PLATOONING OF CONNECTED AUTOMATED VEHICLES ON FREEWAYS: A BIRD'S EYE VIEW

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ABSTRACT

A platoon can be defined as a group of consecutive vehicles that exchange information, so that they drive in a coordinated way, allowing very small spacings and still travelling at relatively high speeds. The concept of vehicle platooning is not new. In fact, scientific articles on platooning were published as early as the 1970s, and the first large-scale pilot test on platooning was carried out at the end of the 1990s. The main purpose of these early research works was to improve traffic efficiency and reduce consumptions, as well as to develop the existing technology.

These contributions were very valuable, although somehow limited by the relevant technology still being in its infancy. Precisely, the development of technology and communications in the last years has given new impetus to research on vehicle platooning on freeways as one of the possible forms of cooperation among connected automated vehicles (CAVs). The point of view of these recent studies has also been extended: in addition to traffic efficiency, the role of platooning is analyzed in terms of safety, sustainability, business productivity, etc.

In this context, there are today many scientific publications on vehicle platooning with different purposes, set in distinct scenarios and based on diverse vehicles and technologies (regular or segregated lanes, cars or trucks, vehicles with different SAE levels, etc.).

In order to organize and consolidate the existing knowledge, a comprehensive and systematic review must be performed.

This work represents a first approximation to this more ambitious objective. Firstly, platooning has been conceptualized in order to facilitate its analysis and comparisons among studies. Secondly, key publications on platooning have been analyzed to determine the most significant impacts expected from its implementation.

Finally, some important research gaps and disparate findings on the topic have been identified.

1. INTRODUCTION

Since the development of the first intelligent transport systems in the 1980s (Weiland and Purser, 2000), researchers, companies and administrations have been working to apply developments in technology and communications to combat the undesired externalities caused by transport, particularly by road transport. Especially during the present century, decisive advances in vehicle automation, monitoring and communication networks, both Wi-Fi and mobile, have allowed this struggle to be taken to a higher level and definitively visualizing future autonomous and connected mobility as feasible. Several cooperation strategies based on different communication schemes among mobility agents, namely vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-all (V2X) communications, are being developed with the aim of improving traffic flow and safety and reducing transportation environmental impacts (Fagnant and Kockelman, 2005; Maiti et al., 2017; Razmi et al., 2020).

One particular form of cooperation, the concept of vehicle platooning, started to attract interest as early as the 1970s. At that time, vehicles involved in platooning projects and research were passenger cars and, mostly, heavy vehicles, fitted with *ad hoc* designed sensors (Tsugawa, 2016). Additionally, the role of infrastructure was often decisive in those years, during which numerous studies on Automated Highway Systems (AHS) emerged. In this early research, the most attractive benefits expected from platooning were those economic ones linked to potentially lower fuel consumption (Browand, 2004; Lammert et al., 2014; Alam et al., 2015; Tsugawa, 2016). On the contrary, current studies mainly focus on light vehicles with a high degree of automation *per se* (Maiti et al., 2017; Bian et al., 2019; Sala and Soriguera, 2020). In addition, the importance of infrastructure is decreasing in relative terms, while that of communications is increasing (Bian et al., 2019; Jia et al, 2019; Li et al., 2020). Also, the expected benefits of platooning in terms of improved traffic flow and safety are tipping the balance towards research in these areas (Xu et al, 2013; Ye and Yamamoto, 2018; Jo et al., 2019; Calvert et al, 2019).

Nevertheless, the most addressed platooning-related topic is the so-called *string stability*. Researchers of different fields propose varied longitudinal and lateral control strategies to avoid that, due to the close vehicle formation within a platoon, state disturbances propagate and amplify along the string of vehicles.

These studies start by mathematically defining string stability, continue using particular analysis methods to derive conditions that ensure this stability and, finally, design controllers that satisfy them (Feng et al., 2019). Each of these steps can have many variants, depending not only on the approaches used, but also on the target platoon system characteristics (e.g. vehicle features, following policies, etc.). The great variety and complexity of string stability studies would require a particular comprehensive review. Therefore, this topic is out of the scope of this paper.

Instead, the present work is aimed at providing an overview on research and developments on platooning, particularly focusing on its expected impacts on areas such as traffic flow, road safety, human drivers' behavior, consumptions and emissions (Figure 1). An extensive literature review has allowed identifying and summarizing the most significant results on each topic, taking into account both the distinct contexts considered and the different analysis methodologies employed. Previously, a brief classification of platooning typologies is provided, in order to facilitate the understanding of their possible influence on the results. Finally, the paper highlights those issues with more uncertainty, either because they have hardly been addressed or because the results obtained have been disparate.

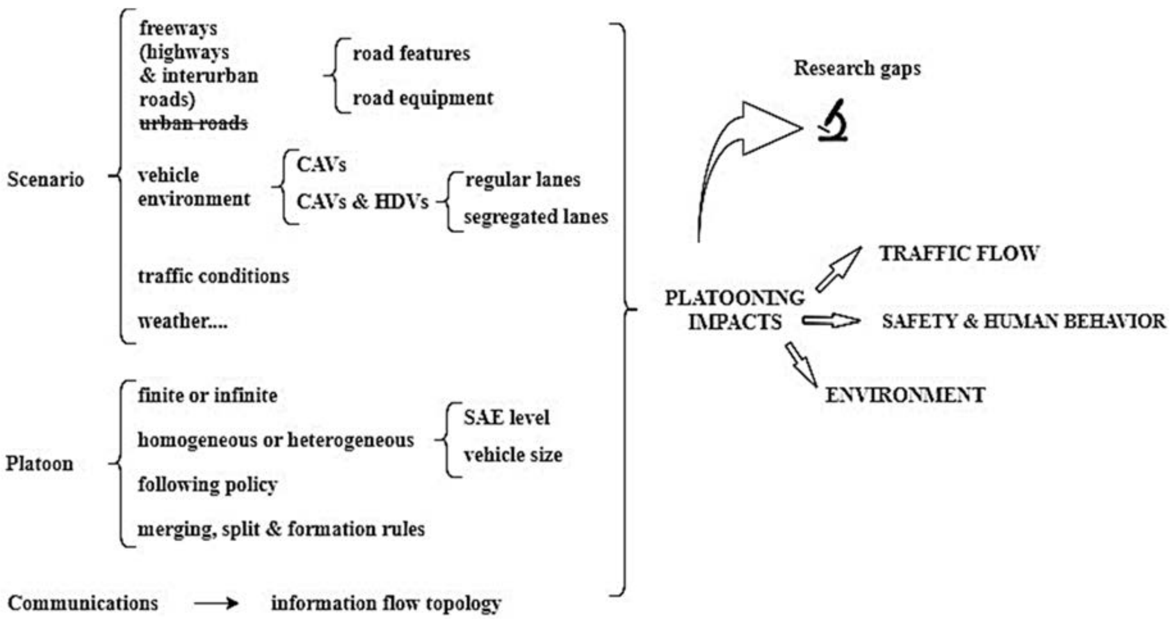

Figure 1. Graphical abstract of the article (own elaboration).

Authors have used a semi-structured approach to choose the papers that underpin this review. In the first stage, only those studies published in scientific journals indexed in the Journal Citation Reports platform were considered. From these studies, the ones containing the words *platoon*, *platooning* or *road train* in the title, abstract or keywords were searched in the Scopus database. A quick scan of the abstract allowed identifying those referring exclusively to traditional vehicles, urban environments or intersections (the word *platoon* is often used to identify a set of vehicles arriving at/leaving a signalized intersection during a particular cycle), which were disregarded.

Also those published in journals from fields other than transportation, vehicle or communications engineering, or associated areas (e.g. environment, psychology). Among the remaining papers, those with the highest number of citations were selected. Increasing minimum thresholds were established according to their year of publication. The final set of chosen references was supplemented with studies obtained from backward snowballing, being the acceptance criteria (e.g. indexing or number of citations) in this case looser than for the main papers.

The remainder of the paper is structured as follows: Section 2 classifies platooning according to three different criteria, which is important for the subsequent comparison of studies. Sections 3, 4 and 5 respectively summarize, as per the performed review, platooning impacts on traffic flow, safety and human behavior, and the environment. The most important conclusions of the analysis are extracted in Section 6, in which remaining research gaps are also highlighted.

2. PLATOONING TYPOLOGIES

It would be possible to differentiate numerous typologies of platooning based on diverse criteria. The following subsections attempt to perform this classification in a simple and concise way, according to the type and number of platooned vehicles, the information flow topology and the following policy within the platoon.

