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Published in:
Accident Analysis and Prevention

DOI:
10.1016/j.aap.2021.106397

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2021

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Dillmann, J., den Hartigh, R. J. R., Kurpiers, C. M., Pelzer, J., Raisch, F. K., Cox, R. F. A., & de Waard, D. (2021). Keeping the driver in the loop through semi-automated or manual lane changes in conditionally automated driving. *Accident Analysis and Prevention*, *162*, [106397]. https://doi.org/10.1016/j.aap.2021.106397

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Accident Analysis and Prevention 162 (2021) 106397

Contents lists available at ScienceDirect

Accident Analysis and Prevention

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

Keeping the driver in the loop through semi-automated or manual lane changes in conditionally automated driving

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ARTICLE INFO

Keywords:
Human-automation interaction
Function allocation
Lane change
Vehicle automation
Perception-action

ABSTRACT

In the current study we investigated if drivers of conditionally automated vehicles can be kept in the loop through lane change maneuvers. More specifically, we examined whether involving drivers in lane-changes during a conditionally automated ride can influence critical take-over behavior and keep drivers' gaze on the road. In a repeated measures driving simulator study ($n = 85$), drivers drove the same route three times, each trial containing four lane changes that were all either (1) automated, (2) semi-automated or (3) manual. Each ride ended with a critical take-over situation that could be solved by braking and/or steering. Critical take-over reactions were analyzed with a linear mixed model and parametric accelerated failure time survival analysis. As expected, semi-automated and manual lane changes throughout the ride led to 13.5% and 17.0% faster maximum deceleration compared to automated lane changes. Additionally, semi-automated and manual lane changes improved the quality of the take-over by significantly decreasing standard deviation of the steering wheel angle. Unexpectedly, drivers in the semi-automated condition were slowest to start the braking maneuver. This may have been caused by the drivers' confusion as to how the semi-automated system would react. Additionally, the percentage gaze off-the-road was significantly decreased by the semi-automated (6.0%) and manual (6.6%) lane changes. Taken together, the results suggest that semi-automated and manual transitions may be an alarm-free instrument which developers could use to help maintain drivers' perception–action loop and improve automated driving safety.

1. Introduction

The safe interaction of the human with the automated vehicle will likely remain a relevant road safety objective for the coming decades (Chan, 2017; Fagnant & Kockelman, 2015; Parasuraman & Wickens, 2008). This article focusses on conditional vehicle automation (SAE Level 3),

which is one of the intermittent steps between manual driving (SAE Level 0) and full automation (SAE Level 5). At this level of automation drivers may delegate the driving task to the automated vehicle. However, this is only possible under the condition that drivers remain capable of taking back control from the vehicle rapidly and adequately (SAE, 2018a; SAE, 2018b). In other words, drivers must remain fallback ready in case of automation-initiated transitions (Lu et al., 2016). However, the quality of drivers' reactions in safety critical take-over situations has been shown to be lower if the driver has been driving with automation (de Waard et al., 1999; Gold et al., 2013; Louw et al., 2017b). This performance decrement has been linked to drivers' reduction of physical control of the vehicle and perception of the driving scene, which is reflective of the driver being out-of-the-loop (Merat et al., 2018). To counteract this safety critical out-of-the-loop problem it is of interest how motor-perceptual mapping and gaze patterns can be maintained while driving with automation (Mole et al., 2019).

1.1. The perception-action in loop in conditionally automated driving

Recent empirical research on the out of the loop problem has utilized perception–action theory (Dillmann et al., 2021). This approach focusses on how driving behavior emerges from the interaction of the driver with environment through iterative loops of perception and

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https://doi.org/10.1016/j.aap.2021.106397
Received 29 April 2021; Received in revised form 30 August 2021; Accepted 9 September 2021

action (Bootsma, 1998; Fajen, 2005; Fajen & Devaney, 2006; Mathieu et al., 2017). For example, the driver may be attuned to a visual variable such as a looming stop sign. The optical expansion of the stop sign specifies how much the driver needs to brake (DeLucia et al., 2016; Lee, 1976; Morando et al., 2016). For an adequate motoric reaction to emerge the driver needs to be calibrated so as to apply the right amount of braking force in respect to the visual information (Brand & de Oliveira, 2017; Fajen & Devaney, 2006). The question this approach raises is how drivers can be kept visually attuned to the road and maintain motor-calibration while driving with conditional vehicle automation. In line with this approach, Dillmann et al. (2021) investigated if drivers motor-calibration while driving with conditional automation can be affected by exposing drivers to four recurring automation-initiated take-overs in a 13-minute ride. They found that automation-initiated take-overs influenced drivers behavior in critical take-over situations by reducing reaction time and the sharpness of the steering behavior (see also Bourrelly et al., 2019). However, the effects of automation-initiated transitions only reached significance in the condition where drivers' gaze was experimentally manipulated to remain on the road (Dillmann et al., 2021). Given that drivers of conditional automation may engage in self-paced visual non-driving-related-tasks (NDRT, Ahlstrom et al., 2016; Jamson et al., 2013), it is unclear which effect recurring transitions would have had on drivers' uncontrolled gaze behavior.

In perception–action theory, perception is construed as visual attunement to information in the environment in the service of action (Mathieu et al., 2017; Wilson, 2002). Therefore, it could be expected that a task demand such as a degree of recurring take-overs (action) would increase the extent of gaze on the road (perception). Indeed, even the potential of a task demand has been shown to affect where we look (Sullivan et al., 2012). These findings are coherent with research suggesting that being out of the loop is associated with more visual attention below the windscreen (Schnebelen et al., 2020) and less cumulative time spent looking at the road ahead (Feldhütter et al., 2017; Jamson et al., 2013; Louw et al., 2017a). Gaze off the road in manual driving has been associated with higher crash likelihood (Seppelt et al., 2017) and slower reaction times (Lamble et al., 1999). Although the question of how safe gaze patterns can be maintained has been raised (Mole et al., 2019), it is unclear if recurring take-overs can contribute to maintaining in-the-loop gaze patterns while driving with conditional vehicle automation. While recurring automation-initiated mandatory take-overs may help improve motor calibration, they also have disadvantages. Apart from the obvious inconvenience of posing drivers with frequent mandatory take-overs, they may also habituate drivers to take-over alarms. This could lead to a so-called cry wolf effect leaving drivers insensitive to critical alarms (Bresnitz, 1984; Naujoks et al., 2016). Therefore, an alarm free manner of maintaining drivers' motor-calibration is necessary.

