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Overtaking automated truck platoons: Effects of platoon organisations and traffic situation on driving behaviours of nearby manual vehicle drivers

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Abstract

Automated truck platooning is a promising technology that is expected to be mainstream within the next decade. For the foreseeable future, automated truck platoons will coexist and interact with human drivers. Resembling a train-like formation, automated truck platoons may present challenges for drivers wishing to overtake them, and it is not currently clear how these new formations affect driver behaviour. Therefore, this paper aims to examine driver behaviours in the overtaking process under various platoon organisations. A high-fidelity driving simulation experiment was conducted to investigate the influence of platoon speed (80km/h and 100km/h), size (three trucks and five trucks), inner gap (5m and 25m) and the surrounding traffic situation, e.g., the presence of a lead vehicle, on drivers' overtaking behaviour. Thirty-eight participants were recruited in the experiment. Results revealed that compared to 80km/h conditions, the 100km/h conditions prompted more drivers to exhibit extreme behaviours—either failing to overtake or performing a risky overtaking. Regarding platoon size, drivers tended to deviate farther from the lane center to maintain a larger lateral distance from the platoon under five-truck conditions. With respect to the inner gap, a 25m inner gap significantly reduced the proportion of successful overtaking maneuvers. Moreover, in critical conditions, a 5m inner gap extended drivers' response time but did not significantly impact collision probability. The presence of the lead vehicle increased drivers' mental workload and impaired longitudinal stability. These findings may offer insights for managing automated truck platoons. For instance, the platoon speed and inner gap can be regulated in different traffic conditions, to optimize efficiency, while ensuring safety for all road users.

Keywords: automated truck platooning, driving simulator, driver behaviour, overtaking

1. Introduction

Connected and autonomous vehicle (CAV) technology has made significant progress and holds the potential to revolutionize the transportation system. One of the most promising CAV technologies is automated truck platooning (Ma et al., 2022). Unlike automated vehicles (AVs) that solely rely on sensor data, Dedicated Short-Range Communication (DSRC) technology enables multiple trucks to virtually link with each other, maintaining a constant and short inner gap within the platoon. This inner gap can be reduced to about 5m at a speed of 80km/h (Tsugawa, 2014). This close arrangement effectively reduces fuel consumption, emissions, and promotes traffic efficiency (Fagnant & Kockelman, 2015; Hussein & Rakha, 2021; Tsugawa et al., 2016). Additionally, it has been proposed that automated truck platooning can alleviate the workload of the truck drivers. Some cutting-edge platooning technologies can even achieve unmanned operation for the following trucks (Watanabe et al., 2021). It is proposed that less involvement of human drivers significantly reduces the risk of human-factors-related accidents. Automated truck platooning has undergone successful testing on public roads in various countries and is expected to be introduced to the market within the next decade (Fagnant & Kockelman, 2015).

Despite the numerous benefits, the introduction of automated truck platoons can also give rise to a range of issues. One major concern is the interaction between manual vehicles (MVs) and automated truck platoons (Axelsson, 2017). Given that mixed traffic of autonomous vehicles (AVs) and MVs is an essential step in the development of automated driving technologies, it is inevitable that manual drivers will share the road with automated truck platoons for the foreseeable future (Guhathakurta & Kumar, 2019). However, when several trucks create long formation exceeding 100 meters in length, they can present a perplexing scenario for other road users, which is not currently well-known by the average road user. Consequently, other road users may respond unexpectedly to this new system, a phenomenon termed 'behavioural adaptation' (OECD, 1990). To ensure compatibility between automated truck platoons and the transportation system, it is imperative to fully explore the behavioural adaptation of drivers in MVs, using the same road space as automated truck platoons.

While previous studies have examined behavioural adaptation during manual driving to automated truck platoons in various driving processes (Chen et al., 2022; Gouy et al., 2014; Lee et al., 2018; Razmi Rad et al., 2021), the overtaking process has been overlooked. Although overtaking only lasts a few seconds, it is a complex procedure requiring accurate situation judgment and flexible operation (Yang et al., 2018). On freeways, overtaking poses the risk of rear-end and lateral collisions. Statistics from the Ministry of Public Safety of China show that overtaking accidents account for about 30% of accidents on freeways (Ministry of Public Safety of China, 2021). Compared to overtaking a car, the risk of accidents can further increase when overtaking a truck. Existing studies have found that even a single truck can lead to changes in the driving behaviour of surrounding drivers (Figueira & Larocca, 2020), their attention allocation (Zhang et al., 2016) and mental workload (de Waard et al., 2009), during the overtaking process. Due to its length, an automated truck platoon may exacerbate these impacts and result in unexpected behaviours of surrounding drivers during overtaking.

Therefore, to ensure the safety of mixed traffic, it is crucial to understand how automated truck platoons influence surrounding drivers' behaviours during overtaking. This study aims to examine the effects of platoon organisation and traffic situations on the overtaking behaviours of nearby manual vehicle drivers. The results of this study can provide practical implications for the operational strategies of automated truck platoons.

1.1 Impacts of trucks on other drivers' overtaking behaviours

Accidents involving trucks contribute to approximately one-third of China's total traffic accidents on freeway (Ministry of Public Safety of China, 2021). In the USA, this number is approximately 50% (National Highway Traffic Safety Administration, 2023). One of the primary reasons behind this high ratio is the conspicuous size disparity between trucks and cars. This discrepancy becomes especially pronounced when other vehicles attempt to overtake a truck. Drivers not only contend with a lengthier longitudinal overtaking distance but also endure lateral pressure from the truck, due to its size and weight. This disparity can not only escalate the mental workload of overtaking drivers, but also possibly alter their driving behaviors, resulting in greater speed variability and reduced minimum time headway (de Waard et al., 2009; 2008).

Extensive research has explored the impact of trucks or long combination vehicles on the behaviour of other drivers during the overtaking process. Drivers have been found to exhibit more hesitation (Barton & Morrall, 1998) and frustration (Sabek et al., 2024) when preparing to overtake a truck compared to overtaking a car. Surprisingly, however, drivers have shown an even stronger willingness to overtake when confronted with a truck in comparison to a car (Gao et al., 2023).

In terms of driving behaviour, overtaking a truck has been shown to significantly increase both the time and distance required for overtaking, thereby elevating the risk of collisions with oncoming vehicles on two-lane highways (Hanley & Forkenbrock, 2005). Figueira and Larocca (2020) observed that a truck prompted drivers to maintain a larger following distance at the beginning of the overtaking maneuver. Furthermore, studies have investigated the impact of overtaking a truck on drivers' gaze behaviour. Zhang et al. (2016b) discovered that the presence of a truck led to a significant increase in both the duration and frequency of drivers' general gaze during the overtaking process.

The above studies have shed some light on how a single truck influences drivers' overtaking behaviour. However, when multiple trucks form a platoon, they collectively introduce a new dynamic to other drivers on the road. The platoon's exceptionally elongated length and unconventional arrangement may intensify the pressure felt by drivers, thereby influencing their decision-making and potentially leading to different driving behaviours during overtaking maneuvers. Consequently, it is imperative to examine how other drivers respond to automated truck platoons during the overtaking process.

1.2 Behavioural adaptations of human drivers to automated vehicle platoons

Due to its composition of multiple vehicles in close proximity, an automated vehicle platoon stands out conspicuously on the road, setting it apart from traditionally human-driven vehicles. Consequently, other drivers may exhibit different behaviours when interacting with automated vehicle platoons compared to interacting with human-driven vehicles, including changes in speed management, following strategies, and more. This shift in behaviour can be classified as 'behavioural adaptation,' denoting "*unintended change in the behavior of the users with the introduction of a new system against the system's intended designed operation*" (OECD, 1990).

Numerous studies have explored the behavioural adaptations of drivers to automated vehicle platoons using driving simulation. The number of trucks in a platoon as well as the inner gap of the platoon, are considered key influencing factors in affecting surrounding drivers' behaviour. Among these, the car-following process has been extensively examined (e.g., Chen et al., 2022; Gouy et al., 2014, 2013; Razmi Rad et al., 2021; Suh et al., 2017). Results show that drivers tend to mimic the close arrangement of the platoon and adopt smaller time headways during car-following, when compared to their usual behaviour (Gouy et al., 2013; Razmi Rad et al., 2021). This tendency becomes more pronounced as the inner gap of the platoon decreases (i.e., trucks in the platoon operate within a shorter distance to each other) (Chen et al., 2022; Gouy et al., 2014). Furthermore, a smaller inner gap is seen to intensify drivers' effort and alertness (Gouy et al., 2014). In addition to car-following, some studies have investigated the influence of automated vehicle platoons on the lane-changing behaviour of nearby drivers. The presence of automated vehicle platoons prompts drivers to engage in riskier lane-changing behaviours, such as accepting smaller gaps and making more drastic swerves (Razmi Rad et al., 2021; Trende et al., 2019). Moreover, the inner gap changes drivers' attention allocation during the lane change process (Guo et al., 2019). A few studies have also focused on the merging and diverging behaviours of drivers when interacting with automated vehicle platoons, and show that the size and inner gap of the platoon are contributing factors influencing the merging and diverging behaviours of surrounding drivers (Aramrattana et al., 2022; Wei et al., 2023; Yang et al., 2023). In addition, the recognizability of platoon significantly affects driving safety during the merging and diverging process of other vehicles (Sultana and Hassan, 2024).

Studies above have offered valuable insights into how drivers adapt their behaviour when interacting with automated vehicle platoons across various scenarios (e.g, car-following, lane-changing, merging and diverging). However, there has been comparatively less focus on the implications of automated vehicle platoons for the overtaking safety of other drivers. Particularly for truck platoons, their unique characteristics, resembling long and train-like formations, pose significant challenges for drivers attempting to overtake them. Using numerical computation, some studies have demonstrated a significant reduction in sight distance caused by automated truck platoons on freeways (Brewer & Fitzpatrick, 2017; Garcia & Pastor-Serrano, 2022; Haq et al., 2022; Thomas & Martinez-Perez, 2015). A study by Song (2024), investigating the collision risk associated with overtaking truck platoons revealed an increased risk of collision with longer platoon lengths or for higher speeds. These studies suggest that the organisation of the platoon, especially the number of trucks used and the inner gap between these, should be carefully considered to ensure overtaking safety by the surrounding traffic.

To the best of the authors' knowledge, only one existing study has investigated the influence of platoon size on drivers' acceptance of overtaking trucks (Larburu et al., 2010). However, this study primarily focused on participants' subjective feelings, overlooking their driving behaviours. Additionally, the platoon model in this study consisted of a leading truck and over ten following cars, differing significantly from prevalent automated truck platoons. Therefore, to ensure the safe deployment of automated truck platoons, there is a strong need for research into the influence of automated truck platoons on other drivers' behaviours, during overtaking.

1.3 Research gap and the current study

Based on the existing literature, we can conclude that extensive studies have been conducted to unveil the impact of the organisation of automated vehicle platoons on nearby drivers. Additionally, the impact of a single truck on drivers' overtaking behaviour is also well studied. However, three main research gaps remain. Firstly, the influence of automated truck platoons on nearby drivers' behaviours during the overtaking process is overlooked. Due to their sheer length, and an operating process that is not yet experienced on the real road, it can be argued that automated truck platoons may pose a big challenge for drivers who intend to overtake these formations. Therefore, the organisation of automated truck platoons should be carefully managed for the safety of mixed traffic. Secondly, the synergistic effect of multiple platoon-organisational factors has not been thoroughly studied. While existing research has explored individual factors, no study has holistically examined how these factors interact to influence drivers' behaviours. Thirdly, while it is known that the platoon organisation may cause a difference in drivers' alertness (Gouy et al., 2014) and visual attention allocation (Guo et al., 2019), the extent to which these differences impact drivers' response and collision risk in critical situations remains unclear. Therefore, it is crucial to investigate how different organisations of automated truck platoons affect drivers' behaviours during overtaking in both non-critical and critical scenarios.

