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Platooning of connected autonomous vehicles in freeway traffic: state of the art

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Abstract

Connected and Autonomous Vehicle (CAV) technologies have the potential to disrupt and change transportation networks and impact on mobility patterns. CAVs have faster response times and can better grasp traffic conditions (in terms of speed, position, acceleration, etc.) with respect to human-driven vehicles. Consecutive CAVs for example can travel maintaining very short gaps (i.e., in a platoon) taking advantage of their onboard sensors and of their communication capabilities, according to pre-defined car-following strategies. In fact, the ability of CAVs to communicate with each other (V2V) and with the infrastructure (V2I) allows them to take collaborative decisions in order to maximize efficiency while ensuring a smooth and safe journey. Therefore, CAV platooning on freeways stands out as a collaborative management strategy with great potential. Various studies have been published regarding autonomous vehicles and platooning impacts on freeway traffic with a broad range of scopes, assumptions, results, and conclusions. The focus of this paper is to present a summary of the available literature on CAV platooning, which is categorized into different groups focusing on platoon stability, effects on road capacity, traffic safety, and on energy consumption. There is common agreement that CAV platooning can have a positive impact on global road capacity and overall traffic safety and efficiency. However, further research is needed to achieve these objectives.

Keywords: Connected Autonomous Vehicle; Platoon; Platoon stability; Road capacity; Safety

1. Introduction

With recent advancements in the research and application of robotics, sensory devices, and Intelligent Transport Systems (ITS), autonomous vehicles are expected to become an integral part of the future road transport system. These vehicles can sense the road infrastructure environment and other vehicles and road users in the network through various

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communication and sensing devices and provide safe movement or guidance with very little or no human input, thus greatly reducing the cognitive burden and physical exhaustion linked to car driving.

The Society of Automotive Engineers (SAE) and the U.S. National Highway Safety Administration (NHSTA) have defined different levels of automation ranging from Level 0 (manually driven vehicles with no automation) to Level 5 (full automation vehicles, commonly known as autonomous, self-driving, or driverless vehicles). [SAE International. 2021].

Vehicles that can communicate with each other (Vehicle-to-Vehicle, V2V), with the roadside infrastructure (Vehicle-to-Infrastructure, V2I), or with any other devices (Vehicle-to-anything, V2X) are termed “connected vehicles” in the literature. In turn, vehicles that perceive and process information in real-time, using artificial intelligence and other computer algorithms, and allow the vehicle to navigate in a safe and appropriate way without direct driver input, are defined as “autonomous vehicles”. In the present paper, Connected Autonomous Vehicles (CAVs) are defined as vehicles that can process information in real-time and also have the ability to communicate with other vehicles, infrastructure, or with any other device. For its part, CAV platoons are defined as “a formation of vehicles that are connected to each other and coordinated, allowing them to travel together at close proximity, reducing aerodynamic drag, improving fuel efficiency, and potentially providing other benefits with improved traffic conditions.” (see Fig.1). The deployment of CAV platooning could also yield increased road capacity (Van Arem et al., (2006); Shladover et al., (2012); Lioris et al., (2017)), and the efficiency of overall traffic.

Such benefits of connected and autonomous vehicle technologies, and platooning strategies in particular, for traffic safety, mobility, and the environment, are attracting an increasing amount of research from the transportation modeling and vehicle control areas (Bian et al., (2019)) together with funding for their development. Take as an example the studies on inter-platoon (Chen et al., (2017); Ghiasi et al., (2017)) and intra-platoon (Seraj et al., (2018)) headways. Martínez-Díaz, M. et al (2021) present a review of the main results achieved within the platooning context. Still, there are research gaps to be addressed. For instance, the impact of the platoon size on the road environment has not been thoroughly investigated. The advantages of platooning technology can be more fully realized with a long platoon (Liu et al., (2018a)), but the superior lateral agility of a small platoon size is an attractive counterpoint (e.g., lane change and merging). For motorway traffic operations, Liu et al. (2018b) advised a maximum platoon size of 10–20 cars based on the trade-off between capacity and maneuverability.

