Transportation Research Interdisciplinary Perspectives 10 (2021) 100381

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.elsevier.com/locate/trip

Safety and experience of other drivers while interacting with automated vehicle platoons

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ARTICLE INFO

Keywords:
Automated vehicle platoon
Cut-in
Merging
Highway on-ramp
Interaction
User experience
Perceived safety
eHMI

ABSTRACT

It is currently unknown how automated vehicle platoons will be perceived by other road users in their vicinity. This study explores how drivers of manually operated passenger cars interact with automated passenger car platoons while merging onto a highway, and how different inter-vehicular gaps between the platooning vehicles affect their experience and safety. The study was conducted in a driving simulator and involved 16 drivers of manually operated cars. Our results show that the drivers found the interactions mentally demanding, unsafe, and uncomfortable. They commonly expected that the platoon would adapt its behavior to accommodate a smooth merge. They also expressed a need for additional information about the platoon to easier anticipate its behavior and avoid cutting-in. This was, however, affected by the gap size; larger gaps (30 and 42.5 m) yielded better experience, more frequent cut-ins, and less crashes than the shorter gaps (15 and 22.5 m). A conclusion is that a short gap as well as external human–machine interfaces (eHMI) might be used to communicate the platoon's intent to "stay together", which in turn might prevent drivers from cutting-in. On the contrary, if the goal is to facilitate frequent, safe, and pleasant cut-ins, gaps larger than 22.5 m may be suitable. To thoroughly inform such design trade-offs, we urge for more research on this topic.

1. Introduction

Platooning is a Cooperative Intelligent Transportation System (C-ITS) application that enables automated vehicles to drive close together with short inter-vehicular distances, or gaps, in road trains (i.e. automated vehicle platoons). Expectations are that this will improve traffic efficiency and safety. With the use of wireless Vehicle-to-Vehicle (V2V) communication, vehicles in the platoon connect to each other and share information such as their speed and acceleration. This makes it possible to control vehicles in a platoon safely by synchronizing their maneuvers via V2V, which is quicker than relying on each vehicle's on-board sensors (Shladover et al., 2015; Bergenhem et al., 2012; Englund et al., 2016; Ploeg et al., 2016). For instance, using solely radar sensors for controlling the distance between the vehicles introduces a delay in reaction time, due to the processing time of the radar signals. And, a vehicle could only react when the preceding vehicle has reacted. Consequently, the longer the platoon the longer the delay between the time when the first vehicle brakes and the last vehicle detects it. With V2V communication, the information delay between the front vehicle and the back vehicle is eliminated. It also allows higher utilization of road space, since the vehicles are allowed to drive with shorter inter-vehicular gaps. Additionally, short gaps lower air resistance, leading to lower energy consumption (Liang et al., 2014).

From a technical perspective, automated platooning has been studied thoroughly in several projects such as SARTRE (Robinson et al., 2010), COMPANION (Eilers et al., 2015), Energy ITS (Sugimachi et al., 2013), KONVOI (Keßler et al., 2006), PATH (Shladover, 2007), CHAUFFEUR (Gehring and Fritz, 1997, Grand Cooperative Driving Challenges (Englund et al., 2016), and the European Truck Platooning Challenge (ETPC) (van Nunen et al., 2016). However, from a socio-technical perspective there is a lack of knowledge on how drivers of other vehicles in the vicinity will perceive platooning (Eilers et al., 2015; Fusco et al., 2016). Therefore, in this study, we aim to investigate the social acceptance of platoons from the perspective of drivers in vehicles outside the platoons. Theoretical studies on acceptance of automated vehicle technologies highlight that acceptance of such technologies will be affected by how other road users perceive

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https://doi.org/10.1016/j.trip.2021.100381

and experience them (Kyriakidis et al., 2015; Ward et al., 2017)—indicating that there is a need to further study prerequisites for a smooth introduction of vehicle platoons into society.

The aim of this study was to create an initial knowledge-base on how drivers of manually operated cars interact with automated car platoons on highways, and how different inter-vehicular gaps between the platooning vehicles affect the frequency of cut-ins by other drivers and crashes. The study also captures drivers' experience in terms of perceived safety, comfort, and merging ease. An additional aim was to investigate if drivers might need support in interactions with automated platoons, and whether human–machine interaction (HMI) means could facilitate safe, seamless, and pleasant engagement. For instance, this could be in the form of an external HMI (eHMI) on the platooning vehicles that conveys certain information about the platoon to drivers in its vicinity. More specifically, the study addressed the following research questions:

- How do manual car drivers experience interactions with platoons of automated passenger cars on highways?
- How do different inter-vehicular gaps affect the safety and experience of manual car drivers?
- Will manual car drivers need any support, and could eHMI facilitate safe and efficient interaction in this context?

These questions were addressed in the context of a highway merging scenario that might pose a significant concern for the adoption of automated vehicle platoons (Wang et al., 2019; Rijkswaterstaat, 2016; Tsugawa et al., 2016). While merging onto a highway, drivers of manually operated vehicles may cut-in between platooning vehicles, thereby splitting them and impeding both safety and energy efficiency.

The study was conducted in a driving simulator and involved 16 participants. The participants drove a passenger car on a highway on-ramp and encountered an automated passenger car platoon while merging onto the highway. Each participant experienced four different gaps between the platooning vehicles twice. We collected and analyzed data on their driving behavior (e.g., number of cut-ins and crashes) as well as experience (e.g., perceived safety, comfort, mental effort) and support needs.

The rest of the paper is organized as follows. Section 2 introduces related work in this field. Section 3 describes the experimental setup and methodology. The results are presented in Section 4, while Section 5 discusses implications of the results in terms of car driver experience, safety and support needs. Finally, the work is concluded in Section 6.

2. Background

The technical aspects of platooning (especially trucks) are quite well-understood today. The effect platooning has on the merging behavior and experience of those driving manually operated vehicles on highway on-ramps is largely unknown. There are, however, some examples of research projects that address this. Also, some relevant conclusions can be drawn based on the interactions between manually operated vehicles on busy highways as well as recent studies of extra-long trucks on some European highways.

2.1. Interactions between manually operated vehicles

Studies on how human drivers interact with each other show that these interactions are complex and affected by various factors including vehicle speed, time-to-collision (TTC), traffic density, size of the gap between vehicles, road features (such as geometry and signs), weather and light conditions, presence and behavior of other road users, drivers' demographics, driving experiences, knowledge, motivations, cognitive state as well as their expectations and feelings of safety or insecurity (see e.g., Rolison et al., 2018; Mohammed et al., 2019; Thomas et al., 2013). Indeed, to avoid breakdowns and conflicts in road interactions, it is essential that road users have a similar understanding or awareness of the traffic situation (Endsley, 1995).

In busy highway traffic, platoon formations are likely to occur. This can especially be seen on two-lane highways with many heavy vehicles that are prohibited to overtake. As reported by van Maarseveen (2017), studies by *Jongenotte* and *Mansvelder et al.*[1] in the Netherlands (right-hand traffic), have shown that such formations may lead to several behavioral adaptations that negatively affect safety and traffic performance. For instance, there is an increased likelihood of small gaps between vehicles that typically reduce perception of the traffic conditions ahead, which in turn may increase the risk of rear-end collisions and create uncertainty in travel-time. Also, drivers in a platoon formation take more risks when changing lanes. This is because they cannot adapt their speed to that of the target lane before lane-changing. These premature lane changes may cause shock waves in the left lane that increase the risk of rear-end collisions. This can also lead to overburdening the left lane and reducing the overall highway speed below posted limits, thus negatively affecting road capacity and traffic flow. In addition, this could increase the risk of overtaking platoon formations on the right (if there are any lanes), resulting in less predictable situations and reduced traffic safety.

In the context of highway on-ramp merging, there are two interactive traffic streams: merging vehicles and mainline drive-through vehicles (Wan et al., 2014). Several studies imply that mainline drivers adopt a cooperative behavior by changing to the inner lanes or by yielding to create gaps for the merging vehicles (Ward et al., 2017; Gouy et al., 2014; Björnstig et al., 2008; Hjort and Sandin, 2012; Andersson et al., 2011). Similarly, drivers of the merging vehicles adjust their speeds according to the vehicles in the target lane. While these interactions and behavioral adjustments are often smooth, there are situations in busy traffic where inefficient and unsafe behaviors might occur. For instance, if drivers of the merging vehicles perceive that there are only a few sufficient gaps in the target lane, they may choose to merge at the beginning of the acceleration lane. This, in turn, could lead to merging with a relatively low speed and hindering the traffic by causing disturbances. If the acceleration lane is about to end, merging drivers may also brake sharply in order to merge, leading to a relatively low merging speeds or a standstill at the end of the acceleration lane (or in the shoulder lane). In a simulator study (de Waard et al., 2009), it was found that an increase in the number of heavy vehicles on the target lane resulted in merging vehicles reducing their speed and increasing speed variation. They found that drivers of merging vehicles tended to merge later when there was a truck next to their vehicle. In situations with several trucks in the target lane, merging took place at the beginning of the acceleration lane, either behind or in front of the truck that is next to the merging vehicle. Also, safety margins were smaller in such situations (the average minimum time gap and TTC were less than half that in mixed traffic). Similar findings are presented in Gouy et al. (2014).

