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Derleme Makalesi / *Review Paper*

Recent Studies in the Literature on Nonlinear Control of Platoons and Transitional Maneuvers

Mahmut KENAR

Department of Electricity and Energy, Ardahan Vocational School of Technical Sciences, Ardahan University, Turkey

Geliş Tarihi (Received): 01.09.2023, Kabul Tarihi (Accepted): 21.11.2023
Sorumlu Yazar (Corresponding author): mahmutkenar@ardahan.edu.tr*
+90 478 2115192 +90 478 2115238

ABSTRACT

Vehicle Platoons consist of a leader vehicle and a group of connected automated vehicles (CAV) that follow the leader at a predetermined inter-vehicle distance and move together at a certain common speed. This topic has been studied extensively in the literature by academicians in recent years. Therefore, a review of the literature on this topic is needed to understand which problems need to be solved and which issues need further study on vehicle platoons. For this reason, this study was conducted to reveal the latest situation on vehicle platoons with existing studies. This paper includes research and evaluation among themselves of artificial intelligence based nonlinear control techniques such as neural network based controllers, sliding mode controllers, back stepping controllers, fuzzy logic based controllers and machine learning, which are primarily used for CAV control. In addition, it consists of reviewing and comparing the methods and techniques used to solve problems related to different problem situations of vehicle platoons such as longitudinal control, lateral control, adding or removing vehicles from vehicle platoons, and communication methods between vehicle platoons. The latest research is reviewed both in examining these methods and techniques used and in applying these control techniques to vehicle platoons' problem situations. In addition, detailed comparisons were made by analyzing the situation of the platoon members, the purpose of the control technique used, and theoretical or practical applications.

Keywords: Vehicle platoon control, Nonlinear control, Platoon maneuver

Araç Takımların Doğrusal Olmayan Kontrolü ve Geçiş Manevraları Hakkında Literatürdeki Son Çalışmalar

ÖZ

Araç Takımları, bir lider araç ve lideri önceden belirlenmiş bir araçlar arası mesafede takip eden ve belirli bir ortak hızda birlikte hareket eden bir grup bağlı otomatik araçtan (CAV) oluşur. Bu konu son yıllarda akademisyenler tarafından literatürde yoğun olarak çalışılmıştır. Bu nedenle, araç takımları konusunda hangi sorunların çözülmesi gerektiğini ve hangi konuların daha fazla çalışılması gerektiğini anlamak için bu konudaki literatürün gözden geçirilmesine ihtiyaç vardır. Bu nedenle bu çalışma, araç müfrezeleri konusundaki son durumu mevcut çalışmalarla ortaya koymak amacıyla yapılmıştır. Bu makale, öncelikle CAV kontrolünde kullanılan sinir ağı tabanlı kontrolörler, kayan kipli kontrolörler, geri adımlı kontrolörler, bulanık mantık tabanlı kontrolörler ve makine öğrenmesi gibi yapay zeka tabanlı doğrusal olmayan kontrol tekniklerinin kendi aralarında araştırılmasını ve değerlendirilmesini içermektedir. Ayrıca araç takımlarının boylamsal kontrol, yanal kontrol, araç takımlarına araç ekleme veya çıkarma, araç takımları arasındaki iletişim yöntemleri gibi farklı problem durumlarına ilişkin problemlerin çözümünde kullanılan yöntem ve tekniklerin gözden geçirilmesini ve karşılaştırılmasını içermektedir. Hem kullanılan bu yöntem ve tekniklerin incelenmesinde hem de bu kontrol tekniklerinin araç müfrezelerinin problem durumlarına uygulanmasında en son araştırmalar gözden

Mahmut KENAR, https://orcid.org/0000-0003-3986-8686

geçirilmektedir. Ayrıca müfreze üyelerinin durumları, kullanılan kontrol tekniğinin amacı, teorik veya pratik uygulamaları analiz edilerek detaylı karşılaştırmalar yapıldı.

Anahtar Kelimeler: Araç müfreze kontrolü, Doğrusal olmayan kontrol, Müfreze manevrası

INTRODUCTION

Today, with the developing technology and increasing population, the number of vehicles used on the highways is also increasing. This situation leads to many problems that will negatively affect our lives, such as traffic congestion, air pollution, and traffic accidents Guo et al., (2016); Bayuwindra et al., (2019). At this point, intelligent transportation systems (ITS) have become an important research topic due to their potential to greatly affect road transportation and with the thought that they can be a solution to the problems experienced Li et al., (2017); Wen et al., (2019); Zakerimanesh et al., (2021). In this direction, alternative approaches have been researched and new techniques have been proposed in recent years, depending on smart transportation systems, to eliminate such problems in highways and to use the existing highway infrastructure more efficiently. Vehicle platoons are also a promising ITS application to eliminate these issues Li et al., (2018); Wen et al., (2019). In this respect, both in industrial studies and in academia, vehicle platoons have become an important research topic in saving fuel consumption of vehicles due to the decrease in aerodynamic frictions, preventing traffic congestion, and increasing traffic safety due to the increase in the number of vehicles used on highways Liu et al., (2019); Guo et al., (2020).

The process of creating vehicle platoons is possible with the successful execution of some operations. These operations are of two types, which can be done within the platoon and which cause changes in the structure of the platoon Jin et al., (2020).

- *Operations within the Platoon:* Operations in which ordinary vehicle movements such as acceleration and deceleration, braking, and lane changing are performed while driving Maiti et al., (2017); Maiti et al., (2019).
- *Operations That Change Platoon Structure:* These operations comprise the operations related to the platoon structure such as joining the platoon, splitting from a platoon, platoon merging, and platoon splitting Maiti et al., (2017); Maiti et al., (2019).

The creation of vehicle platoons dates back to the PATH program at the University of California, the USA in the 1980s Shladover et al., (1991). Later, studies such as SARTE Robinson et al., (2010) and PROMOTE-CHAUFFER Bonnet et al., (2000) in Europe, ENERGY-ITS in Japan Tsugawa et al., (2011), GCDC in the Netherlands Kianfar et al., (2012) and KONVOI in Germany Kunze et al., (2011) it includes the work that has been done to ensure on the creation and control of vehicle platoons.

The main purpose of platoon control in vehicle platoons is to maintain the predetermined distance between the following vehicles and to ensure that the vehicles in this group move at the same speed. In this way, distances between vehicles are shortened, and as a result, both highway capacity is increased, and fuel savings are provided due to reductions in aerodynamic friction. In addition, it provides a more comfortable and safe driving experience by preventing excessive acceleration and deceleration and offers various advantages such as shortening the travel time and reducing the negative environmental effects to a large extent. All of this is possible by ensuring the flow of information between vehicles, as vehicles are in constant communication with each other, and by applying various control algorithms to these vehicles Liang et al., (2015); Zegers et al., (2017); Li et al., (2018); Liu et al., (2019); Wen et al., (2019).

Constant distance (CD) and constant time headway (CTH) policies are the leading methods commonly used in the literature to establish the desired safe driving distance between vehicles in the platoon. The CD policy, it is aimed to maintain the distance between successive vehicles, while in the CTH policy, the spacing between the vehicles does not remain constant and changes, depending on the speed of the leader Besselink et al., (2017); Zakerimanesh et al., (2021). Vehicle control in a platoon is possible by taking into account the processes such as joining the platoon, splitting from a platoon, and changing lanes, as well as longitudinal control, lateral control, problems in communication or delays or changes that may occur in the topology, and all these processes are expressed as platoon transition maneuvers Orosz (2016). In addition, for the vehicles in a platoon to perform a successful maneuver, the vehicle control system should be designed according to a five-layer hierarchical control structure as shown in Figure 1 Horowitz et al., (2000).

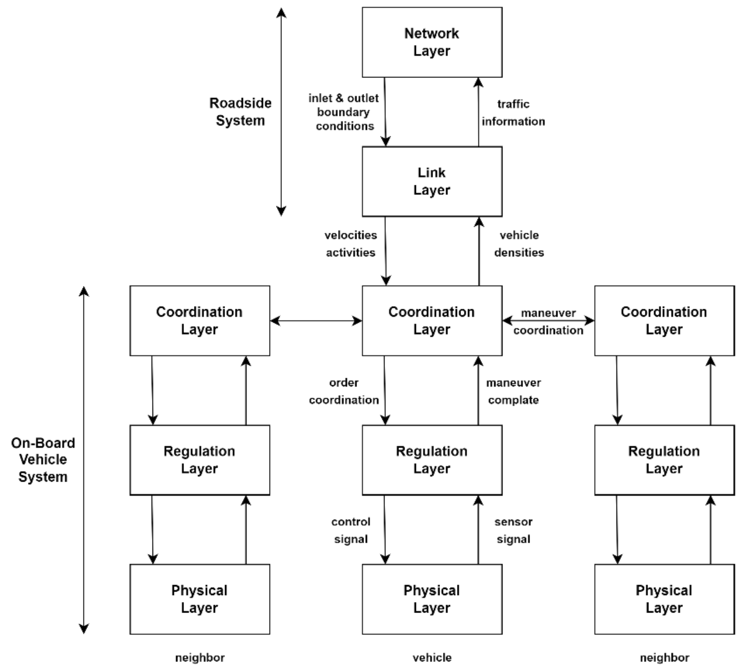

Figure 1. The hierarchical structure of the platoon control system (Horowitz et al., 2000).

