Should the steering wheel rotate? Evaluation of different strategies of steering wheel behaviour regarding controllability and driver acceptance while driving in conditional automated mode

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So far the steering wheel, as an important interface of Driver-Vehicle-Interaction, is not sufficiently investigated in the field of vehicle automation. At the stage of conditional automated driving it is still unclear, how the steering wheel should behave during the phase of piloted hands-off driving and in take-over situations. A driving simulator study was conducted to evaluate three strategies of steering wheel behaviour (full, 50% reduced, no steering wheel movement) regarding controllability of vehicle guidance and driver acceptance. The scenario based on a requested take-over situation in a curve on a rural road. A total number of 62 subjects (36 female, M = 39.2 years, SD = 11.1) participated in the study. The full steering wheel behaviour resulted in the slightest deviation from the autopilot steering reference in the take-over situation and was most accepted by the drivers in the take-over situation. In contrast the 50%-reduced steering wheel movement was evaluated as best in the piloted phase. The waiver of steering wheel movement reduced vehicle controllability and driver acceptance. Further research in on-road driving studies is required to investigate the functions of the steering wheel in conditional automated driving in a more realistic context and to validate these results.

Introduction

According to the statements of numerous OEMs and internet companies, like Google, the vision of self-driving vehicles is no longer in unreachable distance (Wachenfeld et al., 2015). Nowadays, Park and Traffic Jam Assistants enable partly automated driving in certain driving situations. The raising automation levels will contribute to a new quality of individual mobility. Conditional automated driving is considered to be particularly beneficial to the driver, as it is based on a guaranteed time reserve for take-overs (Gasser et al., 2013). Since the automated function enables hands-off driving and permanent monitoring is no longer necessary, conditional automated driving reveals new scopes for executing non-driving related

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activities. In conditional automated driving the driver acts as fall back in case of predictable system limits. That is why the design of the interaction between the driver and the vehicle (human-machine interaction, HMI) is particularly relevant for the safety in conditional automated driving, especially in take-over situations. Such situations are characterized by a shift in the responsibility for the vehicle control between the autopilot and the driver. There is a need for an appropriate HMI in conditional automated driving for resuming control over the vehicle to the driver in various take-over situations. Prior research in the field of conditional automated driving focused on the HMI design of effective take-over requests (Naujoks, Mai & Neukum, 2014), the usability of certain driver-vehicle interfaces for take-over requests (Damböck et al., 2012), the effect of non-driving related tasks on take-over quality (Radlmayr et al., 2014) and the development of design guidelines for a human centred design of take-over situations (Gasser et al., 2013). But there are still open fields of research, for instance the role of the steering wheel in conditional automated driving.

It can be argued that the *steering wheel* represents an important driver-vehicle interface in manual driving giving attention to the fact that the steering wheel serves as operating element for the input of the target course as well as a source of visual and haptic feedback of the actual vehicle trajectory. As conditional automated driving enables hands-off driving, the role of the steering wheel as a salient and intuitive HMI during piloted driving and the take-over situation needs a closer look. It can be argued that keeping full steering wheel movements during conditional automated driving would serve as a source of visual feedback for the driver and would therefore be perceived as transparent and reliable. On the other hand, full steering wheel movements could increase the risk of injuries caused by grasping into the rotating steering wheel. Another disadvantage is the continuous movement that is likely to be experienced as disturbing for non-driving related activities such as reading or texting. Furthermore micro-wheel adjustments may cause a decreased confidence in the automated functions. A complete waiver of steering wheel movements during piloted driving would probably enhance comfort and may decrease the risk of injuries by grasping into the steering wheel. Though the waiver of steering wheel movements would go in hand with the deprivation of visual feedback of the vehicle target heading and would lower their ability to take back control of the vehicle during the take-over situations, especially in curves or turning manoeuvres that result in a dissonance between steering wheel angle and wheel angle.

There is a need for a new definition of the role of the steering wheel in conditional automated driving. The question remains, how the steering wheel should behave during hands-off piloted driving. Should the steering wheel keep rotating or could a total waiver of the steering wheel movement be considered? Google is even considering banning the steering wheel completely out of their fully automated vehicles. To the best of our knowledge no study has given detailed consideration to the functions of the driver-vehicle interface *steering wheel* in the context of conditional automated driving yet.