2.1 Classification according to the type and number of platooned vehicles

Usually, research on platoons focuses on vehicles of similar size, i.e., light (e.g. Gouy et al, 2014; Ye and Yamamoto, 2018) or heavy vehicles separately (e.g. Ramezani et al., 2018, Calvert et al., 2019). So far, only a small number of authors have tried to define strategies for the formation of platoons of vehicles with different sizes (e.g. Sun and Yin, 2019). The diverse mechanical features of these vehicles (acceleration and deceleration capacity, maximum speeds, speeds and gears on slopes, etc.) are obstacles to overcome. However, there are others such as the difficulty that large differences in size between consecutive vehicles may represent for sensors and communications, or the lack of comfort/the feeling of insecurity they may cause to drivers or passengers (think, for example, of a car placed between two large trucks) (Feng et al., 2019). These challenges are compounded by the fact that, unless a particular strategy is defined, the relative position within the platoon of these differently sized vehicles would vary in real time.

Another differentiating factor among vehicles is their degree of automation. In this regard, it should be noted that very few studies specify the SAE level (SAE, 2016) of the vehicles they are considering, and authors refer to them loosely as (cooperative) "autonomous vehicles", “automated vehicles”, “self-driving cars” or “human-driven vehicles”, among others. Therefore, the reader must suppose this automation level based on the capabilities vehicles are provided with throughout the text.

Some researchers argue that, as platooning involves driving at short intervehicle distances for an extended period, and eventually at high speeds, reactions to safety-critical events such as the sudden braking of vehicles ahead should not depend on the human factor.

Accordingly, SAE levels 4 and 5 are preferred, as human intervention is restricted to very limited occasions (Konstantinopoulou et al., 2019). Nevertheless, especially for the case of truck platooning, most current field operational tests and implementations feature heavy vehicles of SAE levels 1 and 2. Eminently video cameras, radars and vehicle-to-vehicle communications are used to keep close formations travelling at medium-low speeds, being drivers still quite actively involved (Kockelman et al., 2016; Kuhn et al., 2017; Knoop et al., 2019; Calvert et al., 2019). Although some improvements are achieved, the overall potential advantages of platooning cannot be maximized with these lower levels of automation. In this context, institutions like the European Road Transport Research

Advisory have assumed a simpler classification (when compared to the SAE one) for heavy vehicles that specifically limits the platooning possibilities they have (ERTRA, 2015). For the remainder of this paper, the term CAVs will refer to cooperative medium-high automated vehicles.

In this context, it is called *homogeneous platoon* that consisting of vehicles of the same (or similar) characteristics in terms of size and degree of automation. On the contrary, a platoon is *heterogeneous* if there are notable differences of any kind among its vehicles, either in size, degree of automation (including traditional human-driven vehicles – HDVs-) or both.

Regarding the number of vehicles in the platoon, it is possible to differentiate between *finite platoons*, for which a maximum number of vehicles is set, and *infinite platoons* (Feng et al., 2019; Zhou et al., 2021). Obviously, real platoons will always be finite, but the use of infinite platoons in research allows simplifying and generalizing the analysis of platoons with a high number of vehicles, seeking to maximize all potential benefits of this mode of cooperative driving. However, some authors question the interest of research on infinite or very long platoons. On the one hand, common challenges of cooperative driving, such as information flow and management, are accentuated. On the other hand, it seems unlikely that a large number of vehicles would decide to take at the same time a same route long enough so as to make a profit, unless it is a predetermined management decision. For example, a decision linked to logistics, i.e., an agreement among different companies whose goods must be transported from similar origins to similar destinations. In case this kind of platoons would be materialized, another aspect to take into account would be their interactions with other non-platooned vehicles. Although this aspect is important for any kind of platoon, some particular measures only advisable for medium-short platoons would have to be imposed for large platoons.

One example would be their driving restricted to the leftmost lane, so as not to prevent other vehicles, for instance, from entering or exiting a freeway or from making a lane change (Eckhardt et al., 2016). Note that, for the case of long truck platoons, this situation would be just the opposite of the current one, in which heavy vehicles usually drive in the rightmost lane. Additionally, very large truck platoons could lead to an accelerated deterioration of existing pavements and structures (Song et al., 2021).

2.2 Classification according to the information flow topology

Although platooning can benefit from V2X communications, the information exchanged among vehicles is key to achieve a good performance and, particularly, to ensure string stability. Not only information on other vehicles' speeds or positions, but even slight accelerations, decelerations or direction changes, among others, must reach each particular vehicle in time so that it can react accordingly. In this way, disturbances diminish and their propagation and amplification along the string of vehicles are avoided.

Logically, for a particular vehicle within the platoon, information coming from its nearest vehicles will be not only relevant, but also more feasibly obtainable from the point of view of sensors and communications. Therefore, information flow topologies (IFTs) such as *predecessor following* (PF), *two-predecessor following* (TPF) and *bidirectional* (BDL) are widely used in research. In parallel to the development of powerful communications, more generalized schemes such as *r-predecessor following* (rPLF) are being increasingly applied. For their part, other studies consider that some information about the leader, especially (but not only) its position, should reach the whole platoon. Taking into account that the leader will be relatively far away from some members of the platoon, the exchange of information among nearby vehicles is considered necessary anyway. In this context, *predecessor leader following* (PLF), *two-predecessor leader following* (TPLF) or the generalized *r-predecessor leader following* (rPLF), as well as *bidirectional leader* (BDL) IFTs are more and more commonly used in the studies (Zheng et al., 2016; Feng et al., 2019; Gong et al., 2019). Figure 2 represents the information flows of these configurations.

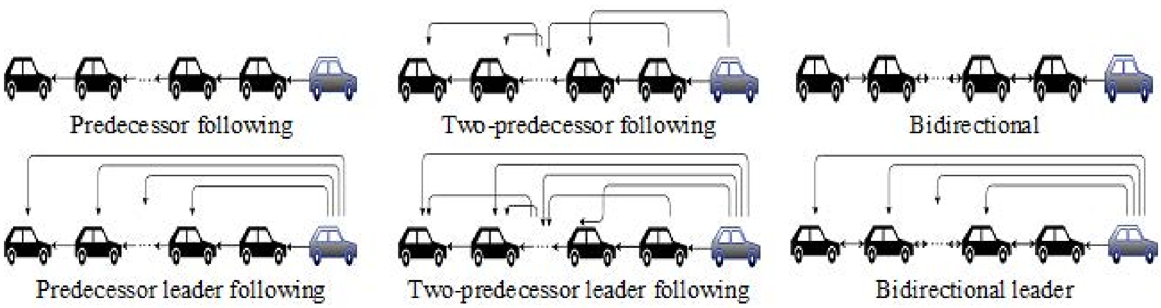

Figure 2. Most typical information flow topologies for platoons (the leader vehicle is highlighted. Own elaboration).

The possibility that an increasing number of vehicles can exchange information with each other despite being at considerable distances is the result of improvements in communications. However, the greater the amount of information transmitted, the greater the likelihood of communication delays, packet losses and other related issues, usually associated with the congestion of the communication channels (Xu et al., 2013; Zheng et al, 2018; Li et al., 2020). Therefore, the fact that more vehicles exchange information does not necessary imply either a higher degree of stability within the platoon or more benefits linked to a particular platooning behavior. Researchers try to find a tradeoff in this regard.

Another aspect that must be highlighted is that neither of the former information flow configurations is static, as both the vehicles and their positions within a platoon change over time. Accounting for these dynamic changes in real time is one of the main challenges for researchers on platooning (Feng et al., 2019).

2.3 Classification according to the formation, split or following policies

The first condition for the potential benefits of platooning to be exploited is that there is a sufficient penetration of vehicles with a level of automation that allows platooning (Bergenhem et al., 2012; Janssen et al., 2015). However, the strategies on the basis of which platoons are formed also play an important role. The *a priori* least favorable strategy in this respect would be the so-called *opportunistic platooning* (Liang et al., 2014; Sala and Soriguera, 2020*)*, also known as *on-the-fly platooning*, according to which only those CAVs that happen to drive consecutively in the same lane would form a platoon. More efficient would be the *cooperative platooning*, whereby all CAVs within a certain range would try to join in a platoon, respecting the maximum lengths established, if any (Sala and Soriguera, 2020). Even more optimal strategies have been designed in the field of logistics. One example is the *online, dynamic planning or real time platooning*, according to which, just before or during the journey, vehicles announce their destination and/or tentative routes so that other interested vehicles can platoon with them during part or the total of the journey. Another example is the *offline, static* or *scheduled platoon planning,* in which trips are announced in advance to facilitate the coordination among companies (Bhoopalam et al., 2018). Many side aspects complicate this coordination, as, for instance, the mandatory rest stops for drivers in the transportation sector (Goel, 2010; Goel, 2014).