1.2. *Utilizing lane changes to keep the driver in the loop*

Considering the goal of exposing drivers to manual control without an alarm, the driver's initiation of a transition may be a safer alternative (Lu et al., 2016). Generally, it should be noted that lane changes are a widely studied and modeled maneuver (Ali et al., 2021; Toledo & Zohar, 2007). However, lane changes have not been studied much in combination with automated driving. From a perception–action perspective, lane changes during automated driving may have the effect of maintaining drivers' perception–action loop through better visual-attunement and more motor-calibration. Indeed, it has been shown that integrating manual lane changes into automated driving can change drivers' gaze behavior, arguably keeping the driver more in the loop (Goncalves et al., 2020). However, it is unclear if keeping the driver in the loop with lane changes can improve motor-calibration and thereby behavior in critical take-overs. Given that intermittent manual control in generic traffic situations has been shown to improve critical take-over behavior (Dillmann et al., 2021), manual lane changes may improve take-over behavior. Such lane changes from automation could be discretionary lane changes (cf. Ali et al., 2020a; Ali et al., 2020b) or mandatory lane changes (Ali et al., 2018). Previous research has shown that discretionary deactivation of the automated system occurs to drive faster and change lanes if the system is not capable of doing so (van Huysduynen et al., 2018). Mandatory lane changes are necessary to reach the desired location (Ali et al., 2020b). For example, a mandatory lane change would be necessary if lane changes are outside the operational design domain of a conditionally automated system (SAE International, 2018b) but necessary for navigational purposes. Although this distinction is generally important, from a perception–action perspective both types of lane changes appear appropriate to keep the driver in the perception–action loop as both involve the driver taking back control from the automated system. From this perspective a central discerning factor would be if drivers take back manual control or if semi-automated systems stay active to assist the driver (van Dintel et al., 2021). Indeed, if a lane change is outside the operational design domain of the conditionally automated system (SAE International, 2018a; SAE International, 2018b), a shared control system with mixed input by driver and automated system might also be used to change lanes (Abbink et al., 2018; Madigan et al., 2018). However, as previous research has shown that shared control has the potential to keep the driver more in the loop (Mulder et al., 2012), it is conceivable but as yet unknown if lane changes in semi-automated design could also improve behavior in critical take-overs from conditional vehicle automation.

1.3. *Current research*

The primary question of this study was whether, compared to automated lane changes, semi-automated or manual lane changes throughout a conditionally automated ride improve critical take-over behavior. The underlying reason would be that drivers are kept more in the loop when performing semi-automated and manual lane changes. We expected semi-automated or manual lane changes throughout the ride to lead to faster and more adequate braking and steering behavior in critical take-over situations than the automated lane-change condition (H1). Regarding the semi-automated and manual lane change conditions, we expected lane-changes in manual control to show faster and more adequate critical take-over behavior than semi-automated control (H2). We also expected semi-automated and manual lane changes to cause less visual attention to a non-driving related task (NDRT) during the ride (H3). Finally, we explored whether differences in acceptance existed between the lane change conditions.

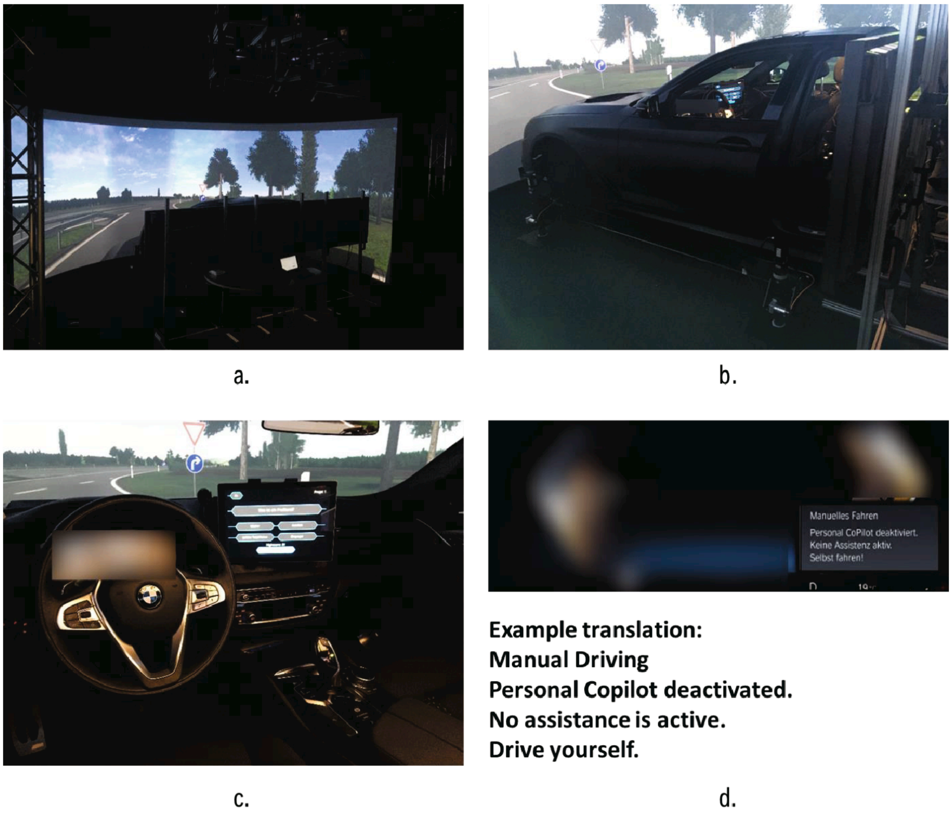
2. Method

2.1. *Participants*

For the current study 87 participants were recruited via an internal employee participant pool. Before the study, informed consent by all was attained and the study complied with the American Psychological Association Code of Ethics. We only included participants who had normal or contact-lens corrected to normal eyesight, did not work in the field of vehicle automation, and had at least 70 000 km driving experience. Two participants had to be excluded for analysis due to technical issues with the driving simulator. The final data set consisted of 85 participants (25 female) whose age ranged from 21 to 61 years ($M_{\mathrm{Age}} = 35.9$, $SD_{\mathrm{Age}} = 10.4$) with a mean lifetime mileage of $M_{\mathrm{km}} = 183{,}000$ $SD_{\mathrm{km}} = 99{,}500$.

2.2. *Apparatus and human Machine interface*

The study was performed in a dynamic driving simulator at BMW group with five projectors and three exterior LCD screens delivering a 220 degrees horizontal and 45 degrees vertical visual field of view (see Fig. 1a). The vehicle-mockup consisted of the front section of a BMW 5



Manuelles Fahren
Personal CoPilot deaktiviert.
Keine Assistenz aktiv.
Selbst fahren!