The main objective of this study was to investigate the influence of an automated truck platoon's organisation on the road, on the overtaking behaviour of nearby drivers. Based on previous studies, the platoon's speed, size, and inner gap are considered as potential influencing factors. In addition to platoon organisations, the presence of a lead vehicle (LV) in the adjacent lane to the platoon was also considered to create a more realistic traffic situation.

The hypotheses of the study were:

H1: A higher number of trucks in the platoon, a higher platoon speed, and the presence of the LV will result in fewer overtaking maneuvers by drivers.

H2: A shorter inner gap within the platoon will prompt drivers to imitate and adopt smaller time headways to the LV. In conditions without an LV, this imitation will manifest as a higher average speed.

H3: A higher number of trucks in the platoon will result in a higher mental workload for drivers (H3a), maintaining a larger lateral distance to the platoon (H3b).

H4: Decreased inner gap will result in a higher mental workload for drivers(H4a), maintaining a larger lateral distance to the platoon (H4b), and reacting more quickly in critical situations (H4c).

The main innovation of the current study is its exploration of how the organisation of automated truck platoons impacts the behaviours of other drivers during one of the riskiest scenarios—the overtaking process. The findings from this study can provide valuable insights for designing the organisation of automated truck platoons.

2. Methodology

2.1 Participants

To calculate the sample size for the statistical analysis, a power analysis was conducted in G*Power. This analysis utilized a power of 0.80, an alpha level of 0.05, and effect sizes of large magnitude (f=0.40 for repeated measures ANOVA, and w=0.60 for a Pearson chi-square test). According to the assumptions above, the sample size for each respective statistical analysis method were determined as follows: 12 for repeated measures ANOVA and 22 for the Pearson chi-square test.

A total of 38 participants were recruited for the study through Internet. However, 3 participants abandoned the study due to driving simulation sickness. Therefore, 35 participants (22 males and 13 females) completed the experiment. All participants had valid driving licenses and normal or corrected-to-normal vision. The participants were aged between 21 to 52 years old (M = 28.1 years, SD = 6.3 years), and their driving experience varied between 2 to 18 years (M = 6.9 years, SD = 3.4 years). The ethical approval was unavailable due to the absence of an Ethics Committee at Tongji university. However, authors extensively deliberated on the experiment ’s risks beforehand and scrutinized the experimental procedures carefully to ensure the safety and the ethical feasibility of the experiment. Before the experiment, participants were informed that the data usage was solely restricted to this program. Additionally, the potential risk of simulator sickness and the privacy protection policy were disclosed to them. All participants gave consent to participate in this study.

2.2 Apparatus

The Tongji University driving simulator was utilized in this study, comprising both hardware and software components (Figure 1). The hardware system incorporates an eight-degree-of-freedom motion system operating on 20 × 5 m XY rails, an immersive 5-channel projection system offering a front image view spanning 250° × 40° at a resolution of 1000 × 1050, refreshed at 60 Hz. Additionally, it includes a vehicle motion control system featuring a fully equipped Megane III vehicle, installed within the cab of the simulation platform. The motion system enables 28.6, 15.6, and 6.95 m payload envelopes in the X, Y, and Z directions, respectively, with a maximum acceleration of 6.5 m/s^2 in all motion directions. The software utilized for rendering the road environment is the SCANeR^{TM} Studio 2023, which encompasses modules for scene modeling, vehicle parameters, scenario scripting, experimental simulation, and data analysis. The simulator's data sampling rate was set at 10 Hz.

Figure 1. Driving simulator of Tongji University

2.3 Driving environment

The simulated roadway comprised a typical two-lane Chinese highway with a speed limit of 120km/h. We deliberately limited the lanes to create a narrower visual setting and intensify the feeling of confinement for our drivers, induced by the truck platoon. A dual crash barrier separated the two carriageways, with a median divider width of 3 meters and each lane measuring 3.75 meters in width. Moderate-density traffic flow was implemented on the opposing carriageway to enhance realism.

The total length of the road model was 19.8km, as depicted in Figure 2. It comprised of four straight segments, with each pair of adjacent straight segments being separated by a transition segment consisting of curves and transition curves. To ensure that the road geometry did not influence drivers' overtaking behaviour, all overtaking maneuvers were conducted within the straight segments. Each straight segment was 2.4 km in length, consistent with the maximum allowable length of straight sections specified in China's highway design code. This length was chosen because, if drivers were unable to overtake the truck platoon within this distance, it would be nearly impossible for them to do so in real-life scenarios. The curves all had radii exceeding 1400m, and the road slope varied between -1.5% and +1.5%, striking a balance between creating a realistic road environment and ensuring moderate difficulty in vehicle manipulation for drivers. Other aspects of the road model adhered to the specifications outlined in China's highway design code.

The ego-vehicle model in the simulation environment was a Renault Megane III, with dimensions of 4.30 meters in length, 1.80 meters in width, and 1.47 meters in height. Its engine provided a maximum power output of 104kW. The trucks comprising the platoon were semi-trailers, each measuring 13.0 meters in length, 2.50 meters in width, and 3.65 meters in height. Driving scenes from the perspective of the ego vehicle are shown as Figure 3.

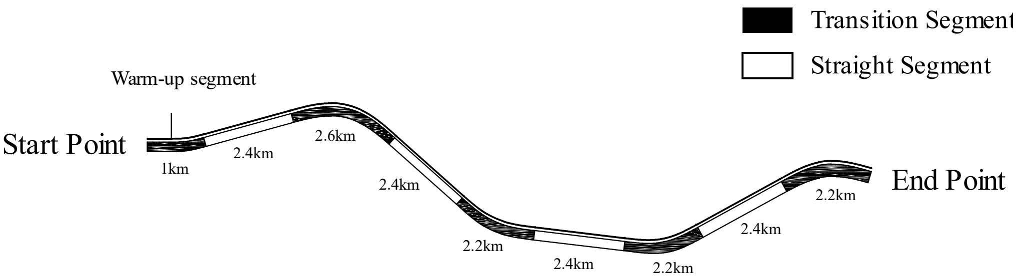

Figure 2. Description of the road

Figure 3. Driving scene from the perspective of the ego-vehicle. The left picture shows the 5-truck platoon with an inner gap of 25 m, and an LV; the right figure shows the 3-truck platoon with an inner gap of 5 m.

2.4 Experimental design and study variables

A repeated measures, within-subject, design was employed in this study, incorporating two distinct scenarios: non-critical and critical. The non-critical scenarios aimed to explore the influence of platoon organisation and traffic situations on drivers' overtaking behaviour in routine conditions, while the critical scenarios sought to assess the impact of platoon organisation on drivers' response to emergencies.

A 2 (platoon speed: 80km/h, 100km/h) × 2 (platoon size: three trucks, five trucks) × 2 (platoon inner gap: 5 m., 25 m.) × 2 (the presence of the LV: present, not present) design was implemented for the non-critical scenarios. Various platoon organisations are illustrated as Figure 4. The detailed specifications of these factors are as follows:

Platoon speed: This factor consisted of two levels - 80km/h and 100km/h. 100km/h was set as the upper level because it is the speed limit for trucks on freeways according to China's road traffic safety law.

Platoon size: Reflecting the number of trucks within the platoon, the platoon size had two levels: three and five trucks. Past field experiments (SAIC, 2020; Watanabe et al., 2021; Yang et al., 2021) have demonstrated variability in the number of trucks, typically ranging from three to five. Additionally, research by Castritius et al. (2020) suggested that a maximum of five vehicles received the highest level of public acceptance.

Platoon Inner Gap: Representing the distance between two adjacent trucks in the platoon, this factor was set at two levels: 5 m. and 25 m. Existing field tests have shown that the minimum inner gap achieved at high speed (exceeding 80km/h) is around 5m (Shladover, 2007; Tsugawa, 2014). Thus, 5m was set as the lower level. However, under certain conditions where fast and precise communication cannot be guaranteed, an increase in the inner gap may be necessary. Based on recent projects with relatively long test distances, an inner gap of 25m was deemed robust enough at high speeds (Castritius et al., 2021; SAIC, 2020).

Presence of the LV: Traffic situations can significantly influence drivers' overtaking behaviour. This factor distinguishes between scenarios with and without an LV. In scenarios with the LV, a vehicle was positioned in front of the ego vehicle during the overtaking process. Conversely, in scenarios without the LV, the ego vehicle was the sole vehicle alongside the truck platoon.

For critical scenarios, a 2 (platoon size: three trucks, five trucks) ×2 (platoon inner gap: 5 m., 25 m.) design was implemented. We did not use an equal number of non-critical and critical scenarios for two main reasons. First, to prevent participants from developing a learning effect on the critical event. Repeated exposure could make drivers anticipate it, potentially altering their natural responses. Second, to control the total experiment duration. A prolonged experiment leads to driver fatigue and simulation sickness, which could affect the results. Across all critical scenarios, the platoon maintained a speed of 100 km/h. Moreover, the LV was consistently present in all critical scenarios. The key distinction between critical and non-critical scenarios lies in the behavior of the

LV: in non-critical scenarios, the LV did not engage in any abrupt deceleration throughout the overtaking process, whereas in critical scenarios, the LV executed an abrupt braking maneuver midway through the overtaking.

In total, the experiment comprised a total of twenty scenarios, with sixteen non-critical scenarios and four critical scenarios. The twenty scenarios were evenly distributed into five road sections in a counterbalanced sequence. Participants encountered four scenarios in each road section. To mitigate any learning effect, four critical scenarios were interspersed among the non-critical ones. To prevent any carryover effect from the experimental sequence, the order of the five road sections was randomized for each participant.

At the onset of each road section, the platoons were stationed statically in the right lane at the start of straight segments, maintaining their predetermined size and inner gap. In scenarios with an LV, a car was positioned statically in the left lane, trailing 200 meters behind the last truck of the platoon. A designated triggering point initiated the motion of both the platoon and the LV, situated 500 meters behind the last truck. This distance was determined through a pre-test conducted before the formal experiment to ensure that participants did not anticipate and adjust their speed unexpectedly. Upon the ego vehicle reaching this point, all trucks within the platoon accelerated at a rate of $1.5 m/s^2$ until reaching the preset speed, concurrently with the LV's acceleration.

During the ego vehicle's approach, the LV's acceleration underwent phased changes designed to mitigate the sense of abrupt acceleration and ensure that both the LV's speed and its distance from the ego vehicle were well controlled. The LV's acceleration process can be divided into three phases:

1. Once the ego vehicle reached the triggering point, the LV would accelerate at 2.5 m/s^2 for 8 seconds, reaching a speed of 72 km/h. Then its speed would maintain until the next acceleration phase. During this period, the distance between the LV and the ego vehicle continuously decreased. This initial acceleration phase was designed to bring the LV from a standstill to a relatively high speed.
2. When the distance between the ego vehicle and the LV decreased to 100 meters, the system would record the ego vehicle's speed at that moment, setting the target speed of the LV in this phase to be 3 m/s lower than the ego vehicle's speed. The system would then calculate the required acceleration for the LV to reach this target speed within 2 seconds. For example, if the ego vehicle's speed was 30 m/s when the

distance decreased to 100 meters, the target speed of the LV would be 27 m/s. Consequently, the LV would accelerate at 3.5 m/s^2 for 2 seconds. After this, the LV would maintain the target speed until the next acceleration phase. This second acceleration phase helped the LV's speed gradually approach that of the ego vehicle, ensuring a smooth transition and preventing abrupt changes in the LV's speed in the following phase.

3. When the distance between the LV and the ego vehicle decreased to 75 meters, the speed of the LV would immediately match that of the ego vehicle. From that point onward, the LV would maintain synchronized speed with the ego vehicle. This phase ensured that the two vehicles reached the expected state of dynamic equilibrium. Pre-test results indicated that the LV's speed adjustment was smooth and did not cause any discomfort or unnatural perception for the participant.

