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The effect of visual advanced driver assistance systems on a following human driver in a mixed-traffic condition

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Abstract

Rapid development in vehicular technology has caused more automated vehicle control to increase on the roads. Studies showed that driving in mixed traffic with an autonomous vehicle (AV) had a negative impact on the time headway (THW) of conventional vehicles (CVs) (i.e., driven by humans). To address this issue, there is a need to equip CV with visual advanced driver assistance systems (ADASs) that helps the driver maintain safe headway when driving near AVs. This study examines the perception of drivers using visual ADAS and their associated risk while driving behind the AV at constant and varying speeds. The preliminary results showed that while visual ADAS could help drivers keep the safe THW, it could affect drivers' ability to react to emergencies. This implies that visual modality alone might not be sufficient and therefore requires some other feedback or intelligent transport systems to help drivers maintain safe driving in a mixed-traffic condition.

Keywords: sustainable transport management platooning; car-following, visual advanced driver assistance system, virtual realtiy

1. Introduction

Rapid improvement in vehicle technology has enabled more proactive vehicle control to improve the road transportation system. Current vehicles can collect information about the environment and other road users to perform

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automated maneuvers. For example, the emergence of vehicle technology that enables a vehicle to communicate with surrounding vehicles (V2V) and Infrastructure (V2I) permits vehicle platooning, a method of driving vehicles in a group. Several studies have shown that platooning can increase road capacity and traffic flow by reducing vehicle time headway (THW)[1], [2]. Another study argues that platooning can also improve fuel consumption, traffic congestion, traffic safety, and energy saving [3]. With autonomous vehicles being progressively introduced, road traffic is seeing a mixed traffic condition in which non-automated vehicles (i.e., driven by humans) share the road and interact with these autonomous vehicles. The increasing intelligence of vehicle technology and automation does not necessarily guarantee improving traffic efficiency. The use of Adaptive Cruise Control (ACC), which is one of the emerging vehicle technologies to improve driver's comfort and passenger safety, can also have an impact on dynamic traffic flow. One study examines that the high penetration of ACC in vehicles can improve traffic capacity provided that the desired time of inter-vehicular gap was smaller than in conventional vehicles [2]. This indicates the need for sustainable traffic management that regulates the use of automated vehicles. Some studies have investigated essential factors regarding the use of automated vehicles to improve traffic capacities, such as desired and safe gaps and the maximum length of the platoons [3], [4]. While many studies have been conducted to assess how automated vehicles influence traffic systems, others revealed a negative impact of automated vehicles (e.g., driving in a platoon) on the surrounding human-driven vehicles. To ensure sustainable transport management, the way automated vehicles affect human-driven vehicles, how to counteract the undesired consequence, and the impact of the countermeasure should be well understood. Therefore, this study aims at extending the current understanding of driving in a mixed-traffic condition, especially driving behind a platoon or automated vehicle, and how a following human driver perceives the use of an assistance system to maintain a safe gap to an automated vehicle. Section 2 presents the review of related works. The methodology and the results of this study are presented in Sections 3 and 4. Section 5 concludes the finding and proposes future studies.