I. Layer (Network Layer): This layer is the first layer where road capacity, travel time of vehicles in the platoon, traffic congestion, and traffic flow are controlled.

II. Layer (Link Layer): In this layer, the connection is divided into sections with a section corresponding to each lane, and each link exchanges information with other neighboring connections. In this way, it is aimed to control the traffic flow with data communication between the connections, to minimize the travel time and traffic congestion.

III. Layer (Coordination Layer): This layer is the layer where maneuvering operations such as joining the platoon, splitting from a platoon, and changing lanes, which are expressed as platoon transition maneuvers, are performed. For this, it is necessary to provide data communication between the vehicles in the platoon.

IV. Layer (Regulation Layer): In this layer, the signals received from the coordination layer are used as inputs in the vehicle actuators for the longitudinal and lateral control of the vehicle to perform the desired maneuvers.

V. Layer (Physical Layer): This layer is the layer where the physical components of the vehicle such as sensors, brakes, and steering systems are located. In line with all these, there are various studies from different aspects of the literature on vehicle platoons. In Jia et al., (2015), a platoon-based driving model has been created and evaluations have been made in terms of increasing the highway capacity, ensuring driving safety and energy efficiency, and analyzing issues such as platoon management, on the inside platoon and inter platoon communication. In Li et al., (2015), a study was carried out on vehicle platoon control techniques according to three main performance criteria such as string stability, coherence behavior, and stability margin. In addition, a general evaluation and analysis of vehicle platoon control techniques are made from the perspective of networked control, basing it on the four basic components of a vehicle platoon system that are related to each other. In Bevly et al., (2016), there are various and detailed studies on longitudinal and lateral control techniques for maneuvering operations such as lane changing and merging. In addition, it is a study that includes simulation and field tests related to vehicle platoons, including control, communication, and positioning systems, other vehicles in the environment, and the effects of different environmental factors on CAV platoons. In Dey et al., (2015), some studies include three important and basic concepts of platoon systems, platoon control, communication, and driver features. There are also discussions and analyses on issues such as the effects of driver behavior on platoon communication and traffic composition, including real-world problems. In Bhoopalam et al., (2018), a study was conducted on the classification and investigation of new and various problem situations in transportation planning problems related to a truck platoon. It is also a study in which different situations such as the comparison of a truck platoon with other transportation systems in planning, the effects of human participation in the platoon on the platoon, real time platoon planning, and the creation of a platoon with network design are examined and discussed. In Zhang et al., (2020), there is a study that analyzes and classifies the articles on fuel consumption reduction related to truck platoons. The scope of the study is only about fuel economy, various factors affecting fuel consumption in truck platoons, control methods that should be used to save fuel consumption, and the coordination of truck platoons have been researched. In Fakhfakh et al., (2020), there is a study that systematically investigates the algorithms used during the creation of vehicle platoons and the strategies used in the control of platoon maneuver operations. To evaluate the accuracy and performance of the proposed control algorithms for platoon formation and maneuvering operations, some of the articles in the literature with simulation and real studies were examined. In Badnava et al., (2021), an analysis and comparison of longitudinal and lateral control algorithms used in performing operations such as platoon joining, splitting from a platoon and changing lanes, which are expressed as platoon transition maneuvers, were made in current articles. The advantages and limitations of these control algorithms are discussed, and different vehicle dynamics are examined according to the homogeneous and heterogeneous structure of platoon members.

To put forth the contributions of this research paper compared to other existing research papers, a comparison has been made in terms of control methods, communication techniques, longitudinal control, lateral control and which are expressed as platoon maneuvers problem situations such as joining the platoon, splitting from a platoon and changing lanes. The results of these comparisons made according to different criteria are given in Table 1. This paper also looks at the latest and most current work on vehicle platoons and analyzes them from various perspectives. In this regard, this article covers studies from 2010 to 2021.

Table 1. Comparison of this research paper with other available papers

Comparison Criteria	Reference								
	Jia et al., (2015)	Li et al., (2015)	Bevly et al., (2016)	Dey et al., (2015)	Bhoopalam et al., (2018)	Zhang et al., (2020)	Fakhfakh et al., (2020)	Badnava et al., (2021)	This Paper 2022
Years Range	*2004 2014*	*2009 2015*	*2002 2015*	*2003 2015*	*2008 2017*	*2008 2018*	*2010 2020*	*2010 2020*	*2010 2021*
Control Methods									✓
Communication Methods	✓						✓		✓
Longitudinal Control	✓	✓	✓	✓		✓		✓	✓
Lateral Control			✓					✓	✓
Join a Platoon	✓		✓		✓		✓	✓	✓
Split from a Platoon	✓				✓		✓	✓	✓
Lane Change	✓		✓				✓	✓	✓

The remaining parts of this paper focus on the nonlinear control methods and techniques used in the control of vehicle platoons and the communication methods used between vehicle platoons. Then operations such as longitudinal control, lateral control, and lane change, which are expressed as maneuver control techniques for vehicle platoons, and control techniques related to platoon operations such as platoon joining, splitting from a platoon, platoon splitting, and platoon merging, which are necessary for the management of vehicle platoons according to these techniques. In the end discusses the summary identifying current issues and open issues for future work and contains the conclusion part.

NONLINEAR CONTROL METHODS USED in THE CONTROL of VEHICLE PLATOONS

In this section, the most commonly used nonlinear control techniques are examined to solve the problems related to different problem situations of vehicle platoons such as longitudinal control, lateral control, adding or removing vehicles from a platoon, and communication methods between vehicle platoons.

I. Sliding Mode Controllers (SMC)

It is a method that is a variable structure control technique in general and is based on the Lyapunov stability theorem. It is an effective control technique based on changing the structure of the controller to reach the desired output value by remaining insensitive to the changes in the parameters in the system, all kinds of system uncertainties, and the electrical noises and vibrations that occur due to the disturbing input and environmental effects that adversely affect the system. Due to the advantages of the sliding mode control technique, there are various and many studies on the control of vehicle platoons by researchers in the literature. In Wen et al., (2021), a distributed control strategy with a two-layer hierarchical structure is proposed to provide trajectory optimization and tracking control in a heterogeneous vehicle platoon. In this direction, the convex optimization method is used to determine the most suitable trajectory that can be used to minimize the desired distance between vehicles. Then, an adaptive sliding mode controller was designed so that the vehicles could follow the most suitable trajectory. As a result of the simulations, it has been shown that the proposed control structure can stabilize the following distance errors as well as provide string stability for heterogenous platoons. Peng et al., (2020) propose the multiple velocity difference model to enable autonomous vehicles to form platoons quickly and maintain this situation depending on the sliding mode control technique. With this method, it is aimed to zero the error between the actual headway and the expected headway and to provide a constant speed and acceleration in the platoon. It has been observed that the sliding mode control method developed in the simulations provides platoon formation in a shorter time and can maintain the speed and acceleration of the vehicles in the platoon. Wu et al., (2019), conducted a study in which a distributed sliding mode control technique including various information flow topologies is used to keep the desired distances between vehicles in a heterogeneous vehicle platoon with nonlinear dynamics and to allow the vehicles to move at a common speed. The effectiveness of this proposed new method has been verified by testing in the simulation environment and under four different topologies. In Guo et al., (2019), two adaptive sliding mode control algorithms, leader-predecessor and leader-bidirectional information flow, are used to ensure string stability of vehicle platoons under unknown external disturbances, parameter uncertainties, and actuator saturation. It has been shown that the vehicle platoons can provide string stability in the simulations made in both of these proposed control algorithms. Tang et al. Li et al., (2018) consider the design of a distributed integrated sliding mode controller in a constant time advance policy for collaborative brake control of vehicle platoons. While the designed controller takes into account the position, speed, and braking force of the leading vehicle, it also includes vehicle tracking interactions such as position, speed, space error, and braking. As a result of the numerical and real field experiments, it was determined that the proposed control method was successful. In Wang et al., (2021), a study on a combined dynamic integral sliding mode controller is presented for a vehicle platoon consisting of a leader and a large number of followers exposed to unknown parameter uncertainties under a bidirectional information flow topology and a constant time progression policy. To ensure the safety and stability of each vehicle, it has been seen that the string stability of the platoon is provided in a finite time with the simulations made in this study, in which the Lyapunov function method is used. In this way, the effectiveness and advantages of the proposed controller have also been verified. Devika et al., (2021) studied the combination of vehicle dynamics and time progression dynamics in heavy commercial road vehicle platoons and as a result, they designed a controller that can provide string stability. It has been demonstrated in the study that the string stability of the vehicle platoon can be achieved in various road conditions and high acceleration and deceleration as a result of the integration of the time interval dynamics produced based on the sliding mode controller with an artificial potential field based string of stable controllers.