Example translation:
Manual Driving
Personal Copilot deactivated.
No assistance is active.
Drive yourself.

Fig. 1. The research setup at BMW Research and Development used in this manuscript: Exterior view of the projection and rear-view television screens (a), the D-Box actuator mockup (b), the driver perspective including the NDRT (c) - with the question: "What is a profiteroles?" and the answer options: "Filled dough sweets, loan shark, anise liquor, and songbird" -, and the speedometer including an original German message with English translation (d).

series chassis with according cockpit elements and was mounted on a 3-Degree of Freedom motion system (D-Box Technologies Inc, see Parduzi et al., 2019; Fig. 1b.). Vehicle and simulation parameters were rendered by BMW's Spider Simulation environment and were recorded at 50 Hz. Eye-Movements were recorded with a Tobii Pro Glasses System controlled by a Tobii Pro Glass controller, which recorded at 50 Hz.

The NRDT consisted of multiple-choice trivia questions such as "What is a red snapper?", "On which planet is a day longer than a year?" or "What is profiteroles?" (see Fig. 1c), presented with one correct and three distractor answering options. This was displayed on a 12.3" Microsoft Surface Pro 7 placed directly under the windscreen above the middle console. To quantify if participants engaged in the NDRT we logged the number of answered questions. To standardize driver's position in the vehicle the quiz was played using a controller in the lower middle console. The human–machine-interface (HMI) included a standard conditionally automated driving vehicle interface (Forster et al., 2016; Manca et al., 2015). It had a conceptual similarity to previous research (Dillmann et al., 2021). Regarding the lane change condition, the HMI differed across conditions.

2.3. *Experimental conditions*

Lane change decision modeling is itself an expansive field of research (Ali et al., 2021; Toledo & Zohar, 2007), encompassing increasing knowledge on initiation points and lane change duration. To standardize the experiment across conditions, the lane change suggestion in the current study was initiated when the ego vehicle, driving 100 km/h, came 90 m close to the vehicle in the ego lane driving 80 km/h. It was ensured that the target lane was free of other vehicles in this situation. At this standardized trigger point the driver received an acoustic signal and a text box in the speedometer (cf. Fig. 1d) explaining the condition specific modality in which the lane change was performed.

2.3.1. *Automated lane change condition*

In the lane change condition with automated lane changes drivers received an acoustic signal paired with a text box in the lower right speedometer display (see Fig. 1d). The text informed them the vehicle was performing an automatic lane change procedure. Although functionally unnecessary this notification was included to standardize the occurrence of signals across conditions. The vehicle then changed lanes and overtook the slower vehicle automatically.

2.3.2. *Semi-Automated lane changes*

In the semi-automated condition drivers received an acoustic signal paired with a text box in the speedometer informing them that a lane change was possible and could be initiated by placing their hands on the steering wheel and pressing the indicator. If the drivers did this, the system shifted to a shared control system (cf. SAE Level 2, SAE International, 2018a) and a lane change at this level of automation was initiated by the vehicle. Simultaneously a text box in the speedometer and an acoustic speech signal informed the driver that the SAE L3 System was deactivated and the driver needed to supervise the system. This is in line with the SAE Level 2 partial automation definition (SAE International, 2018a) which defines that the driver remains responsible for the driving task. In this operationalization the drivers' responsibilities were to keep their hands on the steering wheel and remain responsible for the driving task. Once drivers had changed lanes with the semi-automated system and overtaken the slower vehicle or passed the highway interchange, they were prompted to change back onto the right lane and subsequently prompted to reactivate automation. It should be noted that although the system recommended that the drivers could change lanes, it was the driver who initiated the procedure and the design of the transition is therefore considered a discretionary lane change (Lu et al., 2016).

2.3.3. *Manual lane changes*

In contrast to the semi-automated lane change condition, participants in the manual lane change condition overtook the slower vehicle in full manual control akin to SAE Level 0 (SAE International, 2018a). Specifically, participants received an acoustic signal and a text box in the speedometer (see Fig. 1) informing them that a lane change was possible by deactivating automation. They could then fully deactivate all automation by pressing the activation button or the brake. If they performed this action, conditional vehicle automation was deactivated, and drivers received an acoustic speech message and text in the speedometer informing them that they were driving manually and no driver assistance systems were active. Upon manually changing lanes and after overtaking the slower vehicle or passing the highway interchange, drivers were prompted to change back onto the right lane and to reactive automation afterwards.

2.4. *Procedure*

When participants arrived, they filled out an informed consent and demographic questionnaire. Participants were instructed that the vehicle contained a personal copilot function which could be activated via a button when availability was shown in the display. The system would be only available in the right lane and would only drive 100 km/h. Participants were asked to imagine that they had picked this vehicle up at the airport and would get acquainted with it during the ride. Finally, they were introduced to the NDRT which consisted of a quiz they could engage in at their own discretion. Participants first took part in a general practice trial in which they drove manually for five kilometers while performing lane changes and a critical brake maneuver, then activated the L3 system, and encountered the same critical take-over shown in the experimental rides. It was important to include a first take-over in the practice ride to provide comparability to the take-overs in the following repeated measures experimental rides (Hergeth et al., 2017).

For the experimental trials, participants drove the three lane change conditions in a randomized order. Each trial started with a condition specific practice ride in which drivers had a first contact with the lane change modality. Following the first contact, participants were asked to explain the HMI and misconceptions were clarified by the experimenter. To ensure realistic interactions with the HMI, participants were only provided with information on the use of the system and not on the shift of responsibility. They then drove an approximately 12.5-minute ride in which they encountered four lane change scenarios of which three (Scenario 1,3,4) consisted of overtaking another vehicle, whereas one consisted of a lane change for navigational purposes on a highway interchange (Scenario 2, see Fig. 2).

2.5. *Critical Take-Over*

Near the end of the ride's participants encountered a critical take-over which was identical for each ride: A vehicle in front of them performed a critical braking action due to a crashed vehicle in front of them at 108 m distance and 27 m/s speed. Given the relative speed of the braking vehicle this led to a time-to-collision of 4.7 s which has been shown to be appropriate to detect differences in take-over behavior (Dillmann et al., 2021). Specifically, the take-over needed to be critical enough to avoid floor effects with all participants managing the situation with ease. A take-over with 5 s time-to-collision has been shown to be manageable by most participants but is still critical enough to reveal meaningful differences (Gold et al., 2013). The take-over was communicated by a red signal in the speedometer, an illuminated steering wheel flashing in red color and an urgent acoustic warning signal as used in Dillmann and colleagues (2021). To measure participants' unobstructed behavior, automation was turned off after the take-over signal.