2. Literature review

Despite significant benefits to the road traffic system, there is evidence that AVs' presence negatively impacts CV driving in the vicinity. One study that investigated the effect of driving next to a platoon with short THW in the driving simulator shows that platooning has a 'contagion' effect on the drivers of CV[5]. In that study, it was found that drivers tended to adopt shorter THW and spent more time under critical time headway of 1s. The underlying mechanism of behaviour adaption of CV drivers is complex. However, the reduction of THW and the increased tendency to keep the THW would increase the likelihood of a collision. Behavioural adaptation has always been a critical challenge to tackle when there is a change in a road traffic system. Although introducing vehicular technology increments the traffic safety margin, this benefit can be cancelled out by a change in driver behaviour. In different studies, some scholars also reported that behavioural change while using ACC had a negative effect on traffic safety [6], [7]. This highlights the need to examine an effective preventive measure, especially in addressing the negative behavioural change of CV drivers in a mixed traffic scenario. Effective preventive strategy can only be developed following a comprehensive understanding of the impact of vehicular technology not only on the user but also on the other road users in the surrounding. There is still limited research investigating how drivers of CV perceive driving near AV platooning. One driving simulator study found that merging onto a highway with the presence of a platoon was mentally demanding, unsafe, and uncomfortable [8]. The study also found that drivers would prefer support in interaction with an automated platoon through a Human Machine Interface (HMI) that conveys information about platoon behaviour to the human driver. This way, human drivers can better predict and anticipate whether it is the right time to cut in or wait. Another type of interaction with an automated platoon which is also essential to address is the car-following behaviour. Research in car-following behaviour has been studied for decades [9]. However, there is still a lack of research in understanding the car-following behaviour behind a platoon or automated vehicle. Researchers have found that car-following behaviour in selecting THW can be affected by many factors, such as traffic conditions, weather, driver's current state of mind, road characteristics, and lead vehicles [10]. Besides, the effect of time of day on the driver while driving following AV has not been examined. This is particularly important because car-following behaviour could be influenced by the type of lead vehicle and environmental conditions [11].

According to the literature review, research that investigates the perception of the human driver driving near automated vehicles needs to be extended. Furthermore, a study that examines how in-vehicle technology can help drivers to drive safely close to the automated vehicle and how it impacts their driving performance during emergencies (e.g., sudden failure in an automated vehicle system) is critical to our understanding of developing an effective preventive measure. To extend the knowledge in this field, this study examined how a human driver perceives driving behind an automated vehicle using a visual ADAS at a different time of day (i.e., morning vs. afternoon). The driving scenario was tested under two-speed conditions to represent the actual operating condition of automated vehicle platoons (i.e., constant speed vs. varied speed) [12], [13]. The results of this study present insights into whether drivers can cope well when driving behind an automated vehicle with visual ADAS and how it impacts traffic safety.

3. Methodology

To examine the impact of automated driving to a human-driven vehicle using a visual ADAS, an empirical study was carried out in a lab setting using a driving simulator. This section describes how the study was designed and the procedure to collect data for analysis.

3.1. Procedure

Fourteen healthy participants who held at least three years of driving experience took part in the experiment. Participants were graduate students (Female = 1 and Male = 13) with a mean age of 25.9-year-old (SD = 4.4) and drove regularly at least three hours weekly. Participants were divided into two groups based on different daytime: (1) in the morning from 09:00 am to 11:30 am, and [2] afternoon to early evening (hereafter referred afternoon) from 2:30 pm to 7:00 pm based on studies [14], [15] in which the difference in sleepiness level between both periods was high. Each participant performed two driving tasks that differed in speed conditions, and the test order was counterbalanced. They were told to have enough sleep the preceding night (7-8 h) and avoid alcoholic consumption. Before the experiment began, subjects took five minutes to drive a familiarisation scenario to familiarise themselves with the virtual driving environment, vehicle control, and interaction with other vehicles. They also took a ten-minute adaptation scenario and were instructed to practice two driving tasks similar to the actual driving tasks. The adaptation scenario was aimed to minimise any novelty or learning effect the participant could experience during the driving test. In the actual driving test, the instructor repeated the instructions, and each participant did two driving tasks that lasted for 30 minutes. Participant also took five-minute rest period in between. They filled out fatigue, sleepiness scale, and workload questionnaires during the rest period. After the test, each participant was asked about what they thought and felt during both driving trials.

3.2 Driving Task

The test was carried out in a simulated driving on straight roads where the surrounding environment consisted of trees, grass, and mountains. This condition was chosen to induce monotonous driving representing highway driving at different times of day. Two following platooning conditions were administered:

- Driving at constant speed. Each participant was asked to follow a lead vehicle at constant speed of 40 km/h throughout the drive. This condition was used as a control group.
- Driving at varying speed. Each participant was asked to follow a vehicle travelling at the speed of 40 km/h or 60 km/h at every 30-s interval.