In summary, current platoon formations on highways affect the driving behavior of drivers in their vicinity. At merging points, drivers are likely to adapt their behavior to ease the merging process. However, improper merging might still take place, with negative safety and efficiency implications.

2.2. Interactions between Manually Operated Vehicles and Longer Heavier Vehicles

Different types of Longer Heavier Vehicles (LHVs) with a length over 24 m have been tested and deployed, in some European countries

[1] These studies were reported in Dutch. They were summarized in English by *van Maarseveen* in van Maarseveen (2017).

during the last decades. Given the short gap between vehicles in an automated platoon, there might be some similarities between LHVs and platoons regarding how other drivers perceive them.

In a review of several accident studies in Sweden (right-hand traffic), Hjort and Sandin (2012) concluded that these studies point in different directions and that the safety effects of LHVs cannot be truly established. By interviewing three Swedish drivers of long trucks (30 m), Andersson et al. (2011) found that these drivers had not experienced problems predicted by drivers of ordinary trucks concerning narrow roundabouts and intersections. In a follow-up study using a driving simulator and a field observation, these authors explored car drivers' behavior when overtaking an LHV (30 m) on a 2 + 1 road, where two lanes merge into one. They found that the headway time to the point where the lanes merge was 0.2 s shorter after overtaking an LHV, as compared to overtaking a regular truck. Similar safety issues were noticed, but not validated, in the field observations. Based on these findings, they concluded that LHVs may have a small negative effect on overtaking situations compared to regular trucks, but this needs further investigation. As reported by van Maarseveen (2017), survey studies by *Hoogvelt et al. (1996)* and *Dijkers and Huijgen (2009)*[2] conducted in the Netherlands showed that the perceived safety of drivers interacting with LHVs does not change significantly compared to interactions with regular trucks. The drivers felt that the most unsafe situation was an on-ramp merging situation, when an LHV was in the target lane. In such situations they also tended to underestimate the length of the LHV. Consequently, the drivers needed to accelerate to be able to merge in front of the LHV, which was the preferred option. Furthermore, drivers commonly misjudged the time it takes to overtake an LHV, which could have been a direct consequence of underestimating the length of the LHV. However, the effect of length on safety could not be established from the accident analysis, as reported in van Maarseveen (2017).

Although somewhat contradictory, these studies on LHVs imply that interactions with automated platoons could be different from interactions with regular vehicles, and that analysis of such interactions requires further attention. In particular, overtaking on two-lane highways and on-ramp merging could be valuable to study. Another insight is that perceived safety could differ from actual safety; some of the safety issues that were highlighted in interviews could not be noticed in accident analysis.

2.3. Interactions between manually operated vehicles and automated platoons

Today, knowledge on how other drivers interact with and experience automated platoons is limited, but there are some studies where this topic has been studied or highlighted as important. In a recent driving simulator study, Spasovic et al. (2019) explored how 12 drivers of other vehicles experience and interact with automated truck platoons of different lengths (5, 7 and 10 vehicles) and in different traffic situations on highways with right-hand traffic. For instance, merging onto a highway while encountering a platoon, exiting across the right-hand lane with a platoon, a platoon merges onto the highway, and a platoon moving from the center lane into the right lane in order to exit the highway. They found that the drivers tended to adjust their speed in order to overtake the platoon as soon as possible, or "competed" to avoid being overtaken by the platoon. When it came to merging behavior, the drivers commonly (60%) decreased their speed and merged after the platoon had cleared the merging area. This behavior was especially prominent for the longer platoons. Overall, 17% of the drivers cut-in between the platooning vehicles while merging to the highway. A similar cut-in frequency was observed for all platoon lengths.

The interaction between automated truck platoons and other drivers on highways was also to some extent investigated within the EU-project KONVOI, mainly using a driving simulator (Lank et al., 2017). The study noted that the drivers of manually operated vehicles were more stressed in situations when a platoon was present, especially on on-ramps, as compared to similar situations without the presence of a platoon. However, the drivers rated their overall workload as rather low independently of platoons. While the drivers were generally positive to platoons and did not find them disturbing, some of the drivers highlighted that entering and leaving the highway could be a challenge. Another interesting finding from Lank et al. (2017) is that drivers of manually operated vehicles did not change their behavior when overtaking a platoon, which maintained a 10-meter inter-vehicular gap at 80 km/h, compared to overtaking trucks, which maintained the mandatory 50-meter distance to each other, at the same speed.

In the EU-project, SARTRE, which focused on platoons with a mixture of passenger cars and trucks, it was stressed that interactions with other road users could be challenging (Robinson et al., 2010). Furthermore, Gouy et al. (2014) showed in a driving simulator study that drivers of manually operated vehicles adapted their driving behavior when interacting with platoons by displaying a significantly shorter average and minimum time headway. Based on these findings, they emphasized the importance of examining the possibly negative behavioral effects of drivers interacting with platoons. In the more recent EU-project, COMPANION, it was concluded that acceptance of truck platoons by the end-users and society need further research (Eilers et al., 2015). A similar conclusion was drawn in the ETPC (Rijkswaterstaat, 2016) where the process of joining and exiting highways and the risks associated with unexpected overtaking maneuvers were highlighted as necessary future research topics. In a follow-up interview study with a portion of truck drivers who participated in the ETPC, Andersson et al. (2017) identified that unaware cut-ins may occur on on-ramps and while overtaking on highways; these cut-ins could, in turn, lead to dangerous situations and reduced energy-saving benefits for platoons. They also found that communicating characteristics of platoons, including information such as speed, direction, gaps, and platoon length, to other road users in the vicinity might be needed. In line with this, one of the aims of the recently initiated EU-project, ENSEMBLE, is to explore the impact of platoons on drivers and other road users. Hitherto, there is no publicly available result from the project regarding this topic (Fusco et al., 2016).

In summary, some studies imply that platoons could be introduced without impeding other road users and current rules of interaction on highways. However, there are other studies pointing in a different direction, which suggests more research on this topic is needed. In particular, interactions on highway on-ramps and while overtaking platoons are viewed as potentially challenging. Informing other road users about platoons by means of external vehicle interfaces is suggested as a viable solution for addressing such challenges. This study explores the need for, and the role of, such communication.

2.4. The value of communicating intent in traffic

Communicating intent to other people is a basic social principle that also applies in traffic. In line with this, drivers interpret cues in each other's behavior and communicate their own intentions by various means, including vehicle speed, acceleration, deceleration, placement on the road, time headway, body language, gesture, and eye contact.

Several studies in the field of robotics show that this is applicable to interactions between humans and robots; due to humans' special needs to feel safe and comfortable when interacting with robots, robots and humans need to have a mutual understanding of the situation and each

[2] These studies were reported in Dutch. They were summarized in English by van Maarseveen in van Maarseveen (2017).

other's intentions (Steinfeld et al., 2006; May et al., 2015; Goodrich and Schultz, 2008). As shown in Lichtenthäler et al. (2013), humans often manage to assess the situation correctly based only on the context and motion of the robot. However, several researchers posit that there are situations where social robots should apply non-verbal proactive communication such as navigational intent by means of e.g., facial expression (Breazeal et al., 2001), gaze and turn indicator (May et al., 2015), or light projections (Chadalavada et al., 2015; Watanabe et al., 2015). In addition, recent studies on interaction between automated vehicles and pedestrians show that this might be valid in such interactions as well (Lundgren et al., 2017; Habibovic et al., 2018; Natasha et al., 2019).

Drawing on this knowledge, similar interaction principles and communication needs may be expected to occur between automated truck platoons and drivers of manually operated vehicles. Indeed, while rather sparse, the current understanding of such interactions implies that communicating to other road users that platooning vehicles are in a platoon and that they intend to stay in the platoon may be needed. This might have a positive effect on safety and comfort, and make interaction easier; therefore, we explore this topic further in this study.