Although the relevant legislation has yet to be updated, it is expected that a minimum number of rest stops will continue to be mandatory, except for SAE level 5 vehicles. With lower automation levels, the driver will have to be prepared to react to any emergency. The type of load carried could also be relevant for the suitability or not of forming/joining a platoon in some specific cases (e.g. living beings against dangerous products, etc.) (Meisen et al., 2008).

Other details concerning the formation and split of platoons at the individual vehicle level are also under study. The fact that a vehicle joins a platoon, as well as when it leaves it, is not trivial. Getting these operations right is essential not only to maximize the benefits of platooning, but also to avoid traffic flow disturbances. In terms of merging, some authors advocate that a platoon should maintain its speed and the joining vehicle should accelerate to catch it. This is the so-called *catch-up strategy* (e.g. Liang et al., 2013; Ko, 2019). Other authors are in favor of a *slow-down strategy*, that is, a slight deceleration of the platoon to facilitate the merging of the vehicle that has announced its willingness to join it (e.g. Meisen et al., 2008; Ko, 2019). There are also intermediate solutions (e.g. Saeednia and Menéndez, 2016; Saeednia and Menéndez, 2017; Farag et al., 2019). Additionally, some authors assume that vehicles should join existing platoons at the back, and others consider the merging in the middle or at the front (e.g. Farag et al., 2019; Paranjothi et al., 2020).

Fewer studies address vehicles' leaving of the platoon. These often stress the importance of this maneuver to be announced in advance, especially to the immediate follower, which, among other things, will have to close the gap left by the departing vehicle (e.g. Maiti et al., 2017; Duret at al., 2019; Paranjothi et al., 2020). Again, a single tail split will have different consequences for the platoon's stability and efficiency than a single front split or a split from the middle, and each of them must be separately and deeply analyzed yet (Maiti et al., 2017). In any case, both the merging and the diverging possibilities will also depend on the vehicles' characteristics, especially the size (Maiti et al., 2017, Farag at al., 2019).

Apart from these different building/splitting strategies, any vehicle in a platoon follows a pre-established following policy during its journey. The three main policies considered so far are the *constant distance policy*, the *constant time distance policy* and the *nonlinear distance policy*. In the two first, followers drive respectively maintaining a fixed distance in space, either in terms of gaps or spacings (e.g. Gong and Du, 2018; Jia et al., 2019; Li et al., 2020) or in time, usually in terms of time headways, but also of time gaps (e.g. Dolk et al., 2017; Bian et al., 2019; Wang et al., 2020). These distances vary across the different studies, depending, among others, on vehicles' size and level of automation. Constant time headways between 0.6 and 1 s are quite common in the literature, whereas the variability in space distances is much broader. For example, Zhou et al. (2017) considered a spacing of 7 m for truck platooning, while Zheng et al. (2018) worked with 25 m for generic platoons.

The *nonlinear distance strategy* (e.g. Orosz, 2016) is usually implemented with the aim of improving platooning string stability and overall benefits, as it better accounts for the influence of the road characteristics (mainly of slopes) on the mechanical capabilities of vehicles, especially if they are heavy. Other less used following policies can be found in the literature, some of them more complicated and difficult to implement in practice, and others that, on the contrary, only impose minimum (but not maximum) space or time distances for the sake of safety (e.g. Zhou et al., 2017).

A few authors (e.g. Vukadinovic et al., 2018) have also addressed the definition of following policies for the leader with respect to other platoons or individual vehicles travelling ahead in the same lane.

3. PLATOONING EFFECTS ON TRAFFIC FLOW

Platooning is expected to have a first positive impact on traffic flow directly linked to the fact that vehicles drive maintaining short distances between them, i.e., occupying less space. This allows for a better use of road capacity (van Arem et al., 2006; Shladover et al, 2015; Nowakowski et al.,2015; Lioris et al., 2017). Further research is needed to quantify this improvement, which will in any case depend on the scenarios (penetration rate of CAVs, platoons' frequency and length, following policies, road characteristics, etc.). If these would be really positive, capacity could be doubled or tripled at intersections (Kockelman et al., 2016; Lioris et al., 2017) and even quintupled on freeway stretches (Kockelman et al., 2016; Sala and Soriguera, 2020). Mainly for heavy vehicles, which are normally a minor share of the flow with particular features, coordinated driving within a platoon could lead to an additional improvement for traffic flow as a result of an increase in traffic homogeneity (Nieuwenhuijze et al., 2012; Ramezani et al., 2018). In this context, travel time savings are also expected (Jo et al., 2019).

However, it is also claimed that too long platoons would increase traffic congestion if the capacity of a certain segment would be surpassed (Bhoopalam et al., 2018). Especially for the case of platoon formation under scheduled planning, this could be a consequence of too many vehicles driving the same route if no restrictions are set. An appropriate traffic assignment model could avoid these issues (Angelelli et al., 2016; Bhoopalam et al., 2018).

Platoons' length, especially depending on the driving lane, could cause other undesirable disturbances such as hindering or impeding the maneuverability of other vehicles wishing, for example, to change lanes or enter or leave a freeway (Nowakowski et al., 2015; Calvert et al., 2019). This could cause sudden accelerations or decelerations on their part, resulting in shockwaves and even in dangerous situations. Precisely because of their greater disruption to other vehicles, Calvert et al. (2019) claim that truck platooning should not be allowed in saturated traffic flow to avoid higher delay times in the overall network.

The mixed scenarios with CAVs sharing roads with HDVs will be particularly complex. Indeed, the interactions among these different vehicles and their consequences for both traffic performance and traffic safety are unclear no matter the cooperative driving mode of CAVs, but also widely researched (Razmi et al, 2020). For the specific case of platooning, even with a high penetration rate of CAVs (i.e. a favorable scenario for platoon formation), HDVs could, intentionally or not, interrupt them if no proper strategies are defined.

This would prevent making the most of platooning potential benefits for traffic flow and, again, generate risky situations. In this context, dedicated lanes for CAVs could minimize these interactions and, additionally, favor platoon formation (Kockelman et al., 2016; Talebpour et al., 2017; Lee et al., 2018; Razmi et al, 2020).

Moreover, higher speed limits could be allowed in these lanes without compromising safety and increasing traffic flow benefits (Ye and Yamamoto, 2018). Tsugawa et al. (2016) particularly addressed the use of dedicated lanes for truck platooning, observing a doubling of capacity, albeit under ideal conditions. However, dedicated lanes would only be reasonable for appreciable penetration rates of CAVs, depending the minimum required rate, among others, on the total number of lanes on the target roads. Traffic conditions would also play a role in this regard. Minimum penetration rates of CAVs between 15% (Yang et al., 2019) and 50% (Xiao et al., 2019) so that dedicated lanes are profitable can be found in the literature, which indicates that more research is needed. In fact, some negative consequences linked to dedicated lanes have already been detected and must be further analyzed. For example, a possible congestion increase in the non-dedicated lanes because of the non-cooperating vehicles having less capacity available (i.e., less lanes) and/or the formation of shockwaves because of abrupt lane changes linked to this vehicle distribution (Talebpour et al., 2017; Zhong, 2018; Xiao et al., 2019). Even when no so determining, permanent dedicated lanes would prevent HDVs from taking advantage of the capabilities of CAVs to reduce traffic instabilities for the whole flow (Ntousakis et al., 2015; Gueriau, 2016; Xiao et al., 2019; Amirgholy et al., 2020). Therefore, some researchers opt for dynamically dedicate lanes to platoons (or to CAVs in general) when appropriate (e.g. Chen et al., 2016, Zhong, 2018; Razmi et al., 2020). Most of them agree that their use should be optional, i.a. to prevent abrupt maneuvers of lane changing vehicles that could lead to shockwaves (Talebpour et al., 2017). The possibility of CAVs sharing these lanes with high occupancy vehicles (HOV) of any SAE level or that of allowing general HDVs to use these lanes after paying a toll have also been considered (Xiao et al., 2019; Liu and Song, 2019). Especially this last policy should be carefully implemented so that dedicated lanes are still worth reserving.

A summary of the mentioned findings is included in Table 2. As already indicated, string stability of platoons is beyond the scope of this work. However, it must be noted that it is a prerequisite not only for platooning to contribute to improved traffic flow, but also to ensure that its effect is not exactly the opposite (Ploeg et al., 2011; Nieuwenhuijze et al., 2012; Calvert et al., 2019).

