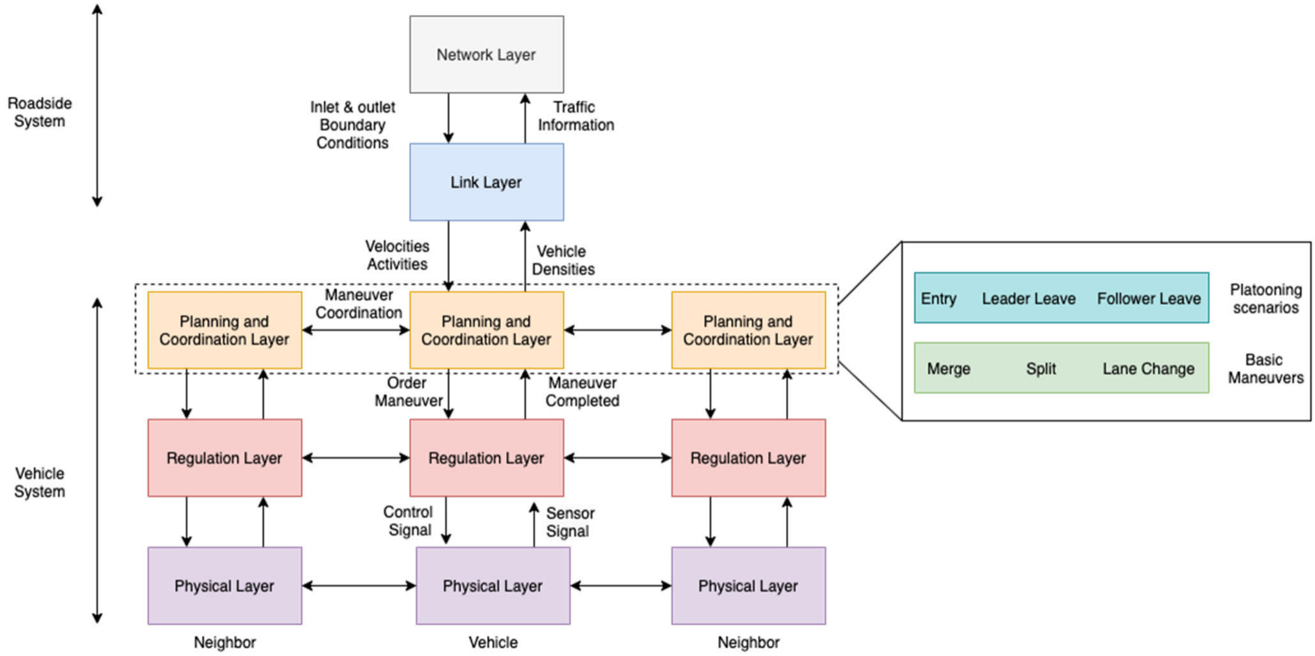


FIGURE 2. **Control hierarchy of platoon maneuvering.**

(for non-platoon vehicles), splitting from the platoon (for a platoon vehicle), and lane changing as detailed in Section II. These tasks will be herein referred to as platoon transitional maneuvers.

To have a successful platoon maneuver, it is necessary to design the control system of the platoon based on five control layers. An overall five-layer hierarchical control structure for a platoon of vehicles shown in Fig. 2 [3].

- *Network Layer:* This first layer controls the entering traffic and routes traffic flow. It is responsible for optimizing the capacity of the road and the average travel time for each vehicle and reducing transient congestions.
- *Link Layer:* This layer is responsible for controlling the link's traffic flow to achieve its full capacity and minimize the travel time of vehicles and traffic congestion. The link is divided into sections, one section for each lane. Each link communicates with the neighboring links and transfers the traffic flow between links. In this layer, aggregated vehicle densities in every section within the link are measured.
- *Coordination and Planning Layer:* This third layer, determines the intents of the different vehicles in the platoon such as join, split and change lane maneuvers. In a join maneuver, one or more vehicles join an existing platoon or form a new platoon. In the split maneuver, however, one or more vehicles separate at a designated position from a platoon. This layer performs a structured exchange of data via communication protocols with the neighboring vehicles to safely execute such a maneuver.
- *Regulation Layer:* This fourth layer deals with the vehicle's lateral and longitudinal control. It receives the commands from the coordination layer and translates them into steering, throttle, and braking inputs to the onboard vehicle's actuators. It uses various continuous-time feedback control laws to generate inputs to the vehicle's actuators to execute the desired maneuvers. This layer handles two longitudinal control tasks, namely maintaining specified velocity and inter-vehicle spacing, and efficiently and safely perform maneuvers outputted by the coordination and planning layer for the platoon leader or free agents.
- *Physical Layer:* The last layer consists of the local physical components which include local sensors, various lateral and longitudinal guidance, steering and brake control systems, and transmission and engine.

Several review studies dealing with different aspects of platoon algorithms have been conducted in the literature. In [4], several research works on vehicle platooning are reviewed and analyzed based on the four main components of the platoon system from the networked control system perspective. Furthermore, string stability, string margin, and coherence behavior have been discussed. However, the scope of this paper is limited to platoon longitudinal control systems and only the longitudinal dynamics of the vehicle are discussed, while the lateral control of vehicles for platoon maneuvering purposes is not considered. In [5], articles on communication, driver characteristics, and control system of the platooning system in the longitudinal direction are reviewed and several real-world issues such as communication effects, traffic composition, and driver behavior that affect the performance of the platoon control modules have been discussed. The objective of this review was also limited to longitudinal motion

TABLE 1. Comparison of this paper with the existing survey articles.

Year	Reference	Control Modes		Platoon Mnaeuvers			Years Range
		Longitudinal Control	Lateral Control	Lane Change	Join a Platoon	Split from a Platoon	
2015	[4]	+	–	–	–	–	2009-2015
2016	[5]	+	–	–	–	–	2003-2015
2016	[6]	+	+	+	+	–	2002-2015
2018	[7]	–	–	–	–	–	2008-2017
2020	[8]	+	–	–	–	–	2008-2018
2021	This paper	+	+	+	+	+	2010-2020

of the platoon and lateral motion with is used lane change, join/leave maneuver is not considered. In [6], a survey on different lateral and longitudinal control algorithms, communication and positioning systems, effects of surrounding vehicles and environment on connected and automated vehicles (CAVs) for lane change and merge maneuvers is provided. Additionally, a study on different simulation tools used for lane change and merge maneuvers have been conducted. In this paper, a few numbers of control techniques and a few numbers of articles related to transitional platoon maneuvers have been studied and reviewed.

In [7], a survey on different characteristics of platoon planning and different problems that arise in platoon planning focusing on truck platooning is conducted and the level of human involvement in platooning is discussed. However, it did not cover the control aspect of the platoon system. In [8] authors reviewed existing articles on truck platooning from the perspective of fuel economy where the articles are classified and analyzed based on air drag reduction and fuel consumption reduction. Various control algorithms are discussed to minimize fuel consumption in truck platooning. The scope of this review paper is limited to fuel economy and only longitudinal motion of platoon is covered.

Table 1 highlights the contribution of this paper with respect to existing review papers where this survey paper is compared with existing review papers based on some criteria such as control modes, platoon maneuvers, years range. This paper provides an overview of the most recent research from 2010 to 2020 conducted on platoon maneuvers' control strategies and highlights their advantages and limitations. Articles are classified and analyzed based on the proposed control algorithm, homogeneously or heterogeneously of platoon members, type of platoon maneuver, the aim of control problem, type of implementation, and used simulation tools. Furthermore, a review on trajectory planning for automated vehicles used in the lateral motion control has been conducted. Finally, this paper explores gaps in the literature that can be studied in future research.

The rest of this paper is organized as follows: Section II presents a brief overview of platoon maneuvers' control objectives. Section III discusses the different models of vehicle dynamics. Section IV focuses on different control techniques used for platoon maneuvers, followed by the trajectory planning in Section V. Finally, conclusion and future research directions are provided in Section VI.

II. PLATOON MANEUVERS OVERVIEW

A. PLATOON MANEUVERS CONTROL OBJECTIVE

Several modules with different requirements are needed to work together to achieve the desired targets of a vehicle platoon discussed in Section I. These modules are the coordination module, perception module, and autopilot module.

A high-level coordination module consists of a strategy management algorithm that specifies the rules required for the communications between vehicles in the platoon. An example is given in [9], where the control hierarchical driving architecture is a centralized platoon strategy, where the platoon leader coordinates with platoon followers in a three-layer architecture: traffic control, management, and guidance layers. Another important subsystem of this module is the inter-vehicle communication topology. In [10], the impact of various communication topologies in the platoon is studied.

The perception module provides information about the surrounding areas and extracts necessary data from the environment to determine the exact locations of the vehicles and to enable the vehicle to find its position with respect to the environment [11].

Researchers have proposed different control techniques for platoon control. These techniques are used for various purposes such as platoon longitudinal and lateral control, platoon (string) stability, and platoon coordination [12]–[14]. The control of the vehicle in a platoon is the primary responsibility of the autopilot module. Some of the tasks carried out by this module using onboard hardware and software are trajectory/path planning, platoon longitudinal and lateral control, and obstacle avoidance [15].

To perform different vehicular platoon maneuvers, a higher-level control is needed to make decisions about the initiation time and the type of the maneuver. The maneuvering vehicle (the vehicle that performs the maneuver(s)) and the vehicles in the platoon receive these decisions through communication links. The maneuvering control tasks can be

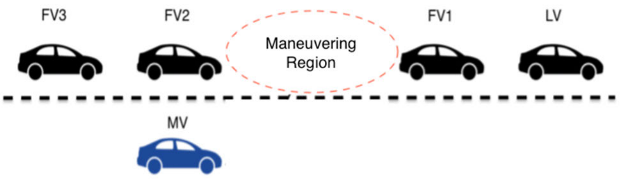


FIGURE 3. Maneuvering region.

divided into two parts, namely, maneuver logic and vehicle control [16]:

1. *Maneuver Logic:* This part decides the sequence of the maneuvers in the maneuvering region shown in Fig. 3. It defines the actual velocity and position of the maneuvering vehicle on the maneuver lane and also which vehicle(s) from the platoon must be included in the maneuvering process. Maneuver logic specifies "which" vehicle will perform the maneuver in "what" order and "where" to go instead of "how" it will do that, which is performed by the vehicle control.
2. *Vehicle Control:* This part controls how the vehicle in the platoon achieves the desired maneuver(s). Maneuver's constraints, pertaining to the vehicle capabilities or space and time constraints, must be considered in the control design.

The vehicle control objective is to longitudinally and laterally maneuver a vehicle to change lanes, join a platoon, or split from a platoon.

- *Lane Change:* The objective of the lane change procedure is to move the maneuvering vehicle laterally from its current position to the desired lane. The lane change process is the first action that needs to be taken by the maneuvering vehicle to join or leave the platoon.

  After a successful lane change operation and joining the platoon, the maneuvering vehicle will be part of the platoon and needs to abide by the platoon's constraints (speed and maximum inter-vehicle distance). In the case of leaving the platoon, a vehicle can also act as a free agent and never joins a platoon after a lane change. In [17], an optimal lane change strategy for vehicle platooning based on the lateral and longitudinal control is studied, and in [18] a PID controller is used to perform the lane change maneuver for an automated vehicle while avoiding any collision with neighboring vehicles.
- *Joining a Platoon:* Joining a platoon involves maneuvering a non-platoon vehicle (designated as MV in Fig. 4) to a position in the platoon lane (middle, ahead, or behind) such that it becomes part of the platoon. In [19], the merging behavior is modeled for a non-platoon vehicle, joining a cooperative adaptive cruise control (CACC)-based platoon and in [15], distributed controllers are used to develop a merging schema that is capable of creating a gap in a platoon to allow a non-platoon vehicle to join the platoon and guarantee a collision-free maneuver.

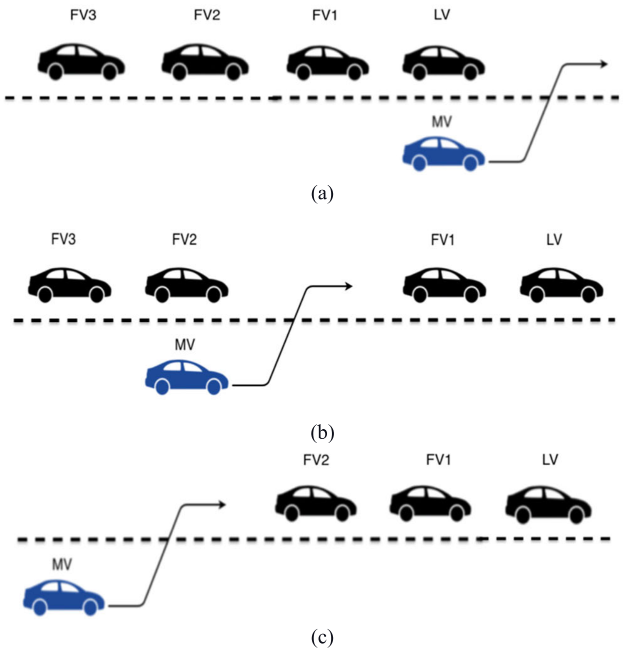
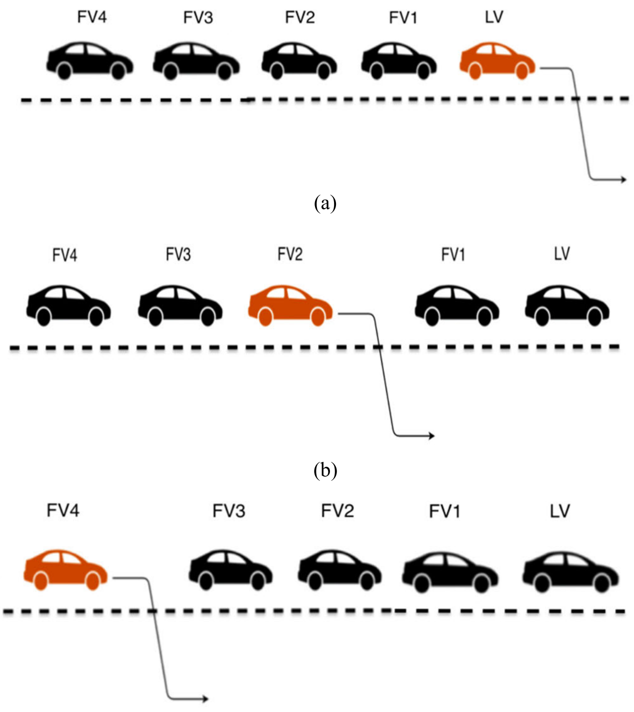


FIGURE 4. A merge procedure: (a) in front, (b) in the middle, (c) at the back.