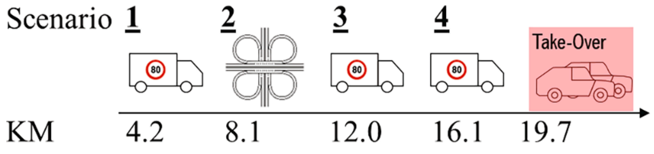


Fig. 2. Schematic presentation of the experimental ride: The figure shows the experimental ride which was repeated three times: once with each of the three lane change conditions.

2.6. *Measures*

2.6.1. *Manipulation checks and exploratory measures*

To confirm that participants engaged in the non-driving-related task, we collected the number of trivia questions they answered throughout each of the rides. The minimum time to collision was controlled to ensure that the take-overs were sufficiently time critical. Additionally, participants were asked to indicate their subjective alertness experienced during the ride by filling in the Karolinska-Sleepiness Scale (KSS, Åkerstedt & Gillberg, 1990). System acceptance was assessed after each experimental ride using an acceptance scale (Van der Laan et al., 1997).

2.6.2. *Critical Take-Over measures*

In the critical take-over both braking and steering reactions were possible. We therefore used appropriate measures to quantify both reaction time and adequacy of both maneuver options. For braking behavior it has been argued that there is not one gold standard for measuring braking reaction time (Green, 2000). In line with literature we measured the initial braking reaction as time from the take-over request to participants' depletion of the brake pedal by 10% (Zhang et al., 2019). However, the initial braking reaction does not provide any information on subsequent braking control or adequacy (Markkula et al., 2016). To understand further braking control, we measured the time from the take-over signal to the moment of maximum vehicle deceleration. Taken together, these two measurements show initial reaction times and braking control.

Regarding steering behavior we used the standard measure, time from take-over signal to hands on the steering wheel, as a reaction time measure (Zhang et al., 2019). As with braking, this measure does not necessarily provide information on further vehicle control. Therefore, we included measured steering adequacy as the standard deviation of the steering wheel angle. The calculation was performed on the six seconds after the take-over signal which was the time it took for all participants to conclude their maneuver and has been used in previous research on take-over behavior (Dillmann et al., 2021). Moreover similar timespans have also been used in modeling of lane change behavior (Ali et al., 2019a; Ali et al., 2019b). This measure shows how smooth the steering behavior is (Mole et al., 2019). Research has shown that the standard deviation of the steering wheel angle increases when taking back control from automation as opposed to continuous manual driving (Eriksson & Stanton, 2017) and it has been used empirically to indicate steering quality (Mole et al., 2019; Dillmann, et al., 2021).

2.6.3. *Gaze behavior during the ride*

Previous research has investigated the percentage of glance duration on the road center (Carsten et al., 2012; Louw et al., 2017a) is lower when driving with automation than when driving manually. However, it has recently been indicated that reduced glances at the mirrors are also indicative of out-of-the-loop behavior (Schnebelen et al., 2020). To account for both the percentage of gaze on the road and the mirrors in a meaningful measure, we measured the percentage of time that was spent in fixations either "on-the-road" areas-of-interest (Road Center/Left/Right, Rear View Mirror, Right/Left Shoulder, Right/Left Mirror) or on the NDRT. To make the measurement comparable between the automated and semi-automated and manual lane changes, we analyzed the timespans between lane changes (see Fig. 3), providing an average of 7.4 min of observed glance time per participant. A filter was applied that interpolated two or more glances in the same area of interest separated by <120 ms (Hergeth et al., 2016; Inhoff & Radach, 1998). To gain a conservative estimate of where participants looked, we calculated the overall percentage of time spent in fixations (>80 ms). As opposed to glance times, fixations increase the likelihood that the visual information is actually perceived (Just & Carpenter, 1980).

2.7. *Statistical analysis*

In hypothesis 1 we expected drivers to perform faster and more adequate take-overs in the semi-automated or manual lane changes than in the automated condition. In hypothesis 2 we expected drivers to take over faster and more adequately in the manual lane change than in the semi-automated lane change condition. To test hypotheses 1 and 2 we first calculated a linear mixed model testing the overall effect of the experimental condition on the dependent variables with the lme4 (V. 1.1–27) package in R Statistics (V 3.5.1). This model is similar to a repeated measures analysis of variance but is capable of analyzing datasets with missing data (Haque & Washington, 2015; Washington et al., 2011). Next, to test hypothesis 1 we calculated a planned comparison (Cohen et al., 2014), contrasting the automated condition with a linear combination of the semi-automated and manual lane change conditions for the dependent variables. The coding scheme consisted of the coding (2, −1, −1) for automated, semi-automated, and manual control respectively. To test hypothesis 2, we contrasted the semi-automated and the manual lane change conditions: For this contrast the coding scheme was (0, −1,1) for automated, semi-automated, and manual control respectively. Each contrast provided a coefficient (b) describing the difference in means of the contrast and a t-test determining its significance. However, the linear mixed model only tests for differences in means between the conditions. Recent research has shown that for reaction time data, more insight into the data can be gained by complementing the linear mixed model with a survival analysis (Haque & Washington, 2015; Yadav & Velaga, 2021). In studies on lane changes it has been used to assess the probability of lane changes (Ali et al., 2019a; Ali et al., 2019b; Ali et al., 2020a; Ali et al., 2020b). To assess how the duration to an event is influenced covariates an accelerated failure time (AFT) survival analysis is particularly appropriate (Ali et al., 2020a; Ali et al., 2020b; Haque et al., 2016; Mahajan & Velaga, 2020; Yadav & Velaga, 2021). The assumption in this analysis is that the covariates can influence or scale (accelerate/decelerate) the response time towards an event (for a formal description see Haque & Washington, 2015; Washington et al., 2011). To calculate statistical significance of monotonously increasing risk, a Weibull distribution with a scale parameter ($P > 1$) and location parameter ($\lambda > 0$) has been used (Haque & Washington, 2015; Washington et al., 2011). This distribution is appropriate for data displaying a monotone hazard function with decreasing survival probability. The confidence interval of the scale parameter P was always > 1 deeming the Weibull distribution appropriate. The interdependence of participants' three rides was corrected for by including a gamma frailty coefficient (cf. Haque & Washington, 2015). This is similar to adding a random factor in a linear mixed model analysis for repeated measures.