The final speed of the LV after acceleration completely dependent on the speed of the ego vehicle. Once the distance between the LV and the ego vehicle decreased to 75 meters, the LV's speed matched that of the ego vehicle, maintaining this synchrony thereafter. This means that in all non-critical scenarios and in critical scenarios before the critical event was triggered, the speed of the LV would change synchronously with that of the ego vehicle without any delay. The reason for aligning the speed of the LV with that of the ego vehicle, instead of maintaining a constant speed, was to deter certain participants from waiting until the LV had overtaken the platoon entirely before initiating their own overtaking maneuvers. This approach aimed to preserve the influence exerted by the LV on overtaking behaviour.

The difference between the non-critical and critical scenarios lies in whether an urgent brake of the LV occurs. In non-critical scenarios with the LV, the LV maintained a constant distance from the ego vehicle throughout the overtaking process, and the platoon's speed remained constant. However, in critical scenarios, when the ego vehicle aligned with the middle truck in the platoon (i.e., second truck for three-truck platoons and third truck for five-truck platoons), the LV would decelerate at 5m/s^2 until reaching 70km/h. Simultaneously, the platoon decelerated at a rate of 2m/s^2 until reaching 60km/h. Participants needed to implement countermeasures promptly to avert potential collisions. Before the LV initiated the urgent brake, the participant was unable to distinguish whether the current scenario was critical or non-critical.

If the ego vehicle had not overtaken the first truck of the platoon in non-critical scenarios or triggered the deceleration of the LV in critical scenarios by the time the first truck of the platoon reached the end of the straight section, the platoon would decelerate to 60 km/h. Furthermore, if there was an LV, it would go to the right lane and decelerate, facilitating the ego vehicle's overtaking maneuver. Nevertheless, this overtaking attempt would be classified as incomplete.

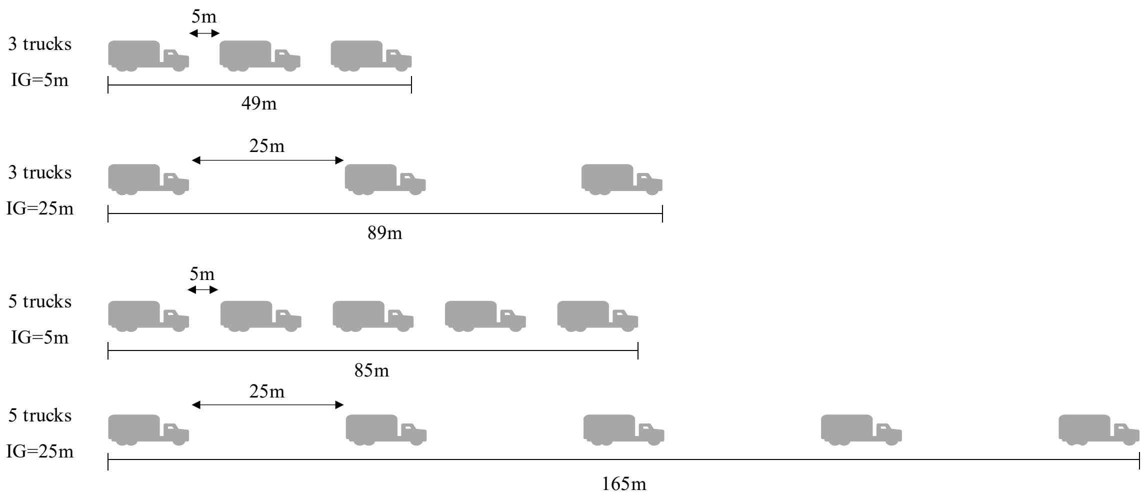

Figure 4. Illustration of platoons with different organisations. IG denotes the inner gap of the platoon

2.5 Procedure

On arrival, participants completed a demographic questionnaire and were asked to sign a consent form. Participants were given instructions about the experiment at the beginning. These asked them to drive on a freeway with a speed limit of 120km/h and specifically stay in the right lane unless they tended to overtake other vehicles. To prevent drivers from adopting overly passive driving maneuvers, participants received the following instruction:

[…] "Imagine that you are driving to the train station to catch a train. However, there is only half an hour left to the departure of the train. Under the premise of ensuring safety, you need to hurry up and try to overtake slow vehicles on the right lane rather than following them." […]

Participants were told that the overtaking was not compulsory. If they deemed an overtaking maneuver to be risky, they did not have to complete the maneuver.

Before engaging in the formal experiment, participants completed a practice session for about 10 minutes, during which they performed several overtaking maneuvers to be acquainted with the simulated driving environment and vehicle controls. Following this practice session, participants proceeded to undertake the formal experiments. After each completed overtaking, the experimenter orally assessed the participant's NASA-TLX score using a microphone. Additionally, participants were granted a 5-minute break between each road section to alleviate potential fatigue. Each participant received a compensation of $15 upon the completion of the experiments.

2.6 Dependent variables

As shown in Table 1, a range of variables were selected to evaluate participants' driving behaviour in non-critical and critical scenarios. Drivers' subjective mental workload were accessed in both non-critical and critical scenarios with NASA-TLX scores.

Table 1

Definitions of dependent variables.

Scenarios	Variables	Abbreviations
Non-critical	Overtaking completion rate	OCR
	Overtaking time	OT
	Mean speed	V_{mean}
	Standard deviation of speed	V_{std}
	Mean lateral position	LP_{mean}
	Standard deviation of lateral position	SDLP
	Maximum lateral acceleration	LA_{max}
	Subjective mental workload	-
Critical	Response time	RT
	Minimum time to collision	TTC_{min}
	Subjective mental workload	-

As described earlier, the truck platoon operates as a significant presence on the road, potentially dissuading drivers from attempting overtaking maneuvers and exacerbating the challenge of such maneuvers. Consequently, overtaking completion rate (OCR) was considered to assess whether the truck platoon posed an obstacle to overtaking. The OCR was calculated as the ratio of the number of participants who successfully completed overtaking and the total number of participants. In addition, overtaking time (OT) was used to assess the efficiency of the overtaking. It was measured from the overtaking start point to the overtaking end point, which will be elaborated upon at the end of this section.

The indicators for longitudinal driving performance evaluation included mean velocity (V_{mean}) and standard deviation of velocity (V_{std}). V_{mean} offered insights into the vehicle's longitudinal motion state during a period, while V_{std} could represent the fluctuation of the vehicle's speed (Chen et al., 2022; Yang et al., 2023). Indicators considered for lateral driving performance were mean lateral position (LP_{mean}), standard deviation of lateral position (SDLP) and maximum lateral acceleration (LA_{max}). LP_{mean} represented the lateral offset to the centerline during a period, reflecting the risk of lateral collision. SDLP represents the stability of lane keeping, which can be used to evaluate the lateral overtaking stability (Chen et al., 2022; Gouy et al., 2014). LA_{max} is good indicator of the jerkiness of the vehicle motion and can evaluate the vehicle's lateral stability in lane-changing process (Madigan et al., 2018).

For critical scenarios, the indicators included the response time (RT) and the minimum time to collision (TTC_{min}). As outlined in the introduction, different platoon formations might influence drivers' alertness and attention, thus affecting their response capability. RT was chosen to evaluate drivers' response ability across various platoon organisation scenarios. It was calculated as the time interval between the initiation of braking by the LV and the detection of a brake pedal application exceeding 10% (note that the steering wheel maneuver was not considered as all drivers initially applied the brakes rather than changing lanes). TTC_{min} is an effective metric for assessing the severity of potential collisions, calculated by dividing the distance gap between the ego-vehicle and the LV by their relative speed. A low value of TTC_{min} indicated a high potential of a rear-end collision with the LV (Louw et al., 2017).

The NASA-TLX (Task Load Index) (Hart & Staveland, 1988) was implemented to evaluate drivers' subjective mental workload after each overtaking. NASA-TLX has six sub-scales: mental demand, physical demand, temporal demand, performance, effort, and frustration, and participants needed to score every sub-scale from 0 to 10. This process was conducted orally. The total NASA-TLX was calculated as a weighted sum. The higher the NASA-TLX, the higher the mental workload felt by the participant.

As shown in Figure 5, four points were used to represent the different stages in the overtaking process. The overtaking start denoted the moment when the lateral position of the vehicle increased continuously for 3 seconds, and the lane-keeping start denoted the moment when the maintained lateral position remained constant or started to decrease for the next one second (Soni et al., 2020).

Correspondingly, the lane-keeping end denoted the moment when the lateral position decreased continuously for 3 seconds, and the overtaking end denoted the moment when the lateral position was constant or started to increase for the next one second. Following extraction, these points were manually inspected to ensure accuracy. As a result, three sections were defined by these points: overtaking start section, overtaking straight section, and overtaking end section. V_{mean} and V_{std} were examined respectively for all three sections. Considering that the lane change was a dynamic process, we only selected the overtaking straight section as the time window for LP_{mean} and SDLP. The time window for LA_{max} covered the lane-changing process, which included overtaking start section and overtaking end section.

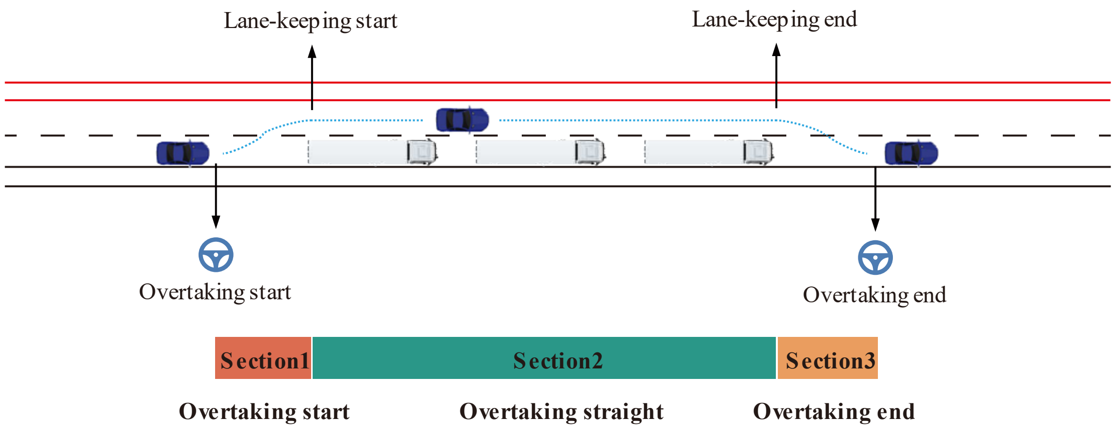

Figure 5. Illustration of different stages in the overtaking process

2.7 Data analysis

No crashes occurred in any of the non-critical scenarios. However, a total of five crash cases were recorded among four participants in the critical scenarios. Due to the impact of crashes on vehicle control metrics and participants' psychology, these incidents were excluded from the analysis of TTC_{min} and subjective mental workload.

The normality and the homogeneity of the variance of the data were examined to test whether the prerequisites of ANOVA could be met. Shapiro Wilk's tests showed that for each dependent variable, except V_{std}, most of the group-level estimates (>83%) were normally distributed, either independently or after logarithmic transformation. Levene's tests were conducted to test the homogeneity of variance. Although variance heterogeneity was found in some dependent variables, the ANOVA was robust enough for such heterogeneity when the group sizes were almost equal (largest/smallest <1.5) (Pituch & Stevens, 2015). Therefore, for the non-critical scenarios, a 2 (platoon speed: 80km/h, 100km/h)×2 (platoon size: three trucks, five trucks)×2 (platoon inner gap: 5 m., 25 m.)×2 (the presence of the LV: present, not present) repeated-measures ANOVA was conducted, for each dependent variable (apart from V_{std}), with the platoon speed, the presence of the LV, the platoon size and the inner gap as factors. For V_{std}, the Wilcoxon signed rank test was applied. For every dependent variable in the critical scenarios, a 2 (platoon size: three trucks, five trucks) ×2 (platoon inner gap: 5 m., 25 m.) repeated-measures ANOVA was conducted, with the platoon size and the inner gap as factors. Due to the limited number conditions, only the main and two-way interaction effects are reported. The α-value of the statistical significance was 0.05, and the partial-eta squared was used as the effect size statistic.