Driving tasks also included maintaining the vehicle's position at the centre of the lane for both driving tests without any external assistance. After 15 minutes of driving, the lead vehicle suddenly braked, and the driver's brake reaction time was recorded from the time the lead vehicle braked (i.e., the rear lights displayed to the following vehicle) to the time the driver pressed the brake pedal. This scenario was designed to test the driver's reaction time in case there was a system malfunction on the automated vehicle that caused a sudden break. Throughout the drive, each participant was assisted by a visual ADAS to maintain safe headway with a lead vehicle. The visual ADAS was put as a head-up display located at the bottom left of the windshield for right-hand traffic, as shown in Fig. 1. The mechanism for displaying safe and unsafe headway were based on time headway and indicated three colours (red-green-red) [16]. These three colours were used in [17] to signify the headway as too close (< 1.8 s), appropriate distance (1.8 < t < 2.5 s), and too far (> 2.5 s) from the lead vehicle. Each participant was required to maintain the safe distance signaled by green light throughout the entire driving. Furthermore, subjects were told before that they would see emergency braking of a lead vehicle at the end of the drive for each session, as they had seen during driving practice, and they were instructed to stop the car entirely by pressing the brake with the right foot. However, subjects were not told about the duration of each driving task.

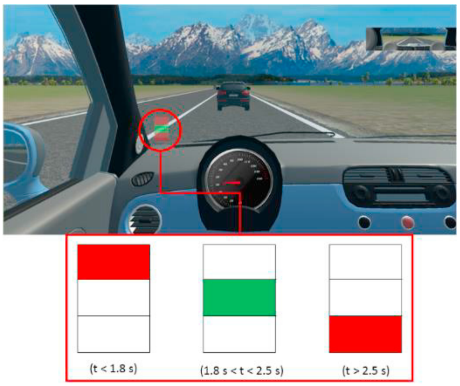

Fig. 1. Visual ADAS for regulating safe headway distance

3.3 Tools and Data Measure

Subjects performed driving tasks in the laboratory using a fixed-based driving simulator. Subjective and objective data measures were recorded to analyse driving behind automated vehicle platoon and how it influences driver's mental perception and driving performance concerning different platooning speed conditions. The simulator consisted of three screens combined providing 36 degrees and 175 degrees on the vertical and horizontal field of view (FoV), respectively. It was also equipped with the steering wheel, pedals, and adjustable driver seat, while the control of the vehicle was implemented with automatic transmission. The following data measures were used for driving tasks assessment:

- Subjective responses. NASA-TLX [18] and Swedish Occupational Fatigue Inventory (SOFI-20) [19] were used to record self-assessment of workload and perceived fatigue, respectively, related to the driving tasks. Workload and fatigue questionnaires were administered in a post-drive.
- Driving performance. The standard deviation of lateral position (SDLP), the standard deviation of steering wheel angle (SDSWM), mean amplitude of steering wheel angle, and brake reaction time was obtained and used as performance indexes for alertness decrement [20].

4. Result and analysis

4.1 Subjective Workload (NASA-TLX).

An analysis of a two-way mixed ANOVA was carried out to assess the effect of speed strategies and time of day on subjective workload. There was no statistically significant two-way interaction between the speed choices and time of day on overall subjective workload, $F(1,12) = 0.004$, $p = 0.953$, partial $\eta2 = 0.052$. The average of all workload dimensions in NASA-TLX: mental, physical, temporal, performance, effort, and frustration produced a greater mean score when drivers varied their speed than when they maintained a constant speed during monotonous driving. However, this result did not show any statistically significant difference between both driving trials, $F(1, 12) = 0.657$, $p = 0.434$, partial $\eta2 = 0.052$. On the other hand, the rating on temporal demand was statistically significantly different,

$F(1,12) = 5.504$, $p < 0.05$, partial $\eta^2 = 0.314$, in which drivers who varied their speed during car-following situation rated a higher degree on this dimension than when they drove with constant speed.