The present paper aims to provide an overall review of the existing research on CAV platooning, focusing on platoon control and stability (Section 2), road capacity (Section 3), traffic safety (Section 4), and energy consumption (Section 5). Finally, the conclusions section (Section 6) draws attention to the existing research gaps and highlights further research questions.

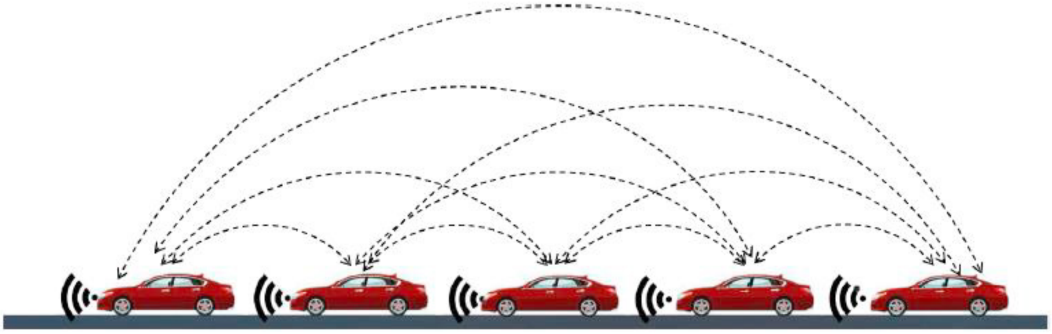
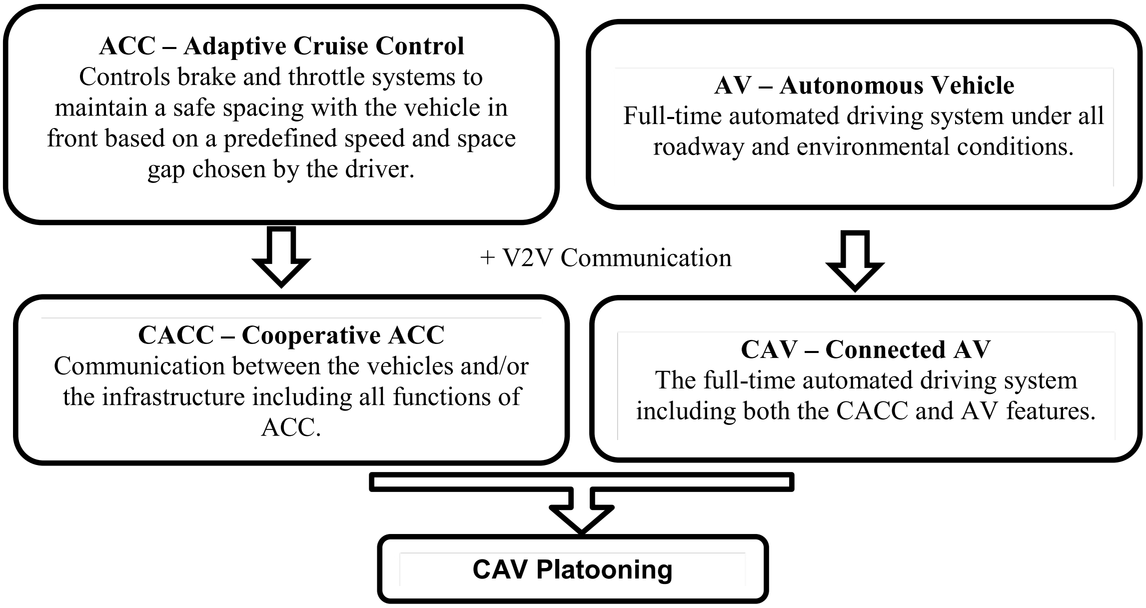


Fig.1 Example of communication-enabled CAV platoon



(b)

Fig.2 CAV Platooning requirements

2. Platoon control and stability

Since the development of the General Motors (GM) stimulus-response models, (Chandler et al., (1958); Gazis et al., (1959); Herman et al., (1959)), considerable effort has been done in modeling drivers' car-following behavior. However, the majority of these models do not address the automated driving behavior in the new connected driving environment. In fact, there are relatively few models in the literature that can capture these new behaviors. In spite of this, there have been significant developments in the modeling of platooning operations (Maiti, S. et al. (2017)). As shown in Figure.3, vehicle platooning involves three different basic operations including i) stable platoon driving, ii) merging, and iii) splitting (Li, Q. et al. (2022)). In this section, we discuss the existing literature with respect to the requirements to achieve a stable platoon.