3. Results

3.1 Non-critical scenarios

3.1.1 Overtaking completion rate (OCR)

Figure 6 shows the OCR under different conditions. The results of Pearson chi-square tests show that the platoon speed (χ^2 = 14.200, p < .001), the presence of the LV (χ^2 = 27.081, p < .001) and the inner gap (χ^2 = 3.896, p = .048) significantly affected the OCR, while the platoon size not (χ^2 = .032, p = .858). Specifically, drivers successfully completed more overtakes when the platoon's speed was 80 km/h (OCR=97.9%) in comparison to 100 km/h (OCR=90.4%). Furthermore, drivers completed more overtakes successfully in the absence of an LV (OCR=99.3%) in comparison to the presence of an LV (OCR=88.9%). Finally, the OCR was significantly higher when the inner gap of the platoon was 5 meters (OCR=96.1%) than 25 meters (OCR=92.1%). The next section outlines drivers' longitudinal behaviour during the study.

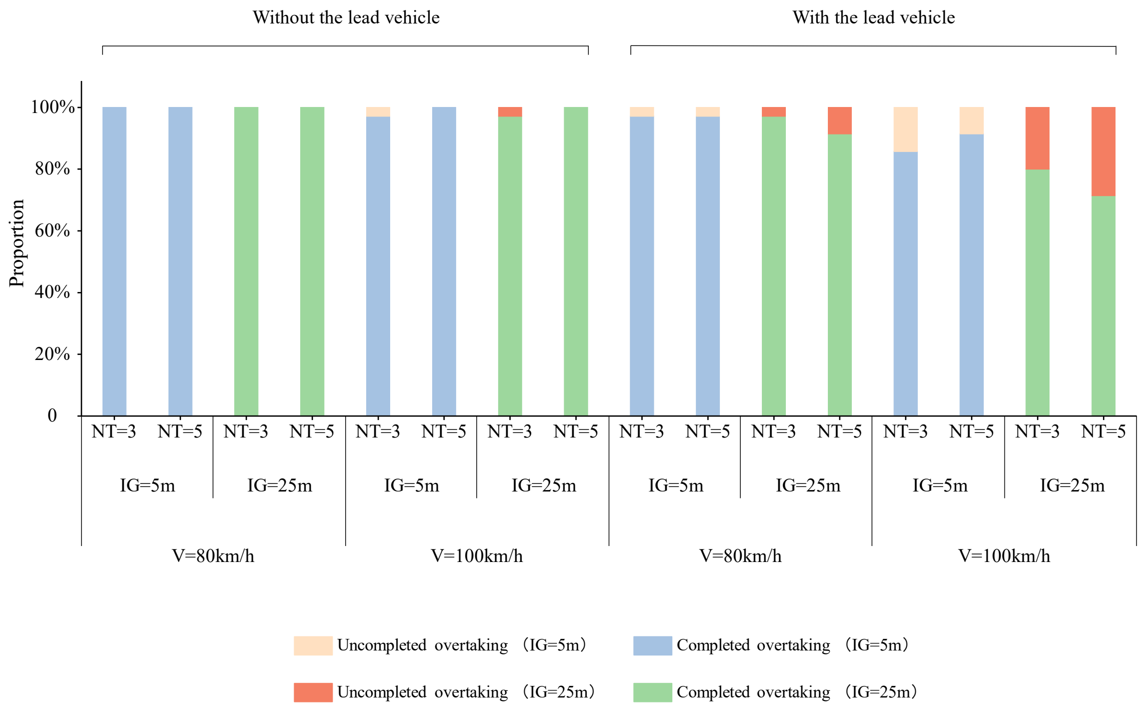

Figure 6. OCR in different scenarios. NT denotes the number of trucks in the platoon, IG denotes the inner gap, and V denotes the speed of the platoon.

3.1.2 Overtaking time (OT)

As shown in Figure 7, the platoon speed (F (1,18) = 208.542, p < .001, η^2_p= .921), the platoon size (F (1,18) = 46.051, p < .001, η^2_p= .719), the inner gap (F (1,18) = 247.295, p < .001, η^2_p= .932) and the presence of the LV (F (1,18) = 12.190, p = .003, η^2_p = .404) all showed significant effects on OT. OT was significantly higher when the platoon's speed was 100 km/h (M = 41.71 s, SD = 13.92 s) than 80km/h (M = 28.96 s, SD = 9.10 s). Additionally, OT was significantly longer with 5-truck platoons (M = 38.61 s, SD = 12.97 s) compared to 3-truck platoons (M = 31.53 s, SD = 12.63 s). Furthermore, OT was significantly higher with an inner gap of 25 m (M = 38.27 s, SD = 13.60 s) in comparison with an inner gap of 5 m (M = 31.99 s, SD = 12.20 s). When the LV was present, OT was significantly greater (M = 36.98 s, SD = 13.55 s) compared to its absence (M = 33.35 s, SD = 12.80 s). A significant interaction effect was observed between speed and inner gap (F (1,18) = 6.994, p = .016, η^2_p = .280), as illustrated in Figure 8(a). Compared to 100km/h, the inner gap had a smaller impact on OT at 80km/h. Additionally, a significant interaction effect was observed between platoon size and inner gap (F (1,18) = 8.088, p

= .011, η^2_p = .310), as illustrated in Figure 8(b). Compared to a 3-truck platoon, the effect of the inner gap on OT became more pronounced in the 5-truck platoon condition.

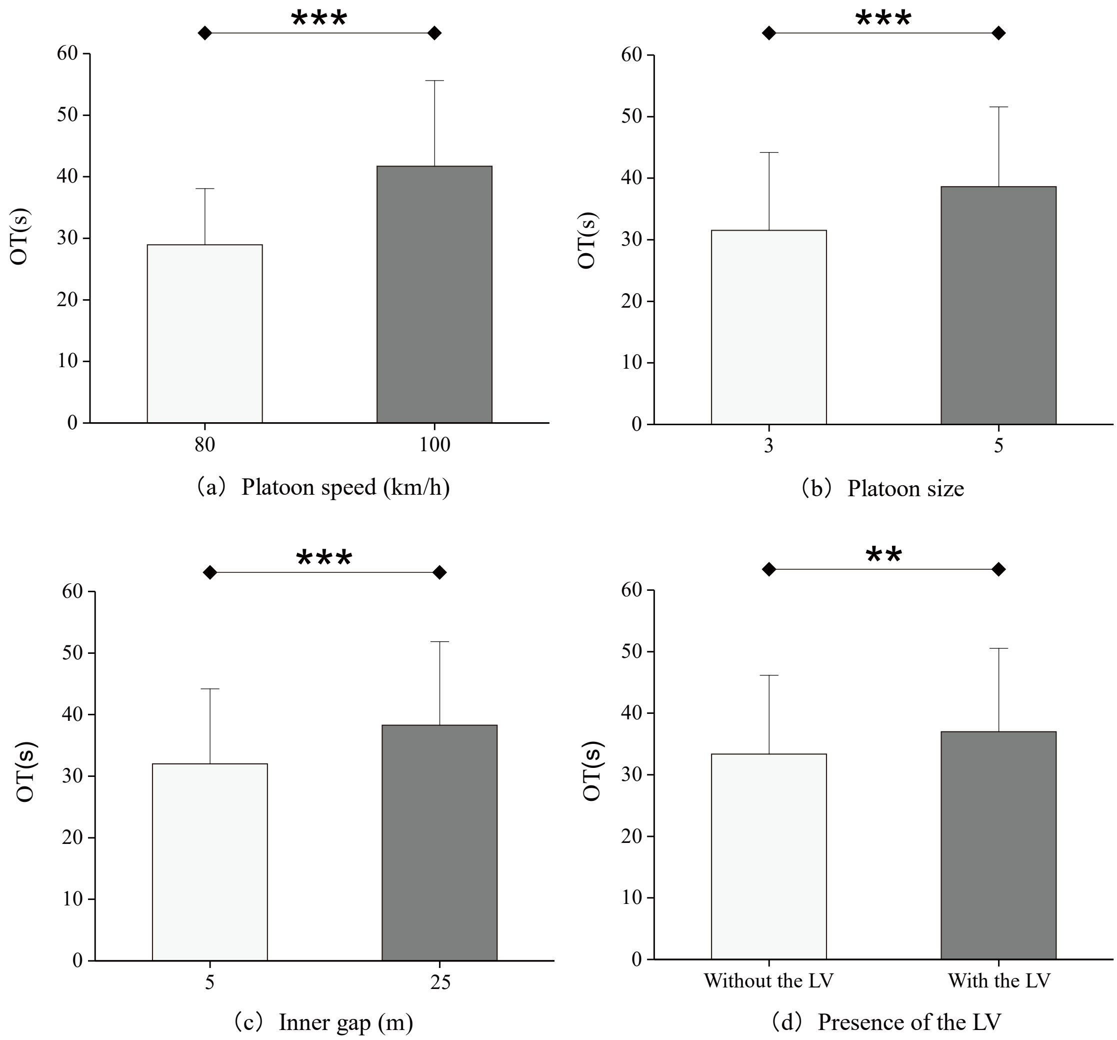

*Figure 7. OT as a function of platoon speed (a), platoon size (b), inner gap (c), and presence of the LV (d). Bars represent means, error bars represent standard deviations (**p <.01, ***p <.001).*

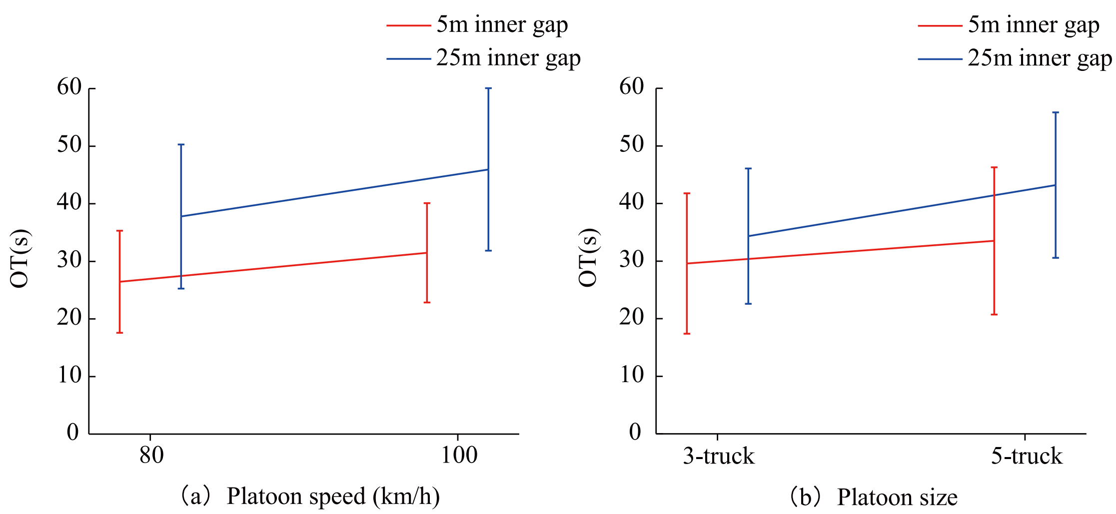

Figure 8. Interaction effects of inner gap and platoon speed (a), and inner gap and platoon size (b) on OT.

3.1.3 Mean speed (V_{mean})

3.1.3.1 Overtaking start section

None of the independent variables showed any significant main effect on the V_{mean} during the overtaking start section. However, a significant interaction effect between the platoon size and the inner gap was seen (F (1,18) = 17.046, p = .001, $\eta^2{}_p$ = .486, see Figure 9). Results indicated that during the five trucks conditions, the V_{mean} was higher for the overtaking start section when the inner gap was 25 m, compared to the 5m condition.