II. Neural Network Based Controllers

Artificial neural networks (ANN) are known as systems that try to mathematically model the nervous system of the human brain and thus can imitate the working logic of the human brain. The human brain has various superior features such as learning information, parallel processing of information, self-organization, and problem-solving. Therefore, neural networks learn the characteristics of the signals at the input and can adapt to any changes in the signal. For this reason, artificial neural networks are accepted as the best-known learning model in terms of their ability to meet changing environmental needs. In Čičić et al., (2017), a study was conducted on the estimation of platoon merging distances of heavy-duty vehicles while cruising on the highway, depending on the vehicle speed estimation according to the changing road slopes. To estimate the merging distances of the vehicles, the velocity estimation was made by the neural network trained on a data set. The effectiveness of the proposed method was evaluated as a result of the use of experimental data collected during platoon merging studies on a highway with varying traffic levels. It has been determined that the error in the platoon merging distance estimations under suitable conditions is less than 8% and there is a reduction compared to other methods. Guo et al., (2017) conducted a study on adaptive platoon control for the vehicle platoon in the presence of cannot be modeled dynamic uncertainties, unknown external disturbances, inter-vehicle distance constraints, and nonlinear actuator dead zone. In this direction, a control algorithm on the neural network-based terminal sliding mode with minimum learning parameters, in which a symmetrical Lyapunov function is used, has been developed to prevent disconnections and collisions between vehicles. As a result of simulation studies, it has been revealed that the adaptive neural network mechanism in the designed structure greatly alleviates the online computational load. Hao et al., (2020) presented a study aiming to combine driving situation recognition with platoon operations and risk estimation to reduce the negative effects of driving status fluctuations and unnecessary platoon operations in vehicle platoons. For this, first of all, a long short-term memory neural network structure with the time window method was used to recognize and determine the driving situation. The effectiveness of the realized long short-term memory structure has been demonstrated by experimental studies and it has been determined that the time window method can effectively reduce the vibrations of driving situations.

III. Backstepping Controllers (BSC)

The backstepping control technique is known as an adaptive control technique for the control of nonlinear dynamic systems. It is based on the Lyapunov stability criterion, which is a stability method, and is a recursive and systematic control technique that can be stabilized by the feedback law. The main purpose of this control method is based on obtaining the control signal required by the system by gradually stabilizing each other in the state equations at each stage. In Song et al., (2022), a study was conducted to obtain a new concept of string stability, called vector string stability, as a result of using distributed adaptive backstepping control method to ensure string stability in vehicle platoons. As a result of the simulation studies, it has been seen that internal stability can be achieved with the string stability in the vehicle platoon. In addition, it has been determined that the distance between the desired vehicles and the vehicle platoon can provide position and speed tracking. Yang et al., (2019) present a robust controller design that can be adapted to the heterogeneous vehicle platoon in the presence of time-varying uncertainties and where the vehicles in the platoon are modeled as nonlinear uncertain dynamical systems. The controller, designed according to the backstep control method and Lyapunov stability theory, aims to avoid collision as a result of the space error between successive vehicles imposing inequality constraints for both sides. As a result of the simulation studies, the efficiency of the designed controller has been revealed. In Chou et al., (2019), a study on the controller designed for autonomous vehicles is presented so that the human-controlled vehicle can be followed by a vehicle platoon. For the linear coordinate system used in transforming the error dynamics into a feedback form, the acceleration limit of the vehicle used by the human was taken into account in the study where the backstepping control method was used. As a result of the simulations, the accuracy of the designed controller has been proven. Zhu et al., (2018), a study of the design of the backstepping controller for the string stability of the vehicle platoons in a networked environment where multiple uncertainties including both unknown system parameters and unknown control coefficients are handled in third-order vehicle dynamics has been carried out. As a result of the simulation studies, it has been revealed that the unknown parameters are defined online and the string stability of the vehicle platoon in the fixed distance interval policy is successfully provided by the designed controller.

IV. Fuzzy Logic Controllers (FLC)

The fuzzy logic-based control technique is a control technique that aims to benefit from human experience and knowledge for machines and computers to reach a desired goal in general. To achieve this aim, symbolic expressions called fuzzy logic and fuzzy set theory, which do not have a certain limit value, are not precise and work according to certain mathematical calculations, unlike numerical data, are used. Olwan et al., (2020) presented a study on the comparison of three different fuzzy logic-based controllers optimized to control the desired safe clearance distance between vehicles in a vehicle platoon using a nonlinear longitudinal vehicle dynamics model. As a result of the simulation studies carried out depending on the reference velocity trajectory created for the vehicles to follow, it has been seen that each controller designed gives the desired results in terms of the desired speed tracking and spacing error convergence. In Dong et al., (2020), a study on an adaptive robust controller in fuzzy structure is presented for the longitudinal model of the vehicle system in which fuzzy theory is used to identify external disturbances and undetectable system parameters. The proposed controller is deterministic and does not depend on the if-then form and guarantees both deterministic and fuzzy performance of the platoon system. In Wang et al., (2015), a controller design was carried out in which the lateral offset and direction angle error are estimated depending on the reference path to provide lateral control of autonomous vehicles and more than one fuzzy logic inference engine is used to determine the given driving speed. The effectiveness of the proposed control method has been verified under different driving tasks in simulation and experimental studies where the Lyapunov stability condition is used for the stability of the system.

V. Model Predictive Controllers (MPC)

Model predictive controllers can generally be expressed as a control algorithm that calculates the adjustment of a set of manipulable variables to optimize predictions of the future state and system behavior of a system. Prediction of system behavior can be obtained with a process model expressed as a forecast horizon in a finite time value. In this way, the model predictive controller algorithm in each control loop is intended to be able to optimize future system behavior by calculating the adjustment of a set of future manipulable input variables. Graffione et al., (2020) presented a study on model predictive controller design to be able to control the longitudinal distance and speed between vehicles according to the leader's behavior in a vehicle platoon. In the structure where factors such as rolling resistance, aerodynamics, and traction force are taken into account to determine the dynamic model of the vehicles, it is aimed to minimize the pulling force to be applied to each vehicle to maintain a constant distance between the vehicles according to the position and speed reference values. In this direction, constant and time-varying speed reference values were applied in two test studies. It has been observed that the controller structure regulates the acceleration and deceleration of vehicles over a time horizon. In addition, in the study where the time-varying reference speed value was applied, it took longer for the controller to reach stability compared to the constant speed reference value. In Shen et al., (2021), a nonlinear distributed model predictive controller design was carried out to minimize the speed monitoring and inter-vehicle space errors under uncertainties in a heterogeneous vehicle platoon. The efficiency and accuracy of the proposed approach for the heterogeneous vehicle platoon model obtained from information flow and vehicle longitudinal dynamics have been proven in simulation studies performed in two scenarios where irregularities of accelerations and real highway situations are simulated. In Lan et al., (2021), a data-driven predictive controller design was carried out to form a platoon in a safe, robust, and stable manner from a mixed structure of both autonomous vehicles and human-guided vehicles and to obtain the control law of autonomous vehicles. Here, a data-based accessibility technique based on noisy vehicle measurements is used to predict the future trajectory of the mixed vehicle platoon due to the uncertainty and randomness in human driving behavior and the difficulties in determining power transmission parameters. In simulation studies on both small and large mixed-vehicle platoons, the effectiveness of the proposed controller has been demonstrated as a result of providing smaller spaces between platoons and ensuring the safety and stability of the platoon. Maxim et al., (2020) discussed a controller based on distributed model prediction on a collaborative adaptive cruise control under time-varying communication delays in their vehicle platoon. The effectiveness of the proposed controller for situations where variable communication delays exist in a platoon of five vehicles following the leader has been tested and successful results have been achieved. Tan et al., (2021) conducted a study on the distributed model predictive controller to address the shortcomings of the random packet loss effect on the control of vehicle platoons. In this direction, the effect of random packet loss probability on the asymptotic stability of the vehicle platoon is investigated in order to eliminate the stability problems under Bernoulli random packet loss. As a result, in many simulation studies, an upper limit of the packet loss probability has been found in order to maintain asymptotic stability and a sufficient condition for the consensus of the vehicle platoons has been determined.