2.5. External vehicle interfaces for intent communication

While discussion about external vehicle interfaces has been intensified during the last 3–4 years, due to potential interaction challenges between automated vehicles and other road users in urban areas, using such interfaces in the vehicle context is not new. Technical means for communication between vehicles and other road users have been around for decades, e.g., vehicle head-, rear and brake lights, indicators, position lights and static signs indicating whether it is a truck or a trailer. A great majority of newly suggested external vehicle interfaces for automated vehicles are built around pedestrians' support needs. Examples of such interfaces include:

i) Bio-mimetic interfaces (Pennycooke, 2012; Jaguar Land Rover, 2019; Mahadevan et al., 2018); *ii)* Dynamic light strip on the windshield/roof communicating mode and yielding intent (Habibovic et al., 2016; Ford, 2019; Daimler, 2018); *iii)* Light projections of motion direction or a zebra crossing on the road surface along with an auditory signal (Mercedes-Benz, 2015; Mitsubishi Electric Corporation, 2015); *iv)* Dynamic light strip around the entire vehicle (Nissan Motor Corporation, 2015; Volvo Cars, 2018); *v)* Flashing stop sign or a robotic hand on the vehicle's door (USPTO, 2015); *vi)* Textual messages on the front and/or sides of the vehicle (Drive.ai, 2017; Song et al., 2018).

In this context, it is important to note that the International Standardization Organization (ISO) has issued a technical report describing principles for the visual external communication development of automated vehicle, mostly directed towards pedestrians (International Organization for Standardization (ISO), 2018). Also, there are ongoing regulatory activities on the international level driven by the United Nations Economic Commission for Europe (UNECE) (UNECE, 2018). To the best of the authors' knowledge, external signaling for platoons has not yet been discussed in these organizations.

2.6. Implications for this study

From the literature review we conclude that there might be similarities between the current interactions in dense highway traffic and future interactions between drivers of manually operated vehicles and automated vehicle platoons. Studies on interactions with extra-long trucks, showing that behavioral adaptation by other drivers is likely to occur, could also be valuable. Similarly, studies from the field of robotics, and interactions between pedestrians and automated vehicles in urban environments, could provide useful insights. However, to truly understand how other drivers perceive and experience automated vehicle platoons, and whether they require any support, it is necessary to conduct studies addressing this topic specifically. To this end, it would be valuable to investigate drivers' mental effort and ability to understand the intent of platooning vehicles as well as drivers' perceived safety, comfort, and difficulty of merging onto the highway. Another relevant topic is whether there is a need for additional support to ease interactions at the merging points. Our study is an initial step in addressing these topics.

3. Methodology

The study was set up as a driving simulator experiment where participants (16) repeatedly encountered an automated vehicle platoon while merging onto a highway. It was a within-subjects study with one independent variable: the inter-vehicular gap between the platooning vehicles. The independent variable was on four levels: 15, 22.5, 30, and 42.5 m. Each level was experienced twice in a random order, resulting in 8 experimental runs for each participant. The gaps as well as the speed of the platooning vehicles (120 km/h) were kept constant for each run. All involved vehicles were passenger cars. We combined quantitative and qualitative methods to collect and analyze several dependent variables. These included the number of crashes and cut-ins between the platooning vehicles that occurred while drivers of manually operated vehicles were merging onto the highway as well as their perceived safety, comfort and merging ease. The study was performed according to the internal institutional guideline for conducting driving simulator experiments at the Swedish National Road and Transport Research Institute (VTI), as well as in line with Halmstad University's code of ethics (the study was conducted when the first author was associated with Halmstad University). Furthermore, an informed consent was obtained from each research participant (see Section 3.5).

3.1. Simulation setup

This study used a high-fidelity moving-based driving simulator facility at VTI in Gothenburg, Sweden (the moving-base motion was not activated in our study). The driving simulator, "SimIV" (Jansson et al., 2014) is used as a driver interface for the participants. Since its inauguration in 2011, it has been validated and used in numerous studies. The forward field of view is about 210 degrees using 9 high resolution projectors. The driver interface includes a passenger car cabin with two side mirrors and a rear-view mirror to allow the driver to see vehicles behind them, as depicted in Fig. 1.

Platooning function is modelled using the *Platooning Extension for Veins* (Plexe) (Segata et al., 2014). This version of Plexe (Plexe-2.0)

Fig. 1. The driver interface used in this study.

(a) View from the ego vehicle at the beginning of merging lane, where a platoon may be seen.

(b) A view from the ego vehicle while merging into the platoon in the simulator.

Fig. 2. Front view from the ego vehicle presented to the test participants.

implements two CACC controllers in Simulation of Urban Mobility (SUMO) (Krajzewicz et al., 2012). The implemented CACC controllers are proposed in Ploeg et al. (2011), Rajamani (2012)[Chapter 5]. The driving simulation software and Plexe are connected as presented in Aramrattana et al. (2019), in order to visualize a platoon to human drivers in the driving simulator.

3.2. Highway cut-in scenario

This study investigated a scenario where a manually operated car encounters a platoon of five passenger cars at a merging point of a two-lane highway as illustrated in Fig. 2b (right-hand traffic). The vehicle that is driven by the study participants, namely *ego vehicle*, starts from a 500-m one-lane highway on-ramp. After the ego vehicle has reached a certain speed and position on the road, a platoon of five vehicles is released on the rightmost lane of the highway. The ego vehicle then encounters the platoon at the merging point while trying to merge onto the highway (note that the platoon may be visible already when the participants are approaching the merging point as illustrated in Fig. 2a). The scenario is illustrated in Fig. 3.

All vehicles in this study are passenger cars, which are 4 m long. Vehicles in the platoon are always driving on the rightmost lane of the highway, while maintaining a desired inter-vehicular gap and a speed of 120 km/h. Four gaps were chosen: *i)* 15 m; *ii)* 22.5 m; *iii)* 30 m; and *iv)* 42.5 m.

They correspond to approximately 0.5, 0.7, 0.9, and 1.3 s time gap at 120 km/h, respectively. The underlying motivation for selecting these gaps was to represent a wide range of inter-vehicular gaps. The range of gaps chosen in our study have been shown to be suitable from different points of views: *i)* 0.6, 0.9, and 1.1 s time gaps for Cooperative Adaptive Cruise Control (CACC) systems, which is one way to enable platooning, were shown to improve response time and string stability compared to Adaptive Cruise Control (ACC) systems, as reported in Milanés et al. (2014); *ii)* 0.5–1.2 s time gaps were approved by authorities in different countries, who allowed testing of truck platoons on public roads in Eckhardt (2016); *iii)* the CACC systems with time gaps of 0.6 and 0.7 s were accepted by test drivers (who are sitting inside platooning vehicles) in Nowakowski et al. (2010); and *iv)* and the gaps from 5 to 18 m were implemented in platooning systems, which were demonstrated on road as summarized in Bergenhem et al. (2012); Nowakowski et al. (2015).

During the experiment, each participant experienced each of the inter-vehicular gaps twice, in a pre-defined order generated by a balanced Latin Square method, which is unique for each participant.

Furthermore, we assume simple sensing capability for the platooning vehicles to represent vehicles that exist commercially today. These vehicles are likely to be adapted for platooning in early deployment stages. Thus, they are assumed to be equipped with one forward looking radar, that detects an object in front, with a field-of-view covering only the vehicle's current lane. That is, the gap, lane placement, and speed of platooning vehicles (120 km/h) were kept constant until the manually operated vehicle enters their lane.

3.3. Participants

Participants were recruited through VTI's database of study participants who are interested in driving simulator studies. We list the selection criteria for this study with a short motivation for each criteria as follows:

- **At least 20 years old, up until 65 years old**: We consider that adults between 20 and 65 years have similar sensory, cognitive and physical abilities when it comes to driving.
- **Have a driving license for passenger cars (category B)**: A person without a driving license might not have sufficient ability to operate the vehicle.

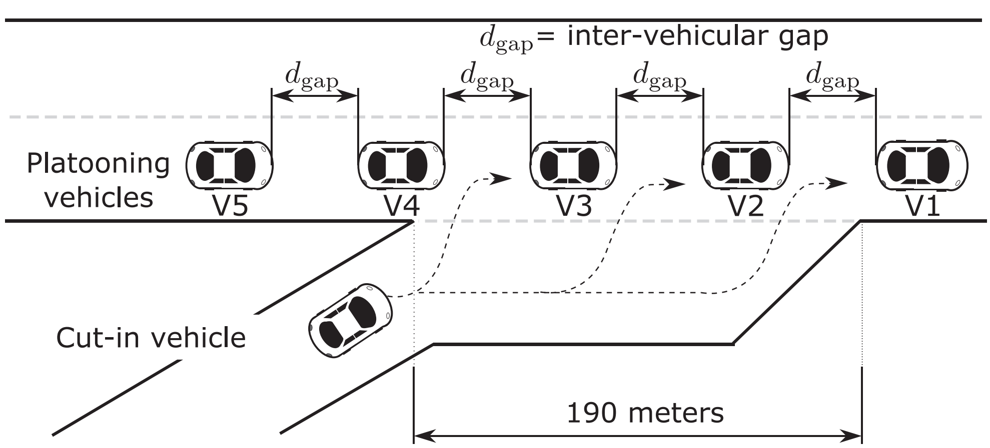

Fig. 3. The highway cut-in scenario where the ego vehicle is operated by the study participant who is attempting to merge onto the highway. The platooning vehicles do not accelerate, decelerate or change lane during the merging process unless the ego vehicle enters their lane.