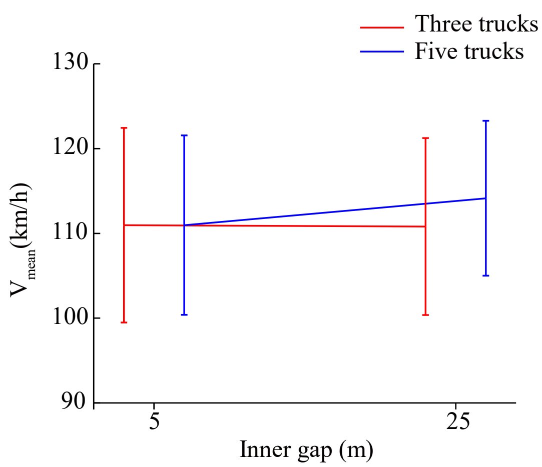

Figure 9. Interaction effects of inner gap and platoon size on V_{mean} in overtaking start section.

3.1.3.2 Overtaking straight section

As shown in Figure 10, the ANOVA results indicate that both the platoon speed (F (1,18) = 28.555, p < .001, η^2_p= .613) and the presence of the LV (F (1,18) = 9.054, p = .008, η^2_p = .335) had significant effects on V_{mean} in the overtaking straight section, while the platoon size (F (1,18) = 1.134, p = .301, η^2_p = .059) and the inner gap did not (F (1,18) = 2.568, p = .126, η^2_p = 0.125). V_{mean} was significantly higher when the platoon's speed was 100km/h (M = 119.67 m/s, SD = 7.22 m/s) in comparison to 80km/h (M = 115.49 m/s, SD = 9.27 m/s). Additionally, V_{mean} was significantly higher in the absence of an LV (M = 120.06 m/s, SD = 7.88 m/s) compared to the presence of an LV (M = 114.64 m/s, SD = 8.49 m/s). A significant interaction effect was found between the platoon size and the inner gap (F (1,18) = 4.802, p = .042, η^2_p = .211), as shown in Figure 11. Results revealed that under the five trucks conditions, V_{mean} in overtaking straight section was higher with an inner gap of 25m compared to 5m.

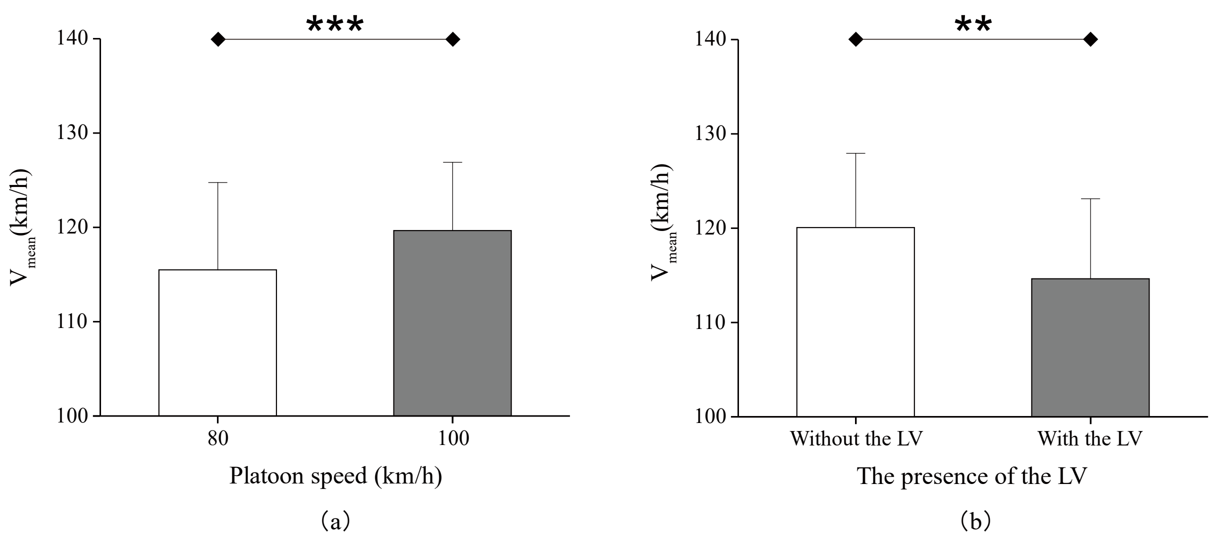

*Figure 10. V_{mean} in overtaking straight section as a function of platoon speed (a) and presence of LV (b). Bars represent means, error bars represent standard deviations (**p <.01, ***p <.001).*

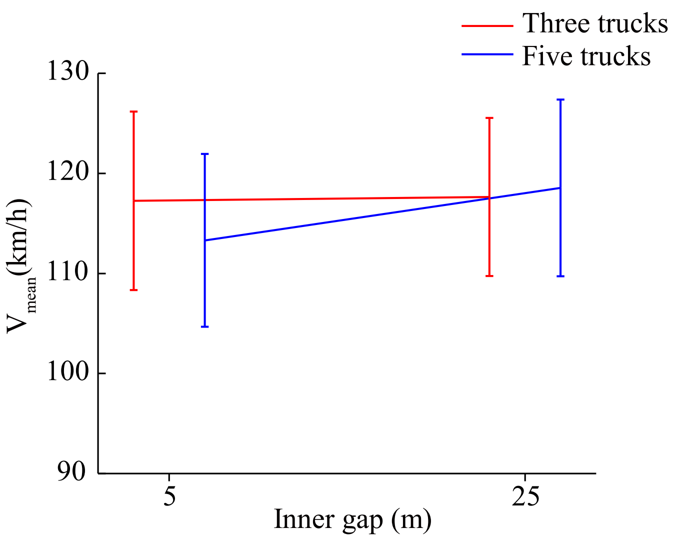

Figure 11. Interaction effects of inner gap and platoon size on V_{mean} in overtaking straight section.

3.1.3.3 Overtaking end section

As shown in Figure 12, only the platoon speed (F (1,18) = 27.880, p < .001, η^2_p = .608) showed a significant effect on V_{mean} in overtaking end section, while the inner gap (F (1,18) = .194, p = .665, η^2_p = .011), the platoon size (F (1,18) = 3.671, p = .071, η^2_p = .169), and the presence of the LV did not (F (1,18) = .996, p = .331, η^2_p = .052). V_{mean} was significantly higher when the platoon speed was 100km/h (M = 120.92 m/s, SD = 12.00 m/s), compared to 80km/h (M = 116.14 m/s, SD = 10.54 m/s). No significant two-way interactions were observed.

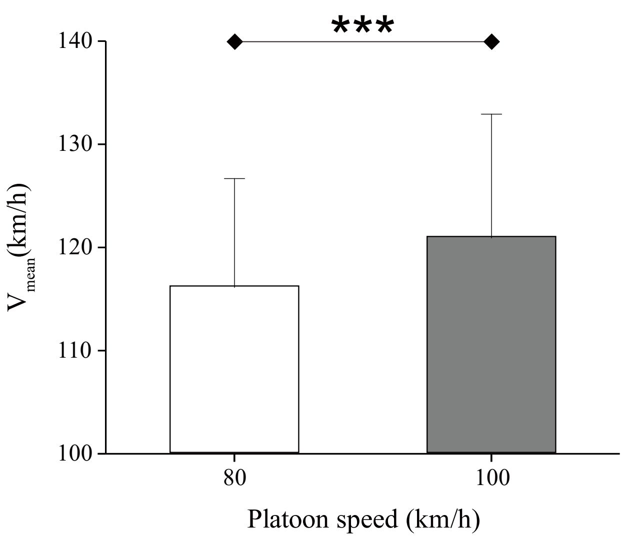

Figure 12. V_{mean} in overtaking end section as a function of platoon speed. Bars represent means,

*error bars represent standard deviations (**p <.01, ***p <.001).*

3.1.4 Standard deviation of speed (V_{std})

3.1.4.1 Overtaking start section

The results of the Wilcoxon signed rank test showed that both the platoon speed (Z = -4.432, p < .001) and the platoon size (Z = -2.497, p = .013) had significant effects on V_{std} in the overtaking start section, as shown in Figure 13. Specially, V_{std} was significantly lower when the platoon speed was 80km/h (M = 1.49 m/s, SD = 1.50 m/s) than 100km/h (M = 2.12 m/s, SD = 2.56 m/s). In addition, V_{std} was significantly lower with 5-truck platoons (M = 1.57 m/s, SD = 1.76 m/s) compared to 3-truck platoons (M = 2.01 m/s, SD = 2.38 m/s).

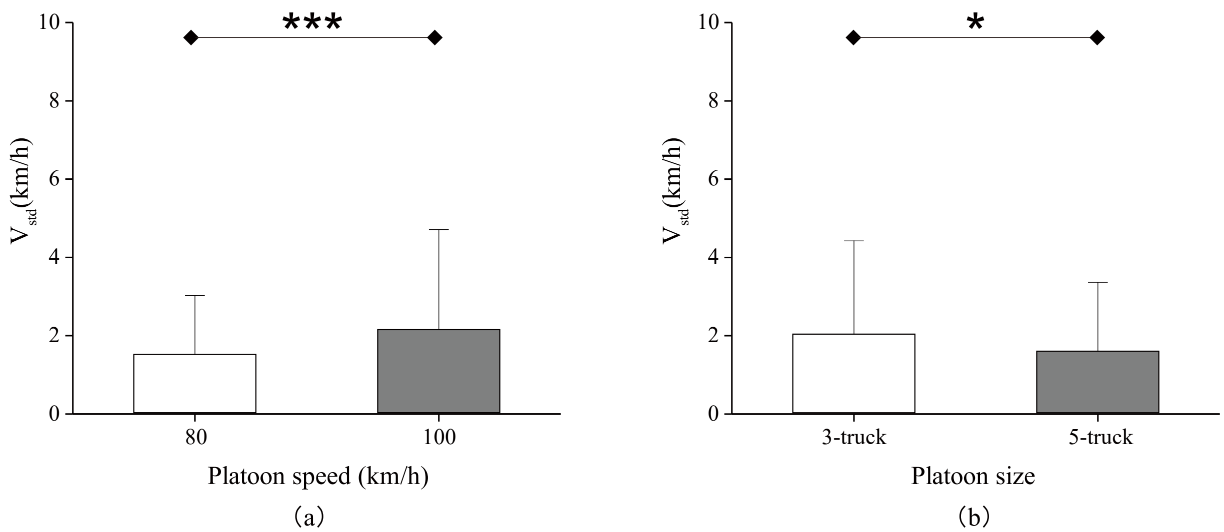

*Figure 13. V_{std} in the overtaking start section as a function of platoon speed (a) and platoon size (b). Bars represent means, error bars represent standard deviations (*p <.05, ***p <.001).*

3.1.4.2 Overtaking straight section

The results of the Wilcoxon signed rank test showed that both the platoon speed (Z = -3.728, p < .001) and the presence of the LV (Z = -5.799, p < .001) had significant effects on V_{std} in overtaking straight section, as shown in Figure 14. Specifically, with a platoon speed of 80 km/h (*M* = 2.78 m/s, *SD* = 2.52 m/s), V_{std} was significantly lower than that of 100km/h (*M* = 4.06 m/s, *SD* = 3.97 m/s). Furthermore, V_{std} was significantly lower in the absence of an LV (*M* = 2.58 m/s, *SD* = 2.71 m/s) compared to the presence of an LV (*M* = 4.29 m/s, *SD* = 3.76 m/s).

