Manoeuvre design in automated driving: investigation of on-ramp situations under the variation of safety distances and traffic flow

Konstantin Felbel, Andre Dettmann, Adelina Heinz, & Angelika C. Bullinger
Chemnitz University of Technology
Germany

Abstract

When designing automated driving, defensive manoeuvre design scores higher in user ratings than dynamic manoeuvre design. Seemingly contradictory, dynamic driving manoeuvres have been shown to render the perception of the drive as more natural and understandable – in specific situations. To examine manoeuvre design in such a specific scenario, a driving simulator study on a highway was conducted with 36 participants. The participants experienced twelve on-ramp situations in which the automated vehicle reacted to a merging vehicle by either changing lanes, braking or continued driving (no reaction). Also, the distance to the merging vehicle and traffic flow were varied. In each situation, participants were asked to assess the experience using a handset control (indicating their desire to react to the situation). After each situation, participants rated their experienced trust and acceptance in the manoeuvre design. Results show that lane change was the preferred decision, resulting in higher trust, comfort and acceptance ratings. Data from speech protocols and handset control indicate that automated cars should react as early as they recognize a merging vehicle on the on-ramp. Interestingly, when traffic density was high, braking was rated comparable to lane change.

Introduction

In the near future, a mixed traffic scenario of manually driven as well as highly automated vehicles (HAVs) is expected (Ghiasi et al., 2017; Patel et al., 2017). This situation will be present until the full transition where only a small quantity of manual driven vehicles are in use, which could take decades (Altenburg et al., 2018). Till then, HAVs must be able to handle situations requiring interactions with other road users (Rasouli et al., 2017; Schwarting et al., 2019). As road traffic is a social system (Müller et al.; Rasouli et al., 2017) these interactions should be efficient, smooth, safe and predictable (ERTRAC, 2019; Felbel et al., 2021). To meet these requirements, HAVs have difficult prerequisites from both a technical as well as a human factors viewpoint. First, sensor data from a demanding environment must be captured and fused (Liu et al., 2017). Second, based on the sensory data real time motion planning is calculated and performed. This motion planning is not only dependent on safety (Artunedo et al., 2019) but also on users' trust (Dettmann et al., 2021; Kraus, 2020; Lee et al., 2004), acceptance (Detjen et al., 2021; Jian et al., 2000) and discomfort

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(Hartwich et al., 2018). Studies on automated driving manoeuvre design have shown a preference for driving trajectories, which are experienced as natural. For example, Rossner and Bullinger (2019) have shown that participants prefer a lateral shift to the right (i.e. away from the oncoming traffic) to increase the lateral distance in situation with oncoming traffic. Contrary, in situations without oncoming traffic a positioning in the middle of the lane was preferred. In a driving simulator study based on real road environments Peng et al. (2021) have shown that drivers are able to distinguish between the natural driving manoeuvres of humans and the more machine-like negotiations of an artificial controller. Natural driving manoeuvres are described as more proactive where they are not only reacting to given situations but predict future driving scenarios. Mullakkal-Babu et al. (2022) compared in a simulation-based approach a cut-in scenario a predictive and a reactive automated driving system. The predictive system resulted in a significant better performance on aspects such as temporal proximity to crash, expected crash severity and the number of aborted lane changes by human-driven vehicles. This machine prediction could be enhanced by incorporating the anticipation capabilities of human drivers and therefore, must be considered while developing automated manoeuvre designs (Dettmann et al., 2021). Drivers' anticipation for upcoming traffic situations seems to be influenced by situational characteristics. According to Muehl et al. (2020), a perceivable reasons (e.g. causal cues or target cues) support the anticipation of other driving behaviour. This indicates that not only the motion of other vehicles needs to be considered to understand the anticipation process but also the context in which the vehicles operate. In addition, context might also influence the evaluation of a performed automated manoeuvre of the own vehicle, especially if it is not in line with the user's expected manoeuvre. Therefore, context needs to be considered when designing and evaluating automated driving functions. There is yet not sufficient knowledge which manoeuvre an automated vehicle should perform. In the present study, we try to fill the identified research gap by investigating three different automated manoeuvre designs in an on-ramp-situation (i.e., highway context).