4.2 Perceived Fatigue (SOFI-20).

A two-way mixed ANOVA assesses the effect of speed and time of day on subjective fatigue perception. There was no statistical two-way interaction between the speed and time of day on overall perceived fatigue, $F(1,12) = 0.001$, $p = 0.974$, partial $\eta^2 = 0.0005$. Drivers rated a lower rating of overall dimensions in the perceived fatigue questionnaire when they drove with varying speed as opposed to constant speed, which was not statistically significant, $F(1,12) = 2.906$, $p = 0.114$, partial $\eta^2 = 0.195$. However, the impact of speed strategies was found to have a statistically significant difference in the dimension of lack of motivation, $F(1,12) = 7.01$, $p < 0.05$, partial $\eta^2 = 0.369$, where there was a decrease in t mean score between driving with constant speed and driving with the varying speed in the platooning task situation.

4.3 Lane Keeping Performance (SDLP).

Fig. 2 shows the comparison of SLDP between constant and varying speed. A three-way mixed ANOVA shows the effect of different speed strategies on driver's lane keeping performance between early and late driving periods at different times of day. There was no statistically significant difference in lane keeping performance between drivers in the morning and the afternoon, $F(1,12) = 1.198$, $p = 0.29$, partial $\eta^2 = 0.091$. The analysis on the main effect of platooning speed and driving periods did not have a statistically significant impact on keeping the lane variability, $F(1,12) = 0.013$, $p = 0.99$, partial $\eta^2 = 0.001$ and $F(1,12) = 1.641$, $p = 0.224$, partial $\eta^2 = 0.120$ respectively.

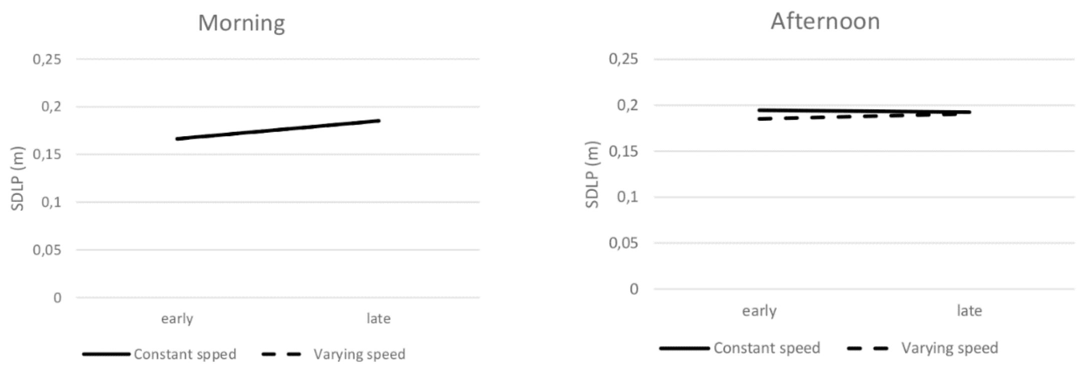

Fig. 2. The effect of different platooning speed conditions, driving period, and time of day on lane keeping performance as assessed by standard deviation of lateral position (SDLP).

4.4 *Steering Wheel Angle Variability (SDSWM)*

Fig. 3 shows the comparison of SDSWM between constant and varying speed. An analysis of a three-way mixed ANOVA revealed that there was a statistically significant increase in steering wheel angle variability between driving with constant speed and varying speed situation, irrespective of the time of day and driving periods, $F(1,12) = 8.297$, $p < 0.05$, partial $\eta^2 = 0.409$. Drivers with both speed choices also exhibited a more stable steering wheel control in the early drive as opposed to the late drive, which was not statistically significant, $F(1,12) = 2.224$, $p = 0.162$, partial $\eta^2 = 0.156$.