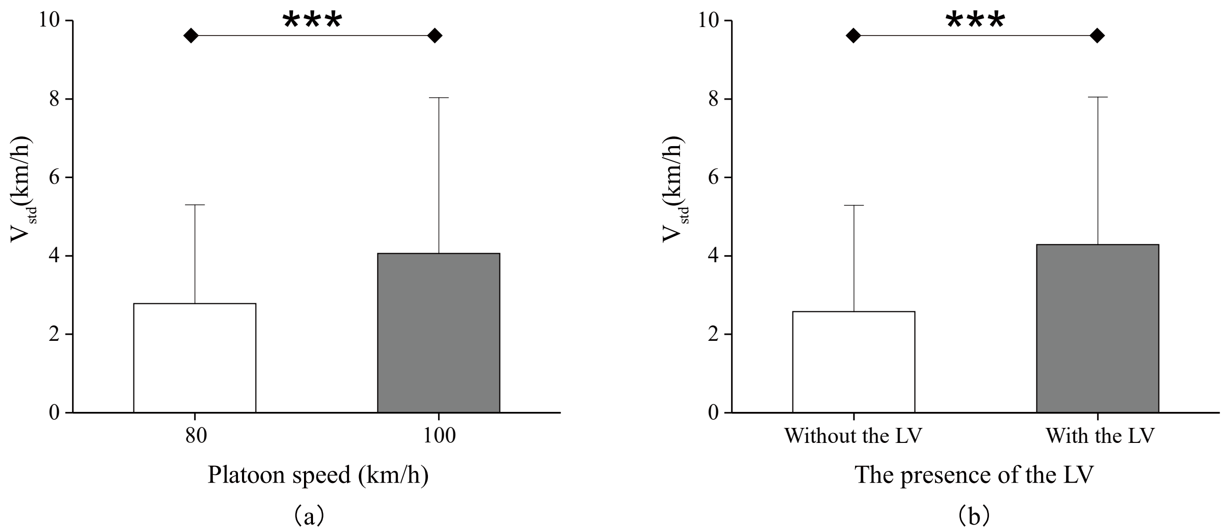

*Figure 14. V_{std} in overtaking straight section as a function of platoon speed (a) and the presence of the LV (b). Bars represent means, error bars represent standard deviations (***p <.001).*

3.1.4.3 Overtaking end section

The results of the Wilcoxon signed rank test showed that only the presence of the LV (Z = -2.520, p = .012) had a significant effect on V_{std} in the overtaking end section, as shown in Figure 15. V_{std} was significantly lower in the absence of the LV (*M* = 0.46 m/s, *SD* = 0.82 m/s) compared to the presence of the LV (*M* = 0.56 m/s, *SD* = 0.70 m/s).

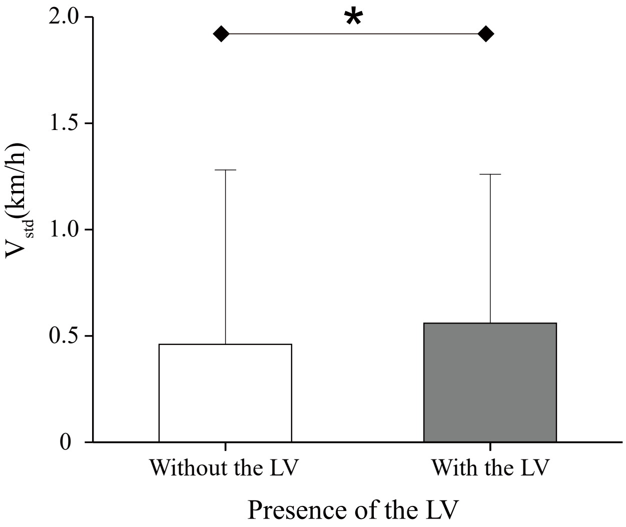

Figure 15. *V_{std} in overtaking end section as a function of presence of the LV. Bars represent means, error bars represent standard deviations (*p <.05).*

3.1.5 Mean lateral position (LP_{mean})

As shown in Figure 16, the ANOVA results indicate that both the platoon size (F (1,18) = 9.256, p = .007, η^2_p = .340) and the inner gap (F (1,18) = 17.966, p < .001, η^2_p = .500) had a significant effect on LP_{mean}, while the platoon speed (F (1,18) = 1.732, p = .205, η^2_p = .088) and the presence of the LV did not (F (1,18) = .026, p = .874, η^2_p = .001). Compared to the conditions with three trucks (M = -0.03 meters, SD = 0.25 meters), LP_{mean} was significantly higher with five trucks (M = 0.07 meters, SD = 0.23 meters). This suggests that in the scenarios with five trucks, the ego vehicle tended to deviate towards the median divider and away from the platoon by an average of 0.1m. For the scenarios with three trucks, the ego vehicle tended to drive in the center of the lane. In addition, LP_{mean} was significantly higher when the inner gap was 25m (M = 0.06 meters, SD = 0.24 meters) compared to 5m (M = -0.02 meters, SD = 0.25 meters). This indicated that drivers tended to deviate farther from the truck platoon by an average of 0.08m under 25m conditions compared to 5m conditions. No significant two-way interactions were observed.

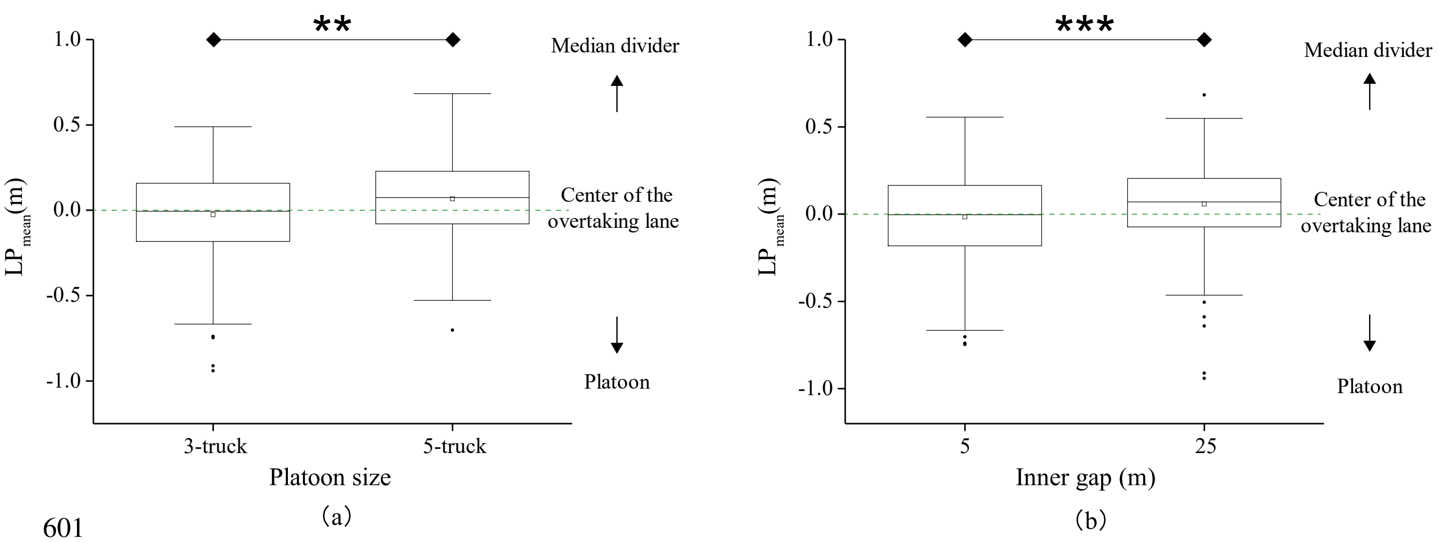

*Figure 16. LP_{mean} as a function of platoon size (a) and Inner gap (b). The green dash line represents the center of the overtaking lane. If a dot located above this line, it means it is closer to the median divider. If a dot located below this line, it means it is closer to the platoon (**p <.01, ***p <.001).*

3.1.6 Standard deviation of lateral position (SDLP)

None of the independent variables exhibited any significant main effect on SDLP, and not interactions were observed (see Appendix).

3.1.7 Maximum lateral acceleration (LA_{max})

3.1.7.1 Overtaking start section

The results of the ANOVA tests showed that both the presence of the LV (F (1,18) = 5.906, p = .026, η^2_p= .247) and the inner gap (F (1,18) = 4.924, p = .040, η^2_p= .215) had significant effects on LA_{max} during the overtaking start section, as shown in Figure 17. Specifically, LA_{max} was significantly lower in the absence of the LV (M = 1.20 m/s^2, SD = 0.62 m/s^2), compared to the condition when the LV was present (M = 1.30 m/s^2, SD = 0.62 m/s^2). In addition, LA_{max} was significantly lower with an inner gap of 25m (M = 1.22 m/s^2, SD = 0.57 m/s^2) compared to 5m (M = 1.27 m/s^2, SD = 0.67 m/s^2). A significant interaction effect was found between the presence of the LV and the platoon size (F (1,18) = 6.115, p = .024, η^2_p= .254), as shown in Figure 18. Results indicated that with five trucks, LA_{max} in overtaking start section was higher in the presence of the LV compared to when the LV was absent.

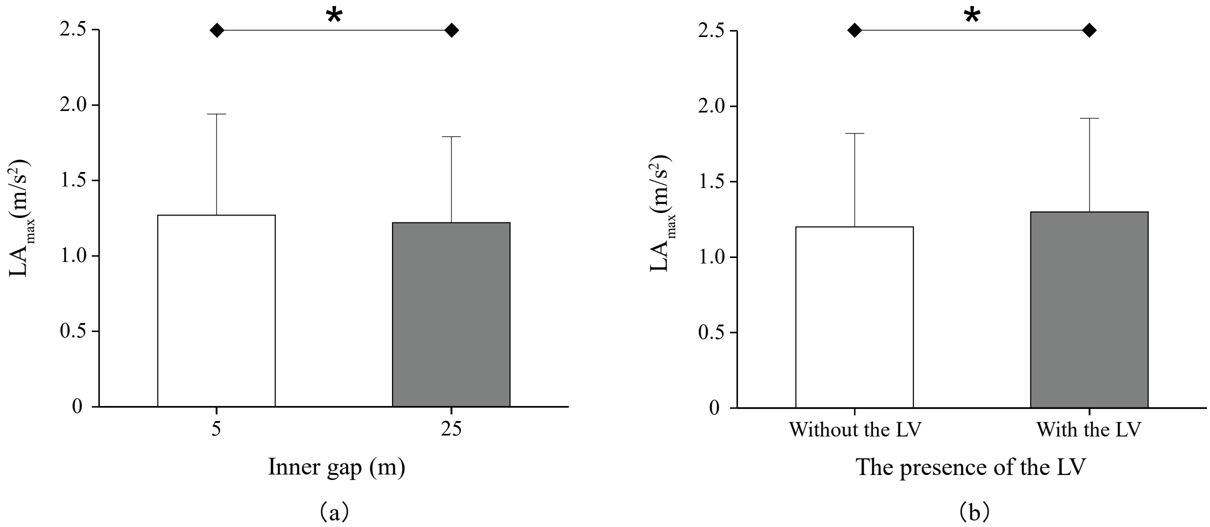

*Figure 17. LA_{max} in overtaking start section as a function of inner gap (a) and the presence of the LV (b). Bars represent means, error bars represent standard deviations (*p <.05).*

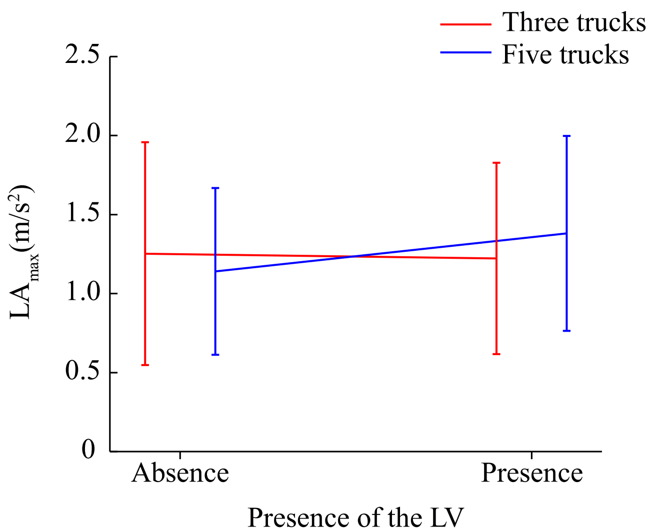

Figure 18. Interaction effects of the presence of the LV and platoon size on LA_{max} in overtaking start section.

3.1.7.2 Overtaking end section

Results of the ANOVA tests showed that only the inner gap (F (1,18) = 4.891, p = .040, η^2_p= .214) showed a significant effect on LA_{max} in the overtaking end section, as shown in Figure 19. LA_{max} was significantly lower with an inner gap of 25m (M = 1.20 m/s^2, SD = 0.67 m/s^2) compared to 5m (M = 1.30 m/s^2, SD = 0.76 m/s^2). No significant two-way interactions were observed.