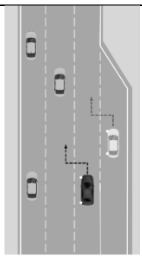
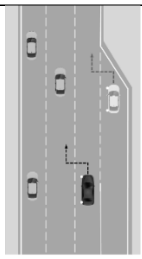
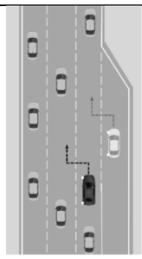
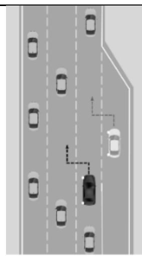
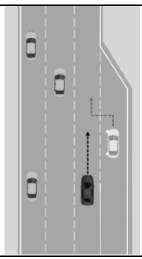
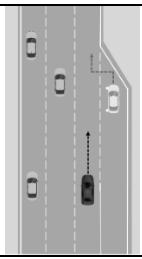
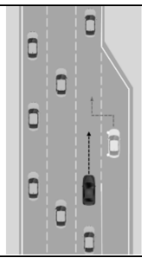
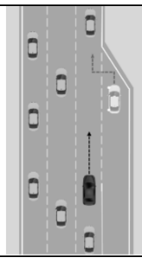
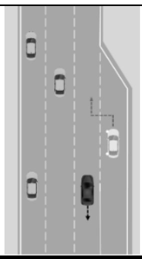
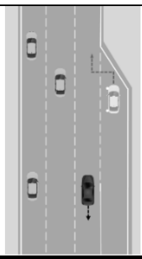
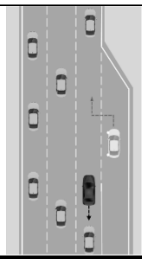
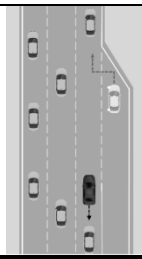
Method

The study sample is based on 36 participants (10 female, 26 male). Their average age was 35.1 years (*SD* = 12.1 years). On average, the subjects drove approximately 59.000 km (*SD* = 42.400 km) in the last five years and had had a driver's license for 16.8 years (*SD* = 11.6). The distribution of travel time among road types was predominantly among urban traffic with 43%, followed by highway (35%) and rural roads (22%). More than half of the participants had no experience with either driving simulator studies (78%) or autonomous driving studies (94%). However, the majority considered themselves moderately to very well informed about the topic on automated driving. Participants assumed that automated vehicles would consistently obey applicable speed limits (86%), drive at a greater distance from other road users than human drivers (69%), and always act cooperatively (81%).

Design and apparatus

To investigate the manoeuvre design of a HAV under variation of distances and traffic flow in a highway on-ramp scenario, a driving simulator study based on a mixed design was applied. Each participant experienced all driving scenarios (within-subject design with repeated measurement).

Table 1. Combinations of the investigated driving scenarios

Manoeuvre design: lane change			
Traffic density: low		Traffic density: high	
Relative position: close	Relative position: far	Relative position: close	Relative position: far
Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
			
Manoeuvre design: continuous driving			
Scenario 5	**Scenario 6**	**Scenario 7**	**Scenario 8**
			
Manoeuvre design: braking			
Scenario 9	**Scenario 10**	**Scenario 11**	**Scenario 12**
			

Black vehicle: automated EGO-vehicle. White vehicle: merging vehicle. The relative position indicates the position of the merging vehicle to the EGO-vehicle.

Three implicit factors were considered in the highway scenarios: i) the manoeuvre design of the automated EGO-vehicle, ii) traffic density (low with 3 vs. high with 7 cars) and iii) the relative position of the merging vehicle (570 m vs. 660 m) to the EGO-vehicle. The manoeuvre design of the EGO-vehicle was perceived and assessed from the participants' first-person perspective. The variations of manoeuvre design involved lane changes (yes/no), continuous driving (yes/no), and braking (yes/no). This resulted in a total of twelve driving scenarios (3 x 2 x 2). The twelve experimental conditions were randomized for each participant to achieve comparability with respect to all conceivable confounding variables as well as to exclude possible sequence effects. Table 1 shows the twelve combinations of the investigated scenarios.