SCENARIO	IMPACT (EX. REFERENCES)
Mixed environments	✓ Capacity increase (Kockelman et al., 2016; Lioris et al., 2017) ✓ Traffic stabilization & homogenization (Ramezani et al., 2018; Amirgholy et al., 2020)
	× Capacity overrun (Angelelli et al., 2016; Bhoopalam et al., 2018) × Disruptions (Nowakowski et al.,2015; Calvert et al., 2019)
Segregated lanes	✓ Capacity increase (Tsugawa et al. 2016; Lee et al., 2018) ✓ Free flow & high speeds (Ye and Yamamoto, 2018; Razmi et al, 2020)
	× Congestion in regular lanes (Zhong, 2018; Xiao et al., 2019) × Shock waves due to abrupt lane changes (Talebpour et al., 2017; Razmi et al, 2020)

Table 2. Main impacts of platooning on traffic flow (✓positive; × negative)

4. PLATOONING EFFECTS ON SAFETY AND HUMAN BEHAVIOR

There are two main points of view when addressing the relationship between platooning and road safety: focusing on the vehicles that form one particular platoon, or in terms of each platoon’s interactions with other single or platooned vehicles (Table 3). Some expected issues regarding the latter perspective have already been appointed, such as those linked to HDVs performing risky maneuvers to, for example, surpass a long platoon (Axelsson, 2017). However, there are more. In fact, driving simulator studies have shown that human drivers change their normal driving behavior when interacting with a platoon, even when this “interaction” is only its observation. The most common consequence is these drivers imitating the platoon intervehicle distances relative to other forward moving HDVs and/or accelerating to run parallel to platoons if their speeds are higher (Skottke et al., 2014; Razmi et al, 2020). Taking into account that humans have longer reaction times than CAVs and are more error-prone, dangerous situations and accidents related to this behavior are expected (Schakel, 2010; Yang et al., 2019). Nevertheless, their importance for the overall computation of the accident rate has yet to be quantified (Razmi et al, 2020).

The factors behind this behavioral change are not completely understood, but a few studies have shed some light on the topic. For example, trust in technology seems to play a role (Al Haddad, 2020; Zhao et al., 2020). In fact, the effect of trust has already been observed in studies addressing the acceptance and intention to use of different systems.

These studies also showed that trust is dynamic and evolves over time and with extended exposure to automation (Ghazizadeh et al., 2012). This may be the reason why previous experience with automated vehicle (AV)-like functions, such as adaptive cruise control (ACC) or cooperative adaptive cruise control (CAAC) systems, is often associated with greater relaxation/confidence and bolder behavior on the part of drivers interacting with platoons. Indeed, even in traditional environments, drivers tend to drive faster and in a more aggressive way (shorter gaps, more abrupt maneuvers, etc.) if their vehicles are equipped with these systems (Hoedemaeker and Brookhuis, 1998; Bianchi et al., 2014; Balk, 2016). Notwithstanding, CACC reduces drivers' stress and fatigue, which could mitigate the potential unfavorable consequences of this tendency (Stanton and Marsden, 1996). Going back to mixed environments, drivers of traditional vehicles are influenced differently depending on the period interacting with the platoon and on the platoon significance in terms of length or height. In this regard, the longer the time or the more significant the platoon (e.g. long truck platoons), the shorter their accepted distance to the vehicle ahead (Gouy et al., 2014; Yang et al., 2019). As mentioned, more research is needed to fully understand these interactions, both analyzing the aforementioned factors under different boundary conditions, and addressing other remaining questions such as the impact of drivers' gender, age, driving experience, physical and mental condition, etc.

CONTEXT	IMPACT (EX. REFERENCES)
Mixed environments	✓ More stability (Stanton and Marsden, 1996; Gueriau, 2016) ✓ Reduced human role (Nieuwenhuijze et al., 2012; Turri et al., 2017)
	× Risky interactions (Axelsson, 2017; Calvert et al., 2019) × Drivers' bolder behavior (Skottke et al., 2014; Razmi et al, 2020)
Safety within the platoon	✓ Coordination (Xu et al., 2013; Bhoopalam et al., 2018) ✓ Minimal human role (Axelsson, 2017; Rahman and Abdel-At 2018)
	× String instabilities (Axelsson, 2017; Feng et al., 2019) × Disengagement & takeover (Varotto et al., 2015; Favaro et al., 2019)

Table 3. Main impacts of platooning on safety (✓positive; × negative).

Within a platoon of CAVs, lower reaction times, vehicle coordination and an inferior role, if any, of the human factor are expected to reduce the number of rear-end collisions (Xu et al., 2013; Bhoopalam et al., 2018). This improvement has already been demonstrated by means of microscopic simulations.

For example, for a penetration rate of CAVs of 40%, Rahman and Abdel-At (2018) observed a significant reduction in the longitudinal crash risk along a dedicated lane for platoons (for CAVs in general), in which these followed a constant time headway policy of 0.6 s. However, side aspects such as those pointed out in section 3 (e.g. the effects of the disturbations caused by vehicles trying to change lanes) or the aforementioned possible changes in human drivers' behavior were neglected in the study. These authors also observed that safety conditions, albeit to a lesser extent, also improved with the presence of the same rate of CAVs with no vehicle segregation. Again, there is need for further studies considering, among others, different road geometries, different policies both for the platoon formation, split and driving and different overall traffic conditions. (Axelsson, 2017). Moreover, this must be done considering *homogeneous* and *heterogeneous* platoons separately, as specific formations accounting for vehicles' size, engine capabilities, etc. can also influence the consequences, for example, of an emergency braking (Bhoopalam et al., 2018). String instabilities, often linked to unsafe situations, must be specifically analyzed and addressed.

It must be borne in mind that the human factor cannot be disregarded within the CAV-platooning framework either. Unless platoons consist of SAE level 5 vehicles, drivers will continue to play a role, at least in emergency contexts. Depending on the vehicle level of automation, there will be certain situations that CAVs will not be able to handle. Thus, they will require drivers to resume the control of the driving task. Within a platoon, i.e., with short distances among vehicles and at relatively high driving speeds, both the drivers' reaction time and the quality of these reactions will be key to avoid multiple vehicle collisions. A study performed by Varotto et al., (2015) with ACC-equipped vehicles showed that drivers needed on average 3.85 s to resume control after sensor failure. Note that this could be a cause for disengagement of CAVs, also in platooning scenarios.

Eriksson and Stanton (2017) additionally observed that reaction times rose to 6.06 ± 2.39 s if drivers were performing a secondary task. Still not on platooning but with platooning-capable vehicles of SAE levels 2 or 3, studies analyzing real data collected in California found that their drivers' reaction times to take control of the vehicle after disengagement had a stable distribution at 0.83 s (Dixit et al., 2016). However, there were differences depending on the type of disengagement (the cause, if active or passive, etc.), the type of road and the previous number of miles travelled in these automated vehicles. Reaction times were found to increase with increased vehicle miles travelled, which was assumed to be related to a gradual increase in trust (Lv. at al., 2018). Simulation has also been used to assess disengagement and takeover in highly automated vehicles. Favaro et al. (2019) analyzed the reactions of 40 human drivers (50% male and 50% female) placed in 36 simulated autonomous technology disengagement scenarios. The study showed that vehicle speed significantly affected the takeover, much more than other factors as, for instance, the driver's age. A similar observation can be found in Zhang et al (2019).

In addition, they noticed that reactions were faster and more appropriate in very risky situations, if drivers had had previous similar takeover experiences and if they were not performing another visual task during the automated driving. Zeeb et al. (2016) also confirmed the role of distraction. For their part, Roche et al. (2020) found a link between drivers' stress level and takeover overreactions. If these same tendencies apply to the specific case of platooning and which their consequences would be taking into account platooning specific driving characteristics is still a research niche. As leaders play a special role in platoons, driver's reactions should be specifically analyzed for this position in the string.

5. ENVIRONMENTAL IMPACTS OF PLATOONING

Most authors agree that platooning will have positive effects from the environmental point of view. Indirectly, platooning is expected to contribute to the improvement of traffic flow and, therefore, to avoid the overconsumptions and harmful emission peaks linked to congestion. Directly, platooning lowers air drag (Wadud et al., 2016; Turri et al, 2017). As aerodynamic drag accounts, for example in highway driving, for 50%–75% of tractive energy requirements (Kasseris, 2016), platooning would allow reducing the average energy consumption and emissions when compared to those linked to single non-cooperative vehicles (Scora and Barth, 2006).

Focusing on platooning direct benefits, their relevance will depend on several factors.

