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Understanding take-over performance of high crash risk drivers during conditionally automated driving

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ABSTRACT

Understanding driver behavior of conditionally automated driving is necessary to ensure a safe transition from automated to manual driving. This study aimed to examine the difference in take-over performance between high crash risk (HCR) and lower crash risk (LCR) drivers in emergency take-over situations during conditionally automated driving. In the current simulator study, a 3 × 3 (within-subjects) factorial design was used, including the task factors (no task, reading the news, and watching a video) and time budget factors (time budget = 3 s, 4 s, and 5 s). Forty-eight participants completed a test drive on an approximately 10 km long two-way six-lane urban road. The participants firstly were in manual control and then switched to the automated driving mode at a speed of 50 km/h. The automated driving system was able to detect a broken car in the ego-lane and requested the driver to take over the control of the vehicle. There are at least one or two other vehicles or motorcycles on each side of the ego-vehicle, resulting in fewer escape paths. For the two non-handheld non-driving-related tasks (NDRTs), the participants were asked to be fully engaged in a task without any need to monitor the road environments. Each participant completed nine emergency take-over situations. The participants were classified into two groups that were labeled LCR (N ≤ 2) and HCR drivers (N ≥ 3) according to the number of accidents per driver. The results show that LCR drivers had shorter brake reaction time compared to HCR drivers. For all drivers, the engagement in a task led to longer response times, and the time budget affected the longitudinal vehicle control. In addition, the task affected the response times for LCR and HCR drivers, but only the time budget affected the longitudinal vehicle control for LCR drivers. For all drivers, LCR and HCR drivers, the time budget and task affected the safety of take-over. Especially, the two non-handheld everyday tasks seem to have a similar effect on the drivers' workload. Therefore, the HCR drivers had a lower hazard perception compared to the LCR drivers, and the factor regarding the individual difference of driving ability in take-over situations should be considered to design safe take-over concepts for automated vehicles.

1. Introduction

One of the most benefits of automated driving is to improve safety by reducing human errors. According to the definitions of SAE J3016 (SAE J3016, 2018), in conditional automation (level 3) the automated driving system can perform the entire dynamic driving task (e.g., monitoring of environment, longitudinal and lateral control), but the drivers still need to be ready for taking over (within a predefined time) at all times. When the system reaches its operational limit in a given situation (e.g., the environmental complexity or sensor failures), a take-over request (TOR) for drivers is necessary. Therefore, this human-machine interaction could lead to the possibility of human error. To realize the full potential of an automated vehicle in improving road safety, it is necessary to investigate the drivers' cognitive and physical abilities to interact safely and appropriately with the driving task in take-over situations.

Numerous studies examined the influence of TOR lead time (also called "time budget") on take-over performance (e.g., Gold et al., 2013; Mok et al., 2015; Eriksson & Stanton, 2017a; Wan & Wu, 2018; McDonald et al., 2019; Zhang et al., 2019a; Naujoks et al., 2019). Eriksson and Stanton (2017a) reviewed 25 papers and found the most frequently used time budgets were 3 s, 4 s, 6 s, and 7 s and that the corresponding mean take-over reaction times (TOrts) were 1.14 s, 2.05 s, 2.69 s, and 3.04 s. The optimal take-over performance was observed when the time budget ≥ 10 s, and significantly longer minimum Time to collision (TTC) was observed when the time budget ≥ 6 s (Wan & Wu, 2018). The time budget significantly affected the take-over lateral and longitudinal control, as well as the choice of maneuver-lower

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time budgets, led to more braking responses (McDonald et al., 2019). Zhang et al. (2019a) found a strong effect of time budget, with a higher mean take-over time for a large time budget compared to a smaller time budget. Moreover, Naujoks et al. (2019) found a range of median values of 2.71 s to 4.90 s in noncritical situations, and handheld reading task and the search task led to the prolonged take-over times. These findings indicate that around 7 s time budget might be accepted from the perspective of take-over safety and shorter time budgets lead to shorter take-over times and worse take-over control.

Drivers during highly automated driving are inclined to pick up NDRTs (de Winter et al., 2014; Wandtner et al., 2018b). Many studies examined the influence of NDRTs on take-over performance. Handheld NDRTs have been shown to increase the take-over time (Wan & Wu, 2018; Wandtner et al., 2018a; Zeeb et al., 2017; Zhang et al., 2019a; Zhang et al., 2019b). However, for non-handheld NDRTs, its effect on take-over time seems unclear. Some studies indicated that there was no significant influence of NDRTs on the take-over time (e.g., Gold et al., 2016; Gold et al., 2017; Zeeb et al., 2016). Some other studies have shown the opposite results (e.g., Dogan et al., 2017; Eriksson & Stanton, 2017a; Zeeb et al., 2017; Feldhütter et al., 2017). The controversy among these studies might be due to an interaction effect between environmental complexity, time-critical and cognitively demanding responses, and NDRT (Gold et al., 2017; McDonald et al., 2019; Radlmayr et al., 2014). Numerous studies showed NDRTs deteriorated take-over quality compared to no task condition (e.g., Merat et al., 2012; Radlmayr et al., 2014; Bueno et al., 2016; Gold et al., 2016; Körber et al., 2016; Zeeb et al., 2017; Wan & Wu, 2018; Wandtner et al., 2018a). For the reaction type, some studies have also found that drivers who engage in the NDRTs prefer to braking actions rather than steering in response to a TOR (Naujoks et al., 2017). Generally, these findings indicated that NDRTs significantly impact take-over performance, especially NDRTs could deteriorate take-over quality compared to the drivers without a task, and drivers with NDRTs are more likely to brake than to steer.