- *Splitting From a Platoon:* To split from a platoon, a vehicle (designated as FV2 in Fig. 5) needs to create enough distance from the neighboring vehicle (scenarios b and c in Fig. 5) or make a lane change (scenario (a) in Fig. 5). After the split, the platoon vehicles need to adjust their inter-vehicle distances. At the end of the maneuver, the maneuvering vehicle becomes a free agent. In [20], a distributed and consensus-based approach is proposed to control both platoons' joining and leaving maneuvers.

III. VEHICLE MODELING

In the context of longitudinal and lateral control for vehicles in the platoon, vehicle models are used to investigate the effect of input signals (position, velocity, acceleration, steering angle) on the orientation and velocity of the vehicle in time and space. The most used vehicle models based on complexity are mass point models, kinematic models, and dynamic models. Mass point models are the most basic model of vehicles that express the dynamics of the vehicle as a mass point. These models are rarely used in control and automation applications since they do not involve other dynamics which affect the speed and steering angle of the vehicle [21]. Kinematic Models are achieved through geometric relations that describe the vehicle motion without considering the effect of forces on the motion. This model can be used in low-speed vehicle control applications [22]. Dynamic models are the most used model in applications where longitudinal and lateral forces on the vehicle body and vehicle tire are used to model the vehicle dynamic. Vehicle dynamic models can be used in various applications based on a different degree of freedoms such as models based on all four wheels of



(a)

(b)

(c)

FIGURE 5. **A split procedure: (a) from the front, (b) from the middle, (c) from the back.**

the vehicle; models based on two wheels, models based on vertical vehicle dynamics (longitudinal vehicle dynamic); models based on horizontal vehicle dynamics (lateral vehicle dynamic); and models based on both horizontal and vertical vehicle dynamics (longitudinal and lateral vehicle dynamic) [22].

In a platoon maneuver, it is essential to integrate both longitudinal and lateral dynamics of the vehicle. The longitudinal vehicle dynamic model is based on the dynamics of the vehicle that generate forward motion. Due to some nonlinearities such as aerodynamics drag, brake system, driveline, and engine, the vehicle longitudinal dynamics are nonlinear.

Some of the papers such as [23], [24] used a nonlinear model of vehicle longitudinal dynamics directly into the platoon design system. Indeed, linear vehicle dynamics are the most common dynamics used for tractable problems. The single integrator model, double integrator model, third-order model, and single-input-single-output (SISO) model are the commonly used linear vehicle dynamics.

The simplest case is the single integrator vehicle dynamic model, where only the velocity of the vehicle is being controlled. The main advantage of this model is the simple theoretical analysis for some controller synthesis. However, due to the simplicity of this model, it is not sufficient for complex control applications such as platoon transitional maneuver. In [25] and [26], a single integrator model is used for longitudinal vehicle dynamics in platoon formation. The second-order vehicle dynamic model uses acceleration as a control input to improve the stability of the system. In this model, the platooning vehicle is considered as a point mass. In [27], a second-order vehicle model is used to control the inter-vehicle distance between vehicles in platoon using a non-linear consensus algorithm. The second-order model still does not include some of the properties of the vehicle dynamic such as inertial delay in vehicle powertrain dynamic, and this could cause instability in the real-world [28]. A third-order dynamic is used to solve this issue. In this model, the braking torque and engine torque are used as control inputs. In [29] and [30], a third-order vehicle dynamic is used for the platoon vehicle.

The lateral vehicle dynamic model is based on the dynamics of the vehicle that generates a perpendicular motion to the forward motion. The bicycle model and dual model are the common lateral vehicle dynamic models. In the bicycle model, front and rear tire forces are acting at the centerline at the front, and rear axles; however, in dual-mode, front and rear tire forces are acting at the four vehicle corners. Based on the application, different degrees of freedom can be used for lateral vehicle dynamic modeling. Quarter vehicle model with 2-degree-of-freedom (lateral, yaw), half vehicle model with four or five- degree-of-freedom (longitudinal, lateral, yaw, roll) and full vehicle model with 7 or 18- degree-of-freedom are the example of different degree of freedom associated with vehicle dynamic [31]. The lateral vehicle dynamic model can be written in two forms: linear and nonlinear models. The linear model uses the linear model of the tire; however, the nonlinear model uses the nonlinear model of tire. In literature, it has been indicated that the linear model can predict reasonable responses up to slip angles of 2 degrees and lateral accelerations of 0.5g, and, for higher slip angles and lateral accelerations, the nonlinear model has a better response [32]. In [33], [34] a linear two-degree-of-freedom(2DOF) bicycle model of vehicle is used which represents the vehicle lateral position and the vehicle yaw angle to control the lateral motion of the vehicle for lane change purpose. In [35], a nonlinear 2-DOF bicycle model is used for the lateral dynamics of the vehicle to design a lateral controller to minimize the lateral displacement error with respect to the reference path. In [36], a nonlinear lateral dynamic of the 2-DOF dual vehicle model is used to investigate the performance of the controller in the steering control.

IV. PLATOON MANEUVER CONTROL TECHNIQUES

As discussed in Section II, lane change and join/split maneuvers can involve both lateral and longitudinal control. The platoon maneuver control system can be divided into longitudinal control and lateral control. The longitudinal control aims to ensure that the vehicles in a platoon keep a pre-specified inter-vehicle distance while traveling at the same longitudinal velocity. The objective of lateral control is to control the lateral motion of the platoon in a case of transitional maneuvers such as lane change, join a platoon, and splitting from the platoon.

A. LONGITUDINAL CONTROL

Researchers have extensively studied the longitudinal control problem. Several longitudinal controller techniques have been used to address this problem while attempting to simultaneously achieve other objectives such as optimizing fuel consumption or ensuring platoon stability [37]. In what follows, various longitudinal controllers proposed in the literature are presented and discussed.

1) PROPORTIONAL INTEGRAL DERIVATIVE CONTROL

The Proportional Integral Derivative (PID) control technique is widely used in various industrial control applications because of its effectiveness and simplicity [38]. Designing the PID controller is very simple since it only requires tuning three parameters, the proportional gain, the derivative gain, and the integral gain. The tuning process can be performed manually or automatically using advanced software tools. This controller works by considering the difference between the set point (desired inter-vehicle distance) and the controlled variable (the measured inter-vehicle distance) [39].

A PID feedback controller is proposed in [40] in the presence of the noise signal such as sensing lags, actuation lags, a gust of air, weather condition, and inaccuracy in the traction force, for the longitudinal control of the leading vehicle and following vehicles. The designed controller has been applied on six vehicles with nonlinear dynamic moving in a platoon. The performance of the platoon under sudden braking and acceleration in critical conditions us studied and it has been observed through the numerical simulation results that the designed PID feedback controller follows the pre-defined velocity and inter-vehicle space only once the steady-state behavior is obtained. The PID controller is mainly developed based on the constant distance (CD) policy where the desired inter-vehicle spacing in the platoon is independent of the vehicle's velocity and is constant. Using CD policy requires more attention on the communication connections and controller parameters to ensure the string stability of the platoon. Therefore, CD policy is not proper for the autonomous purpose. String stability of the platoon refers to a property in which the disturbances such as errors in spacing and velocity are not amplified when propagating towards the tail of the platoon. The developed control law in [40] only requires the information of the predecessor vehicle, which is not sufficient to guarantee the string stability of the platoon. To ensure string stability and have safe control of the platoon, in addition to the state of the predecessor vehicle, the information of the leading vehicle in the platoon and spacing error dynamics is essential to be added in the control law. Additionally, it is proposed to replace the PID controller with a sliding mode controller with constant time headway (CTH) policy where the distance between two adjacent vehicles varies linearly with the vehicle's velocity. In [41], to keep the headway distance between vehicles in the platoon as constant as possible and the difference between the velocity of platoon vehicles as small as possible, equal PID controllers are applied to all vehicles, except the leading vehicle. A nonlinear vehicle dynamic with feedback PID control and feedforward control based on an inverse model of nominal dynamics of vehicle is used to study the performance of the designed controller. To simulate and analyze the performance of each vehicle and platoon, MATLAB/Simulink is used, and it is shown that the desired behavior of the velocity and inter-vehicle space of each following vehicle in the platoon is successfully achieved using the proposed approach. However, for the PID controller in case of the nonlinear model or changes in initial conditions the controller gains should be tuned to keep the desired performance.

2) SLIDING MODE CONTROL

Sliding mode control (SMC) is a variable structure controller, where the closed-loop nonlinear system dynamics are changed through a high-frequency switching control. This approach has two main advantages comparing to other controllers. First, by choosing particular switching functions, the dynamic behavior of the controller can be modified. Second, for a particular class of uncertainty, the response of the closed-loop system becomes insensitive to disturbance. Moreover, this controller can specify the performance directly, which makes it attractive from the design perspective [42].

An SMC was designed in [43] to control the inter-vehicle distance between vehicles in the platoon while maintaining the pre-defined platoon velocity with CTH policy and to ensure the string stability of the platoon. A second-order vehicle dynamic with parasitic time delays and lags of the sensors and actuators is designed to study the string stability of the platoon. Based on the simulation results, the developed control schema showed a fast response under external disturbance and it can ensure the string stability of both the homogeneous (platoon of vehicles with same dynamics model) and the heterogeneous (platoon of vehicles with different dynamics model) platoon. Furthermore, it has been shown that it is essential to consider the parasitic time delays and lags in studying the string stability of the platoon; otherwise, it will produce impractical results.

A neural adaptive sliding-mode control strategy using novel output feedback was proposed in [44] to control the platoon vehicles longitudinally with a bidirectional communication strategy and constant time headway (CTH) policy. A neural adaptive sliding-mode control algorithm based on the integrated-sliding-mode (ISM) technique is designed to guarantee the desired inter-vehicle distance in the platoon base on the CTH policy. Additionally, to decrease the communication load and the measurement complexity, a higher-order sliding-mode controller is designed to obtain the required information such as position, velocity, and acceleration of the platoon vehicles. The stability theorem is used to ensure string stability. To simulate and verify the effectiveness and feasibility of the developed sliding-mode controller, a simulation study is conducted, and it has been observed that the developed controller converges faster to the pre-defined velocity and inter-vehicle space; therefore, it is more practical, and pragmatic compared to the traditional sliding-mode controller.

In [45], a switched fuzzy adaptive double coupled sliding mode algorithm is designed to control the platoon longitudinally and to guarantee its string stability. The controller is imposed into a third-order vehicle dynamic model with external disturbance and sufficient and necessary conditions are provided for coupling coefficients of sliding mode surfaces about neighboring vehicles to guarantee the robust string stability of the platoon system. Additionally, to overcome the chattering problem in the sliding mode method, a controller with a switched parameter is designed. It has been observed through the numerical simulation results; the developed method has better tracking performance compared to the traditional sliding mode control on acceleration, position, and speed of the vehicles in the platoon. Additionally, the results showed that at the presents of disturbance in the system, the pre-defined space between two vehicles in the platoon can be appropriately kept. It is noted that as the speed of the platoon increases the following vehicles are able to track the leading vehicle with the constant displacement error.

3) MODEL PREDICTIVE CONTROL (MPC)

Model predictive controllers (MPCs) predict the future response of the system by employing an explicit process model [46], [47]. In [48], a model predictive control (MPC) combined with a frequency domain controller using a control matching approach is designed to involve both constraint satisfaction (safety and physical) and string stability for a vehicle platoon application. The proposed controller is verified both in the field test and in the simulations. Three vehicles with third-order vehicle dynamics are used to evaluate the proposed control strategy in three scenarios: constraints satisfaction, string stability, and vehicle following. Experimental and simulation results indicated that the string stability could be ensured using a single MPC controller while considering the constraints resulting from limitations, safety, and performance.

A model predictive control (MPC) for longitudinal control of a vehicle platoon proposed in [49] with the main aim to decrease fuel consumption and enhance road safety by controlling the vehicles' speed in the platoon and adjusting their inter-vehicular distance using a centralized MPC method. The longitudinal dynamics of the vehicles in the platoon are modeled based on the forces involved during the brake and the acceleration, such as rolling resistance, tractive force, and aerodynamic. The control law is devoted to regulating the longitudinal spacing and velocity of the following vehicles based on the behavior of the leading vehicle. The developed controller adjusts the vehicle speed over a time horizon with the main aim is to optimize the cost function, which reduces the square deviations of the inter-vehicular space, tractive forces, speeds, and positions of the vehicles in the platoon. The developed control system has been simulated under two different scenarios: constant speed reference value and time-varying speed reference value and it has been observed that the proposed control system is more effective in a constant speed reference case. It has been noted that the proposed controller can handle constraints of the system therefore more desired performance is obtained. However, the performance of the proposed controller is sensitive to the accuracy of the prediction model and it required a large tuning parameter set.