Zabat et al. (1995) analyzed some of them using wind tunnel tests and numerical simulations to assess fuel savings for van platooning in different scenarios. These comprised, among other variables, different intervehicle distances and platoon lengths. The total savings range for all boundary conditions was between 10%-30%, but values between 20%–25% were the most frequent. Clearly, longer platoons achieve higher total savings (Zabat at al., 1995; Bhoopalam et al., 2018). Fuel economy also improves for smaller intervehicle spaces (Zabat at al., 1995; Zhang et al., 2020). Platooning speed, on the contrary, does not seem to play an important role in this regard (McAuliffe et al., 2018; Zhang et al., 2020).

For its part, the size of the platooned vehicles is determinant. Several studies have demonstrated that consumption-related benefits can be especially significant for truck platooning, particularly on highways (Patten et al., 2012; Silberg 2013; Nowakowski et al., 2015; Bhoopalam et al., 2018). As for lighter vehicles, intervehicle distances again have a strong influence. For example, Browand et al. (2004) observed in track tests with tandem trucks that fuel consumption savings reached 11% when these distances were of 3-4 m, but descended to 8% for distances between 8-10 m. Humphreys et al. (2016) perceived this tendency using simulation. Masses and loads limit savings, but their influence is weaker (Lammert et al., 2014, Zhang et al, 2020).

However, for any specific vehicle size, namely for heavy vehicles, individual reductions in energy consumption significantly differ depending on their position within the platoon, consistently with the physical concept of air drag. Indeed, after intervehicle spaces, position is the variable with the greater impact (Zhang et al, 2020). In track tests, leaders were found to save 2.7% to 5.3% of the average fuel needs, while followers increased these figures to 2.8-9.7% (Lammert et al, 2014). Although the exact percentages for savings/consumptions depend on many other boundary conditions, the role of position can be unambiguously observed. For instance, Lu and Shladover (2011) reported, for a test performed with a 3-truck platoon on a real road, reductions in fuel consumption of 18% and 23-24%, respectively for the leader and the followers. Computational fluid dynamics are also often used to assess air drag reduction and, subsequently, consumption savings.

Using this method, Davila et al. (2013) observed that benefits for the followers were double those for the leader. Taking into account the influence of position, some authors have proposed different strategies to proportionally divide the total savings achieved by the whole platoon during a common trip among all members of the string. This distribution is especially suitable for the case of truck platooning under scheduled planning (Bhoopalam et al., 2018). In fact, without a solution to balance out these unequal gains, effective platoon formation would probably be undermined, as no company would want their trucks to be leaders. On the contrary, a good coordination among companies could result in benefits for all and, thus, promote platooning (Zhang et al, 2020).

SCENARIO	IMPACT (EX. REFERENCES)
All (stronger impacts for automated heavy vehicles & uninterrupted traffic)	✓ Reduced energy/fuel consumptions linked to reduced air drag (Lu and Shladover, 2011; Turri et al., 2017) ✓ Reduced energy/fuel consumptions linked to traffic flow improvements (Alam et al., 2015; Bhoopalam et al., 2018) ✓ Lower emissions linked to lower consumptions (Scora and Barth, 2006; Wadud et al., 2016)
	✗ Improvements dependent on many variables (Zabat at al., 1995; Zhang et al., 2020) ✗ Unequal distribution of savings in the platoon (Davila et al., 2013; Lammert et al, 2014)

Table 4. Main environmental impacts of platooning (✓positive; ✗ negative).

Table 4 summarizes the preceding findings. It must be noted that most of the aforementioned studies have been performed using vehicles with a low-medium level of automation and petrol or diesel engines. Higher energy savings are expected when vehicles are fully automated and electric.

On the one hand, SAE level 5 vehicles will allow for smaller intervehicle spacings and squeeze eco-driving modes. Indeed, Stephens et al., (2016) predict consumption savings to reach, at least 25%, for highway car platooning during non-peak hours. Higher percentages would apply for truck platooning. On the other hand, Alam et al. (2015) have demonstrated that energy savings while platooning are higher than fuel consumption savings, and internal losses are expected to be negligible for electric engines. Other factors such as not needing to implement significant rest periods for drivers will also allow optimizing consumptions (Zhang et al, 2020). Nevertheless, additionally *ad hoc* strategies such as cooperative look-ahead control could help to achieve extra savings in fuel and energy consumption until highly automated vehicles hit the road (Alam et al., 2015).

6. CONCLUSIONS AND REMAINING CHALLENGES

The development of automated and connected transport will offer users new forms of mobility that are more pleasant and comfortable, in which travel times can be used to perform other activities. It will also allow for an increase in the competitiveness of companies associated with the expected reduction in transportation costs and route optimization, among others (Martínez-Díaz et al, 2018). However, the main objective of future mobility is to put an end to current transport problems, i.e. congestion, accidents and environmental damage. The performed analysis confirms that platooning is one of the forms of cooperative driving with the greatest potential in this respect.

First, the frequent formation of medium length platoons could lead to an increase in road capacity due to the small intervehicular distances maintained. In addition, string-stable platoons could accentuate the proven ability of cooperating vehicles to reduce traffic instabilities and, thus, to improve traffic flow. This latter improvement over traditional driving would be even more noticeable when heavy vehicles are involved. Second, coordination within vehicles and, thus, the avoidance of abrupt maneuvers carried out on an individual basis, would also lead to an enhanced safety. This improvement would become more noticeable as the penetration rate of vehicles with a high degree of automation increases, in parallel with the decrease in the weight of the human factor.

Third, platooning would involve a reduction in energy and fuel consumption while driving, which would also result in a drop of harmful emissions. These improvements are mainly linked to lower air drag for the followers and would be particularly advantageous in the case of truck platooning. In addition, there are also environmental benefits linked to the aforementioned improvement of traffic conditions.

Notwithstanding, in order to fully reap these benefits and to avoid potential unwanted effects of platooning, studies must consider increasingly realistic (and thus complex) contexts. Although more gaps exist, research on the following issues is especially required (Figure 3):

- *General IFT*. Most research on platooning (including research on string stability) assumes one or several specific IFTs. Therefore, their results are associated with these particular configurations. Such fixed schemes could be imposed in certain circumstances, e.g. scheduled platooning in logistics. However, it is expected (and desirable) that future platoon formation will be dynamic and highly volatile. I.e. vehicles may join or leave the platoon quite fluently. There is need for more general platooning strategies reliable for all possible IFTs.
- *Heterogeneous platoons*. As indicated, only a few studies consider the possibility of vehicles of different sizes and/or automation capabilities conforming a platoon. Indeed, their feasibility has yet to be determined. If suitable strategies could be derived, platoons would form more frequently and, consequently, their potential benefits could be better exploited.
- *Mixed environments*. Although already addressed, the large number of possible scenarios makes it necessary to dive deeper into this topic. The simultaneous presence of platoons and single vehicles on the same road should be analyzed comprising all vehicles' degree of automation, size and mechanical characteristics, road features (e.g. number of lanes, longitudinal profile), general traffic management strategies set (e.g. variable speed limits, lane change restrictions, dedicated lanes), weather conditions, etc. Platoons' actual impacts will ultimately depend on their interactions among them and with other vehicles.

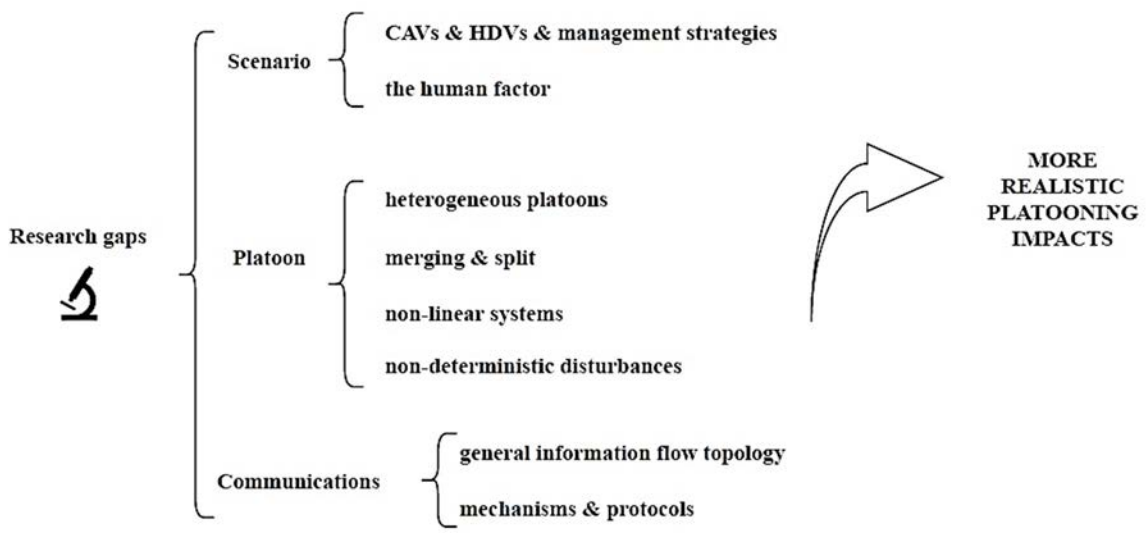

Figure 3. Key research gaps on platooning (own elaboration).