A vehicle's longitudinal control algorithm that considers information from surrounding vehicles forms the backbone of a platoon control system. Today, the most extensively used longitudinal control algorithms are ACC systems, typically employing linear state feedback control, with the controllable acceleration proportional to i) the deviation of the gap from a target value under a constant time gap policy and ii) the relative speed with the preceding vehicle (Mullakkal-Babu et al., (2016); Ploeg et al., (2014)). One of the issues linked to ACC is string instability, also known as asymptotic stability, which examines whether the perturbations of a lead vehicle in a vehicle string are magnified as they spread backward to many subsequent vehicles in the vehicle string. The key influencing aspects for vehicular string stability (i.e. platoon stability) are the time delays of the vehicle dynamic system (e.g. the latency of the communications in CAV platooning), and control (design) parameters, such as the required gap and feedback gains (Sun et al. (2018)).

In turn, in the presence of V2V communications, CACC is a common control technique that builds on the foundation of ACC (see Fig. 2). Platooning can be achieved by CAVs in a CACC system, in which they share information about one another through a wireless connection and drive as a group. Enhancing CACC algorithms in the platooning context has been the focus of several researchers.

Talebpour and Mahmassani (2016), simulated the influence of platoon size on the stability of human-driven vehicles, connected vehicles, and autonomous vehicles. The results indicated that platoon stability declined as the number of vehicles increased in the platoon. Seraj et al. (2018) conducted a simulation study on the effect of CAV penetration rate and maximum platoon size on mobility, safety, and environmental effects, concluding that an increase in platoon length enhances mobility and provides higher environmental benefits but it results in lower traffic safety.

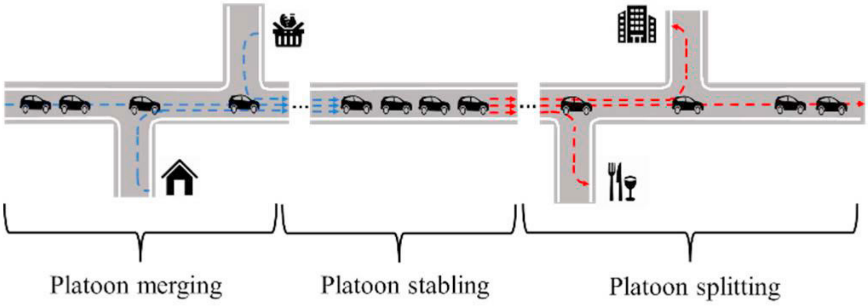


Fig.3 Platoon operation (Li, Q. et al. (2022))

In spite of all the existing research, in general, the proposed CAV car-following control schemes tend to be string unstable, which might be one of the explanations for the difference between theoretical predictions and practical reality. String instability yields traffic oscillations and may even cause stop-and-go traffic, reducing the theoretical expected road capacity (Chen et al., (2014)), as discussed in the next section.

3. Road Capacity

One of the most significant components of the platoon control algorithm is the longitudinal spacing strategy, which defines the following distance between consecutive vehicles. The design of the spacing strategy has a direct influence on traffic safety and road capacity. The shorter the distance for a given traveling speed, the greater the chance of rear-end crashes if not properly designed, but the larger the achieved road capacity. Therefore, it is not surprising that ACC/CACC systems could increase road capacity by reducing the average headway between vehicles and by reducing traffic disruptions, as shown in Chen et al. (2019) with different types of mixed scenarios: ACC/manual vehicles, CACC/manual vehicles, and ACC/CACC/manual.