Across all analyses, nine participants' rides were excluded because they had to be discontinued due to issues in the hydraulic system, steering wheel integration or software errors which could not be resolved within the participant's session. Regarding the analysis of the critical take-over data, 29 of 255 rides needed to be excluded due to irregularities in the critical take-over situation. Specifically, in these cases the vehicle in front of the crashed vehicles switched lanes instead of braking which led to lower times to collision and made the rides incomparable with other rides (see Table 1). The cause of this error was the attempt of giving simulation vehicles natural driving behavior which caused idiosyncrasies in vehicle behavior for the excluded rides. Further 4 rides needed to be removed from the take-over analysis because the participants had placed their hands on the steering wheel before the take-over request making them incomparable.

For the eye-tracking data 22 trials were generally excluded due to eye-recognition <85% throughout the ride. For the self-report questionnaire data on trust and acceptance, an additional two rides were removed as they were incomplete.

3. Results

3.1. *Manipulation checks and exploratory measures*

To confirm that participants engaged in the non-driving-related task, i.e., the quiz on the middle console, we calculated the number of answered quiz-questions per condition (see Table 2). The average minimum time to collision after the take-over did not differ significantly between the automated, semi-automated or manual control lane change conditions, $F(2,130) = 1.61$, $p = .87$. The level of alertness did not correlate significantly with reaction time $r = 0.12$, $t(140) = 1.43$, $p = .15$ for brakers, and standard deviation of the steering wheel angle; $r = 0.17$, $t(73) = 1.50$, $p = .13$ for steerers. Although minimum vehicle speed correlated with the standard deviation of the steering wheel angle, $r = -0.41$, $t(73) = 1.50$, $p < .001$, a repeated measures linear mixed model for steering participants did not indicate any systematic differences in minimum speed between the conditions, $F(2,45) < 1$, $p = .74$ (see Table 2).

The analyses of acceptance show that ratings on the scale of −2 to + 2 were generally high see Table 3). Differences between the experimental conditions existed in both subscales: satisfaction, five items, $\alpha = 0.76$, $F(2,130) = 41.67$, $p < .001$, and usefulness, four items, $\alpha = 0.87$, $F(2, 130) = 53.35$, $p < .001$. Satisfaction was scored highest in the automated condition when contrasted to a linear combination of the semi-automated and manual lane change conditions, $b = -0.20$, $t(130) = -8.24$, $p < .001$, but satisfaction was higher in the semi-automated than the manual lane change condition, $b = -0.16$, $t(130) = -3.66$, $p < .001$. On the subscale usefulness, we found the same pattern: The automated lane change condition also scored higher than the semi-automated and manual lane change conditions, $b = -0.26$, $t(130) = -9.45$, $p < .001$, and the semi-automated lane change was perceived as

Table 1
Number of rides per condition after exclusions.

Measure	Lane Change Condition		
	Automated	Semi-Automated	Manual
Take-Over	79	66	69
Eye-Tracking	80	68	78
Acceptance	79	66	72

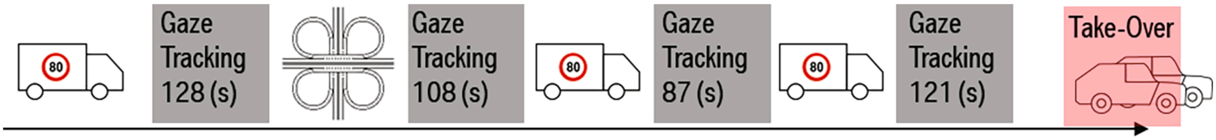


Fig. 3. Schematic presentation of the gaze tracking average duration of the interval in seconds.

Table 2
Descriptive Statistics.

Measure	Lane change condition		
	Automated	Semi-Automated	Manual
Answered Quiz Questions(count)	70 (21)	53 (22)	54 (20)
TTC (s)	2.36 (1.00)	2.44 (0.99)	2.64 (1.00)
Minimum Velocity (m/s)	20.35 (5.36)	20.89 (6.46)	20.87 (5.86)
Satisfaction [−2,2]	1.26 (0.35)	0.82 (0.69)	0.48 (0.71)
Usefulness [−2,2]	1.38 (0.58)	0.81 (0.78)	0.40 (0.80)

Note. The table includes the mean and the standard deviation in parenthesis.

being more useful than manual lane change, $b = -0.19$, $t(130) = -3.90$, $p < .001$.

3.2. Critical Take-Over behavior

We expected that semi-automated or manual lane changes throughout the ride would lead to faster and more adequate braking and steering behavior in critical take-over situations than in the automated lane-change conditions (H1). Secondly, we expected that critical take-overs in the manual lane change condition would be faster and more adequate than in the semi-automated lane change condition (H2). To test these hypotheses, we separated the dataset into 134 rides where participants avoided the collision by braking and 80 rides in which participants changed lanes to avoid the collision. We could not find evidence that the maneuvers which participants chose were systematically influenced by the lane-change condition, $\chi^2(2) = 0.65$, $p = .72$.

Regarding the braking reaction time, a linear mixed model showed that differences in the time to the begin of the braking maneuver existed between the automated condition, $M = 1.81$, $SD = 0.44$, the semi-automated condition, $M = 1.94$, $SD = 0.66$ and the manual condition, $M = 1.66$, $SD = 0.46$, $F(2,73) = 3.60$, $p = .032$. Regarding hypothesis 1, the planned contrasts did not find any differences between automated lane change condition and a linear combination of the semi-automated and manual lane change conditions $b = -0.007$, $t(73) = -0.25$, $p = .802$. Unexpectedly, the contrast for hypothesis 2 found that participants were slower in the semi-automated than in the manual lane change condition, $b = 0.144$, $t(73) = 2.68$, $p = .009$. To gain a deeper understanding of how the lane change conditions influenced the reaction time, we investigated braking reaction time in the Weibull AFT Analysis (see Table 3). This analysis quantified how the lane change conditions increased or decreased the duration from the take-over signal to start of braking reaction.

Regarding hypothesis 1 the results showed that participants in the semi-automated lane change condition started braking an average of 11.9% later than participants in the automated lane change condition. It appears semi-automated lane changes increased the braking reaction time. This result is significant in the opposite direction of our expectation, that semi-automated lane changes to lead to faster reaction times. Indeed, two seconds after the take-over signal, visual inspection of the fitted model (see Fig. 4) shows that 43% of participants in the semi-automated condition had not started braking as opposed to 26% in the automated condition.