- *The human factor*. Especially for safety reasons, drivers /passengers' behavior in the aforementioned mixed environments, both within and out of platoons, must be further examined. This analysis should cover people's expected role, highly linked to vehicles' automation level, but also users' particular features, both identifying (e.g. age) and circumstantial (e.g. fatigue level).

- *Communication mechanisms and quality*. It is key to determine the information type (i.e. variables), quantity (i.e. how many agents it comes from, including infrastructure) and frequency (i.e. how often it is updated) that needs to be exchanged among vehicles in order for a platoon to circulate efficiently and safely. Given platoons' dynamic nature, this exchange is a challenge in itself. However, there are additional problems, such as the limited capacities of communication networks. Research must account for the possibility that these become congested, resulting in delays in the reception of information and/or in some data not reaching the intended recipients. In addition, a balance must be struck among interoperability, privacy protection and the prevention of cyber-attacks.
- *Non-linear platooning systems and non-deterministic system disturbances*. Most studies, also those focusing on string stability, consider vehicle dynamics within the platoon to be linear either *per se* or by the introduction of linearization techniques. In addition, stochastic external disturbances that can affect the platoon are usually disregarded. Both assumptions allow simplifying the analyses, but also affect any derived results, as none of them matches reality.

As mentioned, more questions remain in topics as diverse as platoons' string stability, above all the lateral, platooning planning and routing in logistics, or network design accounting for platooning, among others. The authors would like that this overview encourages new research contributions on this promising form of cooperative driving.

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REFERENCES

AL HADDAD, C., CHANIOTAKIS, E., STRAUBINGER, A., PLÖTNER, K. and ANTONIOU, C. (2020). Factors affecting the adoption and use of urban air mobility. Transportation Research Part A: Policy and Practice, 132, 696-712,

ALAM, A., BESSELINK, B., TURRI, V., MÅRTENSSON, J. and JOHANSSON, K.H. (2015). Heavy-Duty Vehicle Platooning for Sustainable Freight Transportation: A Cooperative Method to Enhance Safety and Efficiency. IEEE Control Systems Magazine, 35(6), pp. 34-56.

AMIRGHOLY, M., SHAHABI, M. and GAO, H. O. (2020). Traffic automation and lane management for communicant, autonomous, and human-driven vehicles. Transportation Research Part C: Emerging Technologies, 111, pp. 477–495.

ANGELELLI, E., ARSIL, I., MORANDI, V., SAVELSBERGH, M. and SPERANZA, M.G. (2016). Proactive route guidance to avoid congestion. Transportation Research Part B: Methodological, 94, pp., 1–21.

AXELSSON, J. (2017). Safety in Vehicle Platooning: A Systematic Literature Review. IEEE Transactions on Intelligent Transportation Systems, 18(5), pp. 1033-1045.

BALK, S.A., JACKSON, S. and PHILIPS, B.H. Cooperative Adaptive Cruise Control Human Factors Study: Experiment 2-Merging Behavior. FHWA report 16057, 2016.

BERGENHEM, C., SHLADOVER, S. and COELINGH, E. Overview of platooning systems. Proceedings of the 19th ITS World Congress, 22-26 October 2012, Vienna, Austria.

BIAN, Y., ZHENG, Y., REN, W., LI, S.E., WANG, J. and LI, K. (2019). Reducing time headway for platooning of connected vehicles via V2V communication, Transportation Research Part C: Emerging Technologies, 102, pp. 87-105.

BIANCHI, G.F., RODRIGUES, C.M., LEITÃO, M. and SIMÕES, A. (2014). Driver's behavioral adaptation to Adaptive Cruise Control (ACC): The case of speed and time headway. Journal of Safety Research, 49, pp. 77.e1-84.

BHOOPALAM, A. K, AGATZ, N. and ZUIDWIJK, R. (2018). Planning of truck platoons: A literature review and directions for future research. Transportation Research Part B: Methodological, 107, pp. 212-228.

BROWAND, F., MCARTHUR, J. and RADOVICH, C. Fuel Saving Achieved in the Field Test of Two tandem Trucks, University of California, Berkeley, Berkeley, CA, USA, 2004

CALVERT, S.C., SCHAKEL, W.J. and VAN AREM, B. (2019). Evaluation and modelling of the traffic flow effects of truck platooning, Transportation Research Part C: Emerging Technologies, 105, pp. 1-22,

CHEN, Z., HE, F., ZHANG, L. and YIN, Y. (2016). Optimal deployment of autonomous vehicle lanes with endogenous market penetration. Transportation Research Part C: Emerging Technologies, 72, pp. 143–156.

DAVILA, A., ARAMBURU, E. and FREIXAS, A. Making the best out of aerodynamics: platoons. Proceedings of the SAE Technical Paper Series, USA, 2013.

DIXIT, V., CHAND, S. and NAIR, D. (2016) Autonomous Vehicles: Disengagements, Accidents and Reaction Times. Plos One, 11(12), e0168054.

DOLK, V. S., PLOEG, J. and HEEMELS, W. P. M. H. (2017). Event-Triggered Control for String-Stable Vehicle Platooning. IEEE Transactions on Intelligent Transportation Systems, 18(12), pp. 3486-3500.

DURET, A., WANG, M. and LADINO, A. (2019). A hierarchical approach for splitting truck platoons near network discontinuities. Transportation Research Procedia, 38, pp. 627-646.

ECKHARDT, J., AARTS, L., VAN VLIET, A. and ALKIM, T. (2016). European truck platooning challenge 2016. Lessons learned. Storybook, The Hague.

ERIKSSON, A. and STANTON, N.A. (2017). Takeover time in highly automated vehicles: noncritical transitions to and from manual control. Human Factors, 59, pp. 689–705.

European Road Transport Research Advisory Council. Automated Driving Roadmap. (2015). In: https://www.ertrac.org/uploads/documentsearch/id38/ERTRAC_Automated-Driving-2015.pdf, Accessed on 5th April 2021.

FAGNANT, D. J. and KOCKELMAN, K. M. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations for capitalizing on Self-Driven vehicles. Transportation Research Part A: Policy and Practice, 77, 1– 20.

FARAG, A., MAHFOUZ, D. M., SHEHATA, O. M. and MORGAN, E. I. A Novel ROS-Based Joining and Leaving Protocols for Platoon Management. 2019 IEEE International Conference on Vehicular Electronics and Safety (ICVES), 4-6 September 2019, Cairo, Egypt.

FAVARO, F. et al. Analysis of Disengagements in Semi-Autonomous Vehicles: Drivers' Takeover Performance and Operational Implications. Mineta Transportation Institute, San José State University. Project Report 1710, 2019.

FENG, S., ZHANG, Y., LI, S.E., CAO, Z., LIU, H.X. and LI, L. (2019). String stability for vehicular platoon control: Definitions and analysis methods. Annual Reviews in Control, 47, pp. 81-97.

GHAZIZADEH M, PENG Y, LEE JD and BOYLE LN (2012). Augmenting the Technology Acceptance Model with Trust: Commercial Drivers' Attitudes towards Monitoring and Feedback. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 56(1), pp.2286-2290.

GOEL, A. (2010). Truck driver scheduling in the European Union. Transportation Science, 44(4), pp. 429–441.

GOEL, A. (2014). Hours of service regulation in the United States and the 2013 rule change. Transportation Policy, 33, pp. 48–55.

GONG S., ZHOU A. and PEETA S. (2019). Cooperative Adaptive Cruise Control for a Platoon of Connected and Autonomous Vehicles considering Dynamic Information Flow Topology. Transportation Research Record, 2673(10), pp. 185-198.

GONG, S. and DU, L. (2018). Cooperative platoon control for a mixed traffic flow including human drive vehicles and connected and autonomous vehicles. Transportation Research Part B: Methodological, 116, pp. 25-61.

GOUY, M., WIEDEMANN, K., STEVENS, A., BRUNETT, G. and REED, N. (2014). Driving next to automated vehicle platoons: How do short time headways influence non-platoon drivers' longitudinal control? Transportation Research Part F: Traffic Psychology and Behaviour, 27(B), 264-273.