VI. Consensus Based Control

Consensus control is a situation that expresses the ability of group members in a group to make decisions in a way that serves the interests of the whole group during the decision-making phase. When this concept is evaluated in terms of the control of autonomous vehicles, the main aim for vehicles is the algorithms developed to form a platoon and to ensure that each member of the platoon reaches a consensus in terms of distance and speed between the vehicles. In this way, it is aim for the autonomous vehicle platoon to realize a safe, stable, and robust driving policy. In Yang et al., (2019), a consensus-based control approach for the stability of the vehicle platoon is carried out in a vehicle platoon using a linearized third-order vehicle dynamics model, in which both fixed time delay and time-varying delays are taken into account. To create a platoon that can move at the same speed and equal intervals, an upper limit of the time delay is derived for the control algorithm obtained based on the consensus based on the Lyapunov-Razumikhin theorem for the fixed time delay vehicle platoon and sufficient conditions for the stability of the platoon are obtained. The Lyapunov-Krasovskii theorem was used to determine the sufficient conditions for platoon stability for a time-varying delayed vehicle platoon. The numerical data obtained in this direction revealed the accuracy of the theoretical results. In Li et al., (2018), a study on a nonlinear consensus-based control strategy under finite time stability for vehicle platoons under fixed and switched communication topologies is presented. The finite time stability of the proposed method and the consensus were analyzed according to the LaSalle invariance principle and the Lyapunov technique. The simulation results obtained by numerical experiments under four different scenarios, the convergence times in terms of position and velocity profiles, and the effectiveness of the proposed method in terms of stability have been verified. Yan et al., (2018) carried out a study including the design of a control algorithm for the vehicle platoon system according to the consensus criteria to solve the packet loss and limited time-varying delay problems in the vehicle platoons with the Bernoulli distribution. The Lyapunov technique is used to analyze the exponential stability of the system with sufficient conditions for vehicle platoon control stability in terms of matrix inequality. The results of the simulation studies show the accuracy and stability of this proposed controller. In Li et al., (2018), the design of a consensus-based algorithm for formation control protocols of vehicle strings with a vehicle-to-vehicle communication structure is discussed. For this, a longitudinal controller was designed for single and multiple strings by including the space and speed differences between the vehicles of the follower vehicle according to the situation of the previous and leading vehicle. In addition, a lateral controller is designed for single and multiple strings according to the artificial function method. The stability of the proposed control protocols was analyzed using the Routh-Hurwitz and Lyapunov techniques. As a result of the numerical experiments, it has been seen that in the proposed technique, the follower vehicles follow the leader in each string asymptotically and a consensus has been reached on their position and speed. Di Bernardo et al., (2014), a study on solving the problem of a platoon to create due to the effects of heterogeneous time-varying delays due to communication between autonomous vehicles, by considering it as a problem of reaching a consensus of dynamic systems. In this respect, it has been revealed that the platoon-building problem can be reshaped as a closed loop consensus problem, and the platoons' stability can be achieved despite the presence of delays. Table 2 provides information about the control methods commonly used in vehicle platoons and the advantages and disadvantages of these methods.

Table 2. Comparison of commonly used controllers in vehicle platoons

Control Method	Advantages	Disadvantages
Sliding Mode Controllers	➢ It can be applied to nonlinear systems. ➢ It is an effective method to stabilize the system despite parameter changes, system uncertainties, external disturbances, and environmental effects. ➢ The system response is fast despite the negativities caused by the uncertainties and external disturbances in the system.	➢ A chattering effect is observed around the sliding surface due to the high-frequency switching signal. ➢ Mechanical wear may occur in the system. ➢ The life of the system may be shortened and the energy loss may increase.
Neural Network Based Controllers	➢ It is a flexible control method that can be learned by training. ➢ It is also possible to train the network with missing data. ➢ It can create input-output relationships from data without any known connection. ➢ Many learning algorithms can be created that can be adapted to a particular problem.	➢ Training data is needed to use neural networks and learning can take a very long time. ➢ Since it only works with numerical information, the problem situation needs to be converted to numerical representation. ➢ The fact that the parameter values of the network cannot be determined according to any rule creates a problem.
Back Stepping Controllers	➢ It is an effective technique to eliminate mismatched perturbations while providing asymptotic stability. ➢ Controller design can be performed more easily because it divides the entire system into smaller subsystems for controller design.	➢ it is necessary to have accurate model information of the controlled system and to know all system states. ➢ The requirement to assume that the purpose of the controller in the subsystem is satisfied before activating the controller in the upper system can be a problem in controller design.
Fuzzy Logic-Based Controllers	➢ They do not need a mathematical model of the systems. ➢ It has a flexible and adaptable structure. ➢ It is easy to understand and apply.	➢ The performance of the controller largely depends on the experience and knowledge of the expert. In this regard, there is a need for expert personnel who know the system. ➢ Proper membership functions and rule tables are not easy to prepare.
Model Predictive Controllers	➢ It can be successfully applied to complex and multivariate systems. ➢ Considering the design constraints of the systems, they can be systematically incorporated into the design processes. ➢ They can be used with different control strategies. ➢ It is a very useful technique if future directions are known.	➢ To calculate the control rule, more calculations are needed compared to the classical controllers. ➢ Predictive controllers cannot be tuned if there is no clear model of the dynamic behavior of the system. ➢ Considering the limitations of the system, the solution is made iteratively and the calculation time loses its importance.

COMMUNICATION METHODS USED IN VEHICLE PLATOONS

Autonomous vehicle platoons can be expressed as an ITS application that can adjust their distance and speed with each other to act together as a group. It aims to solve many traffic problems on highways, thanks to its ability to act as a platoon on its own. To solve these problems, autonomous vehicles need to be able to form platoons, and for this, each vehicle in the platoon needs various information about its surroundings, as well as information such as the speed, distance, and kinetic status of the other vehicles in the platoon. This information is necessary for the platoon to be able to control the acceleration and deceleration of the vehicles in the platoon, and for the safety of the platoon, as well as for its efficient movement Zeng et al., (2019); Boubakri et al., (2020). A study investigating the effect of communication in multi-vehicle CAV on vehicle platoon dynamics was conducted by Zhang et al., (2013). To obtain this information, traditional sensors such as radar or camera were used at first, and problems such as communication delay and packet loss were encountered due to the limitations of such sensors Jia et al., (2016); Hong et al., (2020). The effects of these communication delays in vehicle platoons on vehicle platoons were examined in a study conducted by Qin et al., (2013). In this respect, the concept of vehicle communication has been introduced depending on the rapid technological developments in the field of communication to eliminate these problems experienced during the information exchange between vehicles. In this way, it aims to eliminate the problems experienced during the information exchange between the vehicles and to drive the vehicle platoons safely and efficiently Hong et al., (2020). Communication types in these network structures used in the exchange of information between vehicles are generally; classified as vehicle to vehicle (V2V), vehicle to infrastructure (V2I), vehicle to everything (V2X), cellular vehicle to everything (C-V2X), and vehicles to pedestrians (V2P) Zeng et al., (2019); Fakhfakh et al., (2020).

- *V2V Communication:* It is a type of communication used to exchange information from vehicle to vehicle and is used to exchange information such as speed, acceleration, and high-definition map data between vehicles. To enable this method, technologies such as Visible Light Communication (VLC), Vehicle Ad hoc Networks (VANET), and cellular network structures must be used. Here, VANET is widely used to increase energy efficiency and reduce traffic congestion and traffic accidents, but it has several disadvantages such as security and data loss issues. For this reason, VLC technology is presented as an alternative solution. However, the most important disadvantage of this method is that it is adversely affected by sunlight. In case of too many connections to cellular networks, the density in the network causes data communication to be unreliable Jia et al., (2015); Segata et al., (2016); Fakirah et al., (2020).

- *V2I Communication:* It is the type of communication used to provide data communication from the vehicle to the infrastructure. In this communication method, there are Roadside Units (RSU) to provide information about the status of road conditions and rules for autonomous vehicles. The density of these units affects the connection quality Fakirah et al., (2020).

- *V2X Communication:* It is used to exchange information from vehicles to everything Gyawali et al., (2020).

- *C-V2X Communication:* It is a communication method that makes it possible to exchange information from the vehicle to everything on a cellular basis Gyawali et al., (2020).

- *V2P Communication:* It is used to exchange information between vehicles and pedestrians Gyawali et al., (2020).