In traditional MPC controllers, to compute the control inputs, it is usually assumed that all states are known to the control system. Traditional MPCs are mainly used in a centralized manner. However, in some traffic system scenarios, centralized information is not possible. To address this issue, distributed MPCs (DMPCs) were introduced. In distributed MPC, each controller uses the traditional MPC method to control its system by considering the objectives, constraints, disturbances, dynamics of the subsystem, and the interactions between various systems [50]. Local controllers use local information to generate local control inputs and share the obtained information with other controllers to enhance the system's performance.

DMPC is used in [51] for a vehicle platooning application to control the inter-vehicular distance between two adjacent vehicles in the platoon and adjust the speed of the platoon's leading vehicle based on the pre-defined constant velocity. A distributed model predictive control strategy is used to control all vehicles in the platoon with input constraints. The author modeled the vehicle dynamic based on the more realistic vehicle dynamic model. Each vehicle in the platoon receives control information from the predecessor vehicle, which is used to solve the local optimization problem and transmit the resulted optimal solution to the successor vehicle in the platoon within the same sampling instant. It has been proved through simulation results that the developed control strategy is feasible and effective. The developed DMPC algorithm needs to be validated against environment disturbance, communication failure, and lags from sensors and actuators to ensure the string stability of the platoon.

In [13], a DMPC scheme is proposed for a platoon with nonlinear vehicle dynamics, which uses unidirectional topology to exchange information between vehicle platoons. Through simulation results, the string stability of the platoon using the proposed DMPC is guaranteed. It is noted that by including the state of the follower vehicle into the optimization problem, a collision-free environment can be generated. Additionally, the effects of communication failure have been investigated in this paper. It has been observed through simulation results that the developed DMPC is not able to overcome this issue. Hence, a new DMPC model, which can handle steady-state error due to the communication failure, is designed and verified through a simulation environment. The proposed DMPC algorithm is shown to be an effective and powerful tool for managing and modeling bidirectional topology. The proposed DMPC algorithm can be further improved by considering random delays.

4) CONSENSUS CONTROL

Researchers have worked on consensus problems in distributed computing for many years. The consensus control is used to develop algorithms for a number of vehicles to agree on a single data value regarding a specific quantity of interest (inter-vehicle distance and velocity) through exchanging data with neighboring agents [52]. Single-integrator strategy is the most used continuous consensus strategy [53], [54] and is expressed as:

$$\dot{x}_i(t) = -\sum\nolimits_{j=1}^{n} a_{ij}(t)\left(x_i(t) - x_j(t)\right), \quad i=1,\ldots,n \tag{1}$$

where $a_{ij}(t)$ is the (i,j) entry of the adjacency matrix of the associated communication graph of the system at time t, $x_i(t)$ is the information state (distance to the preceding car, velocity) of the vehicle i at time t, and n is the number of vehicles. The consensus is reached (meaning the vehicle i and its adjacent vehicle are agreed on a single value of inter-vehicle distance and velocity) when the information state of vehicle i is driven toward the information state of the adjacent vehicle.

For modeling the vehicles' dynamics in a platoon, a double-integrator strategy can be obtained from the single-integrator distributed consensus algorithm's extension [55], [56]. The double-integrator distributed consensus strategy is expressed as:

$$\begin{aligned}\ddot{x}_i(t) = -\sum\nolimits_{j=1}^{n} a_{ij}(t)\Big[&\left(x_i(t) - x_j(t)\right) \\ &+\gamma\left(\dot{x}_i(t) - \dot{x}_j(t)\right)\Big], \quad i=1,\ldots,n\end{aligned} \tag{2}$$

where $\gamma > 0$ is a tuning parameter which indicates the weight of the difference between the derivatives of the states $x_i(t)$ and $x_j(t)$. This system can be used to tackle the vehicular platooning control issues [57], where $x_i(t), \dot{x}_i(t)$, and $\ddot{x}_i(t)$ are longitudinal position, velocity, and acceleration, respectively, of the agent i at time t. The value of the acceleration of vehicle i can be computed based on the acceleration and velocity of the agent itself and the adjacent agents. A consensus of this scheme is reached once both position consensus $x_i(t) - x_j(t)$ and velocity consensus $\dot{x}_i(t) - \dot{x}_j(t)$ are reached by all the vehicles in the network.

In [58], a double-integrator distributed consensus-based cooperative adaptive cruise control (CACC) scheme is designed to control the speed and inter-vehicle distance between members of the platoon. In this paper, heterogenous vehicles without considering time delay and lags are used to test the proposed control strategy using MATLAB/Simulink simulation environment. The simulation results indicate the ability of the proposed algorithm in maintaining the platoon velocity and inter-vehicle space in the presence of different disturbances such as communication delay and sensor lags. Additionally, the proposed control system was able to carry out the platoon joining and leaving maneuvers. In this paper, the authors considered the system level of the vehicles, and the actual vehicle dynamic has not been considered.

A second-order consensus algorithm is developed in [59] to obtain platooning of vehicles affected by heterogeneous time-varying delays due to wireless communication between vehicles in the platoon. Lyapunov–Razumikhin theorem is used to assure the stability of the platoon in the presence of time-varying delay. Results obtained from the numerical implementation confirm the validity of the proposed algorithm in the presence of disturbances.

Time delay due to communication failures and packet losses in the communication channel will affect the platoon's string stability. To overcome these issues, a consensus-based control algorithm is proposed in [60] where a control law with Bernoulli distribution is designed to solve the problem of variable time delay and packet losses. Non-linear vehicle dynamic is used to test the effectiveness of the proposed controller under time-vary delay and packet losses. The effectiveness and validity of the proposed method are proved through both theoretical and simulation results.

A consensus-based control schema for nonlinear vehicles following application with time delay is presented in [61] where the exact feedback linearization technique is used to derive a linearized third-order dynamic model for vehicles. A consensus-based control algorithm is proposed with a constant and variable time delay to control the inter-vehicular distance between vehicles and adjust the speed of the platoon. Lyapunov-Razumikhin theorem and Lyapunov-Krasovskii theorem are used to acquire sufficient conditions that ensure the string stability of the platoon. The correctness and feasibility of the proposed algorithm are verified using numerical simulation results and theoretical results.

A unified consensus-based control scheme is designed in [62] to address various problems of vehicular platoon such as collision avoidance, gap closure, and platoon formation in the urban environment. A double-integrator vehicle dynamic model is used in this paper. The proposed algorithm aims to obtain the position and velocity consensus of the vehicles in the platoon by considering the nature of the motion in the traffic. To achieve a gap closure scenario, an algorithm for adjusting the controller parameters online is proposed. Additionally, the collision avoidance scheme is developed and integrated with the consensus-based controller to ensure the minimum safe space between vehicles in the platoon. To verify the feasibility and efficiency of the developed controller, a realistic simulator known as ICARS with actual vehicle dynamic models is used to implement the proposed algorithm. The simulation and theoretical results demonstrated the efficiency and feasibility of the developed control scheme under various driving conditions.

5) NEURAL NETWORK-BASED CONTROLLER

Computational systems with artificial neural networks (ANN) imitate the functioning of the human brain. This kind of system has self-learning capabilities and solves difficult or impossible problems proven by statistical standards or humans; therefore, they will have a high acceptance rate among users. An artificial neural network is capable of processing the information much quicker than other controllers, with a response time in nanoseconds. An artificial

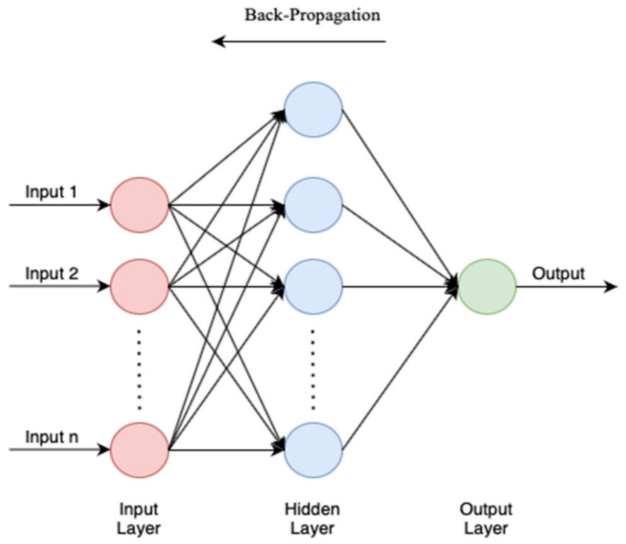


FIGURE 6. **ANN architecture.**

neural network is formed from thousands of artificial neurons known as processing units and interconnecting each other by nodes. These processing units consist of input units and work in unison to produce output units. The input units receive different structures and forms of data according to the internal weighting system, and the artificial neural network gains experience through the given information and produce an output unit. In most cases, an artificial neural network changes its form and structure during a learning phase. Similar to human behavior that follows some guidelines and rules to produce an output or result, artificial neural networks also need learning guidelines known as backpropagation Network (BPN) to produce an accurate output [63]. In BPN, errors from the output layer are propagated backward through the hidden layer to the input layer (Fig. 6).

In [64], a neural network-based distributed adaptive scheme is integrated with a sliding mode controller for vehicle-following platoons, based on traditional constant-time headway (TCTH) and modified constant-time headway (MCTH). MATLAB simulation environment is used to verify the feasibility of the proposed controller. It is noted that the designed controller can control the velocity of the vehicles in the platoon and maintain the specific inter-vehicle distance between vehicles in the presence of input saturation, external disturbances, and unknown unmodeled nonlinear dynamics. Therefore, the controller is accurate in the presence of disturbance. However, a large number of data is need for training. The proposed controller can guarantee string stability by using two spacing policies while the effect of time-delay and measurement noise is not considered. In [65], to maintain a safe inter-vehicle distance between two vehicles in the platoon and control the speed of the platoon, a neural network controller with a back-propagation network (BPN) is developed. The input of the neural network controller was speed error and distance error between the following vehicle and the leading vehicle and the output of the controller was the amount of brake and throttle needed for the safe control of the vehicle in the platoon. The developed controller is tested practically using two motorcycles and the result was satisfying, where the following vehicle successfully maintained the specified inter-vehicle distance with the leading vehicle. It should be noted that in [65], the proposed controller is only tested on two wheels vehicles.

6) H_∞ CONTROLLER

H_∞ control is a robust controller that can handle the maximum level of uncertainty and inaccuracy in the system model. It synthesizes controllers to obtain stabilization with promised performance. The H_∞ method represents the control problems as mathematical optimization problems; and then determines controllers to solve these mathematical optimizations with the main aim to find a stable dynamic feedback controller which generates control signals by manipulating the measured outputs that minimize the H_∞ norm between undesired signals and error from outputs and stabilizes the whole system. This technique is considered to be a robust control system since it reduces the effects of undesired signals at worst-case while stabilizing the overall system [66].

In [67], a robust and distributed H_∞ controller is developed for a large-scale platoon of automated and connected vehicles with undirected topologies (having information exchange between all vehicles in the platoon). In this paper, external disturbances are considered while designing the controller. It is shown that the controller synthesis and robustness performance are highly affected by the communication topology and affect the poor communication conditions such as packet loss and time delay is considered in their design. Additionally, the proposed controller is only applicable for linear systems. In [68], a distributed control scheme is studied for a platoon of vehicles with different dynamic controllers. A simulation study has been conducted to validate the feasibility and effectiveness of the proposed controller. It is noted that under various disturbances such as vehicle dynamics uncertainties, wind speed, and different road slopes, the heterogeneous string stability, sufficient tracking performance, and robust stability of the developed control system can be ensured. Therefore, the proposed controller can guarantee sufficient performance under disturbances. Additionally, it is noted that the information from the leader has a significant influence on the robust stability.

B. LATERAL CONTROL

Lateral control is used to perform transitional maneuvers such as lane change, join a platoon, and splitting from the platoon as discussed before. Platoon lane change maneuvers are two-layer procedures, namely the strategy layer and the control layer. By considering collision avoidance, the strategy level decides how and when to perform the lane-change operation or join/leave maneuver. The control level decides how to perform the lane-change operation or join/leave maneuver by turning the steering wheel, braking, or throttling [69].

For the strategy level, proposed a model is proposed in [70] that mimics the driver control behavior during the lane change operation and it includes planning a suitable trajectory (discussed in part C in this paper) from the original lane to the destination lane.

At the control level, two different control processes are needed to achieve transitional maneuvers, namely lateral guidance algorithm and tracking control problem [71]. For the lateral guidance algorithm, to achieve the desired lane change or join/split maneuvers, the desired yaw rate generator is responsible to produce the desired yaw rate. To perform the lane-change maneuver, a yaw rate reference signal is used in [72] and a robust switching controller is designed to generate the desired steering angle commands. For the tracking control problem, and to ensure improved passenger ride comfort, it is important to account for lateral jerk and lateral acceleration while planning for the "virtual" desired trajectory.

A two-layer adaptive nonlinear steering controller is introduced in [73] to track the desired lateral trajectory for the lane change maneuver. The Boltzmann-Hamel technique in quasi-coordinates is used to obtain the vehicle dynamic model with unknown inertial parameters. Cycloidal trajectory planning is used to generate the desired path in real-time. Matlab/Simulink is used to simulate and validate the feasibility of the proposed control system for lane change purposes. Based on the simulation study, the lane change maneuver is successfully obtained in the presence of unknown inertial parameters of the vehicle dynamical model.