Regarding the difference between the manual lane change and automated lane change conditions the Weibull AFT analysis did not indicate a significant difference (see Table 3). Considering our hypothesis 2 the expected differences between semi-automated and manual lane changes approached significance, as evidenced by confidence intervals of the estimate in Table 3.

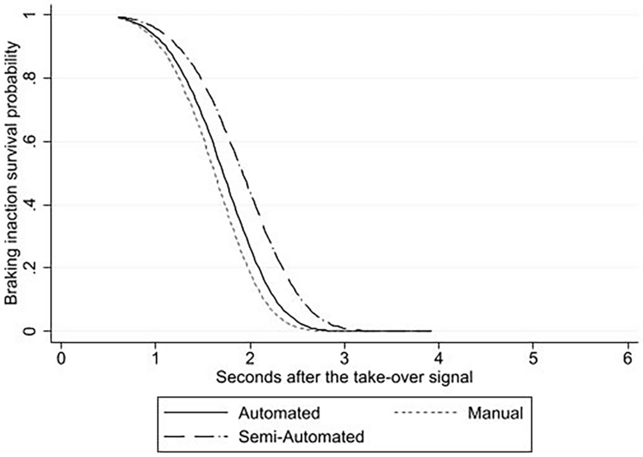


Fig. 4. Braking reaction survival graphs across experimental conditions. For visual inspection we plotted the survival functions per condition with a formula visible in Haque et al. 2015 and the model data from Table 3:

Table 3
Model results of the Weibull AFT with gamma frailty for time to maximum deceleration.

Variable	Estimate	SE	z-statistic	p-value	Exp(β)	95% CI	
						Lower	Upper
Constant	0.626	0.042	14.87	<0.001	–	0.543	0.708
Semi-Automated	0.113	0.055	2.05	0.041	1.119	0.004	0.221
Manual	−0.055	0.535	−1.03	0.304	0.946	−0.159	0.049
P	4.291	0.349	–	–	–	3.658	5.033
Variance of Gamma frailty θ	0.271	0.140	–	–	–	0.098	0.747

$LL(\widehat{\beta}) = -28.98$; $LL(0) = -33.28$; Likelihood ratio $\chi^2(2) = 8$; p-value = 0.010; AIC = 67; No. of observations = 134; No. of groups = 59.

Table 4
Model results of the Weibull AFT with gamma frailty for time to maximum deceleration.

Variable	Estimate	SE	z-statistic	p-value	Exp(β)	95% CI	
						Lower	Upper
Constant	1.147	0.057	19.97	>0.001	–	1.034	1.259
Semi-Automated	−0.144	0.064	−2.23	0.026	0.865	−0.271	−0.017
Manual	−0.186	0.066	−2.82	0.005	0.830	−0.316	−0.056
P	3.684	0.295	–	–	–	3.147	4.312
Variance of Gamma frailty θ	0.321	0.162	–	–	–	0.119	0.866

$LL(\widehat{\beta}) = -48.63$; $LL(0) = -53.14$; Likelihood ratio statistic = 9.02; p-value = 0.011; AIC = 107; No. of observations = 134; No. of groups = 59.

$$\boldsymbol{S}(\boldsymbol{t}=2)_{\boldsymbol{Semi-Automated}} = \boldsymbol{EXP}\left[-\boldsymbol{EXP}(-4.29(0.62+0.11\times 1))\times 2^{4.29}\right] = 0.43 = 43\%$$

In the next step we investigated our expectation that the adequacy of the braking would be improved in the semi-automated and manual lane change conditions compared to the automated lane change condition. The linear mixed model suggested that the time to full deceleration differed between the automated condition, $M = 2.96$ s, $SD = 1.67$ s, the semi-automated, $M = 2.64$ s, $SD = 0.89$ s, and manual condition, $M = 2.49$ s, $SD = 0.71$ s, $F(2,73) = 3.18, p = 0.47$. The contrast for hypothesis 1 showed that participants took longer to reach full deceleration in the automated condition than in a linear combination of the semi-automated and manual lane change conditions, $b = 0\ 0.127,\ t(73) = 2.40, p = .018$. The contrast for hypothesis 2 did not indicate a difference between the semi-automated and the manual condition in the time to full deceleration, $b = 0.068,\ t(73) = 0.70,\ p = .48$.

The AFT Weibull analysis shows that participants in the semi-automated and manual condition were on average 13.5% and 17.0% faster at coming to a full deceleration than participants in the automated condition. Visual inspection of the fitted model (see Fig. 5) shows that after three seconds 43% of the participants in the automated condition had not reached full deceleration as opposed to 24% in the semi-automated and 19% in the manual condition. Visual inspection of Fig. 5 illustrates that the automated lane change condition displayed longer durations to full deceleration. As the time to deceleration was faster in the in the semi-automated and manual lane change conditions as opposed to the automated lane change condition, hypothesis 1 was confirmed. Hypothesis 2 was not confirmed as no differences between the semi-automated and manual lane change conditions were found.

$$\boldsymbol{S}(\boldsymbol{t}=3)_{\boldsymbol{Semi-Automated}} = \boldsymbol{EXP}\left[-\boldsymbol{EXP}(-3.68(1.14+0.11\times 1))\times 3^{3.68}\right] = 0.43 = 43\%$$

Regarding the steering reaction time from the take-over signal to hands-on the steering wheel, the difference between the automated condition, $M = 1.56$ s, $SD = 0.47$ s, the semi-automated condition, $M = 1.44$ s, $SD = 0.46$ s and the manual condition, $M = 1.41$ s, $SD = 0.55$ s was not significant $F(2,42) = 2.78$, $p = .073$ at $\alpha = 0.05$. Regarding the accelerated failure time model for steering reaction time, the model fit was also not significant, Likelihood Ratio $\chi^2(2) = 2$, $p = 0.27$. In conclusion both hypotheses 1 and 2 were not confirmed for steering reaction time.

However, regarding steering adequacy in the take-over, differences in the standard deviation of the steering wheel angle were found between the automated condition, $M = 14.12$ degrees, $SD = 9.07$ degrees, the semi-automated condition, $M = 9.65$ degrees, $SD = 5.88$ degrees, and the manual condition, $M = 10.04$ degrees, $SD = 5.17$ degrees, $F(2,42) = 3.40, p = .042$ (see Fig. 6). As expected, contrasts for hypothesis 1 showed that participants displayed higher standard deviations of the steering wheel angle in the automated condition than in a linear combination of the semi-automated and manual lane change conditions, $b = 0.017,\ t(42) = 2.46, p = .018$. Contrasts for hypothesis 2 did not indicate any differences between the semi-automated and the manual lane change conditions, $b = -0.010,\ t(42) = 0.30,\ p = .762$.