In Li et al., (2019), a study on platoon control within the scope of vehicle to everything (V2X) communication method is presented. For this purpose, a consensus-based longitudinal control algorithm and an artificial function-based lateral control algorithm were designed to ensure platoon control, and the convergence analysis of the proposed consensus-based control method was performed with the Lyapunov technique. At the same time, stability analysis was performed using the perturbation method, and a new vehicle tracking model was proposed to express the local interactions and vehicle tracking behaviors between connected vehicles. As a result, the effectiveness of the proposed method in terms of spacing, speed, and trajectory characteristics between connected vehicles has been demonstrated in real experiments such as joining the platoon, splitting from a platoon, and forming a platoon. In Hidayatullah et al., (2021), apart from platoon uncertainties such as vehicle dynamics and road slope, the analytical stability of the platoon in platoon uncertainties expressed according to the homogeneous or heterogeneous structure of the platoon is examined within the framework of central control. By using the integrated PreScan and Matlab/Simulink simulation programs, the string stability of the platoons in both homogeneous and heterogeneous situations in the minimum time interval was carried out in simulations. In the next step, the string stability of the platoons under packet loss and communication delays for both platoon cases were investigated, and as a result of the simulations, it was verified that the analytical string stability of the homogeneous and heterogeneous vehicle platoons was achieved. Zhao et al. Zhao et al., (2020) conducted a study on the effects of the presence of communication disturbances such as random packet losses and limited communication range on control performance in vehicle platoons in a constant time progression policy. For this, a systematic method using different packet loss scenarios was used to analyze the string stability. In this respect, at first, the case of independent and random packet losses when the vehicle in front moves at a constant speed is examined. Depending on the stability of the matrix polynomials to ensure ideal communication under these conditions, the necessary conditions for control gains, sampling time, and internal delay have been obtained to ensure the stability of the vehicle platoon. Secondly, the matrix perturbation method is used to obtain an analytical upper bound of the packet loss ratio to ensure the string stability of the instruments in the constant time progress policy in case of random homogeneous packet losses independent of time. In the third case, if the latest information is used as input, necessary and sufficient conditions for the string stability of the vehicle platoon are obtained by the Markov hopping linear system method, and in the comprehensive numerical analysis, the result is that the random packet loss rate and the mean convergence time increase. In Wang et al., (2021), the situation in which the previous and next vehicle information is used to prevent back collisions and increase the efficiency of road use capacity is examined. Unlike the existing platoon controllers, a new model predictive controller algorithm has been developed, which aims to control the platoon according to the trajectory of the vehicle ahead and focuses on the switched communication topology in the presence of abnormal communication. To evaluate whether the proposed control algorithm for platoon control can prevent the collision, the designed controller; has been tested in three different scenarios normal communication, vehicle leader in abnormal communication, and following vehicle leader position in abnormal communication. For this, after the desired vehicle spacing policy is created according to the basic communication topology, the control algorithm of the vehicle platoon is established, and the asymptotic stability and L2-norm string stability criteria are taken into account in the proposed model predictive controller. Afterward, a simulation environment was developed for the CAV platoon based on the PreScan/Matlab/V2X communication simulator. As a result of the experiments carried out in the simulation environment, it has been proven that communication topologies can be changed in different communication environments thanks to the proposed control algorithm, besides, distance, speed, acceleration, and string stability between vehicles are provided. Xu et al., (2019) presented a separate control method for a homogeneous vehicle platoon in the presence of communication delay and external factors to reduce the energy consumption of each vehicle and to ensure the string stability of the vehicle. First of all, it proposes a new type of variable interval strategy, which is expressed as an energy-oriented distance policy and based on the comparison of the ideal speed values of each vehicle traveling at the optimum speed in a fixed interval policy concerning the geometry of each vehicle. Then, after the dynamics of the homogeneous discrete vehicle platoon consisting entirely of electric vehicles, under external factors and communication delays, were created depending on the energy-oriented distance policy, a robust discrete vehicle controller control system was designed according to the Lyapunov-Krasovskii method. In the presence of communication delays and external factors, the H-infinity method ensures that each vehicle travels at the most appropriate speed in terms of energy efficiency and that the string stability of the platoon is ensured. The discrete controller designed as a result of the simulations has realized the increase in the efficiency of each vehicle in terms of energy and the string stability of the platoon under a proposed new energy-oriented spacing policy. Gao et al., (2015) proposed the H-infinity control method for heterogeneous vehicle platoons to ensure robustness, tracking performance, and string stability despite uniform communication delays and uncertain dynamics. To solve the decentralized controllers with numerical methods, linear matrix inequality is derived depending on the delay, and many communication topologies can be formulated following the linear matrix inequality norm and covered. In this regard, the delay-dependent Lyapunov method, which includes a quadratic linear function of the states occurring during the uniform communication delay time, is used to theoretically analyze the string stability and robustness of the platoon. As a result of the theoretical analysis and simulations, it has been proven that the robustness, tracking performance and string stability of the proposed H-infinity control technique vehicle platoon are provided despite uniform communication delays and uncertain dynamics for heterogeneous vehicle platoons. In Hong et al., (2020), it is aimed to increase the success rate of the platoon leader's information sharing by ensuring that the information sharing of the leader vehicle in the platoon and the information sharing of the followers following the leader are in the form of separate information sharing. In this way, a systematic design is proposed to improve platoon communication, increase platoon safety, and reduce position errors between following vehicles. It is suggested to use relays in the system to expand the communication range of the platoon leader and the scale of the platoon. The controller designed for the implemented system, on the other hand, is an adaptive model predictive based controller, where the control parameters can be adjusted according to the situation of the platoon, thus aiming to avoid collisions, and a good controller performance is aimed. At the same time, auxiliary communication techniques are used to prevent communication errors. As a result of the simulations, it has been confirmed that the systematic design can prevent position errors, as well as prevent collisions and thus improve the safety of the vehicle platoon. In Chen et al., (2021), a distributed fuzzy adaptive control method is proposed for the consensus problem of multi-factor high-order systems, where the communication topology is uncertain and the precision is unknown, defined by the Takagi-Sugeno fuzzy logic model, under disturbing input and unknown parameters. In this proposed method, it is ensured that the consensus errors approach zero asymptotically according to the Lyapunov stability theorem as a result of the simulations made under conditions where the dynamics of the leader vehicle are not known by any factor by the followers following the leader. In di Bernardo et al., (2015), in the presence of heterogeneous and time-varying communication delays, the control problem of vehicles in a platoon to reach the specified distances and desired speeds is expressed as a high-order network consensus problem. It has been proven as a result of experimental studies that the desired distances and speeds can be achieved by using Lyapunov-Razumikhin functions within the scope of both fixed and switched communication network topologies. Thus, it has been confirmed that the communication problems and maneuvering problems of vehicles joining and splitting from a platoon are solved with the proposed method. Yan et al., (2017) present an output feedback control algorithm to simplify the information communication topology and reduce the communication load by rationalizing the formation geometry when each vehicle can communicate with successive vehicles under a fixed time progression policy. For this, a neural adaptive sliding mode controller algorithm is designed to establish the desired distance between vehicles according to the integrated sliding mode method. Then, an output feedback control technique, in which only position information is used, is proposed in order to eliminate the measurement complexity and thus reduce the communication load. In addition, a high order sliding mode controller is used to predict other needed information such as acceleration and velocity. As a result of the simulation studies, it has been proven that the proposed control method provides the string stability of the vehicle platoon and thus vehicle collisions are prevented. In Zhu et al., (2020), the effectiveness of a distributed adaptive control algorithm for third order nonlinear CAV platoons in the presence of nonlinearizable parametric uncertainties and unknown external disturbances was investigated. Here, a vehicle to vehicle communication based adaptive backstepping control algorithm is used as an online parameter estimator to estimate the distortion limits and unknown parameters. As a result of the simulations, it has been verified that the designed backstepping control algorithm provides the string stability of the vehicle as well as determines the parameter uncertainties with the help of the online parameter estimator. Table 3 contains a summary of the most recent articles on communication methods in the vehicle platoons and provides information on communication type, application pattern, and problem status.

Table 3. Recent studies of communication methods in vehicle platoons

Year Reference	Communication types			Implementation		Control problem
	V2V	V2I	V2X	Simulation	Real	
2019 Li et al., (2019)			✓		✓	Platoon control and collision avoidance
2021 Hidayatul-lahandJuang (2021)			✓	✓ Matlab/Simulink PreScan		Analytical platoon stability
2020 Zhao et al., (2020)	✓	✓		✓ Matlab LMI Toolbox		Effects of random packet losses on the control performance of vehicle platoon
2021 Wang et al., (2021)			✓	✓ Matlab/Simulink PreScan	✓	Collision avoidance and increasing road capacity for connected autonomous vehicles
2019 Xu et al., (2019)	✓			✓		Ensuring string stability under communication delays and external disturbances and minimizing energy consumption
2015 Gao et al., (2015)	✓	✓		✓		Ensure robustness, tracking performance, and string stability despite communication delays and uncertain Dynamics
2020 Hong et al., (2020)	✓			✓		Improving platoon communication, increasing platoon safety, and reducing position errors between the following vehicle
2021 Chen et al., (2021)	✓	✓		✓		Control method for consensus problem under distorting input and unknown parameters
2015 di Bernardo et al., (2015)	✓				✓	To reach the distances between vehicles and desired speeds determined in the presence of time-varying communication delays
2017 Yan et al., (2017)	✓			✓		To simplify the information communication topology and reduce the communication load
2020 Zhu et al., (2020)	✓			✓		The effectiveness of a distributed adaptive control algorithm in the presence of non-linearizable parametric uncertainties and unknown external disturbances.