In [74], a PID controller is proposed to control the yaw rate and sideslip of a two-degree-of-freedom bicycle vehicle model. The main aim of the proposed controller is to follow the desired trajectory for the lane-change maneuver, by controlling the yaw angle and reducing the sideslip of the vehicle as much as possible. The main reason for using the PID controller in this paper was due to its simplicity and practicality compared to other controllers. MATLAB/Simulink is used to simulate the proposed controller and the controller has been tested with different vehicle speeds for single and double lane-change maneuvers. It has been concluded that the designed controller is valid only at low speed. For lane change processes, the quintic polynomial approach is used in [18] to generate a feasible and smooth trajectory and the lateral motion of the vehicle is controlled using a PID controller while the kinematic model of the vehicle is used. To ensure a safe maneuver, a collision-avoidance technique is integrated into the main controller. Even though the simulation results indicate a feasible lane change process; however due to the simplicity of the PID controller is not satisfying for applications that need high tracking accuracy. A PID controller was also used in [75] to perform the lane-change processes with a bicycle vehicle dynamic model driving at low speed. This controller aimed to control the steering wheel angle according to the lateral displacement and yaw motion of the vehicle. The developed controller was tested practically and simulated in MATLAB/Simulink and it has been observed through both practical and simulation results that the developed controller can perform smooth lane changes at moderate steering wheel angles and low speeds.

In [34], to perform the lane-change maneuver, an adaptive sliding mode control for a nonlinear vehicle dynamic model is designed. A fuzzy boundary layer is used to prevent the chattering effect in adaptive sliding mode control and according to the boundary conditions, various maneuver periods, and path planning for the lane-change purpose are studied. CarSim simulator integrated with MATLAB/Simulink is used to simulate the proposed controller under different road conditions. For dry road conditions, the proposed controller indicated a perfect tracking; however, for wet and icy roads, an acceptable tracking has been obtained. To generate the steering angle commands for lateral trajectory tracking, a virtual yaw signal and a robust sliding-mode controller were proposed [76] where a two-degree-of-freedom (2-DOF) vehicle dynamic model is used to estimate the desired slip angle and yaw rate for the lateral trajectory tracking. To evaluate the developed controller, CarSim software is used, and the double lane change process is performed and the robustness and efficiency of the developed controller under side wind disturbance have been confirmed through the simulation results. It has been concluded that the proposed controller is robust against external disturbances, however it requires prior knowledge of disturbance bounds.

In [77], an H_∞ controller is developed using the loop shaping technique to control the steering angle of the vehicle in the lateral displacement and yaw motion where the reference trajectory is assumed to be known. The bicycle model of the vehicle is used to evaluate the performance of the proposed controller and the simulation results indicated the capability of the proposed controller in tracking the reference trajectory with deficient tracking error. The controller has been tested with different vehicle speeds, and it has been confirmed that the designed controller is sufficiently robust while performing lateral displacement. Therefore, it has been concluded that the proposed H_∞ control scheme ensures an acceptable behavior in practical use.

A Model Predictive Controller (MPC) is developed in [78] to control the vehicle steering angle and wheel torque where eight-degree-of-freedom (8-DOF) vehicle dynamic model and the Dugoff tire model are used. MPC controller is used to predict the future behavior of the vehicle for the lane change maneuver and minimize the error between the actual and desired trajectory. MPC controller includes the system constraints in the design producer and considers the whole vehicle dynamical model. Therefore, it can provide an effective and efficient solution for the control problem. A collision-free trajectory for the lane-change maneuver is generated based on the convex optimization technique. A collision-free lane change maneuver is performed by developing an MPC-based control scheme that controls wheel torques, front and rear wheel angles to follow the reference path. Based on the simulation results, the developed MPC controller performs a feasible lane change maneuver while avoiding collision with other vehicles. In [79], a nonlinear model predicted control algorithm is proposed for a 3-DOF nonlinear extended bicycle model of vehicle dynamics for a lateral motion purpose. The standard quadratic cost function is used to minimize the tracking error by calculating the optimal longitudinal force and steering angle of the vehicle. Additionally, anti-side split constraint and anti-rollover speed constraint are considered in the design of the controller. Carsim software is used to design the 4-wheel vehicle dynamical model and MATLAB/Simulink is used to simulate the proposed controller. The simulation results confirmed the feasibility of the proposed controller in performing path tracking action while ensuring the stability of the vehicle under different road conditions and different vehicle speeds. In [80], a model predictive control (MPC) controller is developed with switched tracking error to control the steering angle of the vehicle to follow the reference path. The controller aimed to minimize the lateral tracking deviation while maintaining vehicle stability under different speed conditions. A 2-DOF bicycle model is simulated in the CarSim-Simulink platform to investigate the feasibility and effectiveness of the proposed controller. The simulation results confirmed that the proposed controller could accurately track the reference path while maintaining vehicle stability in different speed scenarios. Model uncertainties and external disturbances are not included in the controller design.

In [81], a vehicle lateral stability control system is proposed for lateral maneuvering purposes, such as the lane change process, based on fuzzy logic control theory. The designed fuzzy logic controller aimed to increase the vehicle lateral stability by following the desired yaw rate and side-slip angle generated by the reference model. The controller has been implemented on a dual vehicle dynamic model and tested on a simulation environment. The simulation results have confirmed the feasibility and effectiveness of the developed control strategy. Additionally, it is noted that the proposed controller is able to follow the desired reference trajectory smoothly, however it does not guarantee the stability of the vehicle.

In [82], a combined sliding mode control, fuzzy control, and neural network-based controller is developed to control the lateral motion of an intelligent vehicle. The performance of individual and combined controllers has been compared through simulation results. It has been noted that the combined sliding mode control, fuzzy control, and neural network-based controller have smoother and more robust performance in trajectory tracking than the performance of each controller separately. A robust steering controller combined with an adaptive neural network (ANN) is proposed in [83] to ensure the yaw stability of the vehicle and reduce lateral trajectory tracking error while performing the lateral motion. A 2-degree-of-freedom (2-DOF) vehicle dynamic model is used to investigate the validity of the proposed controller in both simulation and practical environments. Obtained results confirmed the effectiveness and feasibility of the proposed controller in tracking the reference path while maintaining yaw stability in the presence of unknown external disturbances. In [84], a three-degrees-of-freedom vehicle dynamic model is used to evaluate the combined fuzzy PID control with a neural network based-controller in generating the steering angle commands for the lane-change maneuver. Real-time long-short term memory (LSTM) deep neural network, a special type of recurrent neural network (RNN), is used in the controller design and it has been observed through the simulation results that the proposed controller with fuzzy PID control and neural network-based controller has an excellent performance in following the reference trajectory. However, to have very accurate performance, this controller requires a large amount of data for training.

In [69], an LQR controller is proposed to control vehicle steering torque for an automated trajectory following purpose. A simple bicycle model of the vehicle is designed to study the performance of the proposed controller. Velocity, position, yaw rate, and yaw angle of the vehicle are used by the proposed controller to generate the desired steering angle to follow the reference trajectory for lane-change maneuver. CARSIM simulator is used to investigate the performance of the proposed controller. It has been confirmed that the developed controller can change the lane successfully. The controller has not been tested under external disturbance and plant uncertainties. In [85], to generate steering commands for following the desired path in different driving maneuvers such as lane changing and lane-keeping, a linear quadratic regulator (LQR) is proposed, and the performance of the proposed controller is compared with the PID controller in terms of steerability and stability of the vehicle. MATLAB/Simulink is used to investigate the validity and effectiveness of the proposed controller by implementing on the vehicle with eight degrees of freedom (8-DOF) dynamic model. It has been observed that LQR has a better performance in terms of maneuverability and stability of the vehicle compared with PID.

To summarize, Table 2 presents a comparison of the reviewed longitudinal and lateral control techniques proposed in the literature for the platoon transitional maneuver. Based on this table, the PID controller is the simplest and easiest controller to implement, however, it is not sufficient for applications with large disturbances. The neural network is the most accurate and quickest controller to process the information compared to other controllers, however sufficient training is required. MPC controller is the most common controller used in publications due to its ability to handle multi-inputs and multi-outputs simultaneously, it can handle constraints.

C. MANEUVER CONTROL

In [86], Cooperative Adaptive Cruise Control (CACC) system is developed for a platoon of vehicles to analyze the impact of external disturbances such as interferences caused by non-automated vehicles while performing a join maneuver. Moreover, the impact of the packet loss on the platoon join maneuver is studied. Veins simulator is used to prove the

TABLE 2. Comparison of the longitudinal and lateral motion controllers.

Control Strategy	Advantages	Limitations	Vehicle Model
PID [40][41][74][75][82]	▪ Easy to implement ▪ Established method with good performance for non-linear systems ▪ It is efficient and robust against some common uncertainties such as plant uncertainties	▪ The performance of PID controller reduces in the presents of non-linearities and large disturbance	▪ Kinematic or dynamic vehicle model required
SMC [43][44][45][34][76]	▪ Fast response under system uncertainties and external disturbances ▪ Suitable for nonlinear systems ▪ Provides constant and small displacement errors when the speed of the plant increases	▪ Chattering effect (finite-amplitude oscillations) ▪ Requires prior knowledge of uncertainty and disturbance bounds ▪ Control law is sensitive to path curvature variations ▪ Controller sampling rate effects on the performance of the controller	▪ Kinematic or dynamic vehicle model required
H_∞ [67][68][77]	▪ Achieves stabilization with guaranteed performance	▪ A high level of mathematical understanding is needed and it is only applicable for linear systems.	▪ Accurate kinematic or dynamic vehicle model required
MPC [48][49][51][13][78] [79][80]	▪ Consider the whole vehicle model in the control problem ▪ Inclusion of system constraints in the design procedure ▪ Robust against plant parameter variations	▪ Computational requirements of online optimization making this controller unsuitable for high-speed ▪ Larger tuning parameter set compared to PID controller ▪ The performance is sensitive to the accuracy of the prediction model	▪ Kinematic or dynamic vehicle model required
Fuzzy logic [81]	▪ Robustness to sudden changes in the environment ▪ Provides smooth response	▪ Stability is not guaranteed ▪ Formal stability analysis needed to achieve a systematic controller tuning ▪ A major number of variables can lead to uncontrollable rules	▪ Model-free
Neural network [64][65][82][83][84]	▪ More accurate results can be obtained through sufficient training	▪ A large amount of real-world (training) data is necessary to train the controller.	▪ Model-free
LQR/LQG controller [66][85]	▪ Robust against measurement noise ▪ Offline gain optimization results in a simple online controller	▪ It is not easy to design the controller in the presents of high uncertainties	▪ Accurate kinematic or dynamic vehicle model required

validity of the proposed system and simulation results indicated the validity and feasibility of the proposed controller for a join maneuver in case of interference. Additionally, from simulation results, the robustness of the CACC controller to packet losses which results in a safe maneuver has been proved. The validity of the proposed system is not analyzed under a sudden deceleration of the leader or large size of the platoon. In [87], the merging maneuver process of a platoon of vehicles is discussed.

The author proposed two different lateral trajectory generation methods: Adaptive Polynomial Lateral Trajectory and Adaptive Cyclodidal Lateral Trajectory and compared their performance under three different platoon speeds. To investigate the efficiency and feasibility of the proposed trajectory generation methods, three different longitudinal controllers: PD with preceding vehicle information, PD with preceding and follower vehicles information, and Sliding Mode controllers are used and compared their performance for merging a platoon of two vehicles into an existing platoon. The effectiveness of the proposed methods has been tested and verified using the recently developed simulation tool known as SimPlatoon.

In [88], Cooperative Adaptive Cruise Control (CACC) system along with wireless communication through Vehicle Ad Hoc Network (VANET) is used to develop a platoon management system for basic platoon maneuvers: platoon merging, platoon splitting, and lane-change. In the developed system, non-platoon vehicles can join or leave the platoon longitudinally (having a non-platoon vehicle in the same lane as the platoon) and laterally (having a non-platoon vehicle in the adjacent lane of the platoon). VENTOS simulator, which is based on SUMO and OMNET++ simulators, is used to test the effectiveness and validity of the proposed system and it has been indicated that the developed system can effectively perform platoon maneuvers and guarantee traffic flow stability in the presence of communication loss.

A high-order consensus controller is proposed in [89] to ensure the convergence to the desired velocity and desired inter-vehicle space between vehicles while guaranteeing robustness in the presence of time-varying heterogeneous delays due to join or leave maneuver and communication failure. Numerical simulations have been conducted to study the robustness and feasibility of the proposed controller in the presence of disturbances and communication failures. Additionally, in-vehicle experiments have been performed with three vehicles to investigate the feasibility of the proposed controller in convergence to the desired velocity and inter-vehicle distance and perform a joining maneuver.

Simulation and experimental results demonstrate the feasibility effectiveness of the proposed approach and guarantee the string stability in the presence of heterogeneous time-varying delays.

In [90], a PID controller along with NARX neural network has been proposed to study the join, merge and leave maneuvers in several scenarios of the flexible Platoon in time. NARX predictive model is used to learn and precisely predict the pattern for flexible platoon maneuver purposes. Matlab/Simulink and Stateflow are used to validate the feasibility of the proposed approach. The simulation results indicate the validity of the proposed approach and the effectiveness of the NARX neural network in the case of noises in test data.

In [91], a PID controller is used to achieve the merging and splitting maneuvers for non-linear Heavy-Duty Vehicles (HDVs) dynamic and the validity of the proposed controller for basic platooning maneuvers is verified through both MATLAB and micro-simulator VISSIM. Through simulation results, it has been observed that the proposed controller can guarantee the string stability of the platoon while performing platoon maneuvers such as merging into platoon or platoon splitting from the platoon. Only longitudinal platoon merging or splitting (merging into or splitting from platoon within the same lane of the existing platoon) is discussed in this paper and merging into the platoon for splitting from the platoon laterally is not covered.

A distributed consensus-based CACC system is proposed in [58] for platoon formation, platoon joining and leaving maneuvers. A decentralized communication topology is used for fast and accurate communication between vehicles. A second-order vehicle dynamic is simulated in MATLAB/Simulink to verify the effectiveness and feasibility of the proposed controller under time-varying communication delay. The simulation results indicate that the platoon can be formed, and platoon joining and leaving maneuvers can be done successfully under communication delay, and string stability of the system can be guaranteed. In this study, the actual vehicle dynamics model has been neglected. Additionally, the validity of the proposed algorithm under different realistic conditions such as weather condition, signal fading, packet loss, and signal interference should be studied.