In the study presented here, an exploratory procedure was chosen to give a first look at the new ground of the steering wheel behaviour in conditional automated driving The focus of the driving simulator study was to evaluate the effects of three steering wheel behaviours on the controllability of vehicle guidance and the driver's acceptance. The steering wheel behaviour differed in the magnitude of turning motion during the piloted driving: 1) full, 2) 50 % reduced and 3) no steering wheel movement. The three strategies were investigated in 1) conditional automated piloted driving and 2) in a take-over situation in a curve. The aim of the study is to give a first exploratory look on the question, how the steering wheel should behave in conditional automated vehicles to provide a safe and pleasant driving experience.

Method

Strategies of steering wheel behaviour

In the driving simulator study three configurations of steering wheel behaviour were tested which differed in their magnitude of turning motion: 1) full steering wheel movement 2) 50% reduced steering wheel movement and 3) no steering wheel movement (table 1).

Table 1.Comparison of the three steering wheel behaviour strategies regarding configuration, potential advantages and disadvantages

	Full steering wheel movement	50 % reduced steering wheel movement	No steering wheel movement
Configuration	Full steering wheel angles	50% reduced steering wheel angles	No steering wheel movement, steering wheel always in upright position
Potential advantages	• Familiarity • Visual feedback • Trust	• Reduced risk of injuries while grasping the steering wheel • Visual feedback	• Reduced risk of injuries while grasping he steering wheel • Enhanced comfort
Potential disadvantages	• Risk of injuries while grasping the steering wheel • Feeling of insecurity	• Discrepancy of steering wheel and vehicle wheels	• Discrepancy of steering wheel and vehicle wheels • No visual feedback • Passivity of driver

In the strategy with full steering wheel movement the steering wheel kept rotating in piloted driving like in manual driving. As a result the steering wheel angle was always in accordance with the wheel angle.

The 50% reduced steering wheel strategy was indicated by 50 %-reduced steering wheel movement during piloted driving. The steering wheel movement were halved, so that they reflected only a 50% proportion of the real wheel angle movements. As a result the steering translation was more direct in take-over situations, which means that the turning motion of the steering wheel resulted in a larger turning angle of the wheels.

The strategy with no steering wheel movement was characterized by the complete waiver of steering wheel movement during piloted driving. The steering wheel remained in the straight ahead position during all manoeuvres. Therefore, the strategy resulted in a dissonance between the wheel angle and the steering wheel angle in a curve or during a turning manoeuvre.

A pre-test with eight participants from the Division Group Research of Volkswagen AG (woman = 3) showed that a take-over in a curve or during an overtaking manoeuvre was difficult to manage in the condition with no steering wheel movement when the autopilot was instantly deactivated at the moment of first driver contact. To improve the controllability in the take-over situation the autopilot function was faded out over a period of 5 s after the first driver`s contact. This was done to avoid oversteering in the moment of the take-over. The fadeout of the autopilot was applied to each of the steering wheel strategies.

Driving scenario

The three strategies of steering wheel behaviour were tested in two situations on a rural road: 1) hands-off piloted driving and 2) a take-over situation in a curve. The drivers started each ride in manual mode and handed the vehicle control to the autopilot 10 s after they started. The piloted ride took about 4 min (5km). Subsequently, drivers were requested to take over the vehicle control in an S-curve (figure 1). The left curve was poorly visible because of greenery and a hillock at the left side. The autopilot approached the S-curve with a speed of 75 km/h. The road width was 3.65 m. The drivers were informed about the imminent take-over by a countdown while reaching the S-curve. The countdown was presented via a message at a head-up display (“Please take over in 10 s”, (1)). They were encouraged to take over by steering, braking or accelerating just at the moment when the message counted down to zero, as shown in figure 2 (“Please take over”, (2)). By means of the countdown the time reserve for take-over of 10 s was guaranteed, which is recommended by prior research for ensuring a safe take-over in conditional automated driving (Petermann-Stock et al., 2013). Furthermore the countdown was used to ensure that all drivers take over at the same time in the curve. After the take-over situation the autopilot faded out during a time of 5 s (3). The ride was stopped by the study coordinator after the participants completed the curve.