GUÉRIAU, M., BILLOT, R., EL FAOUZI, N.-E., MONTEIL, J., ARMETTA, F., and HASSAS, S. (2016). How to assess the benefits of connected vehicles? A simulation framework for the design of cooperative traffic management strategies. Transportation Research Part C: Emerging Technologies, 67, 266–279.

HOEDEMAEKER, M. and BROOKHUIS, K.A. (1998). Behavioural adaptation to driving with an adaptive cruise control (ACC).? Transportation Research Part F: Traffic Psychology and Behaviour, 1, pp. 95–106.

HUMPHREYS, H. L., BATTERSON, J., BEVLY, D. and SCHUBERT, R. An evaluation of the fuel economy benefits of a driver assistive truck platooning prototype using simulation. Proceedings of the SAE Technical Paper Series, 2016.

JANSSEN, R., ZWIJNENBERG, H., BLANKERS, I. and DE KRUIJFF, J. Truck platooning; driving the future of transportation - TNO whitepaper, 2015.

JIA, D., NGODUY, D. and VU, H.L. (2019) A multiclass microscopic model for heterogeneous platoon with vehicle-to-vehicle communication, Transportmetrica B: Transport Dynamics, 7(1), pp. 311-335.

JO, Y., KIM, J., OH, C., KIM, I. and LEE, G. (2019). Benefits of travel time savings by truck platooning in Korean freeway networks. Transport Policy, 83, pp. 37-45.

KASSERIS, E.P. Comparative Analysis of Automotive Powertrain Choices for the Near to Mid-term Future. Master's Thesis, Massachusetts Institute of Technology, 2006.

KNOOP V.L., WANG M., WILMINK I., HOEDEMAEKER, D.M., MAASKANT, M. and VAN DER MEER, E-J. (2019). Platoon of SAE Level-2 Automated Vehicles on Public Roads: Setup, Traffic Interactions, and Stability. Transportation Research Record, 2673(9), pp. 311-322.

KO, Y.D., SONG B.D. and OH Y. (2019). Mathematical Analysis of Environmental Effects of Forming a Platoon of Smart Vehicles. Sustainability, 11(3), 571.

KOCKELMAN, K., AVERY, P., BANSAL, P., BOYLES, S.D., et al. Implications of Connected and Automated Vehicles on the Safety and Operations of Roadway Networks: A Final Report. Fhwa/Tx-16/0-6849-1 7, 2016.

KONSTANTINOPOULOU, L., CODA, A. and SCHMIDT, F. Specifications for Multi-Brand Truck Platooning. 8th International Conference on Weigh-In-Motion, 19-23 May 2019, Prague, Czech Republic.

KUHN, B., LUKUC, M., POORSARTEP, M. et al. (2017). Commercial truck platooning demonstration in texas – level 2 automation. Technical Report 0-6836-1 of the Texas Department of Transportation, 2017.

LAMMERT, M. P., DURAN, A., DIEZ, J., BURTON, K. and NICHOLSON, A. (2014). Effect of platooning on fuel consumption of Class 8 vehicles over a range of speeds, following distances, and mass. SAE International Journal of Commercial Vehicles, 7(2), pp. 626–639.

LEE, S., OH, C. and HONG, S. (2018). Exploring lane change safety issues for manually driven vehicles in vehicle platooning environments. IET Intelligent Transport Systems, 12, pp. 1142–1147.

LI, Y., CHEN, W., PEETA, S. and WANG, Y. (2020). Platoon Control of Connected Multi-Vehicle Systems Under V2X Communications: Design and Experiments. IEEE Transactions on Intelligent Transportation Systems, 21(5), pp. 1891-1902.

LIANG, K.-Y., MÅRTENSSON, J. and JOHANSSON, K. H. When Is It Fuel Efficient for a Heavy Duty Vehicle to Catch Up with a Platoon? Proceedings of the 7th IFAC Symposium on Advances in Automotive Control, 4-7 September 2013, Tokio.

LIANG, KY., MÅRTENSSON, J. and JOHANSSON, K.H. Fuel-saving potentials of platooning evaluated through sparse heavy-duty vehicle position data. 2014 IEEE Intelligent Vehicles Symposium (IV), 8-11 June 2014, Michigan, USA.

LIORIS, J., PEDARSANI, R., TASCIKARAOGLU, F.Y. and VARAIYA, P. (2017). Platoons of connected vehicles can double throughput in urban roads. Transportation Research Part C: Emerging Technologies, 77, pp. 292–305.

LIU, Z. and SONG, Z. (2019). Strategic planning of dedicated autonomous vehicle lanes and autonomous vehicle/toll lanes in transportation networks. Transportation Research Part C: Emerging Technologies, 106, pp. 381–403.

LU, X.-Y. AND SHLADOVER, S.E. Automated truck platoon control. UCB-ITSPRR-2011-13, UC Berkeley: California Partners for Advanced Transportation Technology, Berkeley, CA, USA, 2011.

LV, C., Cao, D., Zhao, Y. et al. (2016). Analysis of autopilot disengagements occurring during autonomous vehicle testing. IEEE/CAA Journal of Automatica Sinica, 5(1), pp. 58-68.

MAITI, S., WINTER, S. and KULIK, L. (2017). A conceptualization of vehicle platoons and platoon operations. Transportation Research Part C: Emerging Technologies, 80, pp. 1-19.

MARTÍNEZ-DÍAZ, M., SORIGUERA, F. and PÉREZ, I. (2019). Autonomous driving: A bird´s eye view. IET Intelligent Transport Systems, 13(4), pp. 563-579.

MCAULIFFE, B., LAMMERT, M., LU, X.-Y., SHLADOVER, S.E., SURCEL, M.-D. and KAILAS, A. Influences on energy savings of heavy trucks using cooperative adaptive cruise control. Proceedings of the SAE Technical Paper Series, 2018.

MEISEN, P., HENNING, K. and SEIDL, T. A Data-Mining Technique for the Planning and Organization of Truck Platoons. Proceedings of the International Conference on Heavy Vehicles, 19–22 May 2008, Paris, pp. 389–402.

NIEUWENHUIJZE, M.R.I, VAN KEULEN, T., ÖNCÜ, S., BONSEN, B. and NIJMEIJER, H. (2012). Cooperative driving with a heavy-duty truck in mixed traffic: Experimental results. IEEE Transactions on Intelligent Transportation Systems, 13, pp. 1026–1032.

NOWAKOWSKI, C., SHLADOVER, S.E., LU, X.-Y., THOMPSON, D. and KAILAS, A. Cooperative Adaptive Cruise Control (CACC) for Truck Platooning: Operational Concept Alternatives. Tech. Rep. California Partners for Advanced Transportation Technology, UC Berkeley, 2015.

NTOUSAKIS, I. A., NIKOLOS, I. K., and PAPAGEORGIOU, M. (2015). On Microscopic Modelling of Adaptive Cruise Control Systems. Transportation Research Procedia, 6, pp. 111–127.

OROSZ, G. (2016). Connected cruise control: modelling, delay effects, and nonlinear behaviour. Vehicle Systems Dynamics, 54 (8), pp. 1147-1176

PARANJOTHI, A, ATIQUZZAMAN, M, and KHAN M.S. (2020). PMCD: Platoon - Merging approach for cooperative driving. Internet Technology Letters, 3:e139.

PATTEN, J., MCAUCLIFFE, B., MAYDA, W. and TANGUAY, B. Review of Aerodynamic Drag Reduction Devices for Heavy Trucks and Buses. Technical Report. National Research Council Canada, 2012. .

PLOEG, J., SCHEEPERS, E., VAN NUNEN, N. VAN DE WOU, W. and NIJMEIJER, H. Design and Experimental Evaluation of Cooperative Adaptive Cruise Control. Proceedings of the 14th International IEEE Conference on Intelligent Transportation Systems (ITSC 2011), 5–7 October 2011, Washington D.C., USA. pp. 260-265.

RAHMAN, M.S. and ABDEL-ATY, M. (2018). Longitudinal safety evaluation of connected vehicles’ platooning on expressways. Accident Analysis & Prevention, 117, pp. 381–391.

RAMEZANI, H., SHLADOVER, S. E., LU, X. and ALTAN, O. (2018). Micro-Simulation of Truck Platooning with Cooperative Adaptive Cruise Control: Model Development and a Case Study. Transportation Research Record, 2672(19), pp. 55-65.