Table 1
List of questions in the *Repeated Questionnaire*.

Type	Questions	Scale
Safety	How would you rate the inter-vehicle gap between platooning vehicles in term of safety?	[1–5] (1 = Not safe at all, 5 = Very safe)
Comfort	Do you feel comfortable while driving between platooning vehicles?	[1–5] (1 = Not comfortable at all, 5 = Very comfortable)
Ease	How easy was it to drive between platooning vehicles?	[1–5] (1 = Not easy at all, 5 = Very easy)

- **Have had a driving license for at least 2 years**: A person who has not had a driving license for at least two years is commonly considered a novice driver.
- **Drive at least 500 km per year**: Drivers who drive at least 500 km per year are considered to be actively driving.
- **Drive on a highway[3] at least once a week**: This to ensure that drivers have sufficient experience with highway driving (i.e. similar road environment as in the experiment).

The participants took part in the study on a voluntary basis, and they received two movie tickets each at the end of the experiment. Results from 16 participants are reported in this paper. Among the participants, there were 7 female and 9 male between 19[4] and 53 years old. The average age was about 45 years.

3.4. Data collection and analysis

The data collected included driving behavior of the study participants as well as their self-assessed experience and support needs. These data were captured utilizing both qualitative and quantitative methods. The data were collected and stored anonymously, according to the agreement in the consent form.

- **Driving simulator data logging**. This included number of cut-ins and number of crashes, as well as position and speed.
- **Background Questionnaire**. This includes questions on participants' demographics (age and gender), and previous driving simulator experience. In addition to presenting descriptive statistics, we also calculated the Pearson correlation coefficients between the background items and the "Overall Questionnaire" using MATLAB to measure linear dependencies among the answers.
- **Repeated Questionnaire**. This customized questionnaire consisted of three questions regarding: *i) safety* of the gap between platooning vehicles; *ii) comfort* of driving between platooning vehicles; and *iii) ease* of driving between platooning vehicles, as perceived by the participants, see Table 1. Furthermore, we use Kruskal–Wallis test followed by Dunn's test to analyze statistical differences between the results from each inter-vehicular gap.
- **Overall Questionnaire**. This customized post-experiment questionnaire was inspired by NASA-TLX (Hart and Staveland, 1988) and Technology Acceptance Model (TAM) (Davis, 1989). This approach was chosen since existing questionnaires do not capture questions directly related to our topic of interest. However, several of our questions are slightly paraphrased versions of the questions in the existing questionnaires. Our questionnaire has not been validated, but it has been piloted with experts in traffic safety and human behavior. The *Overall Questionnaire* consisted of 8 questions measuring participants' *habits*, *perceived safety*, *mental demand*, *comfort*, and *ease* to interact with the automated vehicle platoon (see Fig. 4). It also included a question on *understandability* of behavior of the platooning vehicles and whether these vehicles *need to signal* that they are driving in a platoon. The questions were answered by the participants on a 1–7 Likert scale ranging from *Strongly disagree* to *Strongly agree*. The answers were aggregated to identify median, maximum and minimum values. We also calculated the Pearson correlation coefficients using MATLAB to measure linear dependencies among the answers.
- **Interview**. The post-experiment interview was open-ended and elaborated upon participant's overall experience, whether any support is needed to ease the merging process, and how such support may be designed. All interviews started with the open-ended question *"What is your spontaneous reaction to this experiment?"*. If the participants would not mention anything about their support needs, the test leader asked another open-ended question: *"What could make your merging experience better?"*. All interviews were directly transcribed by the test leader (first author). They were later analyzed by the second author using the principles of grounded theory (Strauss and Corbin, 1998). Grounded theory consists of a series of activities; however, due to the nature of the research questions only the first stage of the analysis, "open coding", was chosen. In the initial open coding, the coder identified and labeled 62 codes. Based on this, 24 themes emerged. To put the themes in the context, each theme was exemplified by relevant quotes. The themes were then further grouped into general 10 categories. Under the initial coding, it was noted that only a few new topics emerged after coding the data from 10 participants. To further assess if a saturation has been reached, we removed data from 6 participants without noticing any remarkable changes in the definition of the themes and general categories of the themes. This indicated that a certain level of saturation might have been reached for the given sample and the given conditions. The data analysis was done using the qualitative analysis software ATLAS.ti.

3.5. Procedure

We welcomed one participant at a time. Upon arrival, a test leader gave each participant a brief introduction about the experiment, then the participants were asked to read and sign the consent form before they continued with filling out the *Background Questionnaire*. The participants were then informed that they would encounter a platoon of automated vehicles, on a highway with 120 km/h speed limit. Also, they were asked to merge onto the highway as they would normally do in a similar real-traffic situation. However, they were not informed about the gap settings.

After the introduction, the test leader led the participants to the driving simulator, explaining equipment in the cabin. They were told that they should inform the test leader if they felt any discomfort, or if they want to stop the experiment of any other reason. Each participant was given about 2 min to get familiar with the control of driving simulator, which simulates a passenger car with automatic gearbox. During these 2 min, the participants drove on the same road that would be used for the experiment, but there were no other vehicles on the road during this phase. Finally, each participant drove the scenario eight times with different gap settings as mentioned above in Section 3.2. After each encounter with the platoon, the participants were asked to complete the *Repeated Questionnaire*. When all eight experimental runs were finished, the participants were asked to complete the *Overall Questionnaire*. At the end, they participated in a brief interview. The whole experiment took about 30 min to complete for each participant.

[3] A road with at least 100 km/h speed limit.

[4] An exception was made to include one driver that is under 20 years old.

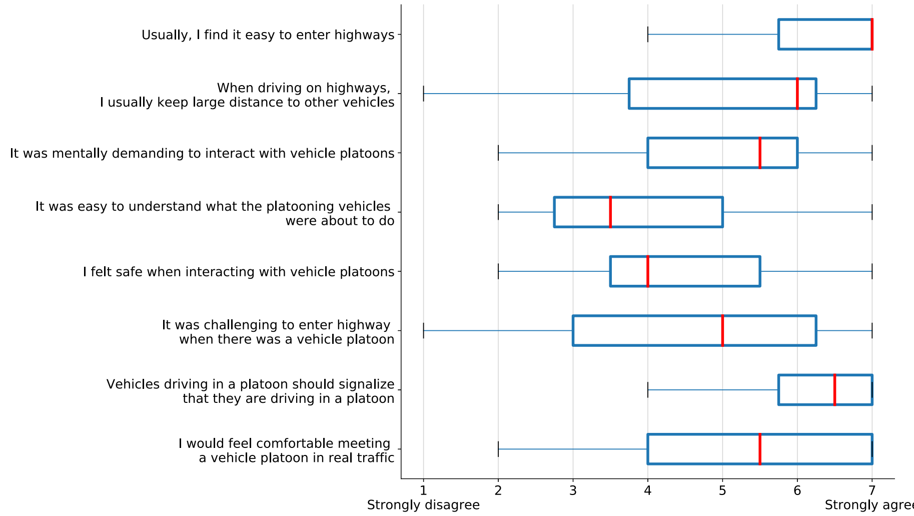

Fig. 4. Questions from the *Overall Questionnaire* and drivers' answers on a Likert scale 1–7 (red shows the median value, while the minimum and maximum values are bounded between black lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Results

In this section, we report on the results from the driving simulator experiment, starting with the drivers' self-assessed perception of safety, comfort, and ease to drive between the platooning vehicles, i.e. the *Repeated Questionnaire* which they completed directly after each encounter with the platoon. We analyze this along with the data on the cut-in or merging behavior and crash frequency as registered in the simulation data. After that, we discuss the results from the *Overall Questionnaire*, that were obtained after all experimental runs were completed. At the end, the results from the *Interview* analysis are reported.

4.1. Merging behavior

In the context of this paper, merging behavior refers to the behavior of participants when merging onto the highway. A merge can occur in front of the platoon, between platooning vehicles (cut-in), or behind the platoon. The merging behaviors of the participants are summarized in Table 2.

The study involved 16 drivers out of which 6 had previous experience with driving simulators. Drivers that had previous experience with driving simulators were involved in less collision compared to those without previous simulator experience. However, they did not show any difference in terms of their chosen speed when merging onto the highway.

Among different gap settings, there were no significant differences between the merging speeds i.e., the speed used at the merge, regardless of whether the merge occurred in front, between, or behind the platoon. The results were obtained using a non-parametric statistical analysis, Kruskal–Wallis test at $\alpha = 0.05$.