Recent studies have shown that take-over performance was affected by some other factors, such as the modality of TOR (Petermeijer et al., 2017a; Petermeijer et al., 2017b; Wandtner et al., 2018a), the traffic density (Radlmayr et al., 2014; Gold et al., 2016; Körber et al., 2016; Gold et al., 2017), and some driver factors. Studies have found that combined visual and auditory feedback is the most common method, and take-over times when using multimodal warnings are shorter than those when using unimodal warnings (McDonald et al., 2019). Several studies have investigated the impact of traffic density on take-over performance. In these studies, the number of vehicles occupying a distance of the roadway was changed, and the results generally showed that high traffic density could increase the take-over time and deteriorate the take-over quality (Radlmayr et al., 2014; Gold et al., 2016; Körber et al., 2016; Gold et al., 2017). Some driver factors affected take-over performance, such as fatigue (Vogelpohl et al. 2019), alcohol (Wiedemann et al., 2018), repeated exposure (Gold et al., 2017; Payre et al., 2016), driver training (Hergeth et al., 2017), trust in automation (Körber et al., 2018; Payre et al., 2016). Recent studies have highlighted the influence of age on take-over performance, which involved a wide range of driver ages (Clark & Feng, 2017; Gold et al., 2017; Körber et al., 2016). For example, Clark & Feng (2017) found that compared with younger drivers (18–35 years), older drivers (62–81 years) in general drove more slowly with a smaller deviation from the road centerline after a take-over, but they did not find the impact of age on reaction times. Körber et al. (2016) found older drivers (60–79 years) braked more often and more strongly and maintained a higher TTC compared with younger drivers (19–28 years), and both two age groups reacted similarly. Gold et al. (2017) found that age did not affect crash probability, but age was a significant predictor of brake application. A possible explanation for the difference between these results is the difference in the range of driver ages. Besides, Zeeb et al. (2015) used a k-means clustering algorithm to separate the drivers into three groups ("high", "medium", and "low-risk" drivers) based on the gaze behavior and examined the relationship between the driver's gaze behavior and the performances in the take-over.

Previous studies have examined some influencing factors that determine take-over performance. Nevertheless, driving performance for drivers with different risk levels after TOR during conditional automated driving has not been well investigated. This study focuses on the effects of time budget and NDRT on take-over performance and examines the difference in the take-over performance between drivers of different risk groups. Moreover, we address the following questions: (1) What is the relationship of the take-over performance between different crash risk driver groups? Accordingly, the hypothesis is that the high crash risk drivers have a lower hazard perception ability compared to the lower crash risk drivers. (2) How do the time budget and NDRT affect take-over performance in emergency take-over situations? We hypothesize that the time budget does not affect the response times but significantly deteriorates the longitudinal vehicle control and safety of take-over, and the NDRT shows the main effect on the response times and the safety of take-over but does not affect the longitudinal vehicle control.

2. Methods

2.1. Participants

48 participants (19 females, 29 males) completed the experiment. The participants were required to hold a valid driver's license. The mean age of the drivers was 31.23 years (SD = 7.07), with a range from 21 to 45 years. The mean driving experience of the drivers was 7.49 years (SD = 5.05), with a range from 1 to 19 years. Informed consent forms were signed and collected, and no participant reported impairments that could affect a driving task.

2.2. Driving simulator

The study was conducted in a driving simulator (Fig. 1). The driving simulator includes a desktop computer, simulation software (UC-win/Road Ver.10.0), an adjustable driver's seat, steering wheel, and foot pedals (Logitech G29 dual-motor force feedback steering wheel). Three LCD monitors (27 inches, 1920 × 1080 resolution) were arranged in front of the driver's seat. The frame rate was fixed to a constant 60 Hz. A driving scenario was shown on three LCD monitors. A 2.1 surround audio system provides a sound of engine and driving sounds of the driver's own and surrounding vehicles. A 4 degree of freedoms (DOFs) vehicle dynamics model is used. Data were recorded at a frequency of 50 Hz, including information such as vehicle's position, accelerations, steering wheel angle, and pedal positions. The functions of automated

Fig. 1. Driving simulator.

driving were implemented using driving simulation software.

2.3. System description and non-driving-related tasks

The conditionally automated driving system used in the study can control the longitudinal guidance of the vehicle and keep the speed of 50 km/h. Therefore, the participants can take their hands off the steering wheel and their feet off the brake or accelerator pedal. A visual-auditory human-machine interface (HMI) was developed in the system. When the system reached the system limit, a TOR was prompted by a generic warning tone ("Automated driving is about to be invalidated, please take-over!"). The female voice was used as the warning signal. For the visual display of the TOR, an icon of hands grasping a steering wheel and a text message ("Please take over!") were displayed. The visual interface was presented on the top of the center display screen. Both the visual and auditory displays were issued at the same time. A Windows tablet that showed the NDRTs was placed in the right of the center console of the vehicle. System activation and deactivation were required pushing one button on the right of the steering wheel. Note that there is a difference in switch mode between this study and some other previous studies. The drivers need to change from automated driving mode to manual control by either pushing the button, braking, or steering in these previous studies.

The participants were required to watch the Windows tablet and not to look at the road. The participants kept their hands loosely at the sides, and their heads switched slightly to the Windows tablet. The NDRTs included reading the news and watching a video. For the news task, one of the most popular Web portals was selected. The news text was a general business article that did not need any particular knowledge about the topic. The video clip was an excerpt from a scenery film that introduced a famous, specific, and beautiful natural scenic site. The news text was selected from the newspaper column, and video clips were also long enough. Therefore, the participants could not finish them before the TOR.

2.4. Experiment Design and dependent measures

The study was carried out in a 3 × 3 within-subjects design (time budget: 3 s, 4 s, and 5 s and NDRT: no task, reading the news and watching a video). All participants completed one test drive with nine take-over conditions in a counterbalanced order. The test drive was on an approximately 10 km long two-way six-lane urban road. The traffic density per lane excepting the ego-lane was about 1200 vehicles per hour. The speed limit of the road was 60 km/h. There are at least one or two other vehicles or motorcycles on each side of the ego-vehicle from the ego vehicle's view, resulting in fewer escape paths.