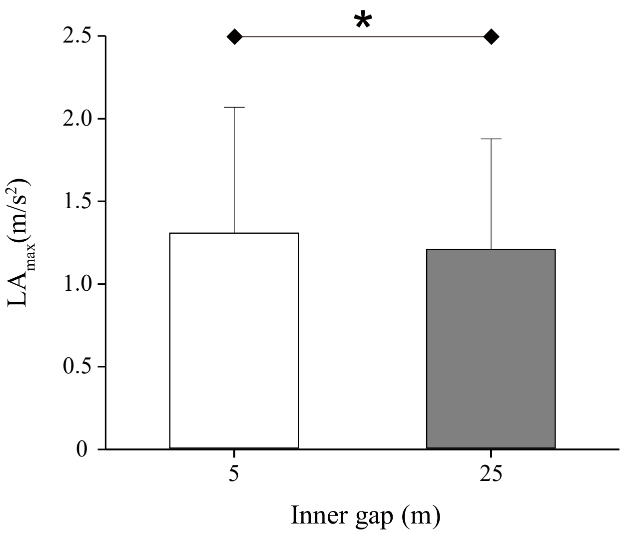

*Figure 19. LA_{max} in overtaking end section as a function of inner gap. Bars represent means, error bars represent standard deviations (*p <.05).*

3.1.8 Subjective mental workload

The results of the ANOVA test on NASA-TLX scores showed that the presence of the LV (F (1,18) =36.200, p < .001, η^2_p = .668), the platoon speed (F (1,18) = 31.178, p < .001, η^2_p = .634) and the platoon size (F (1,18) = 10.184, p = .005, η^2_p = .361) had significant effects on drivers' NASA-TLX feedback, while the inner gap did not (F (1,18) = 2.920, p = .105, η^2_p = .140 - see Figure 20. NASA-TLX was found to be higher for the conditions with LV (M = 3.84, SD = 1.44), when compared to conditions without the LV (M = 3.34, SD = 1.25). In addition, NASA-TLX was significantly higher in the 100km/h conditions (M = 3.86, SD = 1.47), compared to the 80km/h conditions (M = 3.33, SD = 1.22). The 5-truck platoon also resulted in higher average response to NASA-TLX (M = 3.77, SD = 1.41), compared to conditions with a 3-truck platoon (M = 3.39, SD = 1.30), The interaction effect of the platoon speed and the platoon size almost approached significance (F (1,18) =3.893, p= .064, η^2_p= .178), as shown in Figure 21. This indicated that with a platoon speed of 100km/h, the gap of NASA-TLX between five-truck conditions and three-truck conditions increased.

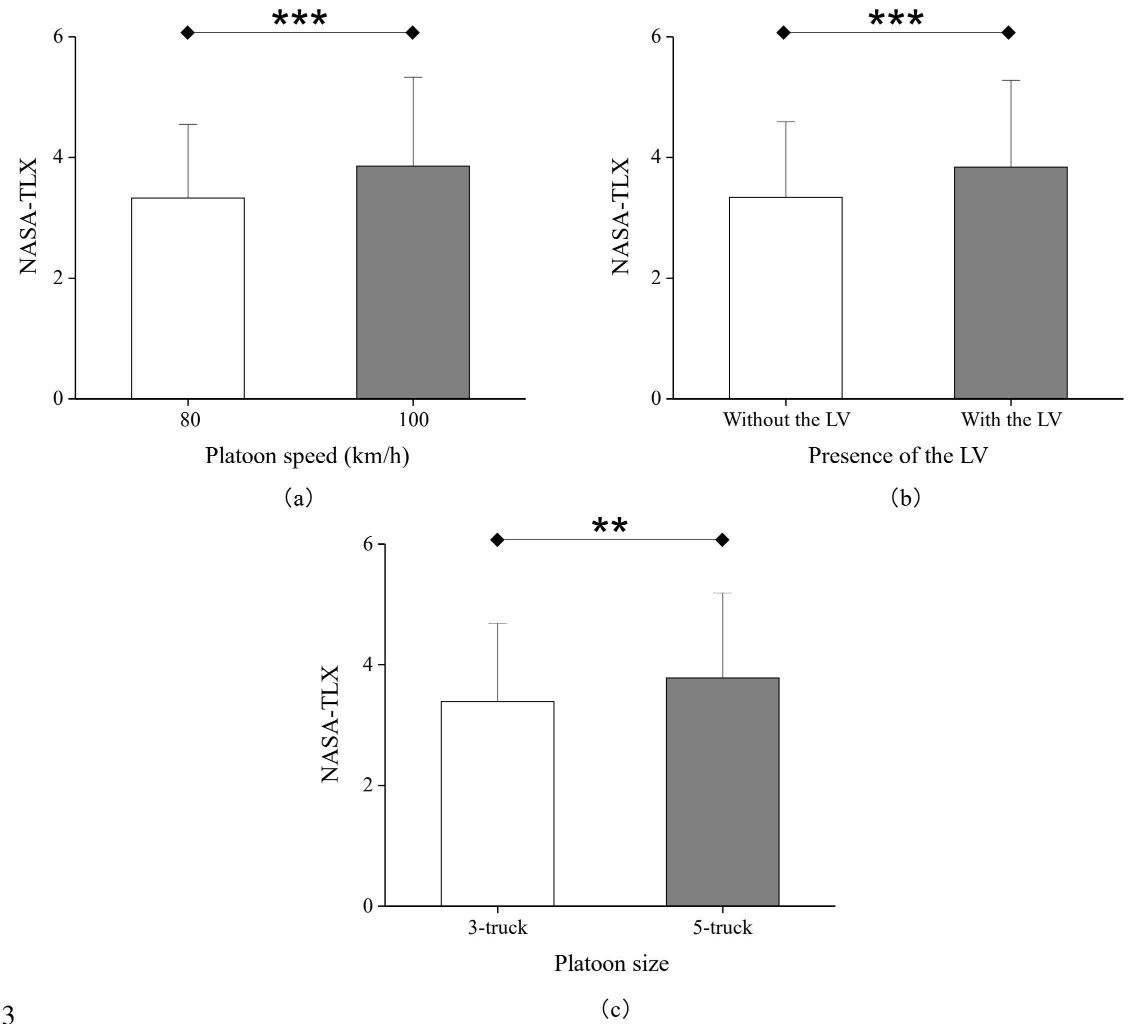

*Figure 20. NASA-TLX as a function of the platoon speed (a), presence of the LV (b) and the platoon size (c). The error bars represent the standard deviation. Bars represent means, error bars represent standard deviations (**p <.01, ***p <.001).*

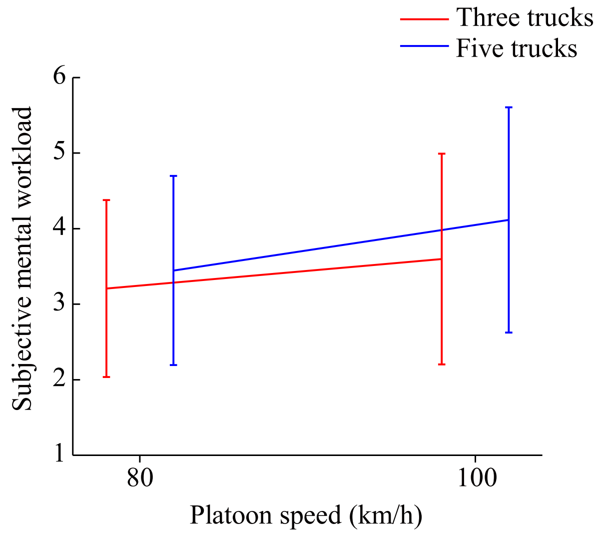

Figure 21. Interaction effects of platoon speed and platoon size on NASA-TLX.

3.2 Critical scenarios

3.2.1 Response time (RT)

As shown in Figure 22, the results of the ANOVA test indicate that the inner gap had a significant effect on RT (F (1,18) =5.873, p = .026, η^2_p = .246), while the platoon size did not (F (1,18) = 2.091, p = .165, η^2_p = .104). With an inner gap of 25m (M = 1.75, SD =0.79), RT was significantly smaller than that with an inner gap of 5m (M = 2.25, SD = 0.98). A significant interaction effect was found between the inner gap and the platoon size (F (1,18) = 4.604, p = .046, η^2_p = .204), as shown in Figure 23.This indicates that for the five-truck conditions, RT with an inner gap of 5m was higher compared to that at 25m.

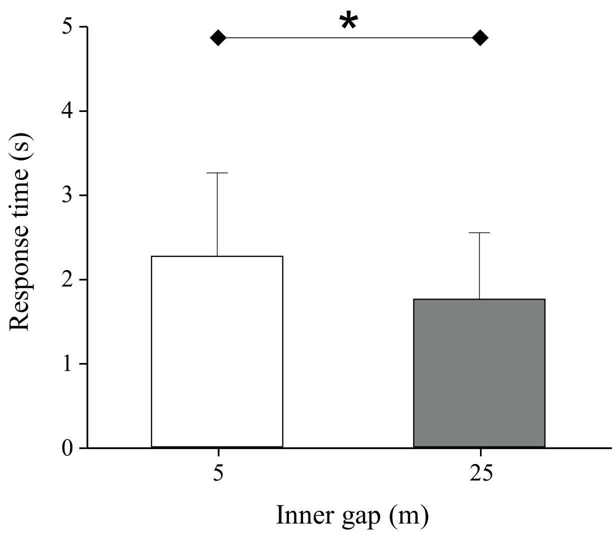

*Figure 22. Response time as a function of inner gap. Bars represent means, error bars represent standard deviations (*p <.05).*

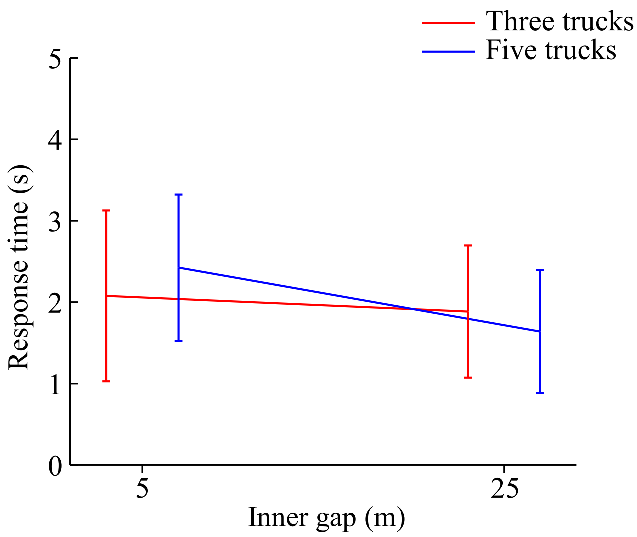

Figure 23. Interaction effects of inner gap and platoon size on RT.

3.2.2 Minimum time to collision (TTC_{min})

Neither the platoon size nor the inner gap showed any significant effect on TTC_{min} (see Appendix). In addition, no significant interaction was observed.

3.2.3 Subjective mental workload

Neither the platoon size nor the inner gap showed any significant effect on NASA-TLX scores in critical scenarios (see Appendix). In addition, no significant interaction was observed.

4. Discussion

This driving simulation study was used to investigate the effects of speed, size, and inner gap of an automated truck platoon, and the presence of the LV on the overtaking behaviour of drivers. In the following sections, the results are discussed based on each dependent variable.

4.1 Effect of platoon speed on overtaking behaviours

The increase in platoon speed resulted in a substantial decrease in OCR, consistent with H1. A previous study in this context found that the speed of the impeding vehicle is a primary factor affecting drivers' motivation to overtake (Kinnear et al., 2015). In this study, higher platoon speeds not only dampened drivers' willingness to overtake, but also increased the difficulty of overtaking maneuvers, thus resulting in a lower OCR.