However, there were significant differences between the overall merging speed when merging occurred in front of the platoon compared to cases where the participants cut-in or merged behind the platoon. According to Table 2, merging in front of the platoon is done at a higher speed compared to the other two merging behaviors. This suggests that the participants sped up significantly to overtake the platoon in most cases (note that the platoon is driving at 120 km/h). On the other hand, merging maneuvers behind the platoon were mostly done at lower speeds, suggesting that the participants might have braked and allowed the platoon to pass before they merged onto the highway.

This behavior is similar to the merging behavior observed in the study by Spasovic et al. (2019), where 12 drivers were tested in a similar merging scenario involving an automated truck platoon. In Spasovic et al. (2019), the inter-vehicular gap used was approximately 15 m, where most drivers were observed to be merging behind the platoon, and a few between or in front of the platoon. Our observation at the 15-m setting shows more frequent merging in front of the platoon. This difference might be explained by the fact that the platoon in our study consisted of cars and not trucks, making it easier for participants to overtake the platoon because of a shorter total platoon length.

4.2. Repeated questionnaire

Prior to analyzing data from *Repeated Questionnaire*, we excluded data from experimental runs where the participant did not cut-in between platooning vehicles. This was due to the nature of the questions, which ask about the opinions assuming that the participants have driven between the platooning vehicles. Also, some of the data (17 experimental runs) were excluded due to simulation errors (e.g., driving speeds of the vehicle were not recorded properly). Thus, *valid runs* in the Table 2 refers to the total number of experimental runs that were analyzed after excluding the runs with simulation errors. Table 3 summarizes results from the *Repeated Questionnaire* after applying these criteria. Note that the higher score from the *Repeated Questionnaire* reflects positive opinions, and that sometimes participants did not answer all the questions, thus the number of analyzed questionnaire data is equal to the number indicated in the *cut-in* column, except for the comfort and ease questions, where each of the questions has two missing answers.

The results show that the drivers cut-in between the platooning vehicles only in 4 out of 30 experimental runs (13%) when the inter-vehicular gap was 15 m. However, collisions were observed in all 4 experimental runs where the cut-in occurred (100%). In line with this, the majority of the drivers reported a low level of safety (median 2) and comfort (median 1.5). Also, the drivers commonly reported that driving between the platooning vehicles was difficult (median 2).

For the inter-vehicular gap of 22.5 m, the cut-ins occurred in 15 of 26 experimental runs (58%). A crash occurred in 4 of these 15 cut-ins (27%). The median values of drivers' self-assessed safety, comfort and ease to drive for this gap were 2, 2.5 and 2.5, respectively, which is similar to the ratings for the 15 m inter-vehicular gap.

The number of cut-ins as well as the ratings increased for the other two inter-vehicular gaps. At the same time, the number of crashes decreased drastically. A cut-in occurred in 21 of 24 experimental runs (88%) for the inter-vehicular gap of 30 m. Only one of these cut-ins

Table 2
Summary of the participants' speed and position when merging onto the highway.

Merging position	Merging count (n)					Merging speed (km/h)		
	Total	15 m	22.5 m	30 m	42.5 m	Min.	Max.	Mean
In front of the platoon	26	18	8	0	0	114	140	128
Between platooning vehicles	66	4	15	20	27	88	134	116
Behind the platoon	19	8	3	4	4	41	109	95

Table 3
Frequency of cut-ins and crashes along with drivers' self-assessment of safety, comfort and ease to drive between platooning vehicles from the *Repeated Questionnaire* where a Likert scale 1–5 was applied.

Gap (m)	Valid runs (nr)	Cut-in (nr)	Crashes (nr)	Safety (median)	Comfort (median)	Ease (median)
15	30	4	4	2	1.5	2
22.5	26	15	4	2	2.5	2.5
30	24	20	1	3.5	4	4
42.5	31	27	1	4	4	4

ended up in a crash (5%). The median value of self-assessed safety, comfort and easy to drive between the platooning vehicles was 3.5, 4 and 4, respectively.

For the inter-vehicular gap of 42.5 m, the cut-ins occurred in 27 of 31 experimental runs (87%). Of these cut-ins, only one resulted in a crash (4%). In line with this, a majority of the drivers reported a high level of safety (median 4), comfort (median 4), and ease to drive (median 4).

Furthermore, we test statistical differences between the answers using non-parametric tests i.e., Kruskal–Wallis test followed by Dunn's test. The Kruskal–Wallis test on differences between answers in the safety, comfort, and ease results in test statistic H = 18.293, 12.749, and 12.605 with p-values 0.000, 0.005, and 0.006, respectively. The results from Dunn's test indicating the differences are presented in Table 4. All the tests were conducted using Python with the following packages: `scipy.stats.kruskal` for Kruskal–Wallis test, and the `scikit_posthocs.posthoc_dunn` (Terpilowski, 2019) for the Dunn's test.

As suggested by Table 4, the statistical analysis shows highly significant differences ($\alpha = 0.05$) between the 22.5 and 42.5 m gaps in all categories. All the other pair-wise comparisons did not show any statistical significance at this level. At a lower significance level ($\alpha = 0.10$), increasing the gap to 30 m shows improvements in safety and comfort compared to 22.5 m, but not the ease. However, the ease opinion for 15 m is different from 42.5 m.

In summary, the results show that cut-ins were rather rare for the short inter-vehicular gaps (i.e. 15 and 22.5 m). However, once they occurred, several of these cut-ins resulted in a crash, and made the drivers feel unsafe and uncomfortable. Also, these short gaps made it difficult for drivers to drive between the platooning vehicles. On the contrary, the two longer inter-vehicular gaps (i.e. 30 and 42.5 m) lead to a high number of cut-ins and only a few crashes, while the drivers' self-assessed safety, comfort and ease to drive increased. Some of these improvements are shown to be statistically significant at different significance levels, as suggested in Table 4. At a confidence level of 95%, 22.5 m and 42.5 m are significantly different in all three self-assessed categories. At 90% confidence level, the safety and comfort ratings are also different between 22.5 m and 30 m, while the participants found it significantly easier to drive between the 42.5 m gap compared to the 15 m.

4.3. Overall questionnaire

Summary of the results from the *Overall Questionnaire* is shown in Fig. 4. The analysis of drivers' self-assessed mental effort when interacting with the automated platoon shows that they felt it was demanding. On the Likert scale 1–7, where 1 is "completely disagree" and 7 is "completely agree", the median value was 5.5. They also felt that understanding what the platoon was about to do was rather difficult (median 4). They found it difficult entering the highway (median 5).

On the contrary, the drivers stated that they usually find it easy entering highways (median 7), indicating that encounters with platoons might be more demanding as compared to regular traffic. In line with this, the drivers reported that they did not feel completely safe when interacting with the platoon (median 4.5). However, the majority of them stated that they would feel comfortable meeting a vehicle platoon in real traffic (median 6). These statements are somewhat contradictory. One possible explanation could be that the drivers believed that the issues experienced in the experiment were generally minor and that these issues would not be substantial in real traffic.

Furthermore, the results from the Pearson correlation coefficient analysis between the items in the *Background Questionnaire* and the *Overall Questionnaire* indicates three significant correlations at $\alpha = 0.05$. Those who stated that they usually find it easy to enter a highway also stated that they would feel comfortable meeting an automated vehicle platoon in real traffic, and vice versa (r = 0.49, p = 0.04). Similarly, those drivers who stated that they did not find it mentally demanding to interact with the vehicle platoons, stated that they would feel comfortable meeting an automated vehicle platoon in real traffic, and vice versa (r = -0.57, p = 0.02). Another interesting correlation is between the gender and distance to other vehicles when driving on highways today, showing that females keep larger distances than men (r = 0.52, p = 0.03). This is also reported in e.g., Aronsson and Bang (2006), Dotzauer et al. (2017).

Another finding is that a great majority of drivers stated that vehicles should signalize that they are driving in a platoon (median 6). This is also in line with what they highlighted in the post-interviews, which we present in the next section.

In summary, the results from the *Overall Questionnaire* show that interactions with platooning vehicles on highway on-ramps were challenging for the drivers of manually operated vehicles. It was mentally demanding to interact with the platooning vehicles and difficult to understand their intentions. Consequently, the drivers felt unsafe and suggested that platooning vehicles should signalize to drivers in their vicinity that they are driving in a platoon. On the contrary, several of the drivers stated that they would feel comfortable encountering a platoon in real traffic. These somewhat contradictory statements could be explained by the fact that these drivers commonly stated that they generally do not find it difficult entering a highway.

4.4. Interviews

The *Interview* analysis shows that the drivers recurrently stated that the platooning vehicles should signalize that they are driving in a

Table 4
Adjusted p-value results of Dunn's test on differences between answers from the *Repeated Questionnaire*. The adjustment is performed according to Holm-Bonferroni method. Significance at $\alpha = 0.05$ is marked with two asterisks (**), and significance at $\alpha = 0.10$ is marked with an asterisk (*).