Experimental design and dependent variables

In the study a within-subjects-design was chosen. The order of the three steering wheel strategies was varied, resulting in six permutations via a Latin square. The participants were randomly assigned to one of the six permutations.

For the dimension *driver reaction* the following parameters were used for a plausibility check: 1) mode of take-over, 2) point in time of take-over, 3) occurrence of a braking reaction and 4) time of first braking as shown in table 2. Three modes of take-over were 1) stepping on the gas, 2) braking and 3) steering. The point in time of take-over was defined by the difference between the actual time and the required time of take-over, indicated by the countdown. A take-over at an early point of time, before the countdown counted down to zero, was seen as an indicator for uncertainty of drivers and a decreased controllability of the situation. Point in time of braking was defined by the time when the driver pushed the braking pedal for the first time in the curve.

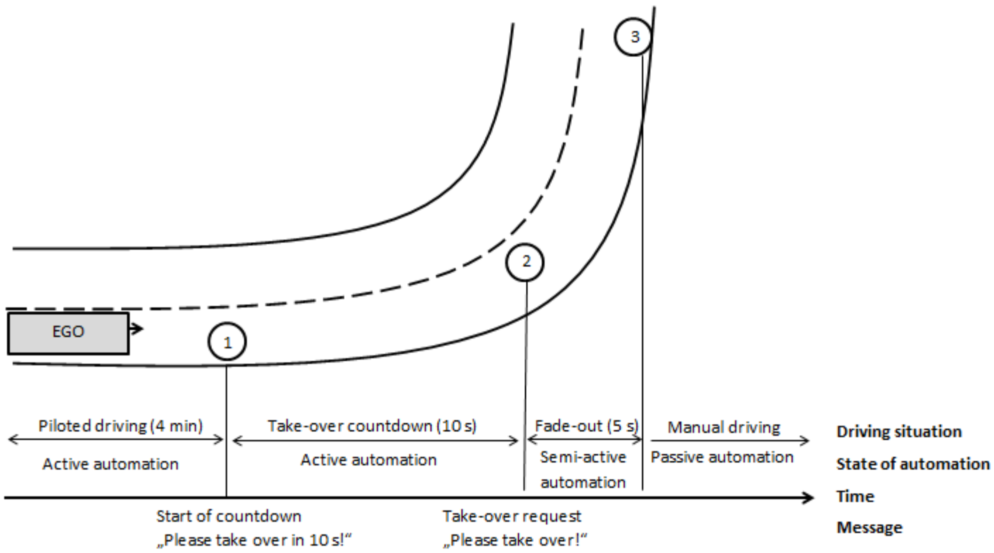

Figure 1. Schematic illustration of the sequence of the take-over situation in the curve.

Figure 2. Screenshot of the driving scenario in the moment of take-over request in the curve (“Please take over!”)

Table 2. *Overview of the recorded driving data for plausibility check and measuring controllability of vehicle guidance in the take-over situation*

Dimension	**Parameter**	**Category/unit of measurement**
Driver reaction	Mode of take-over	Accelerating, braking or steering
	Time of take-over	Time before or after requested take-over in seconds
	Braking reaction	Yes/no
	Time of first braking	Time since requested take-over in seconds
Parameter of steering	Root mean square error of steering wheel angle	Degree
Lateral dynamics	Number of exceedances of road markings	Number

Controllability of the vehicle was measured by driving data in the take-over situation and was divided into two parameters: 1) parameters of steering and 2) lateral dynamics. Regarding the parameters of steering the parameter root mean square error of steering wheel angle was analysed (Schmidt, 2009). For this analysis the steering wheel angle was calculated in relation to the autopilot`s steering wheel and was defined as the root mean square deviation from the reference in degrees. For this purpose, a reference ride without take-over was conducted. Under the dimension of lateral dynamics the number of exceedances of the road markings in the curve at the left and the right were recorded. An exceedance was counted as such if distance of the outer back wheel to the road marking exceeded 0 cm (Östlund, Nielssen, Carsten, & Merat, 2004). A negative distance is therefore interpreted as an exceedance of the road markings. Quantity and duration of exceedances were not considered in the analysis, it was of single interest if the marking was exceeded once to evaluate the controllability of vehicle guidance in the take-over situation. All indicators of controllability were analysed for a time period of 5 s after the required take-over because this was the length of time when the impact of the autopilot faded out.