MANEUVER CONTROL TECHNIQUES AND PLATOON OPERATIONS USED IN VEHICLE PLATOONS

As mentioned before, the most basic objectives of vehicle platoons with ITS implementation are; it can be expressed as preventing traffic accidents, reducing traffic congestion, saving fuel, using highway capacity more efficiently, reducing air pollution, providing safe and comfortable driving, and shortening travel time. To achieve all these aims, besides the application of various control algorithms to these vehicles, the vehicles must be in constant communication with each other and with their environment, thus ensuring the successful flow of information between the vehicles and other components and these autonomous vehicles must be able to form platoons. In Yan et al., (2019), there is a study on the ability of CAV to platoon up under nonlinear dynamics using the dual mode model predictive control technique. In Yan et al., (2020), the vehicle platoon control problems are investigated in the presence of communication delays in a heterogeneous group of vehicles and under conditions where multiple constraints are taken into account. In Ma (2021), a study was carried out involving the control and optimization problem of a vehicle platoon generated from CAV under CTH policy and in the presence of V2V communication delays. In Ma et al., (2018), simulation and experimental studies of a two-layer hierarchical control method based on fuzzy logic are presented for CAV to form platoons. Before, the communication methods and techniques used in providing communication in the CAV and the current studies in this field are given in detail. In this section, operations performed within the platoon such as changing lanes, joining the platoon, splitting from a platoon, platoon merging, and platoon splitting creating changes in the platoon structure will be evaluated. In addition, longitudinal control and lateral control, which are maneuver control techniques in vehicle platoons, and current studies on the creation processes of vehicle platoons will be discussed in detail.

I. Longitudinal and Lateral Control

Maneuvers are one of the most basic components of vehicle platoons and operations such as changing lanes, creating platoons, joining platoons, leaving platoons, merging platoons, and splitting platoons require a vehicle to maneuver longitudinally and laterally. Therefore, the control of vehicle platoons primarily requires successful longitudinal and lateral control of autonomous vehicles Jeon et al., (2001); Santini et al., (2018). In this respect, various models are used to examine the longitudinal and lateral dynamics of the vehicle platoons and the i-th vehicle is expressed as follows, starting from the well known and proven bicycle model Ying et al., (2014).

$$\begin{cases} \dot{u}_i = \dfrac{1}{m}\left(mv_iw_i - mfg + u_i^2(fk_1 - k_2) + c_f\dfrac{v_i + aw_i}{u_i}\delta_i + T_i\right) \\ \dot{v}_i = \dfrac{1}{m}\left(-mv_iw_i - (c_f + c_r)\dfrac{v_i}{u_i} + (bc_r - ac_f)\dfrac{w_i}{u_i} + c_f\delta_i + T_i\delta_i\right) \\ \dot{w}_i = \dfrac{1}{I_z}\left((bc_r - ac_f)\dfrac{v_i}{u_i} - (b^2c_r - a^2c_f)\dfrac{w_i}{u_i} + ac_f\delta_i + aT_i\delta_i\right) \end{cases}$$

$$\begin{cases} \dot{X}_i = u_i\,cos(\varphi_i) - v_i\,sin(\varphi_i) \\ \dot{Y}_i = u_i\,sin(\varphi_i) - v_i\,cos(\varphi_i) \\ \phi_i = w_i \end{cases} \quad (1)$$

Where m is the mass of the vehicle and f is the rotating friction coefficient. k_1 and k_2 represent lift and drag parameters of aerodynamic properties, respectively. c_r and c_f are the cornering stiffness coefficients of the back and front tires, a and b are the distance from the back and front axles of the vehicle to the center of mass of the vehicle, and I_z is the rotational inertia of the z-axis. u_i represents the longitudinal velocity, v_i the lateral velocity, and w_i the yaw rate. X_i and Y_i indicate the position coordinates of the vehicle's center of gravity relative to the road's coordinate system, and φ_i indicates the yaw angle of the vehicle. δ_i is the angle of rotation of the wheels, T_i is two control signals expressing the traction force at the contact point of the tire with the ground. In addition, the dot symbol used in the equations represents the derivative concerning time Ying et al., (2014). Longitudinal and lateral control in CAV in vehicle platoons are two important parameters to ensure platoon stability. Longitudinal control generally includes controlling the gas and brake movements, and it is aimed to ensure that the vehicles in the platoon can go at the speed of the leader vehicle and that the following distance between the vehicles ahead and the predetermined vehicles can be maintained Nobe et al., (2001); Santini et al., (2018). Lateral control, on the other hand, covers the control of steering movements in general, and thus, it is aimed at successfully performing transitional maneuvers such as changing lanes, staying in the same lane decisively, joining the platoon, splitting from a platoon, avoiding obstacles that may come in front of the vehicles Chang et al., (2017).

In the literature, the longitudinal and lateral control problem has been discussed in detail by researchers and many studies have been conducted on this subject. In Xu et al., (2020), a switched fuzzy adaptive double coupled sliding mode controller (SFADCSMC) is designed for the longitudinal control of vehicle platoon with leader vehicle and follower vehicles. First of all, the necessary conditions for the control law and string stability of the third-order longitudinal dynamics of a vehicle in the presence of external disturbances are provided. Then, the designed controller is compared with the traditional double-coupled sliding mode controller. When the results are examined in terms of position, velocity, and acceleration, it has been theoretically proven that the tracking performance of the switched fuzzy adaptive double-connected sliding mode controller and the tracking distance between the determined vehicles are better than the traditional double-connected sliding mode controller. Guo et al., (2017) carried out a study in which an adaptive fuzzy sliding mode controller was designed to control the longitudinal and lateral movements of the vehicles in the platoon to provide platoon control in autonomous vehicles. As a result of the simulation studies, it has been revealed that the controller, which shows low sensitivity to external disturbances and parameter changes in the system, is successful in terms of tracking performance, vehicle stability and driving quality. In Wei et al., (2019), a study is presented to perform longitudinal and lateral control under radar sensors and V2V communication for automatic vehicle tracking. First of all, a feed-forward controller with feedback is designed for longitudinal control to keep a safe distance between vehicles and to follow the speed of the vehicle ahead. Then, a model predictive controller was designed for the trajectory prediction of the vehicle in front based on historical motion data with V2V communication. The stability and applicability of these designed controllers have been verified in simulation and experimental studies. In Mentasti et al., (2020), a study using images obtained from the camera placed on the vehicle is presented to perform end-to-end lateral control of autonomous vehicles. Thanks to this camera, it is a structure in which two convolutional neural network (CNN) controllers are used, which are connected to predict the situation faced by the vehicle and to obtain the steering command according to possible situations. As a result of the experimental studies, it has been revealed that the designed controller achieves high accuracy in the estimation task. Shalaby et al. Shalaby et al., (2019) carried out a study in which three different controllers were applied separately for each vehicle and a nonlinear longitudinal vehicle dynamics model was used for the vehicles to manage the distances between vehicles in a vehicle platoon. The reference speed was determined under different scenarios for the vehicles to follow, and the performance of each controller according to this reference speed was tested in the simulation environment in terms of speed tracking, distance error convergence and realistic control effort. In the simulation results, it was observed that the monitoring performance and distance control of all controllers were provided within the framework of the determined criteria. In Wei et al., (2018), the effectiveness of the supervised reinforcement learning (SRL) based collaborative adaptive cruise control (CACC) approach for longitudinal vehicle dynamics control was investigated in both simulation and experimental studies. During reinforcement learning, a supervisor trained with the data obtained from the human driver is updated under the guidance of the earnings planner during the training process. In the simulation and experimental studies, it has been observed that the proposed controller ensures the efficiency of the system. In Li et al., (2017), the distributed H-infinity control technique is applied to a vehicle platoon with solid formation geometry and the same formation dynamics. In the simulations, it has been revealed that the proposed controller can provide string stability, tracking performance, and platoon stability. In Latrech et al., (2018), an integrated controller design was carried out over a wireless network for longitudinal and lateral control of the vehicle platoon in a given lane. First of all, for longitudinal control, the controller is designed in the presence of actuator saturation and communication delays, which takes into account the inter-vehicle distance proportional to the vehicle speed. Later, a lateral controller was designed to keep the vehicle on the road through the steering. Finally, these two controller structures designed for fully automatic vehicle control were combined and it was revealed in the simulations that this controller can perform longitudinal and lateral control. Zennir et al., (2018), there is a study comparing fuzzy logic-based and PID controllers for longitudinal and lateral control of vehicle platoons. In the study, one of which is controlled by a human, and the other is controlled by two different controllers for longitudinal and lateral control, information exchange, and communication such as speed and direction angle are provided with a fixed safety distance. To control the effectiveness of the controllers, the efficiency of the proposed control designs was examined in the simulation studies in which different structures of reference orbits were used, and it was understood that the controllers should be optimized in case of motion in a curved orbit. In Muhamadinah et al., (2019), a study including the use of backstepping control method is shown in order to preserve the platoon properties in the truck vehicle platoon, at any lateral speed as the lateral controller and at different speeds as the longitudinal controller, and in such a way that the distance between the follower and the leader approaches zero. In the simulation studies, it has been seen that the proposed controller provides platoon control and can adjust the speed of the followers depending on the speed of the leader and maintain the distance between them. Table 4 contains a summary of the most recent papers on longitudinal and lateral control in the vehicle platoons and provides information on the type of maneuver, control strategy, implementation and problem status.