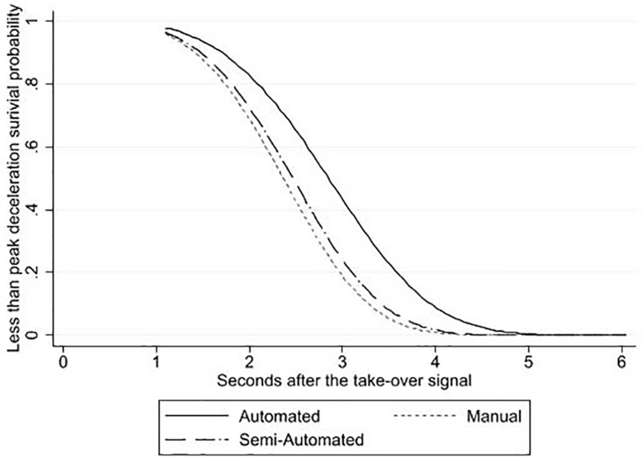


Fig. 5. Maximum deceleration survival graphs across the experimental conditions. For visual inspection we plotted the survival functions per condition with a formula visible in Haque et al., 2015 and the model data from Table 4:

3.3. *Gaze behavior during the ride*

The eye-tracking data show that the percentage of fixations on the road differed between the automated, $M = 10.5$, $SD = 0.09$, the semi-automated, $M = 14.4$, $SD = 0.14$, and the manual condition, $M = 13.8$, $SD = 0.12$, $F(2,142) = 7.11$, $p = 0.001$ (see Fig. 7). In line with hypothesis 1 planned contrasts showed that the percentage of fixation duration on the road was lower in the automated lane change condition than in the combined semi-automated and manual conditions, $b =$ -0.011, $t(142) = -3.76, p < .001$. Regarding hypothesis 2, no significant differences between the semi-automated and manual lane change conditions were found $b = 0.002,\ t(142) = 0.52,\ p = .60$, see Fig. 7.

It was expected that the percentage of fixations on the NDRT between the lane change scenarios would be highest in the automated as opposed to the semi-automated or manual lane change conditions. Analyses revealed that the percentage of fixations on the non-driving-related task differed significantly between the automated condition, $M = 61.9$, $SD = 0.147$, the semi-automated condition, $M = 55.9$, $SD = 0.19$, and the manual condition, $M = 55.3$, $SD = 0.17 F(2,142) = 11.73 p = < 0.001$ (see Fig. 5). In line with hypothesis 1, contrasts showed that the automated condition displayed a higher percentage of total fixation time at the NDRT than in the linear combination of the semi-automated and manual lane change conditions, $b = 0.019$, t(143) = 4.84, p < .001. No differences were found between the semi-automated and manual lane change conditions, $b =$ -0.003, $t(147) =$ -0.529, p = .597.

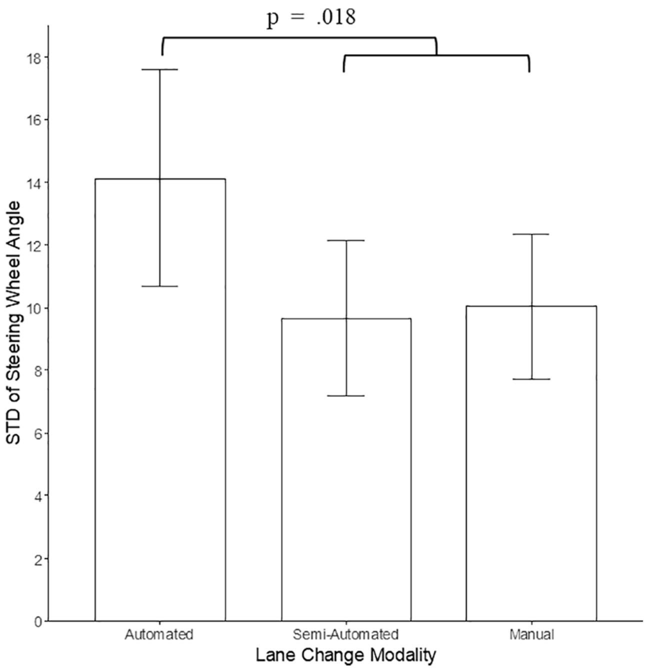


Fig. 6. Bar-graphs of the standard deviation of the steering wheel angle in degrees with 95% confidence intervals.

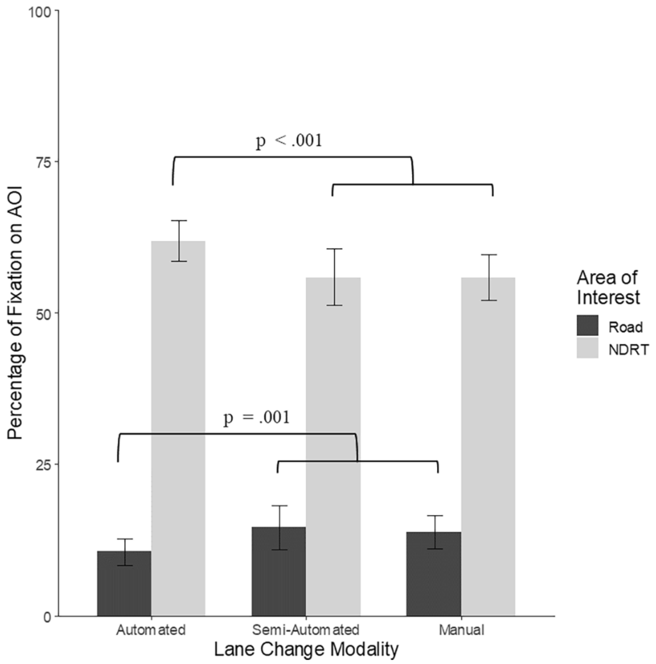


Fig. 7. Bar-graph of percentage of time spent on areas of interest with 95% CIs.