The take-over performance included hands-on time, brake reaction time, maximum longitudinal acceleration, and crash rate. Table 1 shows the definitions of all variables related to take-over performance. We required the participants to press the automation (de)activation switch button while grasping the steering wheel. There is little difference between the time until grasping the steering wheel and the time until pressing the switch button. Therefore, the automation deactivation time was approximately the same as the hands-on time in this study. For brake reaction time, the start of brake was measured by a change of 10% of the maximum brake pedal.

2.5. Take-over scenario

At the start phase of the session, participants were in manual control at the speed of about 50 km/h, and the ego-vehicle was located in the middle lane, with lane widths of 3.5 m. There was traffic flow on the remaining two lanes. After the visual and auditory display about mode switch, participants then switched to the automated driving mode by pressing the switch button. The speed of the automated vehicle changed to 50 km/h within a short time. The participants must fully engage in the NDRTs in automated driving mode.

There were nine take-over scenarios in total. For each take-over scenario, a broken-down vehicle appeared on the lane of the ego-vehicle. Because the system reached a system limit, a TOR was issued with the visual and audio displays when the time budgets were 3 s, 4 s, and 5 s, respectively. For the avoidance maneuver, participants were told to pay attention to the traffic flow on the sides of the ego-vehicle, and they were allowed to drive on lanes of two sides when overtaking, then conducted a lane change back to the center lane.

2.6. Procedure

Participants first signed informed consent and then filled out demographic questionnaires including necessary demographic information, driving mileage and driving experience. Afterward, participants were given an introduction to the experimental procedure and the operation method of the driving simulator, which included an introduction to the visual and auditory displays, how to (de)activate the automated driving system by pressing the switch button, as well as the information about the system limits of the automated system. Participants were told to fully engage in the NDRTs without any need to monitor the road environments in front when the automated driving system was activated. A practice drive was then conducted consisting of ten minutes of driving to allow participants to get familiar with vehicle controls, NDRTs, and urban road environment. The practice drive took about ten minutes.

When participants were ready for the main experiment, participants were asked to stay in the middle lane, and the main experiment began. The study design was a within-subjects design, with each participant taking part in each one of the take-over scenarios. Participants performed one session with nine take-over conditions (in counterbalanced order). Participants must fully engage in the NDRTs in automated driving mode. It also took about ten minutes for the main experiment. When the experiment finished, participants received their rewards.

3. Results

3.1. Drivers classification based on the number of accidents per driver

Firstly, the reaction type was divided into three categories: steering

Table 1
Variables regarding take-over performance.

Variable	Unit	Category	Definition
Hands-on time	s	Response time	The time between the TOR and the moment drivers grasp the steering wheel
Brake reaction time (BRT)	s	Response time	The time between the TOR and the start of brake
Maximum longitudinal acceleration	m/s^2	Take-over quality	The maximum braking acceleration during the take-over situation
Minimum time to collision (TTC)	s	Take-over quality	The TTC during the take-over situation
Crash rate	%	Take-over quality	The ratio of crashes to cases in quantity under certain conditions