In [92], an LQR and Distributed MPC controller is proposed to create additional space to allow a new platoon of vehicles to join and guarantee a smooth trajectory during the platoon joining process. The proposed controller has been tested for a platoon of vehicles with different dynamics. Additionally, the controller is validated for multiple automated vehicles intended to join the platoon from a nearby lane. The effectiveness and feasibility of the proposed controller while taking the safety of the merging process into account have been demonstrated through simulation results. Additionally, the time delay and lags from sensors and actuators need to be considered in the controller design. Moreover, the limitations on acceleration and velocity have not been considered in the space-making process.

In [93], two different control techniques are presented to control the merging process of two adjacent platoons while considering both acceleration limitations and safe space-creation. In the first control technique, the authors used two distributed model predictive control (DMPC) scheme to create a space for the non-platoon vehicle before joining the platoon and controlling the merging vehicle to join the created space in the target platoon safely. In the second control technique, LQR combined with DMPC controller is used for gap creation and controlling the merging vehicle. A double-integrator dynamic model is used to compare the proposed control techniques in the simulation platform. It has been observed that the DMPC controller has better performance in terms of distance errors, speed errors, and time to merge or split. Therefore, it has been concluded that the DMPC controller is more efficient, feasible and consumes less time in gap creation and gap closing for merging and spiting from the platoon, respectively. This paper did not study the behavior of the proposed controllers under realistic conditions such as heterogeneous vehicle dynamics, communication failure, and different road and environment conditions. Additionally, the fuel efficiency of the proposed controllers has not been investigated.

The string stability for the platoon maneuvering process is studied in [20], where a distributed consensus algorithm that guarantees string stability while performing the platoon maneuvering process is proposed. This paper considered the behavior of the proposed control scheme under all platoon maneuvering scenarios: entering and exiting the platoon from the front, middle, and tail of the platoon. Plexe simulation platform is used to validate the effectiveness and feasibility of the proposed controller under realistic conditions such as packet losses, nonlinearity of the plant, and network constraints. It has been confirmed through theoretical and simulation results that the proposed controller can ensure the string stability of the platoon while performing the platoon maneuvering process under realistic conditions.

Distributed controllers for a set of vehicles with first-order dynamics are used in [15] to address the problem of vehicle merging. The main aim of the proposed controller is to guarantee a collision-free merging process by quickly creating enough gap for the vehicle in the adjacent lane to steer in the platoon. A third-order polynomial lateral trajectory is used to generate an appropriate distance trajectory. Simulation studies were used to assess the controller's ability to achieve collision-free maneuverings. String stability of the platoon under time delay due to the communication failure and uncertainties from plant and environment is not considered in this paper. Additionally, only platoon merging scenario is presented, and other platoon maneuvers such as leaving the platoon and lane change are not studied in this paper.

In [94], a combined PID controller and MPC-based controller with a look-ahead design are proposed to control the longitudinal and lateral motion of the nonlinear vehicle dynamics model separately. The controller is used to allow multiple vehicles to join an existing platoon using variable-gap 5th order polynomial lateral desired trajectory. The proposed MPC controller with a look-ahead design improves the trajectory tracking performance by taking actions beforehand. The proposed control strategy is simulated in MATLAB/Simulink with two scenarios. The designed controller is tested with one vehicle joining an existing platoon, and then in the second scenario, multiple vehicles intended to join the platoon. In both scenarios, the controller indicated a robust and feasible platoon merging behavior.

In [95], in order to perform platoon joining and leaving maneuvers, a Lyapunov approach is used to control the speed of a single vehicle in the platoon, a PID controller is used to control the gap between vehicles in the platoon, and an adaptive MPC controller is used to control the lateral position and the steering angle to have a safe lane change and lane-keeping maneuvers. A one-wheel vehicle model is used to study the effectiveness of Lyapunov and PID controllers in the longitudinal direction. Moreover, a bicycle model is used to study the validity of the adaptive MPC controller in lateral motion. MATLAB/Simulink and Gazebo simulator is used to test and visualize the platoon joining and leaving maneuvers. From simulation results, the validity of the developed system for platoon maneuvers has been proved. In this study, perfect communication with no time delay has been assumed. Additionally, the string stability of the platoon has not been studied.

In [96], an MPC controller has been used to track the planned path for platoon joining or leaving maneuvers. In this paper, a linear kinematic bicycle model is used in the design of the MPC controller. Additionally, a cooperative maneuver switching model is developed to switch between vehicle-following mode after merging maneuver and single-vehicle mode after the splitting maneuver. Simulation studies have been conducted to verify the validity and effectiveness of the proposed system under perfect communication conditions. Simulation results indicate the effectiveness of the developed system. String stability of the system has not been studied. This study did not consider the real-world conditions such as communication delay and randomness of sensor errors, as well as interference from other vehicles in the environment.

In [97], a centralized longitudinal Model Predictive Control (MPC) is developed for a non-linear kinematic vehicle model to ensure a safe joining and leaving of a vehicle into a platoon. In this paper, bidirectional topology is used to exchange information in terms of position and speed, between the leading vehicle and followers. The leading vehicle receives the state (position and speed) of each vehicle in the platoon, uses the control process to elaborate the received information, and transmits the optimal control decisions to all vehicles in the platoon in each time interval. It has been indicated through the theoretical and simulation results that the developed control scheme reduces the tractive forces and the square deviations of speed and positions concerning the specified desired values. The numerical simulation results show the feasibility and effectivity of the designed control algorithm. This paper focused on the longitudinal platoon maneuver control system; however, it is important to study both lateral and longitudinal platoon maneuvers.

In [98], to control platoon joining and leaving maneuvers with heterogeneous vehicle dynamics (platoon of vehicles with different dynamics), a Distributed Nonlinear MPC (DNMPC) is developed. A simulation study has been conducted to investigate the validity of the proposed controller with different communication topologies. Simulation results prove the effectiveness of the proposed controller for platoon maneuver, and it is shown that a collision-free maneuver can be guaranteed. The string stability of the system has not been studied. Additionally, the validity of the system under realistic conditions such as time delay from communication failure and sensor lags has not been addressed.

In [99], a feed-back/feed-forward controller combined with a hybrid trajectory planning(Bézier curves and MPC) is used to control and plan the trajectory of a platoon of vehicles willing to join another platoon with the same vehicle dynamic model. AUDRIC/Dynacar simulation environment is used to verify the feasibility and effectiveness of the proposed methods. From simulation results, it has been conducted that a platoon of multiple vehicles can safely and smoothly join another platoon without any perturbations.

To enhance the safe platoon maneuvering process, fault diagnosis and monitoring of the vehicle platoon system should be developed and implemented in the platooning system to detect any fault/failure in vehicles. In [100], a two-level fault detection and isolation system is developed for vehicle platooning systems where the first layer is used to detect system failure and the second layer is used for component element failure detection. The reliability and efficiency of the developed two-level fault diagnosis system and isolation algorithm are verified through both simulation and experimental tests. An active fault diagnosis method is proposed in [101] to detect component failures of members of the platoon system and the effectiveness and feasibility of the proposed system are verified through the CarSim simulation environment.

Table 3 summarizes the most recent articles on platoon control maneuvers and provides information about the type of platoon members (Homogeneous-platoon of vehicles with the same dynamics- or Heterogeneous- platoon of vehicles with different dynamics), the type of platoon maneuver and implementation, and the aim of the control problem. According to this table, the MPC controller is the most used controller for transitional platoon maneuvers. The majority of the articles have used a homogeneous platoon of vehicles and aimed to ensure the safety of the maneuvering process while minimizing the maneuvering time. It is noted that most of the publications have focused on lane change and join maneuver, and some of them have implemented all three different platoon maneuvers. For the concept evaluation majority of the research has simulated the proposed methodology using

TABLE 3. Recent articles on platoon control maneuvers.

Year	Reference	Control Strategy	Type of Vehicles in a Platoon	Platoon Maneuver			Implementation		Aim of Control Problem
				Lane Change	Join a Platoon	Split from a Platoon	Simulation (Tool)	Real-life	
2014	[86]	CACC	Heterogeneous	√	√	×	√ (Veins)	×	Ensure a safe join maneuver in the presents of external disturbances and packet loss
2014	[87]	PD and Sliding Mode Controller	Homogeneous	√	√	×	√ (SimPlatoon)	×	Safe and fast merging maneuver
2015	[88]	CACC	Homogeneous	√	√	√	√ (VENTOS)	×	Safe and fast maneuver
2015	[89]	High-order consensus controller	Homogeneous	√	√	√	√ (Not mentioned)	√	Ensure a safe maneuver in the presence of communication failure and time-varying delays
2016	[90][89]	PID+ Neural Network	Homogeneous	√	√	√	√ (MATLAB/ Simulink/ Stateflow)	×	Improving traffic mobility
2017	[91]	PID	Homogeneous	×	√	√	√ (VISSIM and MATLAB)	×	Reducing fuel consumption
2017	[58]	Distributed consensus-based controller	Homogeneous	√	√	√	√ (MATLAB/ Simulink)	×	Improving driving safety and driving comfort
2018	[92]	LQR+DMPC	Heterogeneous	√	√	×	√ (Not mentioned)	×	Improving safety of maneuvering process and comfort of passengers
2019	[93]	DMPC	Homogeneous	√	√	×	√	×	Ensure safety and reduce travel time
2019	[20]	Consensus-based controller	Homogeneous	√	√	√	√ (Plexe)	×	Maintaining strong string stability in the platoon to ensure the safety
2019	[15]	Feedback and feedforward controller	Homogeneous	×	√	×	√ (Not mentioned)	×	Collision-free and fast platoon maneuver process
2019	[94]	PID+MPC	Homogeneous	√	√	×	√ (MATLAB/ Simulink)	×	Ensure safety and alleviate congestion issues
2019	[95]	Lyapunov-based controller + PID + Adaptive MPC	Homogeneous	√	√	√	√ (MATLAB/ Simulink and Gazebo)	×	Safe maneuver
2019	[96]	MPC	Homogeneous	√	√	√	√ (Not mentioned)	×	Improve traffic safety and efficiency
2020	[97]	MPC	Homogeneous	×	√	×	√ (Not mentioned)	×	Safe and fast maneuver
2020	[98]	Distribute Nonlinear MPC	Heterogeneous	√	√	×	√ (Not mentioned)	×	Safe and fast maneuver, improvement in driving comfort and fuel economy
2021	[99]	Feed-back/Feed-forward Controller	Homogeneous	√	√	×	√ (AUDRIC/ Dynacar)	×	Ensure safe and comfort manuver

TABLE 4. Recent research on trajectory planning techniques for automated vehicles.

Year	Reference	Trajectory Planning Technique	Platoon	Lane change	Mixed Traffic	Cost Tracking	Fuel	Time	Safety
2015	[107]	6th order polynomial	×	√	Connected/Non-connected Vehicles	Yes	Yes	No	Yes
2015	[108]	RRT algorithm	×	√	All automated vehicles	Yes	No	Yes	Yes
2015	[109]	State Lattice Algorithm	×	√	All automated vehicles	Yes	No	Yes	Yes
2016	[110]	7th order polynomial	√	√	CAVs	No	Yes	Yes	Yes
2016	[111]	B-spline	×	√	All automated vehicles	Yes	No	Yes	No
2017	[112]	A-Star Algorithm	×	√	All automated vehicles	Yes	No	Yes	Yes
2017	[113]	Clothoids curves	×	√	All automated vehicles	Yes	No	Yes	Yes
2018	[96]	Artificial potential field	√	√	CAVs	Yes	No	No	Yes
2018	[114]	N-Bézier Curves	×	√	All automated vehicles	Yes	No	No	Yes
2019	[15]	3rd order polynomial	√	√	CAVs	Yes	No	No	Yes
2019	[94]	5th order polynomial	√	√	CAVs	Yes	No	No	Yes
2020	[115]	3rd order polynomial	√	√	Connected/Non-connected Vehicles	Yes	Yes	No	Yes
2020	[116]	Dijkstra algorithm + Bezier curve	×	√	Autonomous trucks	No	No	Yes	Yes
2020	[117]	Bézier Curves	×	√	All automated vehicles	Yes	No	Yes	Yes

MATLAB/Simulink tool while few research works have been tested in the real-life field.

D. TRAJECTORY PLANNING

Maneuvers such as merging into a platoon require lateral motion control as discussed above. To perform these maneuvers efficiently, while avoiding accidents, trajectory planning is needed.

The problem of generating such a trajectory is usually formulated as a constrained optimization problem. Various functions, such as polynomial functions, have been used to represent the lateral trajectory. Trajectory planning needs to account for several constraints. Some of the constraints are related to vehicle capabilities and passenger comfort. Limits are generally placed on the maximum acceleration changes and the maximum jerk. Another considered constraint is the maximum time of the maneuver.

Connected vehicle technology includes various types of data such as weather conditions and infrastructure conditions. However, it is required to design algorithms that combine all this data and generate the desired trajectory. Different techniques, such as Connected Cruise Control (CCC) [102], [103] and Cooperative Adaptive Cruise Control (CACC) [5], [104]–[106] have been developed to generate the trajectory by using communication topologies.

Table 4 provides the most recent research related to path planning for automated vehicles and it clarifies different influencing factors such as trajectory planning technique, platoon or/and lane change, the type of traffic, and the cost functions. Based on this table, the majority of the publications used the polynomial trajectory planning method for trajectory planning of automated vehicles in the platooning system and most of them are aiming to improve safety while performing the lane-changing maneuver. Moreover, most of the articles studied the performance of the proposed trajectory planning technique under the condition where all the vehicles are automated and few of them studied the situation where both automated and non-automated vehicles are used.