	Safety				Comfort				Ease			
	15	22.5	30	42.5	15	22.5	30	42.5	15	22.5	30	42.5
15	–	0.61	0.57	0.20	-	1.00	0.22	0.16	–	0.85	0.12	0.05*
22.5	–	–	0.05*	0.00**	–	–	0.05*	0.01**	–	–	0.12	0.03**
30	–	–	-	0.37	–	–	–	1.00	–	–	–	0.85

platoon, something that is in line with the *Overall Questionnaire*. They also felt that the short gaps were difficult to handle (P1, P2, P3, P5, P10, P11, P13) and that larger gaps would be preferable (P1, P2, P14). However, only few of them realized that the vehicles they encountered were traveling in a platoon. Indeed, several drivers mentioned that external signaling on platoons (i.e., eHMI) would have made it easier for them to recognize platoons and adjust their expectations accordingly (Table 5). Only one driver (P7) stated explicitly that additional information about platoons would not be needed: *"Should not show if they are driving in platoon"*. However, a portion of the drivers (P5, P7), highlighted that additional signaling might not be needed if the platooning vehicles drive like human drivers do today. This implies that the platooning vehicles are expected to adapt their speed and the gap between them when someone is about to merge onto the highway. These expectations were more emphasized when the drivers discussed the overall behavior of the platooning vehicles, see Table 5.

Some of the drivers had suggestions on how signaling could be designed and what information it could convey (Table 6). They suggested using static or dynamic signs (P3, P4, P6, P10, P15), light projections and turning indicators on the platooning vehicles to show that they are one unit and that they want to "stay together"(P7, P9, P11, P12, P13, P15). One driver (P14) suggested that the platooning vehicles could be equipped with light signals that indicate where other vehicles could cut-in.

Interestingly, a few drivers (P1, P6, P15) suggested that information about platoons could be conveyed by means of road signs, or by means of wireless communication (V2X) (P3, P4, P10, P12, P14). The suggestions included use of static road signs on highway on-ramps to inform manual vehicle drivers that they are approaching a road that might be used by platoons. They also suggested using V2X to "open up" the platoon and create a suitable gap for the vehicles that are about to enter the highway. In addition, a few drivers (P3, P5, P9, P12) suggested that the information about platoons could be integrated in the existing blind-spot warnings or conveyed to them using in-vehicle displays. One of the drivers (P5) suggested also that the platooning vehicles should drive closer to each other to avoid cut-ins.

Table 5
Quotes and recurrent themes identified in the interviews regrading support needs and behavioral expectations.

Overall category	Subcategory:"quotes"
Additional HMI might be needed	**Increase situation awareness (P3, P6, P10, P11, P12, P13, P14, P15)**: • "Want to know who my neighbors are" • "Can recognize and know what to expect" • "So you know that they will keep the speed and distance" • "Would make it easier" • "Signal is good" • "It could help" **Make easier to plan actions (P1, P2, P4, P6, P11, P12, P15)**: • "Would considered it as a long truck" • "Then I would have driven differently" • "If I knew that, I would have made space"
Additional HMI is not needed	**Not show it is a platoon (P7):** • "Should not show if they are driving in platoon"
Platooning vehicles should adapt their driving behavior	**Adapt speed (P3, P4, P11, P13, P14, P15)**: • "They should slow down when they see the car coming on the merging lane. If they do what human does, extra signaling should not be needed." **Behave like vehicles today (P7, P15)**: • "It would be easier if they behave like normal cars. If they can interact well, then signaling won't be needed. But if they drive like this, a signal would be needed definitely"
Driving behavior of platooning vehicles did not reflect behaviors of today	**Did not adapt (P3, P7, P9, P10, P11, P13, P15)**: • "Didn't interact with me" • "Did not interact, as opposed to normal cars that would help you" • "Didn't interact with me when I approached on the ramp" • "If the platoon adapted it would make interaction easier" • "Tightly coupled platoon is hard to interact with" **Expected a different action (P1, P3, P4, P5, P7, P11, P13, P14, P15)**: • "Should go to the left lane" • "Expecting the platoon to make space" • "Should know that it is approach the merging point" • "They should react properly" • "Should leave the gap for you and ask back where do you want to go in"

Table 6
Quotes and recurrent themes identified in the interviews regarding design of additional HMI.

Overall category	Subcategory:"quotes"
HMI on the platooning vehicles	**Sign on the platoon showing it is a platoon (P3, P4, P6, P10, P15)**: • "Something like a taxi sign" • "Perhaps it should have a sign" • "They should have sign, like long trucks have" **Other information on the platoon showing it is a platoon (P7, P9, P11, P12, P13, P15)**: • "The platoon should signalize somehow, heads up warning" • "Interact with the turn signal" • "Laser to form a light bound around the platoon" • "How long is the platoon, would be good information" • "Something like braking light would be distracting and frightening" **Platoon showing gap to other drivers (P14)**: • "Important information to know when you get close to the platoon" • "A light on two cars indicating that this is the gap for you"
HMI inside infrastructure or V2X	**Sign in the infrastructure (P1, P6, P15)**: • "Sign on the road that says platoon will be on the left lane" • "Warning sign that the cars on the main road are driving too close" • "Sign that there could be platoon on this highway" **V2V to create a sufficient gap (P3, P4, P10, P12, P14)**: • "I would like to push a button in my car to tell them that I want to join" • "Let them know where I am and that I am coming in, maybe using GPS and V2V" • "Maybe platoon could somehow know from GPS and open up the gap" • "The manually driven vehicle could talk to them and say "I am coming"" **Information in/on the merging vehicle (P3, P5, P9, P12)**: • "Blind spot warning would be enough" • "Some signal in the head-up display would be nice"
HMI as vehicle behavior	**Small gap as a signal (P5)**: • "You expect them to be closer to each other so that other vehicles cannot go in between them"

In summary, the insights from the interviews are in line with the findings from the questionnaires. However, the interviews provide rich information on motivating factors. In particular, the interviews show that the merging might have been difficult due to the non-adaptive behavior of the platoon; it did not correspond to the current behavior of drivers on highways. The drivers suggested that signaling on platooning vehicles that shows vehicles' intention to "stay together" might help create a better situational awareness and avoid unsafe cut-ins. Also, road signs in the infrastructure showing that platoons might be traveling on the road were suggested, as well as wireless communication for information exchange between manually operated vehicles and platoons.

5. Discussion

Improved safety and efficiency are major anticipated advantages of introducing automated vehicle platoons (Sugimachi et al., 2013; Keßler et al., 2006; Englund et al., 2016). Based on studies of new technology acceptance, there is reason to believe that social acceptance of these vehicles in shared spaces is likely to be linked to how other road users, including drivers of manfully operated vehicles, perceive them. Given the current gap in the literature regarding this topic, the main purpose of this study was to gain an understanding of how drivers of manually operated vehicles experience interactions with automated passenger car platoons when merging onto highways, and if they have any specific support need.

5.1. Insights on interactions with automated vehicle platoons

Overall, our results show that the drivers of manually operated vehicles found it challenging to interact with an automated vehicle platoon when merging onto highways, which is largely in line with previous platooning studies such as SARTRE (Robinson et al., 2010) and KONVOI (Lank et al., 2017), as well as studies on LHV on Dutch highways (see van Maarseveen, 2017). Our drivers also commonly stated that merging onto the highway when there was a platoon was mentally demanding. On the contrary, the drivers of manually operated vehicles involved in the KONVOI-study (Lank et al., 2017), rated their overall workload as rather low both in the situations with and without platoons. The researchers in that study noted, however, that the drivers were more stressed in situations when a platoon was present and urged more research on this topic. We echo this recommendation and suggest complementing drivers' subjective assessments of mental demand with physiological measurements, e.g., brain wave patterns (EEG) and heart rate (ECG). Our results also imply that including drivers' background information and how they perceive the interactions in current traffic might help in understanding and anticipating their interactions with automated vehicle platoons. For instance, we found that drivers who stated that they would feel comfortable interacting with an automated vehicle platoon in real traffic, also stated that they usually find it easy entering a highway.

As expected, the inter-vehicular gap (gap) between the platooning vehicles affected both the behavior and experience of drivers of manually operated vehicles. Regarding behavior, cut-ins and crashes occurred for all four gaps (15, 22.5, 30, 42.5 m). However, the number of cut-ins increased and the number of crashes decreased with the increased gap, see Table 3. In terms of experience, we noted that drivers' perceived safety, comfort and ease of driving between the platooning vehicles were rather low ($\leqslant 2.5$) for the two shorter gaps, and rather high ($\geqslant 3.5$) for the two longer gaps. This implies that a short gap of 15 m or 22.5 m did not eliminate cut-ins by other drivers in our experiment. At the same time, these gaps posed a major crash risk and unpleasant experiences. In future studies, it would be interesting to investigate if gaps under 15 m would completely prevent cut-ins, or if some drivers would still try to cut-in.