Each scenario started in a highway parking lot. The automated EGO-vehicle then drove at a constant speed of 100 km/h in the right-hand highway lane. This was followed by an approximately 850 m highway on-ramp situation where the surrounding traffic and the relative speed of the merging vehicle to the EGO-vehicle were varied according to the scenarios in table 1. The merging vehicle had a speed of 80 km/h on the acceleration lane (250 m) and then increased its speed to 100 km/h as soon as it changed the lane onto the highway. The EGO-vehicle pulled into a parking lot again at the next exit. This marked the end of one driving scenario and the next situation started via a trigger by the participants. Each scenario lasted about 90 seconds. The simulator used to recreate the scenarios can be classified as a type C simulator (Rimini-Döring et al., 2004) using a projector-based vision system with a field of view of 180 degrees (Figure 1). The steering wheel and both pedals have force feedback actuators implemented and provide a realistic input to control the simulated vehicle. SILAB 7.0 was used to simulate the situations.

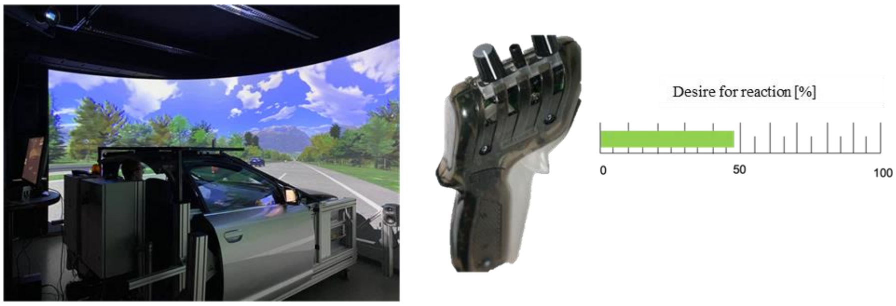


Figure 1. Driving simulator (left), handset controller with "desire for reaction" scale (right)

Procedure and materials

The participants were asked to complete a demographic questionnaire (sex, age, annual mileage). Furthermore, technology affinity was assessed using the ATI Scale (Franke et al., 2019) as well as sensation seeking (Hoyle et al., 2002). Additionally, momentary fatigue was queried. Subsequently, the participants were able to familiarize themselves with the driving simulator in similar situations as described above. After starting the experiment, the participants experienced 12 experimental drives in randomized order. After each drive, they filled out a questionnaire that included the evaluation of the manoeuvre design of the automated EGO-vehicle and the assessment of trust, comfort and acceptance through single items (from 1 to 10; higher is better). To gather an online assessment of subjective data for the evaluation of the manoeuvre design a handset controller was used. Participants had the opportunity to use the controller by pressing the lever to report back their desire for a reaction from the automated EGO-vehicle using a scale from 0% desire for reaction to 100% desire for reaction. More actuation of the hand controller indicated an increased desire for a reaction. This also made it possible to determine the exact location on the highway where a different or earlier vehicle reaction (i.e. manoeuvre design) was desired. After the final experimental drive, a final questionnaire on perceived fatigue and a semi standardized interview was presented. The driving simulator study took about 75 minutes.

Results

Descriptive Analysis

Regarding the assassament of the overall attitude towards automated driving, participants' answer was predominantly positive (70 %). However, only 14% of the participants dealt with the topic of "automated driving" professionally.

Figure 2 illustrates the general subjective ratings of the three experienced manoeuvres. Table 2 gives the description and the numerical value for the ratings. The mean values across all scenarios were summarised to show the tendency which manoeuvre HAVs should perform in an on-ramp situation in relation to a merging vehicle. Lane change and braking were perceived as defensive driving, with lane changes being judged more defensively. Continuous driving was assessed as offensive driving and was perceived as more reckless and riskier compared to the lane change. Braking as well as the continuous driving irritated the participants. The profile diagram shows that lane change manoeuvres tended to be preferred in response to an oncoming vehicle, as they were rated as more predictable, comfortable and cooperative.