RAZMI, S., FARAH, H. TAALE, H., VAN AREM, B. and HOOGENDOORN, S.P. (2020). Design and operation of dedicated lanes for connected and automated vehicles on motorways: A conceptual framework and research agenda. Transportation Research Part C: Emerging Technologies, 117, 102664.

ROCHE, F. THÜRING, M. and TRUKENBROD, A.K. (2020) What happens when drivers of automated vehicles take over control in critical brake situations? Accident Analysis & Prevention, 144, 105588.

SAE J3016A:SEP2016. Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles. Society of Automotive Engineers, 2016.

SAEEDNIA, M. and MENÉNDEZ, M. (2016). Analysis of Strategies for Truck Platooning. Hybrid Strategy. Transportation Research Record: Journal of the Transportation Research Board, 2547, pp. 41-48.

SAEEDNIA, M. and MENÉNDEZ, M. (2017). A Consensus-Based Algorithm for Truck Platooning. IEEE Transactions on Intelligent Transportation Systems, 18(2), pp. 404-415.

SALA, M. and SORIGUERA, F. (2020). Macroscopic modeling of freeway platooning under mixed traffic conditions. Transportation Research Procedia, 47, pp. 163–170.

SCHAKEL, W.J., VAN AREM, B. and NETTEN, B.D. Effects of cooperative adaptive cruise control on traffic flow stability. IEEE Conference on Intelligent Transportation Systems, Proceedings ITSC, 759-764, 19-22 September 2010, Madeira, Portugal.

SCORA, G. and BARTH, M. Comprehensive Modal Emissions Model (CMEM), Version 3.01. Centre for Environmental Research and Technology. University of California, Riverside. User guide, 2006.

SHLADOVER, S.E., NOWAKOWSKI, C., LU, X.-Y. and FELIS, R. (2015). Cooperative adaptive cruise control (CACC) definitions and operating concepts. Transportation Research Record: Journal of the Transportation Research Board, 2489(1), pp. 145–152.

SILBERG, G., MANASSA, M., EVERHART, K. et al. Self-driving Cars: Are We Ready, KPMG LLP, 2013.

SKOTTKE, E.M., DEBUS, G., WANG, L. and HUESTEGGE, L. (2014). Carryover effects of highly automated convoy driving on subsequent manual driving performance. Human Factors, 56, pp. 1272–1283.

SONG, M., CHEN, F. and MA, X. (2021). Organization of autonomous truck platoon considering energy saving and pavement fatigue. Transportation Research Part D: Transport and Environment, 90, 102667.

STANTON, NA and MARSDEN, P. (1996). From fly-by-wire to drive-by-wire: Safety implications of automation in vehicles. Safety Science, 24(1), pp. 35–49.

STEPHENS, T., GONDER, J., CHEN, Y., LIN, Z., LIU, C. and GOHLKE, D. Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles; National Renewable Energy Laboratory: Golden, CO, 2016.

SUN, X. and YIN, T. (2019). Behaviorally stable vehicle platooning for energy savings. Transportation Research Part C: Emerging Technologies, 99, pp. 37-52,

TALEBPOUR, A., MAHMASSANI, H.S. and ELFAR, A. (2017). Investigating the effects of reserved lanes for autonomous vehicles on congestion and travel time reliability. Transportation Research Record: Journal of the Transportation Research Board, 2622, pp. 1–12.

TSUGAWA, S., SABINA, J. and SHLADOVER, S.E (2016). A review of truck platooning projects for energy savings. IEEE Transactions on Intelligent Vehicles, 1, pp. 68–77

TURRI, V., BESSELINK, B. and JOHANSSON, K. H. (2017). Cooperative look-ahead control for fuel-efficient and safe heavy-duty vehicle platooning. IEEE Transactions on Control Systems Technology, 25, 1, pp. 12–28.

VAN AREM, B., VAN DRIEL, C.J. and VISSER, R. (2006). The impact of cooperative adaptive cruise control on traffic-flow characteristics. IEEE Transactions on Intelligent Transportation Systems, 7 (4), pp. 429–436.

VAROTTO, S.F., HOOGENDOORN, R.G., VAN AREM, B. and HOOGENDOORN, S.P. (2015). Empirical longitudinal driving behavior in authority transitions between adaptive cruise control and manual driving. Transportation Research Record: Journal of the Transportation Research Board, 2489, 105–114.

VUKADINOVIC, V., BAKOWSKI, K., MARSCH, P., GARCIA, I.D., XU, H., SYBIS, M. et al. (2018) 3GPP C-V2X and IEEE 802.11p for Vehicle-to-Vehicle communications in highway platooning scenarios. Ad Hoc Networks, 74, pp. 17-29,

WADUD, Z., MACKENZIE, D. and LEIBY, P. (2016) Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. Transportation Research Part A: Policy and Practice, 86, pp. 1-18.

WANG, C., GONG, S., ZHOU, A., LI, T. and PEETA, S. (2020). Cooperative adaptive cruise control for connected autonomous vehicles by factoring communication-related constraints. Transportation Research Part C: Emerging Technologies, 113, pp. 124-145.

WEILAND, R.J. and PURSER, L.B. (2000). Intelligent Transportation Systems. In: Transportation in the New Millennium: State of the Art and Future Directions, Perspectives from Transportation Research Board Standing Committees. Washington, D.C.: Transportation Research Board, 2000.

XIAO, L., WANG, M. and VAN AREM, B. (2019). Traffic flow impacts of converting an HOV lane into a dedicated CACC lane on a freeway corridor. IEEE Intelligent Transportation Systems Magazin, 12, 60–73.

XU, L., WANG, L.Y., YIN, G. and ZHANG, H. Coordinated control and communication for enhanced safety of highway vehicle platoons. International Conference on Connected Vehicles and Expo (ICCVE), pp. 43-47, 2-6 December 2013, Las Vegas, NV, USA.

YANG, D., FARAH, H., SCHOENMAKERS, M., and ALKIM, T. Human drivers behavioural adaptation when driving next to a platoon of automated vehicles on a dedicated lane and implications on traffic flow: a driving simulator and microscopic simulation study in the Netherlands. Proceedings 98th Annual Meeting of the Transportation Research Board, 12-16 January 2019, Washington DC, USA.

YE, L. and YAMAMOTO, T. (2018). Impact of dedicated lanes for connected and autonomous vehicle on traffic flow throughput. Physica A: Statistical Mechanics and its Applications, 512, pp. 588–597.

ZEEB, K., BUCHNER, A. and SCHRAUF, M. (2016). Is take-over time all that matters? The impact of visual-cognitive load on driver take-over quality after conditionally automated driving. Accident Analysis & Prevention, 92, 230-239.

ZHANG, B., WINTER, J., VAROTTO, S. et al. (2019). Determinants of take-over time from automated driving: A meta-analysis of 129 studies. Transportation Research Part F: Traffic Psychology and Behaviour, 64, 285-307.

ZHANG, L., CHEN, F., MA, X. and PAN, X. (2020). Fuel Economy in Truck Platooning: A Literature Overview and Directions for Future Research. Journal of Advanced Transportation, 2020, 2604012.

ZHAO, X., WANG, Z., XU, Z., WANG, Y., LI, X. and QU, X. (2020). Field experiments on longitudinal characteristics of human driver behavior following an autonomous vehicle. Transportation Research Part C: Emerging Technologies, 114, pp. 205–224.

ZHENG, Y., LI, S.E., LI, K. and REN, W. (2018). Platooning of Connected Vehicles With Undirected Topologies: Robustness Analysis and Distributed H-infinity Controller Synthesis. IEEE Transactions on Intelligent Transportation Systems, 19(5), pp. 1353-1364.

ZHENG, Y., LI, S., WANG, J., CAO, D. and LI, K. (2016). Stability and Scalability of Homogeneous Vehicular Platoon: Study on the Influence of Information Flow Topologies. IEEE Transactions on Intelligent Transportation Systems, 17(1), pp. 14-26.

ZHONG, Z. Assessing the Effectiveness of Managed Lane Strategies for the Rapid Deployment of Cooperative Adaptive Cruise Control Technology, NJIT, 2018.

ZHOU, F., LI, X. and MA, J. (2017). Parsimonious shooting heuristic for trajectory design of connected automated traffic part I: Theoretical analysis with generalized time geography. Transportation Research Part B: Methodological, 95, pp. 394-420,

ZHOU, J. and ZHU, F. (2021). Analytical analysis of the effect of maximum platoon size of connected and automated vehicles. Transportation Research Part C: Emerging Technologies, 122, 102882.

ZABAT, M., STABILE, N., FRASCAROLI, S. and BROWAND, F. The Aerodynamic Performance of Platoons: Final Report. Technical Report. California PATH project, University of California Berkeley, 1995.