Driver acceptance of the steering wheel strategies was measured by two questionnaires referring the two situations: 1) the piloted driving and 2) the take-over situation. To compare the effect of the steering wheel strategies between the two situations the items were nearly identical. The questionnaires based on items of the factors trust, comfort, usability and system control of the acceptance questionnaires of driver assistance systems by Arndt (2011) as well as own items. The answer format consisted of 15-point Likert scales based on Heller (1982). Table 3 shows two examples of questions. To gather data about the subjective controllability of the steering wheel strategies the Disturbance Rating Scale by Neukum and Krüger (2003) was used. The scale is clustered in five categories of disturbance rating: 1) not noticeable, 2) noticeable, 3) disturbance of driving, 4) serious disturbance of driving and 5) uncontrollable driving. The categories 2 to 4 are subdivided into three stages, resulting in an 11-point scale.

Furthermore a socio-demographic questionnaire was given to the participants. It included questions about their personal background, annual mileage and experiences with driving simulator studies.

Table 3. Examples of questions of the acceptance questionnaire

How well did you like the steering wheel behaviour during piloted driving?
How well did you like the steering wheel behaviour in the take-over situation?
How comfortable was the steering wheel movement during the piloted driving?
How comfortable was the steering wheel behaviour in the take-over situation?

Participants

A total of 62 drivers (36 female, 26 male) participated in the study. They ranged from 19 to 58 years of age (*M* = 39.2 years, *SD* = 11.1 years) and had held their driver's license for on average of 21.0 years (*SD* = 10.8 years). Drivers were recruited from the participant pool of Volkswagen AG. A majority of the participants already had participated in a driving simulator study and thus were familiar with driving in this simulator. All participants had normal or corrected-to-normal vision.

Experimental setting

For the study, the fixed base driving simulator at Group Research of Volkswagen AG was used (Figure 3). The virtual environment in the simulation was shown on three wide screens (3.00 x 2.25 m), providing a field of vision of about 180°. Furthermore three monitors provided a full rear-view. The driving scenarios were created using the driving simulation software Virtual Test Drive by Vires (Vires, 2014).

Figure 3. Static driving simulator of the Group Research of Volkswagen AG

Procedure

After welcoming the participants they filled in the socio-demographic questionnaire. Then, the participants were introduced to the driving simulator setting. In the beginning, the participants were not informed about the real aim of the study. They were briefed to test a novel function that enables conditional automated driving. During a training session of ten minutes drivers had to activate the autopilot and resume the vehicle control three times after a short piloted ride with full steering wheel movement. This was done to practice the required behaviour regarding the take-over countdown. After the training, the drivers started the first ride with one of the three steering wheel strategies. Afterwards the participants completed the questionnaires concerning the piloted phase and the take-over situation. This procedure was repeated for the other two strategies. At the end, they were briefed about the real aim of the study and were compensated for their participation.

Results

Data analysis

For data analysis the statistical software SPSS 22 was used. Driving data and acceptance rating were analysed by univariate analysis of variance (ANOVA) with repeated measures. Cochran-Q Test was used for analysing the dichotomous dependent variable exceedances of road markings. In case of a violation of the sphericity assumption a Greenhouse-Geisser correction was applied. Post-hoc tests were used to compute pairwise comparisons. The significance level was alpha = 0.05 and was Bonferroni-corrected, if necessary.