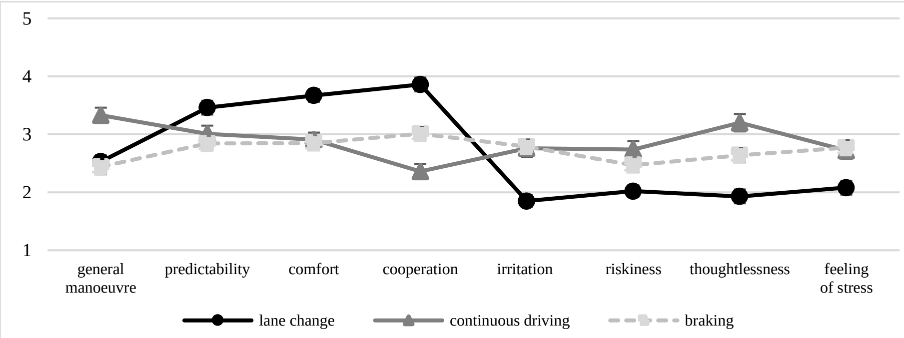


Figure 2. Subjective ratings for the lane change, continuous driving and braking manoeuvre. Error bars reflect Standard Error.

Ratings of trust, comfort and acceptance were compared performing Three-way ANOVAs with repeated measurements including "manoeuvre design" (lane change vs. continuous driving vs. braking), "traffic density" (low vs. high) and "relative position of the merging vehicle" (close vs. far). Figure 3 shows the mean values of the dependent variables for all scenarios.

Trust

A within-subject tests show significantly higher trust ratings for the lane change manoeuvre ($F(2,70) = 13.195$, $p < .001$, $\eta_p^2 = .274$) with a large effect. Furthermore, interaction effects could be identified between first, the three manoeuvre designs and relative position with a large effect ($F(2,70) = 7.687$, $p < .001$, $\eta_p^2 = .180$), and second, between all independent variables: manoeuvre design, traffic density and relative position of the merging vehicle with a medium effect ($F(2,70) = 3.144$, $p = .049$, $\eta_p^2 = .082$).

Table 2. Description and numerical value of the eight subjective single items (see figure 2)

Item	**= 1**		**= 5**
general manoeuvre	very defensive	o o o o o	very offensive
predictability	very unpredictable	o o o o o	very predictable
comfort	very uncomfortable	o o o o o	very comfortable
cooperation	very uncooperative	o o o o o	very cooperative
irritation	very low	o o o o o	very high
riskiness	very low	o o o o o	very high
thoughtlessness	very low	o o o o o	very high
feeling of stress	very low	o o o o o	very high

Inference analysis

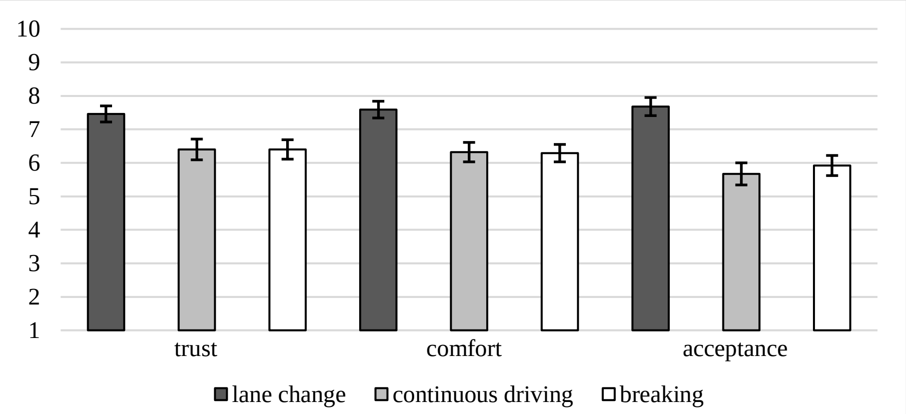


Figure 3. Mean values for trust, comfort and acceptance (single item questions from 1 – 10 after experiencing a driving scenario e.g. lane change + high traffic density + close relative position to merging vehicle). Error bars reflect Standard Error.