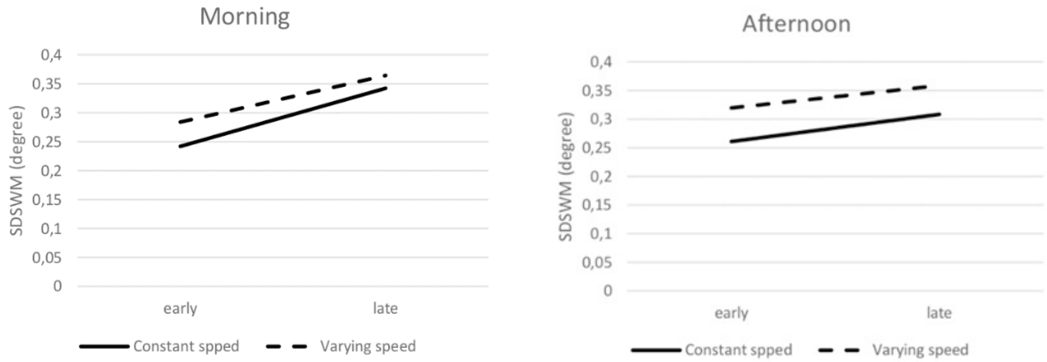

Fig. 3. The effect of different platooning speed conditions, driving period, and time of day on standard deviation of steering wheel movement (SDSWM).

4.5 Mean Amplitude of Steering Wheel Movement (SWM)

Fig. 4 shows the comparison of SWM between constant and varying speed. A three-way mixed ANOVA on the mean amplitude of steering wheel angle revealed a statistically significant change between different platooning speeds, $F(1,12) = 15.397$, $p < 0.05$, partial $\eta^2 = 0.562$. Subjects who drove at varying speed showed a larger value on this variable than when they drove at constant speed. There was also a statistically significant increase in mean amplitude of steering wheel angle over time, $F(1,12) = 3.461$, $p < 0.05$, partial $\eta^2 = 0.224$. Nevertheless, the effect of time of day did not show any statistically significant difference, $F(1,12) = 0.137$, $p = 0.718$, partial $\eta^2 = 0.011$.

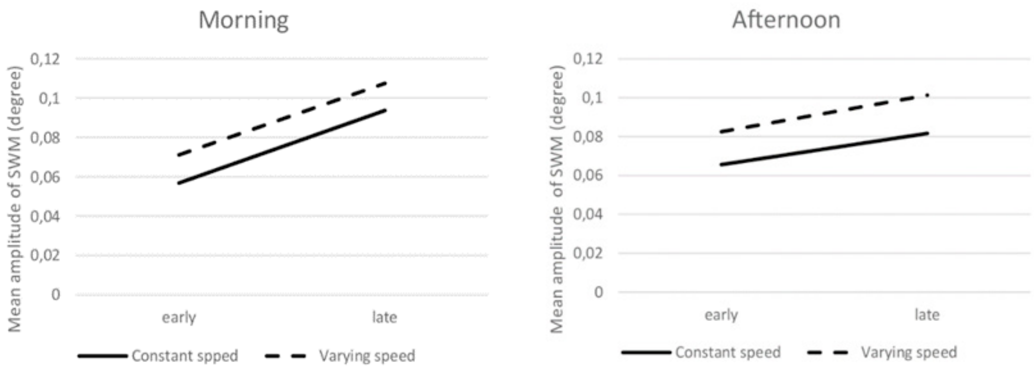

Fig. 4. The effect of different platooning speed conditions, driving period, and time of day on mean amplitude of steering wheel movement (SWM).

4.6 Brake Reaction Time (BRT)

Fig. 5 shows the comparison of BRT between constant and varying speed. Driver's response to an emergency (in this case, a lead vehicle's brake light) was about 0.25 sec longer when the AV platoons' speed was varied than when it was kept constant. A two-way mixed ANOVA analysis revealed that this difference was not statistically significant, $F(1, 12) = 3.114$, $p = 0.103$, partial $\eta^2 = 0.206$. The interaction effect of speed in car following situation and time of day did not reveal any statistical impact on BRT; $F(1, 12) = 0.683$, $p = 0.425$, partial $\eta^2 = 0.05$, and neither did the main effect of time of day, $F(1, 12) = 1.869$, $p = 0.197$, partial $\eta^2 = 0.135$.