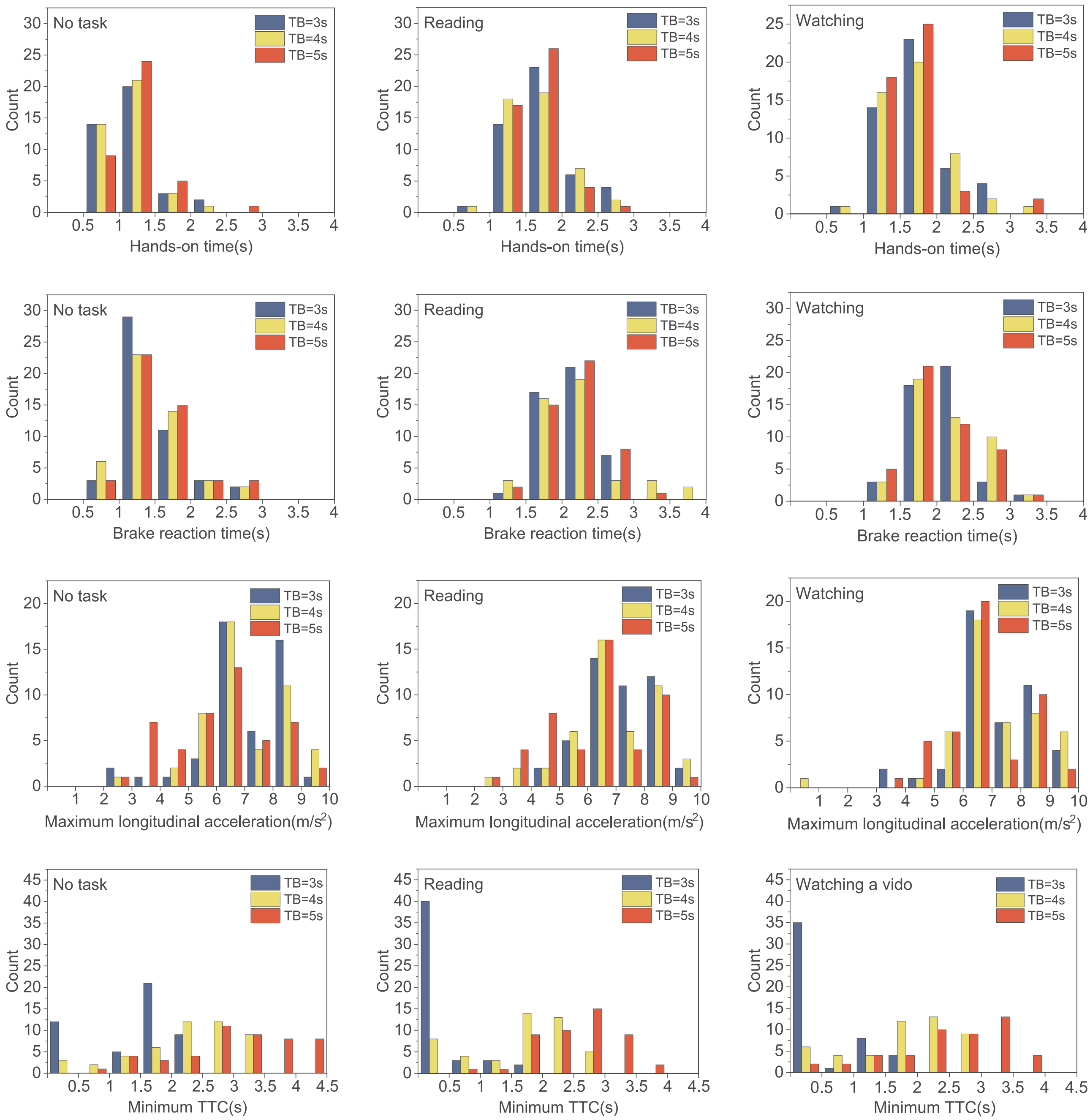


Fig. 2. The distribution of the take-over performance.

only, braking only, and the combination of steering and braking actions. A participant made a wrong operator in a test, resulting in one case that was not recorded. Therefore, the total number of valid cases was 431. The statistic results showed that most drivers tended to brake. There were 7 cases (this was 7 out of 431 cases) that drivers changed lane directly without braking (steering only), which might be mainly due to the influences of the urban road environment (fewer escape paths) and the urgency of the take-over. Therefore, we discarded these 7 cases in the following analysis of the brake reaction time and maximum longitudinal acceleration.

Furthermore, we excluded the two cases that the drivers did not brake or steer to avoid a collision in the analysis of the brake reaction time and maximum longitudinal acceleration. Fig. 2 shows the distribution of the take-over performance under different time budget (TB) and NDRT conditions. For the distribution of the minimum TTCs, TTC = 0 represents crashes, and the range from 0 to 0.5 included the crashes and near-crashes. The general linear model (GLM) was used to analyze the influence of time budget and task on take-over performance in the subsequent analysis.

K-means clustering algorithm was used considering the size and distribution of the sample. The drivers were classified into two groups that were labeled as high crash risk (HCR) and lower crash risk (LCR) drivers according to the number of accidents per driver (LCR drivers: $N \leq 2$; HCR drivers: $N \geq 3$). Consequently, the number of HCR and LCR drivers was 12 and 36. Fig. 3 shows the distribution of the drivers based on the number of accidents per driver, and Fig. 4 shows the distribution of the TOR events based on the number of accidents per driver.

3.2. Response times

Fig. 5 shows the response times under different time budget and NDRT conditions, and Table 2 shows the results of the statistical

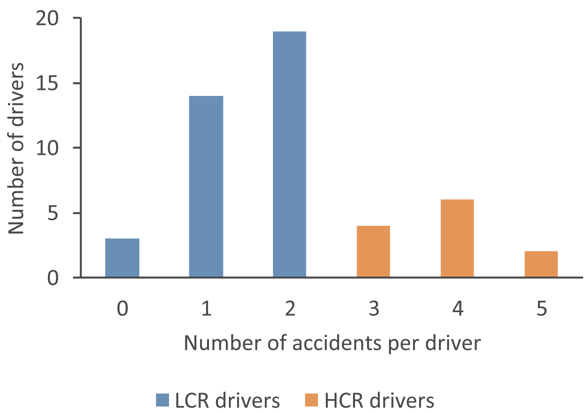


Fig. 3. The distribution of the drivers based on the number of accidents per driver

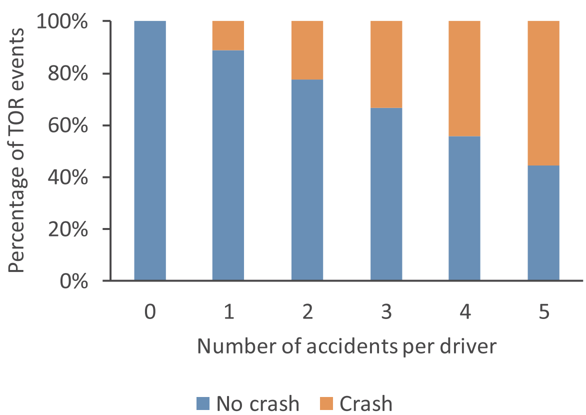


Fig. 4. The distribution of the TOR events based on the number of accidents per driver

analyses of the response times regarding the task and time budget. For the hands-on time and brake reaction time of the three groups of the drivers (all drivers, LCR drivers, and HCR drivers), the time budget did not show a significant main effect, but the task showed a significant effect (see Table 2). Post hoc tests (LSD) showed that the hands-on time or brake reaction time in the absence of the task was significantly shorter compared to the news task and video task conditions. There were no differences in the hands-on time between the two everyday task groups (all drivers: t (285) = –0.549, p = 0.584; LCR drivers, t (213) = –0.068, p = 0.946; HCR drivers: t (70) = –0.998, p = 0.322). Similarly, no differences in the brake reaction time between the two everyday task groups were found (all drivers: t (278) = 1.160, p = 0.247; LCR drivers, t (207) = 1.545, p = 0.124; HCR drivers: t (69) = –0.219, p = 0.827).

In sum, for the three groups (all drivers, LCR and HCR drivers), the time budget did not affect the response times, but the engagement in a task led to longer response times. Additionally, there were no differences in the response times between the two everyday task groups, and there were no interaction effects between the two factors (time budget: 3 s, 4 s, and 5 s, and driver risk classification: LCR and HCR drivers) on the response times (see Table 3).