Nevertheless, determining the magnitude of the capacity increase due to platooning, is a challenging issue, because modeling the impact of current technology on driving and car-following performance is not an easy task. Vehicles' acceleration is the significant car-following variable, which allows for determining whether the proposed space gap between vehicles at a given speed is safe or not. Several researchers studied acceleration behavior extensively for human driving and proposed models of varying complexity to capture the underlying processes of acceleration decision-making (Chandler et al., (1958); Gazis et al., (1959); Herman et al., (1959); Gipps, (1981); Yang and Koutsopoulos, (1996); Hamdar and Mahmassani, (2009); Talebpour et al., (2011)). Unfortunately, this type of research has not seen its equivalent in the CAV platooning environment yet.

The majority of research on road capacity involving CAV traffic is based on simulations (Van Arem et al., (2006); Shladover et al., (2012); Talebpour et al., (2017)). The outcomes of these simulations demonstrated that the CAV penetration rate is a crucial element to increase traffic throughput, as it increases the "platooning intensity" a term introduced by Ghiasi et al. (2017) defining the probability of vehicles circulating in platooning mode. In fact, Ghiasi et al. (2017) achieved similar conclusions by deriving theoretical formulations for the CAV road capacity using the Markov chain technique.

It is possible that the road capacities reported in many of the previous works are overestimated since, in general, no restriction was established for the platoon size (Xiao et al., (2018)). Take as an extreme example the work of Chen et al. (2017) where the road capacity in case of mixed traffic (i.e. traditional vehicles and CAVs together) is assessed by considering that all CAVs are in platooning mode. The size of a CAV platoon strongly relies on the real-time traffic situation (e.g., vehicle arrival rate and CAV penetration rate) and on the traffic management strategies to enhance platooning (e.g., lane management strategy to achieve cooperative platooning formation, in contrast to opportunistic platooning, where platoons are created by chance (Sala and Soriguera, (2021))). Platoon length and frequency (i.e.

yielding the "platooning intensity") are stochastic variables subject to fluctuations (Liu et al., (2018a)) between the minimum length of two vehicles and the maximum permissible size. This approach of varying platoon size, with a maximum allowable length, is considered by Zhou and Zhu, (2021) to study the effect on capacity.

Note that, when defining the maximum platoon length, it is necessary to consider the trade-off between capacity and string stability. Accepting longer platoons favors larger capacity, but the traffic stream is more prone to instabilities (Talebpour et al., (2017)). Also, longer platoons may make it harder for vehicles to merge into or split out and would reduce their lateral mobility (Van Arem et al., (2006); Liu et al., (2018a)). According to Zhou and Zhu, (2021), the maximum platoon size must not be too big, and a reasonable number (e.g., 10 or even less) is sufficient, which is consistent with the platoon size configurations of previous research (Liu et al., (2018a); Liu et al., (2018)). In fact, the work by Sala and Soriguera. (2021), show that platoon lengths over 20 vehicles have almost no positive effect on capacity unless penetration rates of CAV are close to 1 (i.e. 100% of CAVs). In conclusion, the optimal platoon size arrangement is an important open problem.

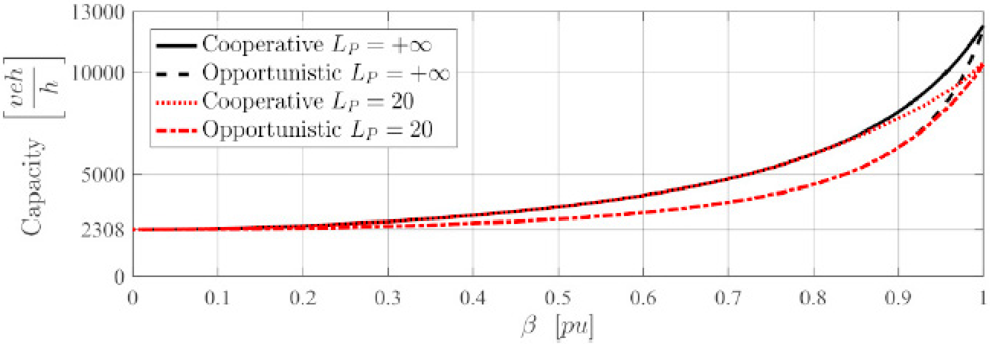


Fig. 4 CAV penetration rate, β , vs lane capacity for cooperative and opportunistic platooning strategies and maximum platoon length of +∞ and 20. (Sala and Soriguera, (2021))