Many trajectory planning methods have been borrowed from mobile robotics and adapted to the new application and environment. These can be classified into four classes, namely, graph theory-based planners, sampling-based planners, interpolating curve planners, and numerical optimization approaches. The most common path planning algorithms are presented below.

1) GRAPH-THEORY-BASED PLANNERS

This approach represents the vehicle's configuration space as a graph, where the vehicles are represented by vertices, and the transitions between vertices are expressed by edges. By searching for a minimum cost path in this graph, the desired lateral path can be found. Graph theory-based search strategies are restricted to optimize only over a limited group of paths [116]. Examples of graph theory-based search techniques are Dijkstra Algorithm, A-Star Algorithm (A∗), and State Lattice Algorithm. These are the most widely used algorithms for finding the shortest path in a graph [109], [112], [115]. Dijkstra Algorithm searches for a single-short path in a set of grids or nodes and it is proper for universal planning in various types of environments; however, the algorithm is slow in large areas because of the large number of nodes and the resulted path is not continuous. Therefore, it is not suitable for real-time applications. A-Star Algorithm (A∗) is based on Dijkstra's algorithm and reduces the time computation; however, the resulted path is not continuous. Therefore, it is not suitable for real-time applications. State Lattices can handle multiple dimensions (velocity, position, acceleration, and time) and it proper for dynamic environments and local planning; however, it evaluates all solutions in the database, which results in costly computation time

2) SAMPLING-BASED PLANNERS

Sampling-based planners solve problems very quickly. To find the desired trajectory, these methods select several points in the space. To bias the direction of the search and maximize the investigation of space, heuristics are applied. Rapidly-exploring Random Tree (RRT) [108] is the most widely used technique from this class. Rapidly-exploring Random Tree (RRT) provides quick results in multi-dimensional systems and it is suitable for universal and local planning.

3) INTERPOLATING CURVE PLANNERS

The planners belonging to this class use a prefined set of way-points to generate a smooth trajectory through interpolation [118]. The way-points are generated to address the different constraints related to the vehicles and the vehicle's environment. Different interpolation techniques were proposed that use, as a basis, the following curves: lines and circles, clothoids, polynomials, Bézier curves, and splines [15], [94], [107], [110], [111], [113]–[117]. The advantage of these techniques is their minimal computational cost [119].

4) NUMERICAL OPTIMIZATION APPROACHES

The techniques of this class generate the desired trajectory by minimizing/maximizing a cost function subject to multiple constraints. Sometimes this is mainly used for smoothing an already generated path obtained from kinematic constraints [120]. In [121], four different trajectory planning techniques are discussed, namely the trapezoidal acceleration, the polynomial approximation, the cosine approximation, and the circular approximation.

Additionally, the safety and comfortability of the passenger and the transition time in the trajectory planning design are considered. The comparison between trajectories shows that the trapezoidal acceleration trajectory is the most suitable one for a lane change maneuver.

V. CONCLUSION

This paper has reviewed different existing control techniques associated with the transitional platoon maneuvers such as merge/split and lane change. The first part of the paper presents an overview of the platoon maneuver as well as different longitudinal and lateral vehicle dynamics that are mainly used in the transitional platoon. In the second part of the paper, the most used control algorithms for both longitudinal and lateral control used for platoon merging, platoon splitting, and lane change maneuvers have been presented. The advantage and limitations of each control strategy, along with the required vehicle model, have been outlined. Additionally, the most recent research on transitional platoon maneuver is studied and summarized based on the proposed control strategy, homogeneously or heterogeneously of platoon members, type of maneuver, the aim of control problem, type of implementation, and used simulation tools. Finally, different trajectory planning techniques used in lateral motion control, as well as the most recent research related to trajectory planning for automated vehicles, are presented.

Extensive study has been done in the areas of platoon longitudinal and lateral control for transitional platoon maneuvers purpose. Some of these control algorithms have been experimentally tested in real-life scenarios. Maintaining string stability to ensure a safe transitional platoon maneuver is generally one of the main aims of the proposed control algorithms in most of the conducted research. To ensure a collision-free maneuver, it is essential to develop a controller that is responsive to real-world traffic conditions such as human factors effects, heterogeneous vehicle dynamics, random delay, sensor lags, mixed traffic environment, and communication failure. However, a few research works have been found which consider these limitations in the design and development of the controller. The length of the platoon and the effect of the number of vehicles in the platoon on traffic mobility, string stability of the platoon, and fuel economy is another research direction that can be further studied. For a large platoon sending information from the leader platoon to the vehicles at the tail may lead to a huge delay or the information might not be received due to the huge distance between the leader and the vehicle at the tail. This will affect the string stability of the platoon. Hence, to ensure string stability, it is necessary to maintain the length of the platoon within a specific range.

Identifying the reasonable longitudinal distance between vehicles in the platoon considering safety, passenger comfort, traffic mobility, and fuel economy is another important direction for future research. To fulfill this objective, the gap between vehicles in the platoon should not exceed a specific range. Therefore, the reasonable gap between vehicles in the platoon should be chosen such that collision-free travel within the platoon is guaranteed in case of sudden brake and also traffic throughput is increased. Additionally, the reasonable longitudinal distance between the vehicle in the platoon can reduce fuel consumption by minimizing air drag force. Hence, further studies are required to identify the suitable gap between vehicles considering different aspects. In this review, few research works have been found which consider this point. Studying the effect of traffic on coordination decisions is another open issue for future research since the majority of the publications considered the ideal situation, where there is no effect of external traffic on the speed, motion, and decision of the vehicle intending to join or leave the platoon. While in a real-life environment, traffic plays a vital role in coordination decisions since it will affect the speeds and maneuvering decisions in various traffic scenarios such as heavy or light traffic. For example, vehicles might not be able to adjust their speeds based on the platoon speed before joining due to the presence of heavy traffic in their current lane or vehicles are unable to leave the platoon at the desired leaving point due to the presence of heavy traffic in the adjacent lane. Finally, experimental validation of any proposed controllers is essential for evaluating the performance of the developed approaches in real-life scenarios and most of the reviewed works in this survey have used simulation study as the validation tool. It is important to investigate how the platoon maneuvering process can work and further be improved in a real-life environment. Based on this review paper only a few articles have studied the performance of platoon maneuver and feasibility of the proposed controllers in a real-life environment, however, more experiments under different conditions need to be conducted to achieve a successful platoon maneuvering process.

ACKNOWLEDGMENT

The findings achieved herein are solely the responsibility of the authors.

REFERENCES

[1] J. M. Anderson, N. Kalra, K. D. Stanley, P. Sorensen, and O. A. Oluwatola, "The promise and perils of autonomous vehicle technology," in *Autonomous Vehicle Technology: A Guide for Policymakers*. Santa Monica, CA, USA: Rand Corporation, 2016, pp. 17–24.

[2] F. Fakhfakh, M. Tounsi, and M. Mosbah, "Vehicle platooning systems: Review, classification and validation strategies," *Int. J. Netw. Distrib. Comput.*, vol. 8, no. 4, p. 203, 2020.

[3] R. Horowitz and P. Varaiya, "Control design of an automated highway system," *Proc. IEEE*, vol. 88, no. 7, pp. 913–925, Jul. 2000.

[4] S. E. Li, Y. Zheng, K. Li, and J. Wang, "An overview of vehicular platoon control under the four-component framework," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Jun. 2015, pp. 286–291.

[5] K. C. Dey, L. Yan, X. Wang, Y. Wang, H. Shen, M. Chowdhury, L. Yu, C. Qiu, and V. Soundararaj, "A review of communication, driver characteristics, and controls aspects of cooperative adaptive cruise control (CACC)," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 2, pp. 491–509, Feb. 2016.

[6] D. Bevly, X. Cao, M. Gordon, G. Ozbilgin, D. Kari, B. Nelson, J. Woodruff, M. Barth, C. Murray, A. Kurt, K. Redmill, and U. Ozguner, "Lane change and merge maneuvers for connected and automated vehicles: A survey," *IEEE Trans. Intell. Vehicles*, vol. 1, no. 1, pp. 105–120, Mar. 2016.

[7] A. K. Bhoopalam, N. Agatz, and R. A. Zuidwijk, "Planning of truck platoons: A literature review and directions for future research," *Transp. Res. B, Methodol.*, vol. 107, pp. 212–228, Jan. 2017.

[8] L. Zhang, F. Chen, X. Ma, and X. Pan, "Fuel economy in truck platooning: A literature overview and directions for future research," *J. Adv. Transp.*, vol. 2020, pp. 1–10, Jan. 2020.

[9] S. Hallé and B. Chaib-Draa, "Collaborative driving system using teamwork for platoon formations," in *Applications of Agent Technology in Traffic and Transportation*. Basel, Switzerland: Birkhäuser, 2006, pp. 133–151.

[10] M. Goli and A. Eskandarian, "The effect of information, and communication topologies on input-to-state stability of platoon," in *Proc. IEEE 19th Int. Conf. Intell. Transp. Syst. (ITSC)*, Rio de Janeiro, Brazil, Nov. 2016, pp. 540–544.

[11] S. Kamijo, Y. Gu, and L.-T. Hsu, "Autonomous vehicle technologies: Localization and mapping," *IEICE ESS Fundamentals Rev.*, vol. 9, no. 2, pp. 131–141, 2015.

[12] C. Chang and Z. Yuan, "Combined longitudinal and lateral control of vehicle platoons," in *Proc. Int. Conf. Comput. Syst., Electron. Control (ICCSEC)*, Dalian, China, Dec. 2017, pp. 848–852.

[13] T. Tapli and M. Akar, "Cooperative adaptive cruise control algorithms for vehicular platoons based on distributed model predictive control," in *Proc. IEEE 16th Int. Workshop Adv. Motion Control (AMC)*, Kristiansand, Norway, Sep. 2020, pp. 305–310.

[14] H. Liu, D. Chu, W. Peng, L. Lu, and F. Peng, "Research on longitudinal following control of platoon based on nonlinear PID," SAE Tech. Paper 2020-01-5206, 2020.

[15] A. Schwab and J. Lunze, "Vehicle platooning and cooperative merging," *IFAC-PapersOnLine*, vol. 52, no. 5, pp. 353–358, 2019.

[16] H. C.-H. Hsu and A. Liu, "Platoon lane change maneuvers for automated highway systems," in *Proc. IEEE Conf. Robot., Autom. Mechatronics*, Singapore, Dec. 2004, pp. 780–785.

[17] R. Zhou, Z. Li, and Z. Yang, "Optimal lane change analysis for vehicle platooning based on lateral and longitudinal control," in *Proc. 39th Chin. Control Conf. (CCC)*, Shenyang, China, Jul. 2020, pp. 5534–5539.

[18] A. Mehmood, M. Liaquat, A. I. Bhatti, and E. Rasool, "Trajectory planning and control for lane-change of autonomous vehicle," in *Proc. 5th Int. Conf. Control, Autom. Robot. (ICCAR)*, Beijing, China, Apr. 2019, pp. 331–335.

[19] J. Hu, H. Wang, X. Li, and X. Li, "Modelling merging behaviour joining a cooperative adaptive cruise control platoon," *IET Intell. Transp. Syst.*, vol. 14, no. 7, pp. 693–701, Jul. 2020.

[20] S. Santini, A. Salvi, A. S. Valente, A. Pescape, M. Segata, and R. L. Cigno, "Platooning maneuvers in vehicular networks: A distributed and consensus-based approach," *IEEE Trans. Intell. Vehicles*, vol. 4, no. 1, pp. 59–72, Mar. 2019.

[21] M. Tomizuka, J. Y. Wang, and N. Tai, "Intelligent control of road vehicles for automated driving: Path architecture for automated highway systems and lateral guidance," in *Control Systems, Robotics and Automation*, P. Hingwe, Ed. 2002, pp. 52–86.

[22] C. M. Kang, S.-H. Lee, and C. C. Chung, "Comparative evaluation of dynamic and kinematic vehicle models," in *Proc. 53rd IEEE Conf. Decis. Control*, Los Angeles, CA, USA, Dec. 2014, pp. 648–653.

[23] J.-W. Kwon and D. Chwa, "Adaptive bidirectional platoon control using a coupled sliding mode control method," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 5, pp. 2040–2048, Oct. 2014.

[24] L. Zuo, Y. Zhang, M. Yan, and W. Ma, "Distributed integrated sliding mode-based nonlinear vehicle platoon control with quadratic spacing policy," *Complexity*, vol. 2020, pp. 1–9, Dec. 2020.

[25] F. Lin, M. Fardad, and M. R. Jovanovic, "Optimal control of vehicular formations with nearest neighbor interactions," *IEEE Trans. Autom. Control*, vol. 57, no. 9, pp. 2203–2218, Sep. 2012.

[26] M. Fardad, F. Lin, and M. R. Jovanovic, "Sparsity-promoting optimal control for a class of distributed systems," in *Proc. Amer. Control Conf.*, San Francisco, CA, USA, Jun. 2011, pp. 2050–2055.

[27] Y. Li, C. Tang, S. Peeta, and Y. Wang, "Nonlinear consensus-based connected vehicle platoon control incorporating car-following interactions and heterogeneous time delays," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 6, pp. 2209–2219, Jun. 2019.

[28] S. S. Stankovic, M. J. Stanojevic, and D. D. Siljak, "Decentralized overlapping control of a platoon of vehicles," *IEEE Trans. Control Syst. Technol.*, vol. 8, no. 5, pp. 816–832, Sep. 2000.

[29] H. Chehardoli and M. R. Homaeinezhad, "Third-order safe consensus of heterogeneous vehicular platoons with MPF network topology: Constant time headway strategy," *Proc. Inst. Mech. Eng. D, J. Automobile Eng.*, vol. 232, no. 10, pp. 1402–1413, Sep. 2018.

[30] J. Chen, D. Bai, H. Liang, and Y. Zhou, "A third-order consensus approach for vehicle platoon with intervehicle communication," *J. Adv. Transp.*, vol. 2018, pp. 1–10, Jul. 2018.