Fig. 6 shows the comparison of the response times between LCR and HCR drivers. The non-crash data in the 5 s time budget situation was used. No difference in the hands-on time between LCR and HCR drivers was found, LCR (M = 1.45 s, SD = 0.41) vs. HCR (M = 1.58 s, SD = 0.37), t (141) = –1.668, p = 0.097. However, the brake reaction time for LCR drivers was significantly shorter than that for HCR drivers, LCR (M = 1.85 s, SD = 0.52) vs. HCR (M = 2.07 s, SD = 0.45), t (140) = –2.186, p = 0.03.

3.3. Maximum longitudinal acceleration

Fig. 7 shows the maximum longitudinal accelerations under different time budget and NDRT conditions. Table 4 shows the results of the statistical analyses of the maximum longitudinal accelerations regarding the task and time budget. For all drivers, the time budget showed a significant main effect, but the task did not show a significant effect. Post hoc tests (LSD) showed that the maximum longitudinal accelerations (M = 6.35 m/s^2, SD = 1.64) for the 5 s group were significantly lower compared to the 3 s (M = 7.12 m/s^2, SD = 1.43) and 4 s (M = 7.00 m/s^2, SD = 1.44) groups (5 s vs. 3 s, p < 0.001; 5 s vs. 4 s, p < 0.001). Whereas there was no difference between the 3 s and 4 s groups (p = 0.513). For LCR drivers, the time budget showed a significant main effect, but the task did not show a significant effect. Post hoc tests (LSD) showed that the maximum longitudinal accelerations for the 5 s group were significantly lower compared to the 3 s and 4 s groups (5 s vs. 3 s, p < 0.001; 5 s vs. 4 s, p = 0.002), and no difference between the 3 s and 4 s group was found (p = 0.262). However, for HCR drivers, the time budget and task did not show a significant effect.

In sum, the task did not affect the longitudinal vehicle control for the three groups (all drivers, LCR and HCR drivers). The shorter time budget deteriorated the longitudinal vehicle control for all drivers and LCR drivers, but the time budget did not show a significant effect on the longitudinal vehicle control for HCR drivers. Besides, there were no interaction effects between two factors (time budget and driver risk classification) on the maximum longitudinal acceleration in different task situations (see Table 5).

Fig. 8 shows the comparison of the maximum longitudinal accelerations between LCR and HCR drivers. For the non-crashes in the 5 s time budget situation, no difference in the maximum longitudinal acceleration between LCR and HCR drivers was found, LCR (M = 6.48 m/s^2, SD = 1.64) vs. HCR (M = 5.95 m/s^2, SD = 1.58), t (140) = 1.687, p = 0.094.

3.4. Crash rate

Fig. 9 shows the crash rates under different time budget and NDRT conditions. Most crashes occurred in the 3 s and 4 s time budget situations, so the statistical analysis of the proportion of the crash occurrence under the 3 s and 4 s time budget conditions was used. A Pearson chi-square test was used to reveal the influence of the time budget and task on crash occurrence. For the influence of the time budget on crash occurrence, the proportion of crash occurrence for the 3 s group was higher compared to the 4 s group (all drivers: χ^2 = 71.996, p < 0.001; LCR drivers: χ^2 = 58.051, p < 0.001; HCR drivers: χ^2 = 11.025, p = 0.001). For the influence of the task on crash occurrence, the proportion of crash occurrence in the presence of the task was higher compared to the absence of the task (all drivers: χ^2 = 29.646, p < 0.001; LCR drivers: χ^2 = 29.569, p < 0.001; HCR drivers: χ^2 = 17.578, p < 0.001). Therefore, the shorter time budget and engagement in a task showed significant negative effects on the safety of take-over.

4. Discussion

4.1. Influence of time budget and NDRTs on take-over performance

4.1.1. Influence of time budget on take-over performance

For all drivers, LCR drivers, and HCR drivers, we found the time budget did not affect the hands-on time and brake reaction time. This result was in line with our hypothesis, which implies that drivers were inclined to react immediately in emergency take-over situations. One explanation for this reason is that the drivers maintain high situation awareness and are always ready to respond quickly. However, some studies indicated that longer time budgets lead to longer take-over times in automated driving studies (e.g., Gold et al., 2013; Gold et al.,