Table 4. Recent studies of longitudinal and lateral control in vehicle platoons

Year Reference	Control Strategy	Maneuver Type		Implementation		Control problem
		Longitudinal Control	**Lateral Control**	**Simulation**	**Real**	
2020 XuandLu (2020)	SFADCSMC	✓		✓		Longitudinal control of the platoon with a leader vehicle and multiple followers
2017 Guo et al., (2017)	SMC	✓	✓	✓		Adaptive fuzzy sliding mode controller design for longitudinal and lateral control in vehicle platoon
2019 Wei et al., (2019)	MPC	✓	✓	✓ Matlab/Simulink CarSim	✓	Longitudinal and lateral control for automatic vehicle tracking
2020 Mentasti et al., (2020)	CNN		✓	✓ Track Attack	✓	End-to-end lateral control of the autonomous vehicle
2019 Shalaby et al., (2019)	BSC, MPC, SMC	✓		✓ Matlab/Simulink		Longitudinal control of vehicles in the platoon using different control techniques
2018 Wei et al., (2018)	SRL based CACC	✓		✓ Matlab/Simulink	✓	Design of SRL-based CACC controller for longitudinal vehicle dynamics control
2017 Li et al., (2017)	H-infinity	✓		✓		H-infinity-based controller design for longitudinal control of vehicles platoon
2018 Latrech et al., (2018)	FLC	✓	✓	✓ Matlab/Simulink CarSim		An integrated controller design for longitudinal and lateral control over a wireless network in a vehicle platoon
2018 Zenniran-dAllou (2018)	PID, FLC	✓	✓	✓ Matlab/Simulink v-rep		Comparison of two controllers for longitudinal and lateral control of vehicles platoon
2019 Muhamadinah et al., (2019)	BSC	✓	✓	✓		Designing a step-back controller for longitudinal and lateral control of truck vehicles platoon

II. Lane Change

The general purpose of lane changing in CAV is expressed as the first action a vehicle must take to join or leave a platoon if it finds a suitable maneuvering opportunity while moving in its current lane. At the same time, the maneuvering process takes place by providing information exchange between RSU or related neighboring vehicles, that is, between vehicles and from vehicle to infrastructure Amoozadeh et al., (2015). In addition, for any lane change operation to be carried out healthily and safely, various conditions must be fulfilled. In this respect, first of all, all vehicles involved in the lane change process should notify the vehicles with human drivers and pedestrians in the vicinity of the lane change request with warnings or various signs, without exceeding the determining speed limits. Another important condition is that the dangerous lane change process to be made by vehicles close to each other needs to be postponed until sufficient maneuvering space is provided. After the space required for the lane change is obtained as a result of the slowing or acceleration of the vehicles by cooperation, the lane change process should be carried out quickly within the framework of the necessary procedures and rules in a way that does not endanger human life and does not adversely affect the traffic flow Hodgkiss et al., (2019). After a successful lane change, the maneuvering vehicle either joins a platoon and then continues its movement with that platoon in the determined conditions, or it leaves a platoon and must continue its movement independently Badnava et al., (2021). In Ahmed et al., (2020), a study was carried out to control the deflection speed of a vehicle during the lane changing process by using a neural network controller and a fuzzy PID controller. In the simulation studies, it has been observed that the fuzzy PID controller is more successful than the neural network controller in controlling both the yaw speed and the sliding angle during the vehicle's lane change. Wang et al., (2021) proposes a dynamic cooperative lane changing method for CAV, taking into account possible accelerations of the vehicle ahead. In this method, the vehicle that will change lanes completes the maneuvering process by following a strategy consisting of three steps decision-making, trajectory planning, and trajectory tracking after collecting information about the vehicles around it, and updating its decisions in real time. The effectiveness of the proposed method has been demonstrated by the increase in success in lane change maneuvers as a result of simulations. Sun et al., (2021) introduce collaborative lane-changing work on a two-lane highway based on two-stage optimization, with both a lane change in the original lane and a lane change in the target lane. With this study, it aims to minimize the factors that negatively affect the traffic flow in both lanes by ensuring the coordination between the vehicle changing lane, the vehicles in the original lane, and the vehicles in the target lane. As a result of the simulation studies, it has been revealed that a smooth and safe lane change process according to the proposed model is successful under the given driving scenario. In Li et al., (2020), a study on a common trajectory plan is shown to ensure the safety and efficiency of traffic flow in case of more than one mandatory lane change request in the CAV. In the study, which solves two problem situations, vehicle grouping and movement planning, first of all, CAVs are divided into different groups, and then trajectory planning is made for vehicles with and without lane change requests for each group. In the simulation studies carried out to evaluate the effectiveness of the proposed method, it has been observed that the vehicles can perform the lane change process safely and effectively in cooperation. In Luo et al., (2019), there is a study on the cooperative multi vehicle automatic lane change maneuver under a situation of eight vehicles and three lanes using V2V communication. Orbital planning; in order to maximize safety, comfort, vehicle dynamic and lane change efficiency, it is considered as an optimization problem based on the MPC technique. In the simulations made with the proposed collaborative lane change model, it has been observed that the vehicles can safely perform the lane change maneuver. Hodgkiss et al. Hodgkiss et al., (2019) discuss two new methods of utilizing vehicle communication for CAVs to perform lane change maneuvers under high efficiency and high safety. The first method is the method in which the lane change maneuver is performed by giving special permissions to the vehicle that will change lanes of the central management, which includes intelligent transportation systems such as RSU and traffic light controllers throughout a certain distance. The second method is called ILACH+ and it is a study in which the maneuvering process is expanded and developed in cooperation with the vehicles near the vehicle making the lane change operation. In both proposed methods, the efficiency and safety of the lane changing process have been tested by studies.

III. Splitting From and Joining The Platoon

Vehicle platoons are a group of vehicles that act in a coordinated manner and can follow each other while maintaining a safe driving distance, although there is no mechanical connection between them. These vehicle platoons generally consist of a leader vehicle that makes decisions on behalf of the whole platoon and follower vehicles that follow this leader Maiti et al., (2017). For the CAV to move safely and healthily to its determined targets, in some cases, it is necessary to join or leave these vehicle platoons by making successful maneuvers. In this respect, as shown in Figure 2, the fact that a vehicle that is not part of the platoon successfully maneuvers into the platoon lane from the front, middle, or back indicates the state of joining the platoon. Similarly, as shown in Figure 3, the vehicle that is a part of the platoon changes lanes by making a successful maneuver or creating a sufficient distance from the neighboring vehicle, which also indicates the situation of splitting from a platoon Jeon et al., (2001).