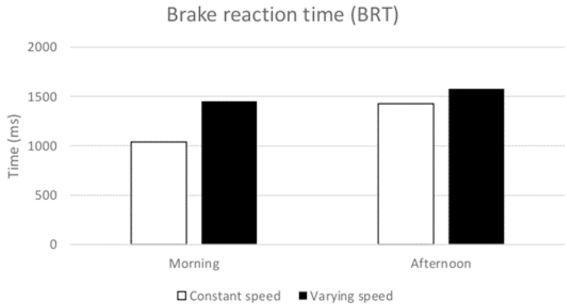

Fig. 5. Different platooning speed conditions and time of day affect brake reaction time (BRT).

5. Discussion

According to the previous study, car-following can induce fatigue which in turn have a negative impact on driving performance. One study found that increased fatigue resulting from car-following led a following human driver to drive with shorter THW, which increases the risk of rear-end collision [21]. In this study, drivers were assisted with visual ADAS to maintain the safe THW during car following. However, it is essential to note that the speed changes in AV platoons had different impacts on drivers' mental perception and driving performance, affecting traffic flow and safety. The assessment of the impact of different platooning speed conditions in this study produced other effects on the subjective responses concerning the perceptions of workload and fatigue on the following human driver. Driving behind an automated vehicle at constant speed was perceived as less demanding than when the AV changed speed regularly. The analysis of subjective workload showed a higher degree of workload at varying speeds, particularly in the temporal dimension, as assessed by NASA-TLX. In terms of fatigue perception, the assessment of SOFI-20 reported a lower level of motivation when following an automated vehicle at a constant speed. The effect on the drivers' perception was that drivers in the varying speed group said they perceived the adoption of varying speed in platooning driving as less boring and shorter in terms of the perceived length of the driving task. This finding may indicate that driving behind AV platoons with visual ADAS at constant speed might not last longer than varying speed conditions as drivers tend to get bored or impatient more quickly. Considering the impact on the traffic flow, the event of overtaking in a mixed traffic condition might be more prevalent when AV platoons operate at constant than varying speeds [22], [23]. The increased overtaking might, in turn, present a detrimental effect on traffic safety [23].

The result from driving performance showed no significant difference in terms of lane keeping performance between both driving settings as reflected by SDLP. However, drivers' ability to respond to emergencies was severely impaired when driving with visual ADAS. In an alert and single task driving condition, it was reported that BRT took an average of 0.75 s from when an object was fixated until initiating braking [24]. In this study, driving with visual ADAS increased BRT by about 0.3 s – 0.6 s at a constant speed and about 0.7 s – 0.8 s at varying speeds. Under 2 s THW, this increment will likely increase the likelihood of rear-end collision. The increase of BRT in response to emergencies while interacting with visual ADAS has also been observed in another study [25]. Therefore, regarding traffic safety, this study presents the finding that visual ADAS can facilitate the driver to keep safe THW while driving near AV platoons. However, it may reduce the driver's ability to respond quickly to emergency braking. This implies that visual modality alone might not be sufficient, and therefore requires some other modes of feedback to help drivers maintain safe driving under mixed traffic conditions and facilitate drivers to react responsively to emergency braking. The time of day assessed in our study appeared not to have any impact on subjective perceptions of workload and fatigue and driving performance in a relatively short period between two driving trials. The effect of time of day would be seemingly more pronounced in prolonged driving, as shown in other studies [14], [15].

6. Conclusion

The increasing number of automated vehicles (AV) introduced on the roads means human drivers face a mixed-traffic condition. To ensure a sustainable traffic management system, studies examining how both AV and conventional vehicles (CV) can co-exist safely and effectively are needed. To extend the knowledge in this field, this study examined how a human driver perceives driving behind an AV using a visual ADAS. The results showed that although visual ADAS could help drivers keep safe THW to AV, more studies are needed to investigate how in-vehicle technology can help the driver react safely in an emergency. Further research will investigate how multi-modal feedback and other means of intelligent transport systems could facilitate safe driving near AVs.

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