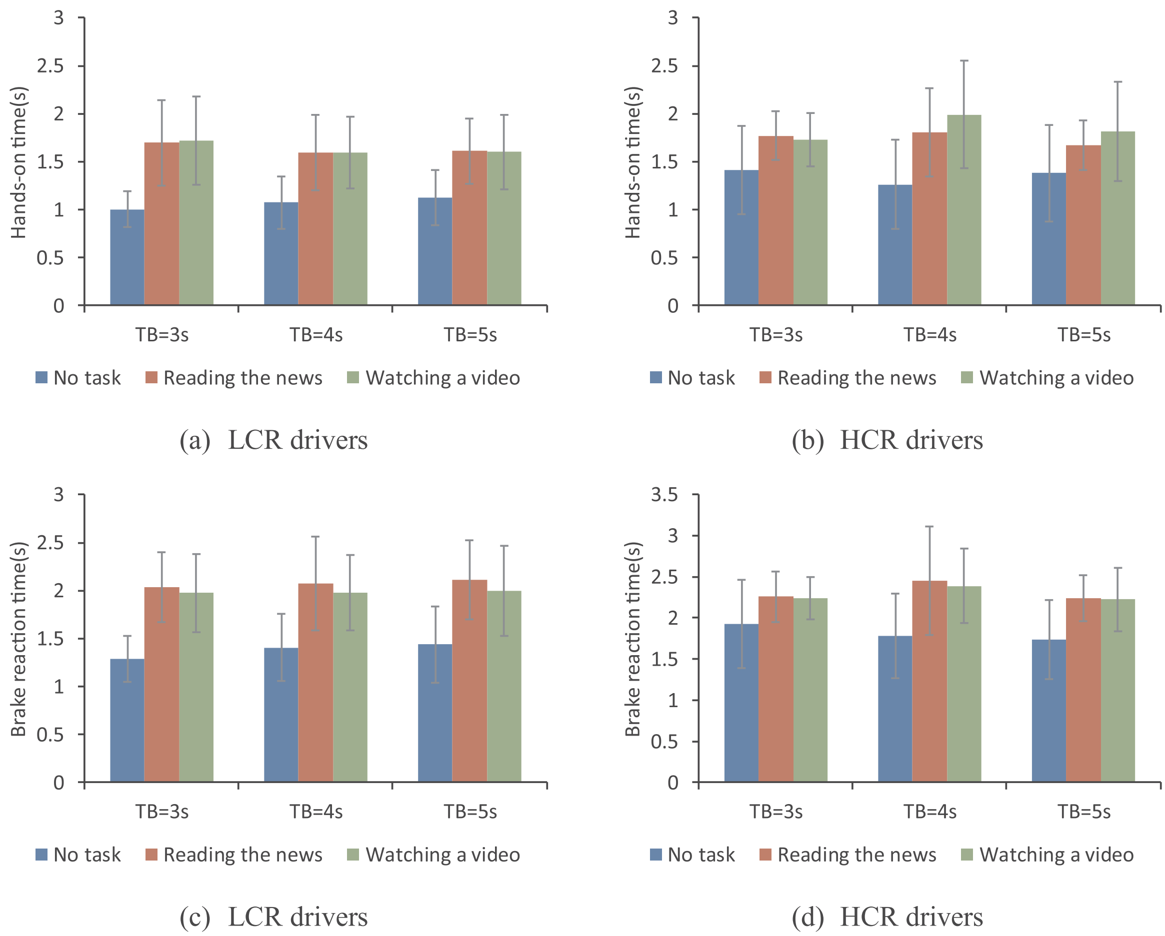


Fig. 5. The response times under different time budget and NDRT conditions

Table 2
Influence of time budget and NDRT on the response times.

Measure	Driver group	Effect	*F*	*df*	*p*
Hands-on time	LCR	Time budget	0.515	2, 314	0.598
		Task	90.073	2, 314	< 0.001
	HCR	Time budget	0.209	2, 99	0.812
		Task	13.289	2, 99	< 0.001
	All drivers	Time budget	0.180	2, 422	0.836
		Task	13.989	2, 422	< 0.001
Brake reaction time	LCR	Time budget	1.215	2, 307	0.298
		Task	96.794	2, 307	< 0.001
	HCR	Time budget	0.798	2, 97	0.453
		Task	13.907	2, 97	< 0.001
	All drivers	Time budget	0.622	2, 413	0.537
		Task	94.265	2, 413	< 0.001

Table 3
Interaction effects between time budget and driver risk classification on the response times.

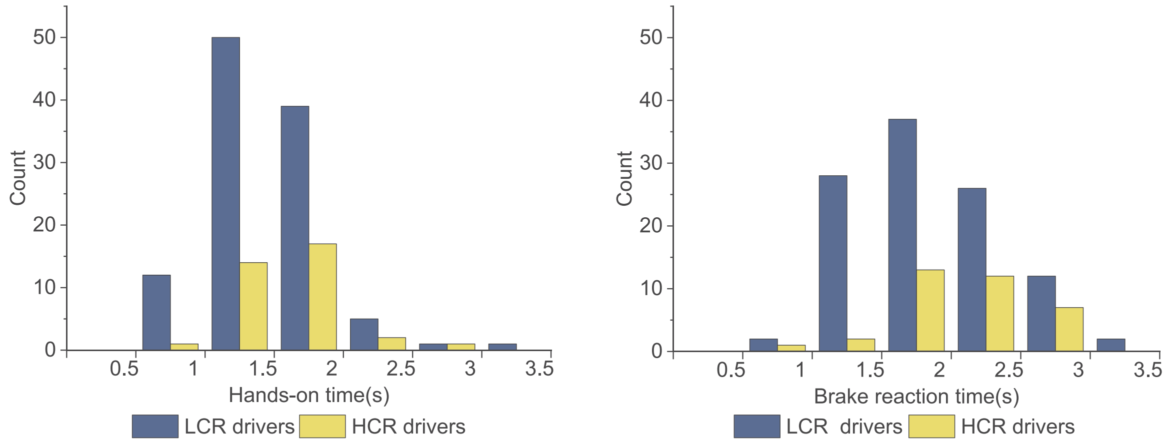
Measure	Task	*F*	*df*	*p*
Hands-on time	No task	1.121	2, 138	0.329
	Reading the news	0.407	2, 137	0.666
	Watching a video	1.837	2, 138	0.163
Brake reaction time	No task	1.939	2, 137	0.148
	Reading the news	0.739	2, 134	0.479
	Watching a video	0.413	2, 133	0.663

2017; Payre et al., 2016; Zhang et al., 2019a). For example, Gold et al. (2013) found that drivers react faster in 5 s time budget compared to 7 s time budget. A similar result was identified in the study of Ito et al. (2016). Automation drivers have sufficient time for "normal" braking and evasive maneuvers, in particular for the 7 s time budget without traffic (Happee et al., 2017). These results were not the same as our results. This might because the time budgets in the present study were high situational urgency.

For all drivers, the maximum longitudinal accelerations decreased with the increase of the time budget (time budget from 3 & 4 s to 5 s), and the number of the crashes also reduced significantly as the time budget increased (see Fig. 9). These results were consistent with our hypothesis and some previous studies (e.g., Wan & Wu, 2018; Mok et al., 2015; Ito et al., 2016). This because driving task demand increased with a reduction in time budget in general, and drivers may modulate their braking intensities to adapt to the different levels of time budget. That is, drivers did not need to use the full brake intensities in the 5 s time budget condition compared to the 3 s and 4 s time budget conditions. However, for HCR drivers, the time budget did not affect the maximum longitudinal accelerations, which suggested HCR drivers could not have the ability to control the vehicle very well.