Comfort

Regarding comfort, a within-subject test shows a significant difference for the manoeuvre design ($F(2,70) = 23.148$, $p < .001$, $\eta_p^2 = .398$), in which the lane change was rated as most comfortable with a large effect. In addition, traffic density ($F(1,35) = 8.589$, $p = .006$, $\eta_p^2 = .197$) and relative position to the merging vehicle ($F(1,35) = 9.889$, $p = .003$, $\eta_p^2 = .220$) had each a significant impact on the comfort rating with a large effect. Furthermore, a significant interaction exists between the manoeuvre design and the relative position ($F(2,70) = 13.811$, $p < .001$, $\eta_p^2 = .283$) with a large effect size.

Acceptance

A within-subject tests show significantly higher acceptance ratings for the lane change manoeuvre ($F(2,70) = 26.915$, $p < .001$, $\eta_p^2 = .435$) with a large effect. Traffic density ($F(1,35) = 10.045$, $p = .003$, $\eta_p^2 = .223$) and relative position to the merging vehicle ($F(1,35) = 25.213$, $p < .001$, $\eta_p^2 = .419$) significantly influence the rating with a large effect. In addition, a significant interaction effect is imminent between the manoeuvre design and the relative position to the merging vehicle ($F(2,70) = 19.914$, $p < .001$, $\eta_p^2 = .363$) with a large effect.

Handset control results

All data was cumulated over the driven distance of 1100 m of the four different scenario combinations. Figure 4 shows the cumulated values for the scenario with **low** traffic density and a **close** relative position to the merging vehicle. The desire for reaction rises approximately at the same time for all three manoeuvre designs. In the lane change manoeuvre scenario, the participants' desire to react is at a maximum about 50 m before the EGO-vehicle changes its lane and falls rapidly after the lane change is completed. In the braking and continuous driving scenario, the strongest desire for reaction is reached at about the same distance. In the lane change scenario, the desire for reaction reaches its maximum and minimum faster compared to the other manoeuvre designs.

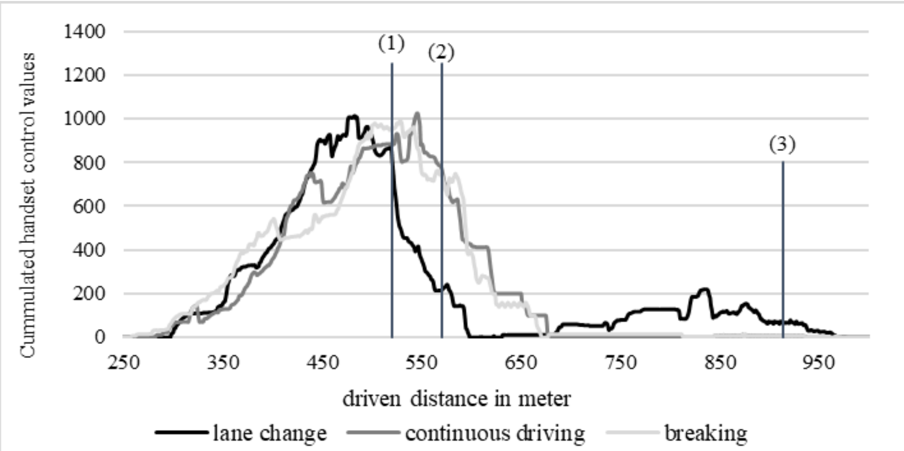


Figure 4. Cumulated handset control values over all participants: low traffic density and close relative position to the merging vehicle. (1) EGO-vehicle reacts to the merging vehicle by changing lanes or braking. (2) Merging vehicle enters the highway. (3) EGO-vehicle changes lane to the right

Figure 5 shows the cumulated values for the scenario **low** traffic density and a **close** relative position to the merging vehicle. The desire for reaction rises approximately at the same time for all three manoeuvre designs. One exception is a small peak in the lane change scenario at about 200 m before the merging vehicle initiates its lane change. Participants "desire to react" falls as soon as a reaction of the EGO-vehicle is noticeable. Only in the continuous driving scenario it stays high till 175 m after the merging vehicle changed its lane onto the highway and falls quickly afterwards. In the lane change manoeuvre design scenario, the desire for reaction reaches its maximum and minimum faster compared to the other manoeuvre designs.