[31] S. Yang, Y. Lu, and S. Li, "An overview on vehicle dynamics," *Int. J. Dyn. Control*, vol. 1, no. 4, pp. 385–395, 2013.

[32] J. R. Kiefer, "Modeling of road vehicle lateral dynamics," M.S. thesis, Dept. Mech. Eng., College Eng., Rochester Inst. Technol., Rochester, NY, USA, 1996.

[33] Z. H. A. O. Jin, "Contribution to intelligent vehicle platoon control," M.S. thesis, Dept. Comput. Eng., Univ. Lille, Lille, France, 2010.

[34] A. Norouzi, R. Kazemi, and S. Azadi, "Vehicle lateral control in the presence of uncertainty for lane change maneuver using adaptive sliding mode control with fuzzy boundary layer," *Proc. Inst. Mech. Eng., I, J. Syst. Control Eng.*, vol. 232, no. 1, pp. 12–28, Jan. 2018.

[35] A. Marashian, "Design of a nonlinear control for the lateral dynamics of intelligent vehicles," Persian Gulf Univ., Bushehr, Iran, Tech. Rep., 2020, pp. 1–7.

[36] S. H. Li and J. Y. Ren, "Driver steering control and full vehicle dynamics study based on a nonlinear three-directional coupled heavy-duty vehicle model," *Math. Problems Eng.*, vol. 2014, pp. 1–16, Jan. 2014.

[37] N. Chen, M. Wang, T. Alkim, and B. van Arem, "A robust longitudinal control strategy of platoons under model uncertainties and time delays," *J. Adv. Transp.*, vol. 2018, pp. 1–13, Jan. 2018.

[38] A. Aboelhassan, M. Abdelgeliel, E. E. Zakzouk, and M. Galea, "Design and implementation of model predictive control based PID controller for industrial applications," *Energies*, vol. 13, no. 24, p. 6594, Dec. 2020.

[39] O. A. Orozco, "PID control: Servo/regulation performance and robustness issues," M.S. thesis, Auton. Univ. Barcelona, Barcelona, Spain, 2010.

[40] Z. A. Memon, S. Jumani, and J. Javed, "Longitudinal control of a platoon of road vehicles equipped with adaptive cruise control system," *Mehran Univ. Res. J. Eng. Technol.*, vol. 31, no. 3, pp. 475–494, 2012.

[41] V. Antoska Knights, Z. Gacovski, S. Deskovski, and O. Petrovska, "Guidance and control system for platoon of autonomous mobile robots," *J. Electr. Eng.*, vol. 6, no. 5, pp. 281–288, Sep. 2018.

[42] J. Liu and X. Wang, "Adaptive sliding mode control for mechanical systems," in *Advanced Sliding Mode Control for Mechanical Systems*. Berlin, Germany: Springer, 2011, pp. 117–135.

[43] L. Xiao and F. Gao, "Practical string stability of platoon of adaptive cruise control vehicles," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 1184–1194, Dec. 2011.

[44] M. Yan, J. Song, L. Zuo, and P. Yang, "Neural adaptive sliding-mode control of a vehicle platoon using output feedback," *Energies*, vol. 10, no. 11, p. 1906, Nov. 2017.

[45] H. Xu and C. Lu, "Design of switched fuzzy adaptive double coupled sliding mode control for vehicles platoon," in *Proc. 5th Int. Conf. Autom., Control Robot. Eng. (CACRE)*, Dalian, China, Sep. 2020, pp. 422–426.

[46] S. J. Qin and T. A. Badgwell, "A survey of industrial model predictive control technology," *Control Eng. Pract.*, vol. 11, no. 7, pp. 733–764, Jul. 2003.

[47] M. Morari and J. H. Lee, "Model predictive control: Past, present and future," *Comput. Chem. Eng.*, vol. 23, nos. 4–5, pp. 667–682, May 1999.

[48] R. Kianfar, P. Falcone, and J. Fredriksson, "A control matching model predictive control approach to string stable vehicle platooning," *Control Eng. Pract.*, vol. 45, pp. 163–173, Dec. 2015.

[49] S. Graffione, C. Bersani, R. Sacile, and E. Zero, "Model predictive control of a vehicle platoon," in *Proc. IEEE 15th Int. Conf. Syst. Syst. Eng. (SoSE)*, Budapest, Hungary, Jun. 2020, pp. 513–518.

[50] R. R. Negenborn and J. M. Maestre, "Distributed model predictive control: An overview and roadmap of future research opportunities," *IEEE Control Syst. Mag.*, vol. 34, no. 4, pp. 87–97, Jul. 2014.

[51] A. Maxim, C. F. Caruntu, and C. Lazar, "Cruise and headway control for vehicle platooning using a distributed model predictive control algorithm," in *Proc. 21st Int. Conf. Syst. Theory, Control Comput. (ICSTCC)*, Sinaia, Romania, Oct. 2017, pp. 146–151.

[52] L. Alvergue, A. Pandey, G. Gu, and X. Chen, "Output consensus control for heterogeneous multi-agent systems," in *Proc. 52nd IEEE Conf. Decis. Control*, Dec. 2013, pp. 23–39.

[53] R. Olfati-Saber and R. M. Murray, "Consensus problems in networks of agents with switching topology and time-delays," *IEEE Trans. Autom. Control*, vol. 49, no. 9, pp. 1520–1533, Sep. 2004.

[54] J. A. Fax and R. M. Murray, "Information flow and cooperative control of vehicle formations," *IEEE Trans. Autom. Control*, vol. 49, no. 9, pp. 1465–1476, Sep. 2004.

[55] W. Ren and R. W. Beard, "Consensus seeking in multiagent systems under dynamically changing interaction topologies," *IEEE Trans. Autom. Control*, vol. 50, no. 5, pp. 655–661, May 2005.

[56] W. Ren and E. Atkins, "Second-order consensus protocols in multiple vehicle systems with local interactions," in *Proc. AIAA Guid., Navigat., Control Conf. Exhib.*, Aug. 2005, pp. 2005–6238.

[57] G. Xie and L. Wang, "Consensus control for a class of networks of dynamic agents: Fixed topology," in *Proc. 44th IEEE Conf. Decis. Control*, Seville, Spain, Dec. 2005, pp. 96–101.

[58] Z. Wang, G. Wu, and M. J. Barth, "Developing a distributed consensus-based cooperative adaptive cruise control system for heterogeneous vehicles with predecessor following topology," *J. Adv. Transp.*, vol. 2017, pp. 1–16, Aug. 2017.

[59] M. di Bernardo, A. Salvi, and S. Santini, "Distributed consensus strategy for platooning of vehicles in the presence of time-varying heterogeneous communication delays," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 1, pp. 102–112, Feb. 2015.

[60] M. Yan, Y. Tang, and P. Yang, "Consensus-based control algorithm for nonlinear vehicle platoons in the presence of time delays and packet losses," in *Proc. Chin. Autom. Congr. (CAC)*, Xi'an, China, 2018, pp. 3339–3344.

[61] P. Yang, Y. Tang, M. Yan, and X. Zhu, "Consensus based control algorithm for nonlinear vehicle platoons in the presence of time delay," *Int. J. Control, Autom. Syst.*, vol. 17, no. 3, pp. 752–764, 2019.

[62] A. Khalifa, O. Kermorgant, S. Dominguez, and P. Martinet, "Vehicles platooning in urban environments: Integrated consensus-based longitudinal control with gap closure maneuvering and collision avoidance capabilities," in *Proc. 18th Eur. Control Conf. (ECC)*, Naples, Italy, Jun. 2019, pp. 1695–1701.

[63] J. Frankenfield. *Artificial Neural Network (ANN)*. Investopedia, Accessed: Aug. 28, 2020. [Online]. Available: https://www.investopedia.com/terms/a/artificial-neural-networks-ann.asp

[64] X.-G. Guo, J.-L. Wang, F. Liao, and R. S. H. Teo, "CNN-based distributed adaptive control for vehicle-following platoon with input saturation," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 10, pp. 3121–3132, Oct. 2018.

[65] P. Sathiyan, M. Cherian, and B. Pratap, "Neural network based vehicle longitudinal controller–design and validation using hardware in loop testing," *Int. J. Sci. Technol. Res.*, vol. 9, no. 3, pp. 7109–7114, 2020.

[66] B. A. Francis, M. Thoma, and A. Wyner, *A Course in H Control Theory*. New York, NY, USA: Springer-Verlag, 1987, pp. 8–46.

[67] Y. Zheng, S. E. Li, K. Li, and W. Ren, "Platooning of connected vehicles with undirected topologies: Robustness analysis and distributed H-infinity controller synthesis," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 5, pp. 1353–1364, May 2018.

[68] S. E. Li, F. Gao, K. Li, L. Wang, K. You, and D. Cao, "Robust longitudinal control of multi-vehicle systems—A distributed H-infinity method," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 9, pp. 2779–2788, Oct. 2018.

[69] D. Soudbakhsh and A. Eskandarian, "A collision avoidance steering controller using linear quadratic regulator," SAE Tech. Paper 2010-01-0459, 2010.

[70] G. Xu, L. Liu, Y. Ou, and Z. Song, "Dynamic modeling of driver control strategy of lane-change behavior and trajectory planning for collision prediction," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 3, pp. 1138–1155, Sep. 2012.

[71] W. Chee, "Unified lateral control system for intelligent vehicles," *SAE Trans.*, vol. 109, pp. 531–539, Jan. 2000.

[72] Y. Luo, G. Yang, M. Xu, Z. Qin, and K. Li, "Cooperative lane-change maneuver for multiple automated vehicles on a highway," *Automot. Innov.*, vol. 2, no. 3, pp. 157–168, Sep. 2019.

[73] P. Petrov and F. Nashashibi, "Adaptive steering control for autonomous lane change maneuver," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Gold Coast, QLD, Australia, Jun. 2013, pp. 835–840.

[74] Z. Zainal, N. R. Baharom, and W. Rahiman, "Yaw rate and sideslip control using PID controller for double lane changing," *J. Telecommun., Electron. Comput. Eng.*, vol. 9, pp. 1–5, Nov. 2017.

[75] A. A. Joshi, D. L. Peters, and J. M. Bastiaan, "Autonomous lane change control using proportional-integral-derivative controller and bicycle model," SAE Tech. Paper 2020-01-0215, 2020.

[76] C. Lu, J. Yuan, and G. Zha, "Sliding mode integrated control for vehicle systems based on AFS and DYC," *Math. Problems Eng.*, vol. 2020, pp. 1–8, Dec. 2020.

[77] R. C. Rafaila and G. Livint, "H-infinity control of automatic vehicle steering," in *Proc. Int. Conf. Expo. Electr. Power Eng. (EPE)*, Iasi, Romania, Oct. 2016, pp. 031–036.

[78] C. Huang, F. Naghdy, and H. Du, "Model predictive control-based lane change control system for an autonomous vehicle," in *Proc. IEEE Region Conf. (TENCON)*, Singapore, Nov. 2016, pp. 3349–3354.

[79] M. Chen and Y. Ren, "MPC based path tracking control for autonomous vehicle with multi-constraints," in *Proc. Int. Conf. Adv. Mech. Syst. (ICAMechS)*, Xiamen, China, Dec. 2017, pp. 477–482.

[80] C. Sun, X. Zhang, Q. Zhou, and Y. Tian, "A model predictive controller with switched tracking error for autonomous vehicle path tracking," *IEEE Access*, vol. 7, pp. 53103–53114, 2019.

[81] B. Li and F. Yu, "Design of a vehicle lateral stability control system via a fuzzy logic control approach," *Proc. Inst. Mech. Eng. D, J. Automobile Eng.*, vol. 224, no. 3, pp. 313–326, Mar. 2010.

[82] L. Li, H. Wang, J. Lian, X. Ding, and W. Cao, "A lateral control method of intelligent vehicle based on fuzzy neural network," *Adv. Mech. Eng.*, vol. 7, no. 1, Jan. 2015, Art. no. 296209.

[83] X. Ji, X. He, C. Lv, Y. Liu, and J. Wu, "Adaptive-neural-network-based robust lateral motion control for autonomous vehicle at driving limits," *Control Eng. Pract.*, vol. 76, pp. 41–53, Jul. 2018.

[84] A. A. Ahmed and O. S. M. Jomah, "Vehicle yaw rate control for lane change maneuver using fuzzy PID controller and neural network controller," in *Proc. IEEE 2nd Int. Conf. Electron., Control, Optim. Comput. Sci. (ICECOCS)*, Kenitra, Morocco, Dec. 2020, pp. 1–6.

[85] N. Tavan, M. Tavan, and R. Hosseini, "An optimal integrated longitudinal and lateral dynamic controller development for vehicle path tracking," *Latin Amer. J. Solids Struct.*, vol. 12, no. 6, pp. 1006–1023, Jun. 2015.

[86] M. Segata, B. Bloessl, S. Joerer, F. Dressler, and R. L. Cigno, "Supporting platooning maneuvers through IVC: An initial protocol analysis for the JOIN maneuver," in *Proc. 11th Annu. Conf. Wireless Demand Netw. Syst. Services (WONS)*, Obergurgl, Austria, Apr. 2014, pp. 130–137.

[87] M. Goli and A. Eskandarian, "Evaluation of lateral trajectories with different controllers for multi-vehicle merging in platoon," in *Proc. Int. Conf. Connected Vehicles Expo (ICCVE)*, Vienna, Austria, Nov. 2014, pp. 673–678.

[88] M. Amoozadeh, H. Deng, C.-N. Chuah, H. M. Zhang, and D. Ghosal, "Platoon management with cooperative adaptive cruise control enabled by VANET," *Veh. Commun.*, vol. 2, no. 2, pp. 110–123, Apr. 2015.