Another insight is that the gap of 22.5 m yielded a larger number of cut-ins and smaller number of crashes than the gap of 15 m. However, the gap of 22.5 m was not large enough to make it easy for the drivers to enter the highway, neither did it make them feel safer nor more comfortable. Also, about one-third of cut-ins at the gap of 22.5 m resulted in a crash. This is also echoed in the statistical tests, which did not show any significant differences regarding the safety, comfort, and ease assessments. This implies that increasing the gap from 15 m to 22.5 m might have "invited" dangerous cut-ins. As such, the gap of 22.5 m might not be the best design choice for a platoon. Generalizing this conclusion is not possible, however, it is an interesting topic for future studies.

Similarly, while the gap of 42.5 m yielded a larger number of cut-ins and a smaller number of crashes compared to the gap of 30 m, it did not yield much higher ratings of the drivers' perceived safety, comfort, and ease to drive between the platooning vehicles. Indeed, the statistical comparison between these two gaps did not show any significant improvements. Along with the fact that the crash rate was similar for both 30 m and 42.5 m gaps ($\leqslant 5\%$), this implies that increasing the gap from 30 m to 42.5 m might not have any notable impact on safety and drivers' experience.

Statistical analysis shows, however, that increasing the gap from 22.5 m to 42.5 m yielded a statistically significant (at $\alpha = 0.05$) improvements on the drivers' perceived safety, comfort, and ease. Less significant (at $\alpha = 0.10$) improvements can be observed in the perceived safety and comfort but not the perceived ease, when the gap changes from 22.5 m to 30 m. A possible interpretation is that the drivers who felt that the 30 m gap was safe, found it still somewhat difficult to handle this gap.

Altogether, these findings suggest that there might be a gap between 22.5 m and 30 m where both actual safety (e.g., number of cut-ins and crashes) and drivers' perceived safety and comfort are optimized. However, further studies are needed to validate this hypothesis and to set a more specific value. It is also questionable if some of these cut-ins would have occurred in real world traffic, especially for the shorter gaps. Naturalistic data from truck platooning in the US indicate that there are no cut-ins if the gap between trucks is 30 m or less (Nodine et al., 2017). Also, the truck drivers from the ETPC witnessed that cut-ins were not frequent when the gap was about 22 m, and that they did not notice any change in other drivers' behavior when the gap increased to 30 m (Andersson et al., 2017; Rijkswaterstaat, 2016). Here, it is important to note that the trucks in the ETPC adapted the gap between them when the system detected that other vehicles were about to cut-in. Differences in the cut-in frequencies could also be seen depending on the country (e.g., cut-ins were more common in the Netherlands than in Sweden due to traffic density and road design).

The inability of the platooning vehicles in our study to adapt the gap at the merging area was something that several drivers noted. Based on current interactions on highways, they commonly expected that the vehicles in the target lane would "let them in". These expectations are in line with findings from several other studies showing that drivers on highways adopt a cooperative behavior by changing the lane, or by yielding, to create gaps for merging vehicles (Wang, 2005; Ward et al., 2017; Gouy et al., 2014; Björnstig et al., 2008; Hjort and Sandin, 2012; Andersson et al., 2011). While these interactions and behavioral adjustments are often sufficient, there are situations in busy traffic where inefficient and unsafe behaviors might occur (de Waard et al., 2009; Gouy et al., 2014). For instance, if drivers of merging vehicles perceive that there are few sufficient gaps in the target lane, they may choose to merge at the beginning of the acceleration lane. It is thus crucial to carefully investigate how platooning vehicles should behave at merging points in order to optimize both the actual and perceived safety of other drivers. As mentioned previously, if the goal is to prevent cut-ins, one may use short gaps between the platooning vehicles to deter drivers from cutting-in. However, given that the short gaps posed a major crash risk and unpleasant experiences in our experiment, using short gaps without any additional support may not be a safe solution.

5.2. Drivers' support need and implications for the design of eHMI

Today, it is largely unknown if introducing automated vehicle platoons on public roads will lead to new interaction principles, and if these interactions could be made safer, more efficient and seamless by means of additional HMI. Our results show that drivers of manually operated cars commonly expressed a need for additional information about the platoon to easier anticipate its behavior and avoid cutting-in. As they explained, noticing in advance that there is a vehicle platoon in the target lane would have helped them anticipate earlier that these vehicles intend to stay together. Indeed, several drivers stated that they would not have attempted to cut-in if they knew that the vehicles in the target lane were traveling in a platoon. Besides interview results, these points were also reflected in the results from the *Overall Questionnaire*; the high median in the drivers' assessment of the statement "Vehicles driving in a platoon should signalize that they are driving in a platoon" shows that they commonly agreed with this statement. Also, the lowest median is seen in response to the statement "It was easy to understand what the platooning vehicles were about to do", indicating that the participants had a hard time understanding the platoon without any additional HMI.

This was, however, tightly related to the gap and behavior of the platoon. If the platoon adopts a human-like behavior (i.e., adapts speed and gap) to allow for smooth cut-ins, additional support might not be needed. On the other hand, if the goal is to prevent cut-ins, the gaps might need to be kept short and drivers might need to be provided with additional information. More specifically, our results show that only a few drivers attempted to cut-in between the platooning vehicles when the gap was 15 m. The question is if this, or a shorter, gap could itself serve as a signal that deters other drivers from interfering with an automated vehicle platoon? Using dynamic behaviors to convey intent has been discussed in the context of interactions between pedestrians and automated vehicles (Dey and Terken, 2017; Moore et al., 2019; Risto et al., 2017), however, large-scale empirical studies are not publicly available yet.

As for the design of additional information, drivers commonly suggested that visual eHMI such as signs and light signals should be used on the platooning vehicles to show their intent to "stay together" as a group. Further design details were not discussed, although our previous study (Habibovic et al., 2019) identified a few potential concepts that could be used as a starting point for a future study. There is also a growing body of literature regarding eHMI for urban areas and interactions with pedestrians (e.g., Habibovic et al., 2018; Nissan News, 2015; Mercedes-Benz, 2015; Jaguar Land Rover, 2019), that might be applicable here to some extent. It should also be noted that some drivers in our study suggested the use of wireless communication (V2X) and static traffic signs in the infrastructure to inform drivers that they are approaching a road used by vehicle platoons. Future studies should explore various design and implementation aspects of this additional information, and how it could be generalized to other types of platooning vehicles (e.g., trucks). Here, it is important to note that all these suggestions were made based on the personal experience of the participating drivers in one potentially challenging traffic situation. These participants may not necessarily be able to see "the whole picture" and foresee the unwanted consequences of vehicles showing information such as intent. For example, there are many pitfalls in showing intent if it is ambiguous who is the intended recipient of such a message. For this reason, it is crucial to continue exploring the design and effect of eHMI for platoons.

While our findings suggest that additional information could have a major role in preventing cut-ins and helping drivers adjust their expectations and actions, the study by Andersson et al. (2017) did not identify any strong need for additional eHMI for automated truck platoons. However, they emphasized that the interviews with the participants indicated a number of scenarios where eHMI, or V2V communication, could be useful. They also pointed out that very few of the participants had experience of interacting with automated truck platoons, which might have affected their opinion. These somewhat contradictory findings call for more studies on this topic.

To this end, we want to also highlight that the value of providing additional information to other drivers might also lay in creating trust in automated vehicles in general (Parasuraman and Riley, 1997). Indeed, the latest trends show that developing safe technologies for automated driving is much more challenging than what was anticipated a few years ago. It might also take time to "convince" society that these vehicles are safe and beneficial; something that proper eHMI might help addressing.

5.3. Limitations of the Study

During the interview, some drivers commented on their overall experience in the simulator and its characteristics. Our interpretation is that the drivers felt generally well-immersed in the simulator ("Feel safe" (P7), "Feel comfortable" (P6, P9), "Not difficult" (P14)), however, dynamics of the simulator was somewhat modest. More specifically, a few drivers stated that they struggled with slow acceleration ("Easier when I got used to acceleration" (P13), "Acceleration is slow" (P3, P4, P8, P11, P12), "Hard to keep the right speed" (P16)) and/or sensitive steering ("Behaves differently" (P8), "Steering was very nervous" (P8), "Sensitive control" (P12), "Feels like a 4WD" (P8), "Feels like driving on a very slippery road" (P11)). In addition, two drivers pointed out that the vision was insufficient ("Simulator limited view was the biggest challenge" (P13), "Usually we can look way more behind" (P16)), while one driver experienced issues with determining the distance to other vehicles ("The cars look closer in the rear mirror" (P9)). Two of the drivers' may have experienced a slight motion sickness ("Feels like I am on a boat" (P6), "A bit dizzy" (P11)). When asked how serious this was, however, they explained that this was only minor. Which is also why we decided to include their data in the analysis. Motion sickness typically affects a similar portion of participants (5–10%) in driving simulators (Henriksson, 2009). Altogether, these issues could have affected how the drivers behaved and interacted with the automated vehicle platoons. However, since a majority of the drivers did not highlight any difficulties or discrepancies there is reason to believe that the simulator was a rather good replication of the real-world car and traffic environment. Therefore, we argue that the ecological validity of the study is sufficient, though it is something that should be verified in a field study.