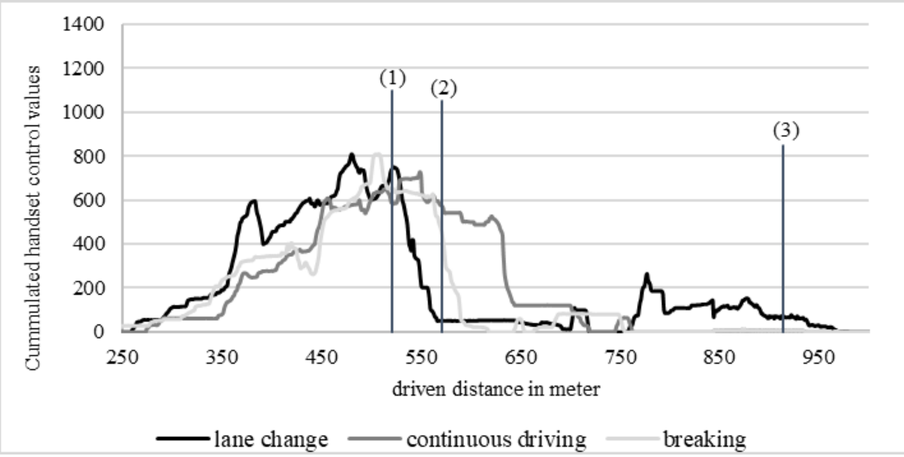


Figure 5. Cumulated handset control values over all participants: high traffic density and close relative position to the merging vehicle. (1) EGO-vehicle reacts to the merging vehicle by changing lanes or braking. (2) Merging vehicle enters the highway. (3) EGO-vehicle changes lane to the right

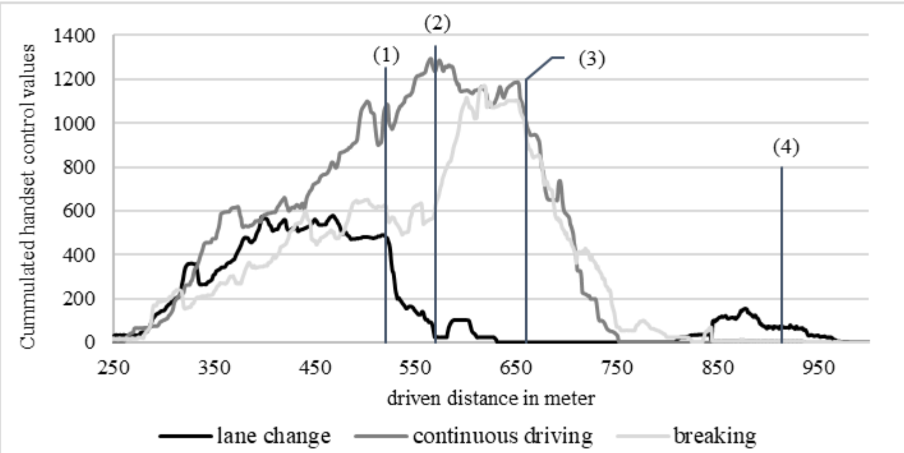


Figure 6. Cumulated handset control values over all participants: high traffic density and far relative position to the merging vehicle. (1) EGO-vehicle reacts to the merging vehicle by changing lanes. (2) EGO-vehicle reacts to merging vehicle by braking. (3) Merging vehicle enters the highway. (4) EGO-vehicle changes lane to the right

Figure 6 shows the cumulated values for the scenario **low** traffic density and a **far** relative position to the merging vehicle. The desire for reaction rises approximately at the same time for all three manoeuvre designs, but stays at a low level in the lane change manoeuvre scenario. Interestingly, the handset control value in the braking scenario has two peaks. An initial peak, when the merging vehicle is visible and another when the EGO-vehicle breaks. In this combination, the reaction values of the manoeuvre breaking and continuous driving have the same peak hight. The lane change manoeuvre has the lowest handset control value.