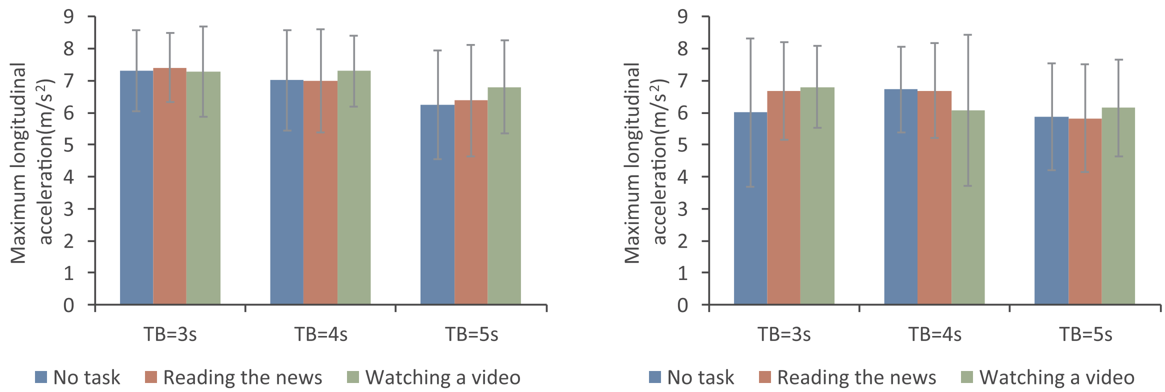
4.1.2. Influence of NDRTs on take-over performance

We observed that drivers in the absence of the task had the shorter hands-on time or brake reaction time compared to drivers in the presence of the task. This result was in line with our hypothesis. One explanation for this result is that the NDRT could consume more mental and physical resources compared to the absence of the task. For example, necessary operational steps like redirecting their gazes from the tasks to the road environments and putting their hands or feet on the



(a) Hands-on time (b) Brake reaction time

Fig. 6. Comparison of the response times of LCR and HCR drivers.



(a) LCR drivers (b) HCR drivers

Fig. 7. The maximum longitudinal accelerations under different time budget and NDRT conditions

Table 4
Influence of time budget and task on the maximum longitudinal accelerations.

Driver group	Effect	*F*	*df*	*p*
LCR drivers	Time budget	9.758	2, 307	< 0.001
	Task	1.022	2, 307	0.361
HCR drivers	Time budget	1.866	2, 97	0.160
	Task	0.341	2, 97	0.712
All drivers	Time budget	10.581	2, 413	< 0.001
	Task	1.352	2, 413	0.26

Table 5
Interaction effects between time budget and driver risk classification on the maximum longitudinal acceleration.

Measure	Task	*F*	*df*	*p*
Maximum longitudinal acceleration	No task	1.115	2, 137	0.331
	Reading the news	0.269	2, 135	0.764
	Watching a video	0.060	2, 133	0.942

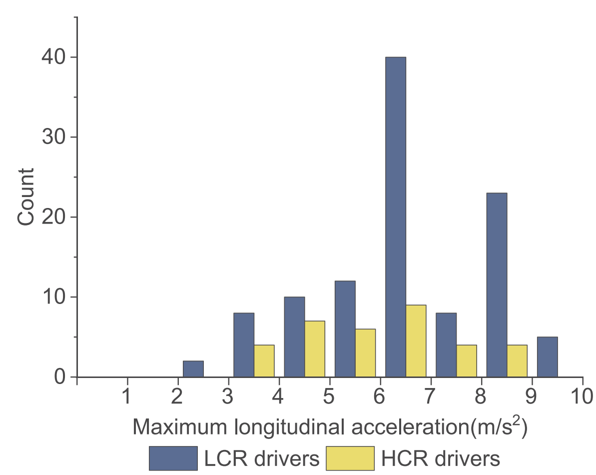


Fig. 8. Comparison of the maximum longitudinal accelerations of LCR and HCR drivers.

steering wheel or brake pedal may prolong the response times needed to take over the control. Similar results were found in some previous studies (e.g., Dogan et al., 2017; Feldhütter et al., 2017; Wandtner et al., 2018b). For example, Dogan et al. (2017) found that performing the NDRT resulted in a longer reaction time. The SuRT and the 20 minutes automation period induced slower reactions (Feldhütter et al., 2017). The system deactivation time (the steering wheel button was used in 92% of the cases) was significantly increased under the secondary task condition compared to no secondary task condition (Wandtner et al., 2018b).

Moreover, the results also showed that there was no difference in the hands-on time or brake reaction time between the news task and

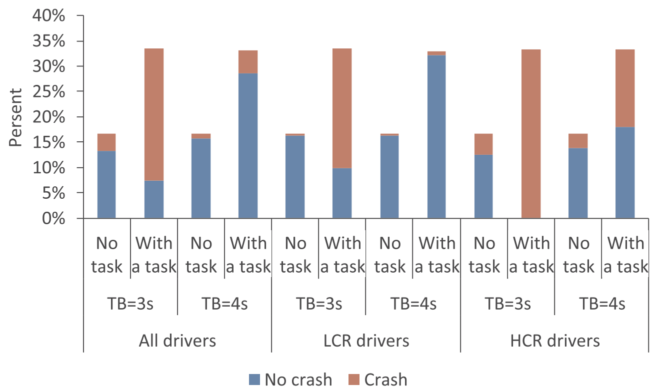


Fig. 9. The crash rates under different time budget and NDRT conditions.

video task groups, which implies that reading the news and watching a video might generate similar drivers' workload. The reason could be that both two non-handheld everyday tasks were relatively simple visual tasks, which did not require higher cognitive demand.