[89] M. di Bernardo, P. Falcone, A. Salvi, and S. Santini, "Design, analysis, and experimental validation of a distributed protocol for platooning in the presence of time-varying heterogeneous delays," *IEEE Trans. Control Syst. Technol.*, vol. 24, no. 2, pp. 413–427, Mar. 2016.

[90] L. Banjanović-Mehmedović, I. Butigan, M. Kantardžić, and S. Kasapović, "Prediction of cooperative platooning maneuvers using NARX neural network," in *Proc. Int. Conf. Smart Syst. Technol. (SST)*, Osijek, Croatia, Oct. 2016, pp. 287–292.

[91] S. Dasgupta, V. Raghuraman, A. Choudhury, T. N. Teja, and J. Dauwels, "Merging and splitting maneuver of platoons by means of a novel PID controller," in *Proc. IEEE Symp. Ser. Comput. Intell. (SSCI)*, Honolulu, HI, USA, Nov. 2017, pp. 1–8.

[92] H. Liu, W. Zhuang, G. Yin, Z. Tang, and L. Xu, "Strategy for heterogeneous vehicular platoons merging in automated highway system," in *Proc. Chin. Control Decis. Conf. (CCDC)*, Shenyang, China, Jun. 2018, pp. 2736–2740.

[93] H. Min, Y. Yang, Y. Fang, P. Sun, and X. Zhao, "Constrained optimization and distributed model predictive control-based merging strategies for adjacent connected autonomous vehicle platoons," *IEEE Access*, vol. 7, pp. 163085–163096, 2019.

[94] M. Goli and A. Eskandarian, "MPC-based lateral controller with look-ahead design for autonomous multi-vehicle merging into platoon," in *Proc. Amer. Control Conf. (ACC)*, Philadelphia, PA, USA, Jul. 2019, pp. 5284–5291.

[95] A. Farag, A. Hussein, O. M. Shehata, F. Garcia, H. H. Tadjine, and E. Matthes, "Dynamics platooning model and protocols for self-driving vehicles," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Paris, France, Jun. 2019, pp. 1974–1980.

[96] Z. Huang, D. Chu, C. Wu, and Y. He, "Path planning and cooperative control for automated vehicle platoon using hybrid automata," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 3, pp. 959–974, Mar. 2019.

[97] S. Graffione, C. Bersani, R. Sacile, and E. Zero, "Model predictive control for cooperative insertion or exit of a vehicle in a platoon," in *Proc. 17th Int. Conf. Informat. Control, Autom. Robot.*, 2020, pp. 352–359.

[98] M. H. Basiri, B. Ghojogh, N. L. Azad, S. Fischmeister, F. Karray, and M. Crowley, "Distributed nonlinear model predictive control and metric learning for heterogeneous vehicle platooning with cut-in/cut-out maneuvers," in *Proc. 59th IEEE Conf. Decis. Control (CDC)*, Jeju, South Korea, Dec. 2020, pp. 2849–2856.

[99] C. Hidalgo, R. Lattarulo, C. Flores, and J. P. Rastelli, "Platoon merging approach based on hybrid trajectory planning and CACC strategies," *Sensors*, vol. 21, no. 8, p. 2626, Apr. 2021.

[100] G. Wang, Y. Ding, Y. Hou, Y. Zhou, and X. Jia, "Two-level fault detection and isolation algorithm for vehicle platoon," *IEEE Access*, vol. 6, pp. 15106–15116, 2018.

[101] A. Lopes and R. E. Araujo, "Active fault diagnosis method for vehicles in platoon formation," *IEEE Trans. Veh. Technol.*, vol. 69, no. 4, pp. 3590–3603, Apr. 2020.

[102] L. Zhang and G. Orosz, "Designing network motifs in connected vehicle systems: Delay effects and stability," in *Proc. ASME Dyn. Syst. Control Conf.*, 2013, Art. no. V003T42A006.

[103] G. Orosz, "Connected cruise control: Modelling, delay effects, and nonlinear behaviour," *Vehicle Syst. Dyn.*, vol. 54, no. 8, pp. 1147–1176, Aug. 2016.

[104] L. Zhang, J. Sun, and G. Orosz, "Hierarchical design of connected cruise control in the presence of information delays and uncertain vehicle dynamics," *IEEE Trans. Control Syst. Technol.*, vol. 26, no. 1, pp. 139–150, Jan. 2018.

[105] J. I. Ge and G. Orosz, "Optimal control of connected vehicle systems with communication delay and driver reaction time," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 8, pp. 2056–2070, Aug. 2017.

[106] V. Milanés and S. E. Shladover, "Modeling cooperative and autonomous adaptive cruise control dynamic responses using experimental data," *Transp. Res. C, Emerg. Technol.*, vol. 48, pp. 285–300, Nov. 2014.

[107] Y. Shui and Ü. Özgüner, "Strategic trajectory planning of highway lane change maneuver with longitudinal speed control," M.S. thesis, Dept. Elect. Comput. Eng., Dept. Mech. Eng., Ohio State Univ., Columbus, OH, USA, 2015, pp. 57–82.

[108] L. Ma, J. Xue, K. Kawabata, J. Zhu, C. Ma, and N. Zheng, "Efficient sampling-based motion planning for on-road autonomous driving," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 4, pp. 1961–1976, Aug. 2015.

[109] S. Wang, "State lattice-based motion planning for autonomous on-road driving," M.S. thesis, Dept. Math. Comput. Sci., Free Univ. Berlin, Berlin, Germany, 2015, pp. 27–56.

[110] I. A. Ntousakis, I. K. Nikolos, and M. Papageorgiou, "Optimal vehicle trajectory planning in the context of cooperative merging on highways," *Transp. Res. C, Emerg. Technol.*, vol. 71, pp. 464–488, Oct. 2016.

[111] L. Wang, X. Zhao, H. Su, and G. Tang, "Lane changing trajectory planning and tracking control for intelligent vehicle on curved road," *SpringerPlus*, vol. 5, no. 1, pp. 1–9, Dec. 2016.

[112] Z. Boroujeni, D. Goehring, F. Ulbrich, D. Neumann, and R. Rojas, "Flexible unit A-star trajectory planning for autonomous vehicles on structured road maps," in *Proc. IEEE Int. Conf. Veh. Electron. Saf. (ICVES)*, Vienna, Austria, Jun. 2017, pp. 7–12.

[113] A. Kahya and K. Schmidt, "Clothoid-based lane change trajectory computation for self-driving vehicles," *Cankaya Univ. J. Sci. Eng.*, vol. 14, no. 2, pp. 152–179, 2017.

[114] R. Lattarulo, L. González, E. Martí, J. Matute, M. Marcano, and J. Pérez, "Urban motion planning framework based on N-Bézier curves considering comfort and safety," *J. Adv. Transp.*, vol. 2018, pp. 1–13, Jul. 2018.

[115] Y. Lee, T. Ahn, C. Lee, S. Kim, and K. Park, "A novel path planning algorithm for truck platooning using V2V communication," *Sensors*, vol. 20, no. 24, p. 7022, Dec. 2020.

[116] F. Zhang, R. Xia, and X. Chen, "An optimal trajectory planning algorithm for autonomous trucks: Architecture, algorithm, and experiment," *Int. J. Adv. Robotic Syst.*, vol. 17, no. 2, p. 1729, 2020.

[117] L. Zheng, P. Zeng, W. Yang, Y. Li, and Z. Zhan, "Bézier curve-based trajectory planning for autonomous vehicles with collision avoidance," *IET Intell. Transp. Syst.*, vol. 14, no. 13, pp. 1882–1891, Dec. 2020.

[118] L. Labakhua, U. Nunes, R. Rodrigues, and F. S. Leite, "Smooth trajectory planning for fully automated passengers vehicles: Spline and clothoid based methods and its simulation," in *Informatics in Control Automation and Robotics*. Berlin, Germany: Springer-Verlag, 2008, pp. 169–182.

[119] Z. Shiller and Y.-R. Gwo, "Dynamic motion planning of autonomous vehicles," *IEEE Trans. Robot. Autom.*, vol. 7, no. 2, pp. 241–249, Apr. 1991.

[120] J. Ziegler, P. Bender, M. Schreiber, H. Lategahn, T. Strauss, C. Stiller, T. Dang, U. Franke, N. Appenrodt, C. G. Keller, and E. Kaus, "Making bertha drive—An autonomous journey on a historic route," *IEEE Intell. Transp. Syst. Mag.*, vol. 6, no. 2, pp. 8–20, Apr. 2014.

[121] L. Li and F.-Y. Wang, "The automated lane-changing model of intelligent vehicle highway systems," in *Proc. IEEE 5th Int. Conf. Intell. Transp. Syst.*, Sep. 2002, pp. 216–218.

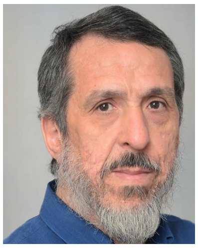
SAREH BADNAVA received the B.S. degree in electrical engineering and computer science from Qatar University, in 2020. She is currently working as a Research Assistant with Qatar University. Her research interests include intelligent systems, robotics, and automation.

NADER MESKIN (Senior Member, IEEE) received the B.Sc. degree from the Sharif University of Technology, Tehran, Iran, in 1998, the M.Sc. degree from the University of Tehran, Tehran, in 2001, and the Ph.D. degree in electrical and computer engineering from Concordia University, Montreal, QC, Canada, in 2008. He was a Postdoctoral Fellow with Texas A&M University at Qatar, Doha, Qatar, from January 2010 to December 2010. He is currently an Associate Professor with Qatar University, Doha, and an Adjunct Associate Professor with Concordia University. He has published more than 230 refereed journal and conference papers. His research interests include FDI, multi-agent systems, active control for clinical pharmacology, cyber-security of industrial control systems, and linear parameter varying systems.

ADEL GASTLI (Senior Member, IEEE) received the B.Sc. degree in electrical engineering from the National School of Engineers of Tunis, Tunisia, in 1985, and the M.Sc. and Ph.D. degrees in electrical and computer engineering from the Nagoya Institute of Technology, Japan, in March 1990 and March 1993, respectively. From September 1985 to September 1987, he worked with the National Institute for Standards and Intellectual Property, Tunisia. From April 1993 to July 1995, he worked with Mitsubishi Electric Corporation, Japan. He joined the Electrical and Computer Engineering Department, Sultan Qaboos University, Oman, in August 1995. He served as the Head for the Department, from September 2001 to August 2003 and from September 2007 to August 2009. He was appointed as the Director with the Sultan Qaboos University, Quality Assurance Office, from February 2010 to January 2013. In February 2013, he joined the Electrical Engineering Department, Qatar University, as a Professor and the Kahramaa-Siemens Chair of energy efficiency. From August 2013 to September 2015, he was appointed as the Associate Dean for academic affairs at the College of Engineering. His current research interests include energy efficiency, renewable energy, electric vehicles, and smart grid.

MOHAMMED A. AL-HITMI (Member, IEEE) received the B.Sc. degree in electrical engineering from Qatar University, Doha, Qatar, in 1992, and the M.S. and Ph.D. degrees in control engineering from the University of Sheffield, in 1994 and 2002, respectively. He is currently an Associate Professor of electrical engineering with Qatar University. He is serving as the Head for the Department of Electrical Engineering, Qatar University. He has conducted many research projects funded by national and industrial funding agencies. He has authored more than 50 research articles in top peer reviewed journals and conferences. He is involved in several administrative committees in leadership roles with Qatar University. He is also serving as a reviewers for many top journals. His research interests include control systems theory, neural networks, fuzzy control, and electric drive systems.

JAWHAR GHOMMAM received the B.Sc. degree in computer and control engineering from the National Institute and Applied Sciences and Technology (INSAT), Tunis, in 2003, the D.E.A. (M.Sc.) degree from the Laboratoire d'Informatique, Robotique et Micro-électronique (LIRMM), University of Montpelier, France, in 2004, and the Ph.D. degree in control engineering jointly from the National Engineering School of Sfax and the University of Orleans, in 2008. From 2008 to 2017, he was with the National Institute of Applied Sciences and Technology, where he held a tenured Associate Professor with the Department of Physics and Instrumentation. In January 2018, he joined the Department of Electrical and Computer Engineering, Sultan Qaboos University, Oman. He is a member of the Control and Energy Management Laboratory and also an Associate Researcher with the GREPCI-Laboratory, Ecole de Technologie Superieure, Montreal, QC, Canada. His research interests include fundamental motion control concepts for nonholonomic/underactuated vehicle systems, nonlinear and adaptive control; intelligent and autonomous control of networked unmanned systems, team cooperation, consensus achievement, and sensor networks. He serves as a regular referee and an associate editor for many international journals in the field of control and robotics.



MOSTEFA MESBAH (Member, IEEE) received the Ph.D. degree in learning control systems from the Department of Electrical and Computer Engineering, University of Colorado at Boulder, Colorado, USA. He is currently an Associate Professor with the Department of Electrical and Computer Engineering, Sultan Qaboos University (SQU), Oman. Prior to joining SQU, he held a teaching and research positions at several universities, namely the University of Colorado at Boulder (UCB), USA, the Queensland University of Technology (QUT), the University of Queensland (UQ), and the University of Western Australia (UWA), Australia. He has published more than 150 publications in international journals and conferences and supervised more than ten Ph.D. students. He was the Lead Guest Editor of a EURASIP Special Issue on Advances in Non-Stationary Electrophysiological Signal Analysis and Processing. His recent research interests include intelligent control systems and signal processing and their applications.

FAIÇAL MNIF (Senior Member, IEEE) received the Ph.D. degree from the Ecole Polytechnique de Montréal (University of Montreal), in 1996. He is currently an Associate Professor of control engineering with the Department of Electrical and Computer Engineering, Sultan Qaboos University. His research interests include control theory and applications and robotics.

• • •