4. Traffic Safety

Implementing CAV technology could also yield safety advantages. Xiao et al. (2017) developed a realistic car-following model for ACC/CACC systems and tested it with a wide range of collision possibilities to prove that the model was collision-free. Sun et al. (2018) found that time delays in the delivery of information are a major aspect of the safety of CAV platooning, as well as it was in string stability. This means that the safety and stability of the platoons are strongly related. Sainct (2020), gives insights into developing predictive control algorithms which can prevent traffic instabilities and mitigate traffic safely, at the same time that can also improve road capacity. Similarly, Shi and Li (2021) explained the trade-off between road capacity stability and the safety of the platoon, with respect to the headway between platooning CAVs. Also, some authors address the safety of the platoon after some breakdown, like Liu et al. (2022), which presents a workaround to maintain the CAV platooning safe following a communication breakdown. Its efficiency serves as a benchmark for future CAV designs with reliable communications. Finally, Wang et al. (2020) analyzed the impact of traditional vehicles and connected vehicles in the event of chain collisions, proposing a mass-spring-damper system for ensuring the safety of the platoon of vehicles.

Safety is a major concern when coming to the acceptance of CAVs. Still, the majority of the studies deal with string stability, being safety only a surrogate result. There are not enough studies focusing on the emergency braking conditions of CAVs and specifically evaluating safety in CAV platooning.

5. Energy Consumption

Energy consumption is a significant contributor to the economic and environmental implications of the transportation industry, in particular being directly proportional to CO2 emissions. The technological design of automated vehicles is a critical aspect of the energy savings potential, and probably CAVs will have the ability to significantly reduce energy needs in the transportation of people and cargo. In spite of this, it could be possible that increasing car mileage might outweigh the energy savings from autonomous and connected driving so that the implications on the global environment might be detrimental.

In any case, CAV platoons could yield large fuel savings, although the actual amount will vary depending on factors such as the level of automation, the size of the platoon, and the driving circumstances (Brost, M. et al. 2021). The main source of this reduction comes from the reduced aerodynamic drag in the follower vehicles of the platoon (Maiti, S. et al. (2017), Hu, M. et al. (2021)), especially if these vehicles are large (e.g. truck platooning). Qin, Y. et al. (2018) found similar results, showing that CAV platooning can decrease fuel consumption and traffic pollution if operated in optimal conditions for stability. Finally, Ma et al. (2021) concluded that a platoon size of 5 to 10 may also be adequate considering both, road capacity and pollution emissions.

6. Conclusions and further research

The paper reviews the existing literature on CAV platooning with respect to platoon stability, road capacity, traffic safety, and energy consumption. The main conclusion obtained is that the majority of studies implement existing car-following algorithms for CACC/ACC systems to analyze platooning. In this context, the headway between vehicles and the platoon size are the major factors affecting the string stability and the resulting road capacity. Existing research mainly focuses on proposing different control methods to improve stability under platooning conditions. In the context of mixed traffic, where CAV and regular vehicles travel together, the CAV penetration rate is found to be the most important aspect affecting the likelihood of platoon formation and the average length of platoons, yielding thus an increase in road capacity. However, as CAVs travel in platooning mode by maintaining short headways, a small perturbation in speeds can lead to string instability hence leading to collisions. Therefore, platoon safety is directly related to its stability.

Finally, when vehicles travel in a platoon with decreased aerodynamic drag, energy consumption can be reduced. However, from the studies conducted it is also clear that fuel consumption depends on the vehicle type, automation level, and platoon size.

Further research should focus on improving the dynamic algorithms for platoon car-following, which should outperform the existing models based on car-following algorithms originally derived for human-driven vehicles without V2V communications. A car-following algorithm specific for CAVs can improve platoon stability and safety while also increasing capacity.

Despite the fact that the platoon might be stable at key speeds and that the magnitude of any perturbation varies at different speeds, it is crucial to determine the ideal platoon operational speeds. Platoon size is proved to be a common attribute in enhancing stability, capacity, safety, and energy usage; yet, different researchers regarded different platoon sizes as best; therefore, it is critical to identify the optimal platoon size using the newly established models.

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