A potential limitation of the study is that the vehicles in the automated platoon included only passenger cars. This was because we did not have access to models of truck platoons. It would be valuable to explore how drivers of manually operated vehicles interact with automated truck platoons, especially given the fact that trucks are generally viewed as potentially more dangerous than passenger cars, and generate different interactions with other road users (Moridpour et al., 2015). The fact that many manufacturers are currently developing truck platoons makes such a study even more appealing (see e.g., Switkes et al., 2019). It is expected that our conclusions regarding drivers support need would be even more evident in interactions with platooning trucks. The studies reviewed in Section 2 point in that direction as well.

Another limitation of the study is that the platooning vehicles did not adapt their behavior until the other vehicle was in their lane. As mentioned previously, this was due to a limited field of view for the simulated radar. Indeed, the inability of the platooning vehicles to adapt was commonly highlighted by drivers in the interview. It is not surprising that drivers expected the platooning vehicles to behave in a similar way to human drivers who either adapt their speed and/or change lane to give space to vehicles entering the highway. Based on our data, it is difficult to determine if, and to what extent, this may have affected their answers in the questionnaires. Future studies should explore more adaptive behavioral models of platooning vehicles. From a solely design perspective, it could be desirable to keep platoons rather non-adaptable, thereby indicating that the vehicles are in a platoon and that they intend to remain in the platoon.

Furthermore, our study involved a limited number of drivers (N = 16) in Sweden, and we believe that a larger and more heterogeneous sample of participants is needed to be able to draw more solid conclusions. In the selection process of participants, we drew some criteria (see Section 3.3) to ensure that the drivers had highway driving experience. With this in mind, the drivers were not exposed to any extensive training in the simulator (they were given 2 min to familiarize themselves with the simulator). This, in combination with the fact that only 6 drivers stated that they had previous simulator experience, could have affected their driving. On the other hand, each gap was experienced twice in a unique pre-defined order [5], which hopefully mitigated such effects. Also, we selected participants in the age interval 20–65 years to ensure that they have similar cognitive and physical abilities to drive. Having said this, we recognize that future studies should investigate the impact of age difference on the experience and performance in interactions with automated vehicle platoons. It is also vital to take into consideration cultural differences in driver behavior, and how these differences may be manifested in interactions with automated vehicle platoons. On a final note, we want to highlight the importance of combining different subjective and objective metrics for thoroughly understanding behavior and experience of participants, and reducing potential self-assessment bias.

5.4. Future work

Given the current lack of empirical studies on the interactions between automated vehicle platoons and other drivers from a socio-technical perspective, there are several topics that should be explored in future studies.

- Quantify how different dynamic behaviors of the platooning vehicles (e.g., adaptation of inter-vehicular gap) affect interactions and experiences of drivers of manually operated vehicles.
- Explore different gaps to find the "transition point" from safe to not safe both in terms of actual safety and perceived safety, and how it affects the efficiency of the platoon.
- Determine what information about automated vehicle platoons needs to be conveyed to drivers of manually operated vehicles in their vicinity. Questions on when and how (modality and placement) such information should be conveyed are also highly relevant.
- Explore whether small gaps (15 m or less) between the platooning vehicles could serve as a signal that prevents cut-ins by other drivers.
- Evaluate how different interface designs affect the safety and experience of drivers of manually operated vehicles as well as energy efficiency.
- Explore interactions with automated truck platoons as well as platoons with mixed vehicle types.
- Conduct longitudinal studies that focus on how automated vehicle platoons (with/without eHMI) affect behavior of drivers of manually operated vehicles over time.
- Our experiment explored platooning vehicles with rather high speed. We recommend that future studies incorporate lower speeds (70–80 km/h).

[5] To prevent order effects, when the participant's behaviour is influenced by the order of the experiment, a balanced Latin Square design is used to generate a sequence for each participant.

- In addition to driving simulator experiments, conduct similar experiments under more realistic conditions (e.g., on test tracks or real-world traffic).

6. Conclusion

This study helps generate an understanding of how drivers of manually operated vehicles interact with automated vehicle platoons on highways, and how different gaps between the platooning vehicles affect experience and safety. It also provides an initial knowledge-base on whether manual vehicle drivers need any support, and whether external human–machine interfaces (eHMI) could facilitate safe and efficient interaction in this context. The study was conducted in a high-fidelity driving simulator and involved 16 participants. It focused on a highway merging scenario where the participant, who drove a passenger car on a highway on-ramp, encountered an automated passenger car platoon while merging onto the highway. By triangulating qualitative and quantitative data on drivers' experience and driving behavior, we conclude the following, with respect to the research questions listed in Section 1.

6.1. How do manual car drivers experience interactions with platoons of automated passenger cars on highways?

Drivers of manually operated cars found it challenging to interact with an automated car platoon when merging onto a highway. They commonly stated that merging was mentally demanding, unsafe, and uncomfortable. It was also difficult for them to anticipate the behavior of the platooning vehicles. Several of them expected that the platooning vehicles would adopt a cooperative driving behavior (e.g., decelerate to leave room for the merging vehicles), similar to the behaviors of vehicles today.

6.2. How do different inter-vehicular gaps affect safety and experience of manual car drivers?

The gap between platooning vehicles affected how frequently the manual car drivers cut-in while joining the highway. It also affected how the drivers experienced the merging process and how often they collided. Their perceived safety, comfort and ease of driving between the platooning vehicles were rather low for the two shorter gaps (15 and 22.5 m), and rather high for the two longer gaps (30 and 42.5 m). On the contrary, the number of crashes was high for the two shorter gaps, and rather low for the two longer gaps. This implies that there might be a gap size (in our case between 22.5 m and 30 m) where both safety and drivers' experience are optimized. Another conclusion is that a short gap (15 m or less) might be used as a signal that deters drivers from cutting-in. However, using short gaps without any additional support may not be a safe solution.

6.3. Will manual car drivers need any support and could eHMI facilitate safe and efficient interaction in this context?

Drivers of manually operated cars commonly expressed a need for additional information about the platoon to easier anticipate its behavior and avoid cutting-in. This was, however, tightly related to the gap size and behavior of the platoon. If the platoon adopts a human-like behavior (i.e. adapts speed and gap) to allow for smooth cut-ins, additional support might not be needed. On the other hand, if the goal is to prevent cut-ins, the gaps might need to be kept short and drivers might need to be provided with additional information. To this end, short gaps between the platooning vehicles might serve as a signal that deters drivers from cutting-in. As for the additional information, drivers commonly suggested that eHMI such as signs and light signals could be used on the platooning vehicles to show their intent to "stay together". Some of them suggested, however, that the information could be conveyed via signs in the infrastructure, or by using V2V communication, implying that it might be worthwhile investigating various information types and placements.

Overall, our conclusion is that interactions with automated vehicle platoons may be challenging and that designers of such platoons should pay attention to how other drivers perceive and experience these platoons. The driving behavior of platoons as well as additional information about platoons may be used to facilitate safe and efficient interaction in this context. Given the limited scope of our study, these conclusions are very preliminary and not validated, and should as such be seen as directions for further research rather than definitive findings. To this end, we hope that this study will help direct the attention of fellow researchers, standardization organizations and regulators towards this topic.

CRediT authorship contribution statement

Maytheewat Aramrattana: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing - original draft, Writing - review & editing. **Azra Habibovic:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Cristofer Englund:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to acknowledge Bruno Augusto, Gunilla Sörensen, Niklas Strand, Alexander Eriksson, Mattias Söderholm Mullaart, and Henrik Nilsson for their support. Also, the authors would like to thank Eric Järpe at Halmstad University for his insights in statistics, Joshua Bronson at RISE for proofreading the manuscript, and all study participants. The research was funded by the Swedish government agency for innovation systems (VINNOVA) through the NGEA step 2 project (ref 2015-04881), SAFER Vehicle and Traffic Safety Centre at Chalmers, Knowledge foundation (KK) through the AIR project (ref 20140220), and the Strategic vehicle research and innovation programme (FFI) through the project External interaction principles for creating trust in heavy automated vehicles (ref 2019-05901).

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