4. Discussion

4.1. *The effect of semi-automated and manual lane changes on critical take-overs*

The goal of this study was to investigate the effect of semi-automated and manual lane changes during a conditionally automated ride on driver's critical take-over behavior. In comparison to rides with automated lane changes, semi-automated or manual lane changes throughout the conditionally automated ride were expected to lead to faster and more adequate braking and steering behavior in critical take-over situations (H1). Unexpectedly, in comparison to the automated lane-change condition we did not find improved braking reaction times in the semi-automated and manual lane changes conditions in the initial braking reaction times. The lack of effects on reaction time was surprising as previous literature found that recurring take-overs to manual control influence reaction time (Dillmann et al., 2021). Closer inspection of the braking data revealed that a lack of differences between the automated and semi-automated and manual lane-change conditions may be due to an unexpected delay in the semi-automated lane change condition. This finding will be further discussed in the discussion of hypothesis 2 below. The data on steering reaction time showed no significant effect of semi-automated and manual lane-changes on the time until hands were placed on the steering wheel. However, the data showed support for our expectation that semi-automated and manual lane changes would lead to more adequate critical take-over behavior in both braking and steering behavior (H1). For braking behavior, we found that the time from the take-over signal to maximum deceleration was lower in both the semi-automated (13.5%) and manual lane change (17%) conditions than in the automated lane change condition. Considering the immediate high urgency of the take-over situation and coinciding looming of the obstacle vehicle (Markkula et al., 2016), we argue that more rapid deceleration represents more adequate braking behavior in this situation.

An effect in the same direction was found for steering maneuvers where the standard deviation of the steering wheel angle was lower in rides with recurring semi-automated and manual lane change maneuvers. A large number of studies associate lower standard deviations of the steering wheel with smoother or more controlled reactions (Mole et al., 2019). Moreover, it has been shown that drivers exhibit a smoother standard deviation of the steering wheel when driving manually, i.e. being fully in the loop, than after taking back control from automation, i.e. coming back into the loop (Eriksson & Stanton, 2017). As the semi-automated and manual take-overs reduced drivers' standard deviation of the steering angle, we conclude that they likely helped keep the driver in the loop.

4.2. *Differences between manual and semi-automated lane changes*

We expected manual lane changes to show more improvements on take-over behavior than semi-automated control (H2). In braking reaction time however we found that participants in the semi-automated condition were 0.28 s slower than in the manual condition. A plausible explanation for this unexpected, delayed reaction may be that it was unclear to participants how semi-automated lane-change system would react in the emergency take-over situations. This uncertainty as to how an automated system reacts has been shown to lead to delayed reactions and has been called an automation expectation mismatch (Victor et al., 2018). This confounding finding points out the intricacies that can occur when drivers transition between different levels of automation (Lu et al., 2016). Although research on semi-automated lane changes is growing (e.g. Goncalves et al., 2020; Madigan et al., 2018), and clear frameworks regarding semi-automated driving exist (Abbink et al., 2018), our results point out that more research would be valuable to understand transitions between different levels of automation (Lu et al., 2016).

Aside from this finding, it was unexpected that we did not find differences in the braking or steering adequacy between the semi-automated and manual lane change conditions. As manual lane changes forced the driver to drive manually, this condition was expected to lead to better calibrated critical take-over than in semi-automated condition, in which case the driver is supported by automation throughout the lane changes. It was unexpected that this was not the case as manual control has been shown to affect take-over behavior (Dillmann et al., 2021). Therefore, more focused perception–action theory research appears to be necessary to understand differences in calibration in manual or semi-automated control. For example, a realistic driving paradigm (e.g. Russell et al., 2016) could be used to investigate how drivers motor-calibration decreases as the extent of support by the semi-automated system increases (e.g. Abbink et al., 2018).

4.3. *The effect of semi-automated and manual lane changes on gaze behavior*

Aside from take-over behavior, we also expected that semi-automated or manual lane changes would lead to less visual attention to a non-driving related task (NDRT) during the ride (H3). The percentage of time spent in fixations on the NDRT, in respect to the automated lane change, appears to be decreased by 6% in the semi-automated and 6.6% in the manual lane change condition. This is relevant as the extent that gaze remains off the road has been shown to increase the risk of crashing (Seppelt et al., 2017). Vice versa, lane changes in the semi-automated and manual conditions appeared to increase the duration of fixations on the road by 4% and 3.3%, respectively. Previous research has shown that longer ride durations lead to increased cumulative time glancing off the road (Feldhütter et al., 2017). This type of glance behavior has been linked with out-of-the-loop experiences by drivers (Schnebelen et al., 2020). A novel finding in this study was that gaze on the road could be increased by introducing semi-automated and manual lane change scenarios, arguably keeping the driver more in the loop.

4.4. *Acceptance of the lane change conditions*

Finally, we explored participants' acceptance of the automated system versus the semi-automated and manual lane change conditions. The data showed that acceptance was significantly higher in the automated condition than in a linear combination of the semi-automated and manual lane change conditions. When contrasting semi-automated and manual lane change conditions we found the semi-automated lane change to be judged as both more useful and satisfactory than the than the manual lane change condition. As acceptance ratings are generally high, however, both manners of keeping the driver in the loop may be well-accepted methodologies.

4.5. *Limitations*

The semi-automated and manual lane changes which are investigated in this paper, depend on an obstacle in the environment for which a lane change is required by the driver. If there are no obstacles in the environment the incentive for a lane-change, and hence this manner of keeping the driver in the loop would be lost. However, given that it is not certain which limitations future conditionally automated vehicles may have, the fundamental effect of using semi-automated or manual lane-changes to keep the driver in the loop may extend to other situations. Further research is necessary to investigate if the effects found in this research extend to automation with more advanced lane change decision algorithms which are embedded in a dynamic environment (cf. Ali et al., 2021) It should also be noted that the study was conducted with BMW employees, ratings of acceptance may therefore be higher as the automated systems were made by participants' employer (Radun et al., 2019).

4.6. *Conclusion*

This study contributes to the literature by using perception–action theory to integrate research on lane changes with research on safety–critical take-overs from conditionally automated driving. The driving simulator experiment provides data indicating that lane changes in the foregoing, conditionally automated, ride affect drivers' behavior in critical take-overs. Although initial take-over reaction times are not faster through semi-automated or manual lane changes, the ultimate braking reaction and steering behavior are faster and smoother, respectively. Additionally, the percentage of gaze on the NDRT could be reduced by over 6%. Hence, semi-automated or manual lane changes may be relevant and well accepted tools that work towards increasing the safety of conditionally automated driving by keeping the driver in the loop.

CRediT authorship contribution statement

J. Dillmann: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **R.J.R. den Hartigh:** Conceptualization, Methodology, Formal analysis, Writing – original draft. **C.M. Kurpiers:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **J. Pelzer:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing. **F.K. Raisch:** Conceptualization, Methodology, Writing – review & editing. **R.F.A. Cox:** Conceptualization, Methodology, Formal analysis, Writing – original draft. **D. de Waard:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

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

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