Figure 7 shows the cumulated values for the scenario **high** traffic density and a close relative position to the merging vehicle. Overall, the same reaction profile as in Figure 6 can be seen. One difference is the higher handset control value for the braking manoeuvre. It reaches is highest peak slightly before the merging vehicle changes its lane from the on-ramp.

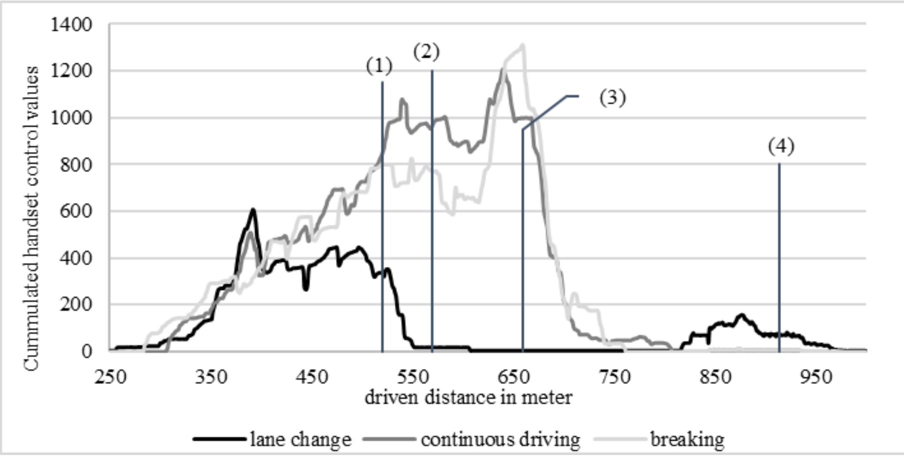


Figure 7. Cumulated handset control values over all participants: high traffic density and far relative position to the merging vehicle. (1) EGO-vehicle reacts to the merging vehicle by changing lanes. (2) EGO-vehicle reacts to merging vehicle by braking. (3) Merging vehicle enters the highway. (4) EGO-vehicle changes lane to the right

Discussion and Conclusion

The aim of the study was to investigate three different automated manoeuvre designs in an on-ramp situation on a highway. The results show that the manoeuvre design, traffic density as well as the relative position of the merging vehicle have a significant influence on the evaluation of trust, comfort, and acceptance. Under the variation of traffic density and the relative position to the merging vehicle, participants' preference for the lane change manoeuvre was identified. Trust, comfort and acceptance ratings were significantly higher. In addition, participants considered the lane change manoeuvre as more cooperative. According to Mullakkal (2022) a proactive automated driving function should be implemented over an reactive. In this case, a more cooperative manoeuvre design (i.e. lane change) can be classified as a proactive driving function. Furthermore, the handset control values for the lane change were the lowest, indicating less demand for another reaction. Over all three manoeuvre designs, participants wanted an earlier reaction, shown by the early increase in the handset control values. This is in line with Roßner and Bullinger (2019), where an early reaction to an imminent obstacle is desired. Although, braking was mentioned positive in the subsequent interview, it was not rated significantly different than the continuous driving manoeuvre in the subjective questionnaires or the handset control data.

It could be explained by insufficient braking reaction of the EGO-vehicle, indicated by the second peak in the handset control values, as the values rises even after the breaking was initiated. While causal cues were kept the same in all scenarios, the participants described the lane change as more anticipatory. It can be explained by the inherent expectation of the participants. The majority assessed the lane change as the correct manoeuvre and may therefore be subject to hindsight bias. Hence, in subsequent studies, the evaluation of anticipation should be examined before the manoeuvre is carried out.

Based on the results, the following recommendations on manoeuvre design can be given:

- early initialisation of automated reaction to merging vehicles through e.g. early vehicle movement or HMIs
- in light traffic, a lane change is preferred. When lane changing, an early use of the indicators is advised
- in heavy traffic, braking is preferred when the adjacent lane is occupied
- continuous driving should be performed only in combination with an HMI. Otherwise there is no feedback from the EGO-vehicle to the passenger as to whether it has recognised the forthcoming situation

Acknowledgements.

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