In addition, an escalation in platoon speed significantly increased V_{mean} in the overtaking straight section and the overtaking end section. V_{std} was also higher in the overtaking start section and the overtaking straight section when the platoon speed increased, as was the subjective workload, based on the NASA-TLX. This corroborates the findings of Chen et al. (2022), who highlighted that a higher platoon speed would prompt drivers to adopt riskier longitudinal driving behaviour, and impose a greater mental workload. It is important to note that, for the 80 km/h platoons, an average travelling speed above the speed limit of 120km/h was only seen for about 30% of the total cases, while this increased to around 44% for the 100km/h conditions. This implies that the increase in platoon speed may heighten drivers' concern that they cannot complete overtaking within straight sections, leading a higher proportion of them to exceed the speed limit. It is important to note that we have adopted the maximum allowable length of straight section in this study to facilitate overtaking. In reality, such lengthy straight segments are uncommon. Consequently, drivers might adopt higher speeds than those observed in this study to overtake a truck platoon, thereby further increasing the risk of accidents.

Although the platoon speed was the most significant influencing factor on V_{mean}, it is worth noting that overtaking start section was the only section in which V_{mean} was not significantly affected by the platoon speed. This indicates that during the initial stage of overtaking, it was hard for drivers to perceive the platoon speed accurately in this driving simulator study, and they did not increase their speed promptly or appropriately to match the higher platoon speed. This delayed response to the platoon speed potentially causes drivers to adopt more radical driving maneuvers to compensate, increasing the risk of accidents.

Overall, the results indicated that a higher platoon speed induced extreme driving behaviours—which either included failed overtaking attempts, or risky overtaking maneuvers, thereby compromising traffic efficiency and elevating the likelihood of accidents. Therefore, it is imperative to consider the speed limit for automated truck platoons, advocating for a limit below the current 100km/h standard for trucks in China, to facilitate safer overtaking opportunities for other drivers.

4.2 Effect of platoon size on overtaking behaviours

A significant interaction effect was found between platoon size and inner gap, for the $V_{mean,}$ during the overtaking start section and the overtaking straight section. Under the three-truck conditions, V_{mean} remained relatively consistent across the various inner gaps. However, in the five-truck conditions, V_{mean} was notably higher with a 25m inner gap, when compared to a 5m inner gap. One possible interpretation is that the inner gap's contribution to the platoon's total length increased as the platoon size increased. With a 5m inner gap, transitioning from three to five trucks only added 40m to the platoon's length. While with a 25m inner gap, this transition added 80m to the platoon's length. Faced with a more substantial increase in platoon length, drivers were more likely to be concerned about completing their overtaking maneuvers, leading them to increase their speed. Thus, the stability of the traffic flow was compromised for these conditions. This finding is consistent with a previous simulation-based study (Zhou and Zhu, 2021), which found that the increase of platoon length led to decreased traffic stability.

It is not surprising that an increase in the inner gap significantly added to OT. However, it is noteworthy that the inner gap demonstrated a significant interaction effect with platoon size on OT. Specifically, compared to 3-truck platoons, an inner gap of 25 m resulted in a greater increase in OT with 5-truck platoons. While we previously discussed how the combination of a large platoon size and a high inner gap extended the total length of the platoon, prompting drivers to increase their speed to facilitate overtaking, it appears that even with the risk of speeding, the negative impact of the increased length on traffic efficiency could not be offset. The combination of a large platoon size and a high inner gap not only compromised the safety of mixed traffic but also degraded overall traffic efficiency (Faber et al., 2020). Therefore, careful consideration of the total length of the platoon is essential to mitigate the risk of speeding among other drivers and to enhance the efficiency of mixed traffic.

When overtaking the three-truck platoons, the vehicle's lateral position deviated approximately 10 cm further towards the median divider and away from the platoon, when compared to the five-truck platoon conditions. This result is in line with H3. Previous studies have indicated that increasing the size of the platoon makes other drivers to be less willing to drive alongside them (Castritius et al., 2020; Larburu et al., 2010), prompting them to keep a larger lateral distance to the platoon to achieve risk compensation (Rudin-Brown and Jamson, 2013). This phenomenon reflected the lateral behavioural adaptation of manual drivers to automated truck platoons. Although a lateral deviation of 10cm might appear negligible, it's important to note that this deviation could vary depending on factors such as road geometry or surface conditions(Chen et al., 2018). For example, in curved sections, the deviation may increase as the curve radius decreases. In these conditions, behavioural adaptation may heighten the risk of side-swipes, necessitating increased attention.

4.3 Effects of inner gap on overtaking behaviours

Compared with an inner gap of 25 m, an inner gap of 5 m led to higher LA_{max} in both overtaking start section and overtaking end section. This finding mirrors the results of a previous study, which indicated that drivers tend to adopt more radical steering maneuvers when changing lane to a lane occupied by a platoon, compared with changing lane into a lane without a platoon (Lee & Oh, 2017). This phenomenon can be attributed to the behavioural adaptation to truck platoons. When encountering platoons with a small inner gap, drivers may perceive the gap for lane change in the target lane as also small, prompting them to conduct the steering maneuver hastily, consequently resulting in higher LA_{max}.

In critical scenarios, RT under 25m conditions was smaller than that under 5m conditions, contradicting our hypothesis H4c. Additionally, RT was not significantly correlated with NASA-TLX scores, suggesting that high mental workload did not account for the prolonged response time. One possible explanation for the extended response time is that an 5m inter-vehicle gap is exceptionally rare in most driving conditions, while a 25m gap is relatively common (Chen et al., 2022). The distinctiveness of the small inter-vehicle gap likely compelled drivers to allocate extra attention to it, thereby slowing their response. As shown in Figure 23, the interaction effect between the inner gap and platoon size on RT could support this explanation. With an increase in platoon size, the exposure time is prolonged, exacerbating behavioural adaptation (Razmi Rad et al., 2021). Consequently, compared to three-truck conditions, drivers faced greater distraction from the smaller inner gap in five-truck conditions. Therefore, the impact of the inner gap on RT was more significant in five-truck conditions. However, the inner gap showed no significant effect on TTC_{min}. Furthermore, collision cases were distributed almost evenly across conditions with different inner gaps—two in 5m conditions and three in 25m conditions. This suggests that although drivers' responses were slowed down by the smaller inner gap, they were still able to implement effective countermeasures to compensate for it.

Compared to the negative impact of a 5m inner gap on RT and LA_{max}, a 25m gap seemed to impose adverse effects substantially on drivers’ overtaking behaviour. The 25m inner gap decreased the OCR and caused drivers to deviate farther from the center of the lane. This result appeared to contradict existing literature, which suggested that a bigger inner gap is more beneficial for other drivers’ performance (Chen et al., 2022; Gouy et al., 2014). However, it is important to note our study focused on overtaking scenarios, whereas previous studies primarily examined car-following situations. Consequently, the disparate results indicate that different platoon organisations should be adopted for different scenarios. For example, if the density of the platoon is high or a dedicated lane for platoons is implemented, then car-following would predominate in most conditions. In such cases, increasing the inner gap can help mitigate the behavioural adaptation of close car-following of other drivers. Conversely, when the density of the platoon is low or the dedicated lane is not implemented, decreasing the inner gap would be beneficial for improving traffic efficiency and other drivers' overtaking performance, as well as decreasing the possibility of other drivers' cutting into the platoon (Aramrattana et al., 2022).

4.4 Effects of the presence of the LV on overtaking behaviours

The presence of the LV resulted in a higher LA_{max} in overtaking start section. A previous study also revealed that higher traffic density caused more radical longitudinal behaviors during the lane-changing process of overtaking (Yang et al., 2018). These findings indicate that higher traffic density could lead drivers to engage in more reckless overtaking behaviours, potentially compromising overtaking safety. Moreover, the interaction effect between platoon size and the presence of the LV suggests that the impact of the LV on increasing drivers' LA_{max} during lane-changing process would be more significant in five-truck conditions. This phenomenon might be explained by the relationship between the platoon length and the ego-vehicle's distance to the LV. When the platoon only contained three trucks, the platoon length was either 49m (5m inner gap) or 89m (25m inner gap). Under these conditions, the LV was either beyond or almost parallel with the first truck when the overtake began. This would reassure drivers, as they felt only laterally suppressed and not completely trapped by the LV and the platoon. However, in five-platoon conditions, the platoon length was either 85m (5m inner gap) or 165m (25m inner gap). Drivers would feel completely trapped with no lateral or longitudinal space to handle any emergency. Under these conditions, they would either gave up overtaking (when the platoon was 165m and the LV was present, the OCR dropped to 75.7%), or become more nervous and behaved more radically during overtaking. This result indicates that the total length of the platoon should be managed considering traffic conditions. For example, the time headway with moderate traffic density in highway is typically between 2.5 and 4 s (Evans & Wasielewski, 1983; Loulizi et al., 2019). If the speed limit on the highway was 120 km/h, then the maximum platoon length shouldn't exceed 83m (distance travelled at 120 km/h for 2.5 s) to avoid the synergistic negative effect of the platoon and the LV on drivers' mental workload.

5. Limitations and future research

In terms of limitations, for practical reasons, this study only investigated overtaking behaviors during straight segments. However, road geometry can also influence drivers' behavioural adaptations. The complex interaction between road geometry and platoon organisation may pose new challenges that need to be addressed in future research. Additionally, this study only demonstrated that an inner gap of 5m was more beneficial for drivers' overtaking behaviour compared to an inner gap of 25m. However, the 5m inner gap may not be the optimal value. Thus, future research could focus on determining the most suitable inner gap for automated truck platoons by testing different inner gap sizes, such as 5m, 10m, 15m and 20m.

6. Conclusions

This exploratory study sheds light on how the organisation of truck platooning and the traffic environment influence other drivers' behaviours during the process of overtaking the platoon. It could be concluded as follows:

(i) The platoon speed was the most significant factor influencing drivers' longitudinal behaviour. An increase in platoon speed resulted in higher average speeds and greater speed fluctuations of the ego vehicle during the overtaking process, thereby increasing the likelihood of speeding. However, the rise in platoon speed also heightened the difficulty of overtaking—the overtaking completion rate was 7.5% lower at a platoon speed of 100 km/h compared to 80 km/h.

(ii) The inner gap of the platoon significantly affected drivers' lateral control. Compared to a 25-meter inner gap, a 5-meter inner gap not only impaired lateral stability during lane changes but also caused drivers to maintain a larger lateral distance from the platoon during overtaking.

(iii) In critical conditions, although drivers' response time to the lead vehicle's brake was 0.5 seconds slower in 5-meter conditions compared to 25-meter conditions, this did not contribute to a higher crash probability.

(iv) The presence of the LV imposes a significant mental workload on drivers. It functioned as an obstruction, reducing the mean speed and increasing the speed fluctuation of the ego vehicle, which consequently resulted in a lower overtaking completion rate.

This study may provide suggestions for the management of automated truck platoons from a human factor perspective. The operating speed of automated truck platoons should be lower than the current speed limit for trucks. In terms of platoon organisations, different speeds and inner gaps of the platoon should be adopted based on varying traffic conditions to strike a balance between efficiency and safety.

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.

CRediT authorship contribution statement

Zijian Lin: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing original draft, Visualization. **Feng Chen:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing-review & editing, Supervision, Project administration, Funding acquisition. **İbrahim Öztürk:** Methodology, Conceptualization, Writing-review & editing. **Natasha Merat:** Methodology, Conceptualization, Writing-review & editing.

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Appendix

Effects of different factors on SDLP.

Factor	**df1**	**df2**	***F***	***p***	η^2_p
Presence of the LV	1	18	.014	.906	.001
Platoon speed	1	18	2.914	.105	.139
Platoon size	1	18	.024	.879	.001
Inner gap	1	18	.502	.488	.027

Effects of different factors on TTC_{min} in critical conditions.

Factor	**df1**	**df2**	***F***	***p***	η^2_p
Platoon size	1	15	.122	.731	.008
Inner gap	1	15	.067	.800	.004

Effects of different factors on subjective mental workload in critical conditions.

Factor	**df1**	**df2**	***F***	***p***	$\boldsymbol{\eta^2_p}$
Platoon size	1	15	1.434	.250	.087
Inner gap	1	15	1.248	.282	.077