Our results indicated that the NDRT did not show a significant effect on the maximum longitudinal acceleration, which was consistent with our hypothesis. One possible explanation is that there is a higher urgency of take-over under the 3 s, 4 s, and 5 s time budget conditions, and drivers must react quickly to avoid the collision with the broken-vehicle in front, which required that the drivers reacted more reflexively in the braking regardless of the current cognitive state and brake strongly. Besides, we found the NDRT showed a significant adverse effect on the safety of take-over, which might due to delayed response times when drivers engaged in a task.

4.2. Comparison of high crash risk and lower crash risk drivers

We found that LCR drivers had shorter brake reaction time compared to HCR drivers for the non-crashes in the 5 s time budget situation, which indicates the characteristic of the hazard avoidance of HCR drivers and the possible causes of the accidents. These results revealed that HCR drivers had lower hazard perception ability to avoid the potential collision in emergency take-over situations compared to LCR drivers in general.

These results were consistent with some previous studies. For example, McKenna and Crick's (1991) found that drivers with a high number of accidents in the previous two years showed worse hazard perception test results. Hull and Christie (1992) also found that the accident-involved drivers took longer to react to danger than the accident-free drivers. According to the study of Horswill et al. (2015), drivers who failed the test were 25% more likely to crash within the following year. Zeeb et al. (2015) found that high-risk drivers started braking later than both medium and low-risk drivers, and they also showed more collisions with the surrounding traffic than low-risk drivers.

According to the definition of major categories of driver errors (NHTSA 2008; Curry et al., 2011), this study showed the recognition errors (e.g., internal distraction and delayed perception) could be the primary critical human reasons for crashes in emergency take-over situations, particularly for HCR drivers. These results were different from the causation of crashes in conventional driving in general. For the NMVCCS study (NHTSA 2008), driver-related critical reasons are broadly classified into recognition errors (40.6 %), decision errors (34.1 %), performance errors (10.3 %) and non-performance errors (7.1 %). For conventional driving, the principal recognition errors are inadequate surveillance (20.3 % out of 40.6 %) and internal distraction (10.7 % out of 40.6 %), and the principal decision errors are selecting a speed that is either too high for the conditions or for a curve (13.3 % out of 34.1 %). Therefore, interior non-driving activity is the typical driver-related crash-associated factor for both automated driving and conventional driving. Note that fatigued drivers could pose a serious hazard in complex take-over situations (Vogelpohl et al., 2019), and this factor was not included in the scope of this study.

4.3. Limitations

Several limitations of the present study were as follows: (1) A driving simulator was used to conduct the tests. The results might be influenced by not being in real dangerous situations. Some studies related to the comparison between real traffic and driving simulator were conducted, for example, there was a strong positive correlation for transition time in the on-road and simulated driving conditions (Eriksson et al., 2017b). Thus, considering the driving safety, the use of the driving simulator could be regarded as reasonable. (2) Limited by the size of the sample, drivers were divided into two categories: HCR drivers and LCR drivers. There is no universally recognized dividing standard to separate crash risk drivers in the automated driving study. In the study of Zeeb et al. (2015), the drivers were categorized into "high", "medium" and "low-risk" according to their gaze behavior. Drivers were divided into two categories: high risk group (novice drivers, aged 17–24 years) and lower risk group (experienced drivers, aged 28–36) (Smith et al. 2009). Therefore, establishing a more specific classification should be considered further. (3) Because of technical restrictions of the software, we chose to grasp the steering wheel as the switch mode from automated driving to manual control, which made a little difference for take-over performance between our study and other studies with deactivating the system by steering or braking or by pressing the button on the steering wheel. (4) The drivers in this study were limited to young and mid-aged drivers. Some participants were university students. Thus, the study results regarding other age and driving experience have to be further examined. (5) In order to create emergency take-over situations, we adopted the shorter time budgets in the tests, so the results can not be generalized to the take-over situations with longer time budgets or other non-critical take-over situations. Therefore, these take-over situations should be considered in future studies.

5. Conclusions

LCR drivers had shorter brake reaction time compared to HCR drivers for the non-crashes in the 5 s time budget situation. This finding showed that HCR drivers had lower hazard perception compared to LCR drivers. Furthermore, recognition errors (e.g., internal distraction and delayed perception) could be the primary critical human reasons for crashes in emergency take-over situations. Therefore, the individual difference of driving ability in take-over situations significantly affects the safety of take-over, and this factor should be considered to design safe take-over concepts for automated vehicles.

This study investigated the effects of time budget and NDRT on take-over performance in emergency take-over situations with fewer escape paths. For the three groups (all drivers, LCR, and HCR drivers), the time budget did not affect the response times, but the engagement in a task led to longer response times, and the shorter time budget and engagement in a task deteriorated the safety of take-over. For the maximum longitudinal acceleration, the task did not affect the longitudinal vehicle control for the three groups (all drivers, LCR and HCR drivers). The shorter time budget deteriorated the longitudinal vehicle control for all drivers and LCR drivers, but the time budget did not show a significant effect on the longitudinal vehicle control for HCR drivers. Notably, the two non-handheld everyday tasks including reading the news and watching a video seem to have a similar effect on the drivers' workload.

Note that there was no interaction effect between two factors (time budget and driver risk classification) on the response times and longitudinal vehicle control, which should be further examined under different take-over scenarios in future studies because it is of the potential implications for designing automated systems to support the needs of HCR drivers in particular.

CRediT authorship contribution statement

Qingfeng Lin: Conceptualization, Investigation, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Shiqi Li:** Writing - original draft, Writing - review & editing. **Xiaowei Ma:** Writing - review & editing. **Guangquan Lu:** Funding acquisition, Software, Project administration.

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Appendix A. Supplementary data

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