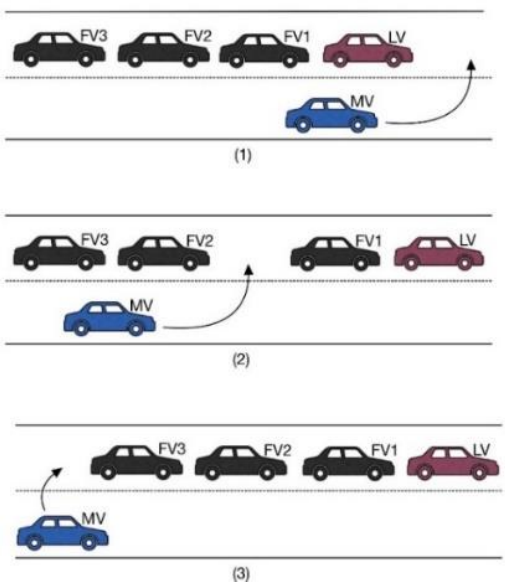

Figure 2. Joining the platoon (1) Front, (2) Middle, (3) Back

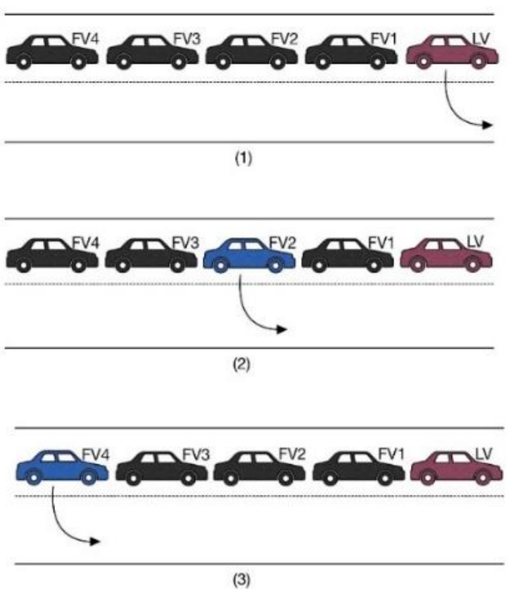

Figure 3. Splitting from a platoon (1) Front, (2) Middle, (3) Back

Farag et al., (2019) present the protocols required for joining or splitting from a platoon in CAVs, taking into account the stability, safety, and performance of the vehicles. This proposed protocol is implemented using a robot operating system (ROS) based visualization vehicle and is implemented in homogeneous and heterogeneous vehicle platoons under the scenarios of splitting from and joining a platoon. According to the experimental studies, it has been shown that after the maneuvering operations, all vehicles in the platoons have reached the desired inter-vehicle distance and speed. In Mena-Oreja et al., (2018), PERMIT, an open-source platoon-building simulator based on SUMO and its extension Plexe, is shown to perform platoon maneuvers such as splitting from and joining platoons in traffic scenarios involving autonomous and nonautonomous vehicles. Researchers present PERMIT as an open source to further investigate the effects of platoon maneuvers on traffic under mixed traffic scenarios and to develop autonomous driving studies. The accuracy of the maneuvering operations applied under various scenarios has been demonstrated by the studies. Heinovski et al., (2021) propose the PlaFoSim simulation vehicle platoon, which was developed to study platoon formation and platoon maneuvers in large-scale highway scenarios. It has been demonstrated in a case study that new algorithms using Python modules can accelerate and facilitate the search for platoon formation and platoon maneuvers and can be easily integrated into the system.

IV. Platoons Merger and Split

The platoon merge maneuver is expressed as the process of forming a single platoon by coming together two different platoons moving toward the same target Fakhfakh et al., (2020). As shown in Figure 4, A and B are two different platoons and each platoon has a leader. The platoon leader requesting a merger sends the request to the other platoon leader with various information such as the speed of the vehicles, the distance between the vehicles, and the common target path. If the conditions are met for both platoons, the merger is performed. The platoon split maneuver is expressed as the process of splitting at least two vehicles from a platoon and forming a new platoon with a different leader. As with the merging maneuver, the split maneuver is a process initiated by the platoon leader Amoozadeh et al., (2015). This situation is shown in Figure 5.

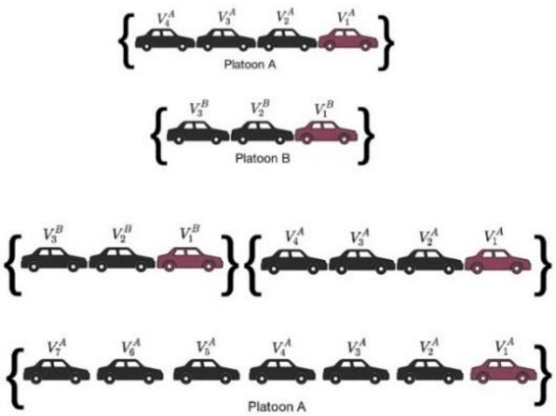

Figure 4. Merger of platoons

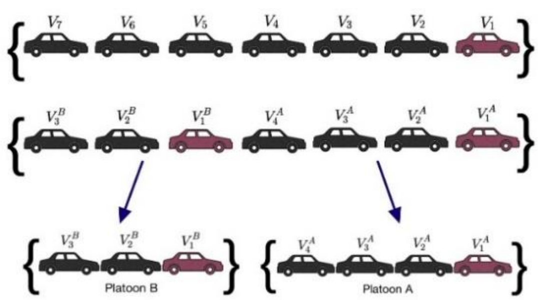

Figure 5. Split of platoons

Min et al., (2019) propose a platoon merger approach with the use of a distributed model predictive controller (DMPC) for CAVs to be used to optimize the trajectories of target platoons, taking into account both the acceleration limits and the safe area. To control the effectiveness of the proposed DMPC algorithm for the vehicles that exchange information with each other, it has been demonstrated that a stable and accurate control input can be applied to the vehicles in the platoon as a result of numerous simulations for a scenario with two platoons. Dasgupta et al., (2017) propose an algorithm to control basic maneuvering operations, such as merging and splitting vehicle platoons. In the study, a PID controller was implemented by using the micro simulator VISSIM for the merging and splitting of the platoons. In the simulation studies, the effectiveness of the PID controller, which is designed for vehicle movements as well as the merging and splitting maneuvers of the vehicle platoons, has been demonstrated. Wang et al., (2017) present a new CACC system based on the distributed consensus algorithm for platoon creating, merging, and splitting maneuvers. A distributed consensus protocol has also been developed to enable the algorithm to work to create platooning, merging, and splitting maneuvers of this CACC system. In simulation studies including platoon creating, merging, and splitting maneuvers performed in Matlab/Simulink under various scenarios, it has been demonstrated by sensitivity analyses that the system is safe, comfortable, and efficient under appropriate parameter values. In Segata et al., (2014), there is a study that proposes an application protocol to support the merging maneuvers of vehicle platoons in different scenarios and includes analysis results. As a result of the simulations, it has been revealed that the proposed protocol is even at high packet losses successful, and can be canceled safely. In Goli et al., (2020), a study has been carried out on platoon creation, control strategies, merger approaches, and reduction of emergency braking during the merging or formation of platoons for vehicles that have effective communication in CAVs and combine as a platoon. First of all, the requirements and strategies were determined for the successful merging of vehicles in a platoon. Then, as a result of obtaining information via communication under several scenarios, several longitudinal controllers are compared in the simulation environment. Again, smooth and safe lateral trajectory plans are proposed for vehicles that combine in a platoon, and finally, the effects of sudden braking on the system during the execution of a multi vehicle merger maneuver in a platoon are investigated. The effectiveness of the strategies proposed in all these studies has been tested with various simulations.

FUTURE RESEARCH

Vehicle platoons are an application that has recently become an important research topic to eliminate problems such as traffic congestion, traffic accidents, air pollution, fuel savings, and more efficient use of the existing road infrastructure. Although the topic of vehicle platoons is an important, popular, and well-studied topic, it is a difficult research topic for many reasons, and many open issues need to be explored and addressed in the future. First of all, considering the parameters such as safety, passenger comfort, travel time, fuel saving, reduction of air pollution, more efficient use of highways, prevention of traffic jams and traffic accidents, dynamic structures of vehicles, sensor failures, communication delays, controllers that can operate stably and safely in a real environment and real traffic conditions, such as the effects of current traffic flow on the vehicle platoon, need to be designed and developed. Although a few real studies on vehicle platoons are included in this article, most of the studies in this field consist of simulation studies carried out under certain conditions, in which the effects of real traffic conditions on autonomous vehicles are ignored and in almost ideal conditions. For this reason, the effectiveness and reliability of controllers commonly used for vehicle platoons must be tested under real conditions and designed and developed following these conditions.

Another future research topic for vehicle platoons is further research and development of vehicle communication methods and techniques. The effectiveness and importance of communication methods are especially evident in platoon length during the creation of vehicle platoons. In a long-vehicle platoon, communication delays or data loss may occur during the exchange of information between the leader vehicle and the follower vehicle at the end of the platoon. In this case, traffic flow, especially the stability of the string, is adversely affected. For this reason, it is necessary to develop more effective methods and techniques for data communication within or between platoons in vehicle platoons. In addition, having too many vehicles in a platoon reduces wind friction and in this case, reduces fuel consumption. At the same time, the high number of vehicles in the platoon directly affects the traffic flow. In this regard, limitations on the number of vehicles in a platoon or the length of the platoon is another issue that needs to be investigated due to their potential to affect traffic flow and fuel consumption.

Another issue to be explored in the future is the determination of optimal longitudinal distances between vehicles. These distances refer to the longitudinal spaces between vehicles and these spaces between vehicles must not exceed a certain distance to ensure string stability. At the same time, these spaces between vehicles affect the wind friction force, which is directly related to fuel consumption. In addition, these spaces are another subject that needs to be investigated, as they affect the safe and comfortable driving of vehicles without collision in sudden braking, excessive acceleration, and deceleration.

CONCLUSION

This paper is a detailed research study that includes current studies on vehicle platoons, which have become an important research topic in recent years. First, information about the control techniques commonly used in vehicle platoons is given, and the advantages and disadvantages of these techniques are summarized in a table. Secondly, by introducing the communication techniques used in the vehicle platoons, the most recent research including communication methods and techniques is summarized in a table according to criteria such as communication type, application method, and problem situation. Then, operations such as lane changing, leaving the platoon, joining the platoon, platoon splitting, and platoon merging, which are made within the platoon and create changes in the platoon structure, and maneuver control techniques expressed as longitudinal control and lateral control are introduced and the latest studies on these are examined in detail. In addition, recent studies on longitudinal and lateral control techniques are summarized in a table according to criteria such as control technique, maneuver type, application type, and problem status. Finally, future work on vehicle platoons and open issues are mentioned.

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