Plausibility check

In most of the take-over situations the drivers took over the vehicle by steering(n = 163, 88 %). The remaining take-over manoeuvers were initialized by accelerating (11 %) or braking (1%). The point in time of take-over varied significantly between the steering wheel strategies ($F(2;122) = 11.8$, $p < .001$). While driving without steering wheel movement the drivers took over the vehicle control significantly earlier (M = -0.06 s, SD = 0.11 s, $p_{50\%-0\%} = .001$, $p_{100\%-0\%} < .001$). The result indicates a reduced perceived controllability of the strategy without any steering wheel movement. Most of the drivers applied the brake during the take-over situation in the curve (96.24 %). No significant difference between the steering wheel strategies on the time of first braking were found ($F(2;122) = .331$,$p = .719$).

Controllability

The analysis showed a significant main effect of the steering wheel strategy on the RMSE of the steering wheel angle ($F(1.6;96.2) = 15.6$, $p < .001$). The full steering wheel movement showed a smaller RMSE of steering wheel angle (M = 8.5°,SD = 4.6°) compared to the 50 % reduced steering strategy ($p_{100\%-50\%} = .009$) and no steering ($p_{100\%-0\%} < .001$). In the 50 % reduced steering strategy RMSE of steering wheel angle totaled up to 11.1° (SD = 6.6°) and differed significantly from the strategy without steering wheel movements (M = 15.2°, SD = 9.8°; $p_{50\%-0\%} = .012$).

Cochran-Q Test showed a significant effect of the steering wheel strategy on the number of exceedances of the left road markings in the curve ($X^2(2, 62) = 13.5$,p = .001). Drivers with 50% reduced steering wheel movements exceeded the left road markings less frequent (n = 15), compared to the full steering strategy (n = 28; $p_{100\%-50\%} = .009$) and the no steering strategy (n = 34; $p_{50\%-0\%} < .001$, figure 5). The steering wheel strategy showed no significant effect on the number of exceedances of the right road marking ($X^2(2, 62) < .001$, $p = 1.000$). In each steering wheel strategy drivers exceeded the right road markings in 46.8 % of the take-over situations (n = 29).

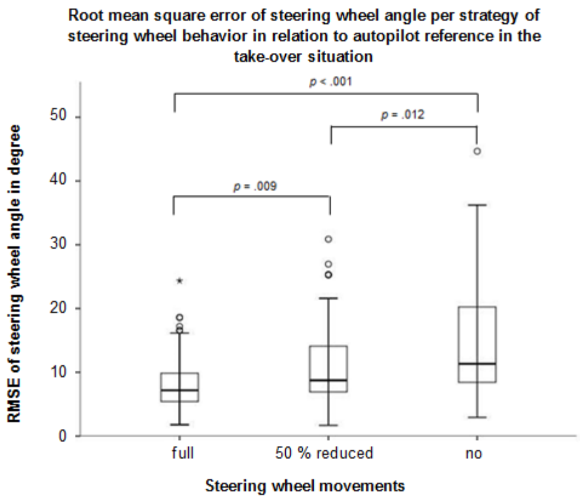

Figure 4. Root mean square error (RMSE) of steering wheel angle per strategies of steering wheel movement shown as boxplot diagrams

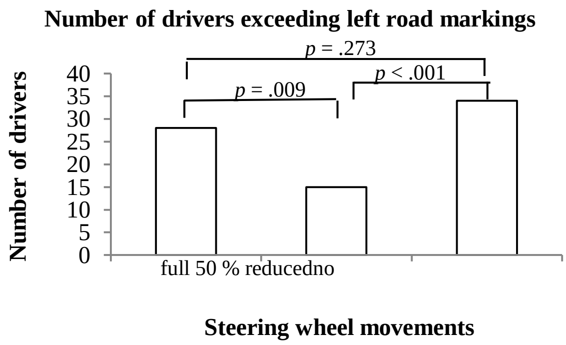

Figure 5. Number of drivers exceeding the left road markings per steering wheel strategy.

Driver Acceptance

Driver acceptance was analysed regarding the two situations of conditional automated driving: 1) piloted driving and 2) take-over situation.

The analysis of the generic evaluation of the three strategies (figure 6) showed a significant effect of the strategies in piloted driving ($F(1.6; 99.5) = 11.3$, $p < .001$) and in the take-over situation ($F(1.8; 110.5) = 30.3$, $p < .001$). In piloted driving full ($M = 10.89$, $SD = 3.1$) and 50% reduced steering wheel movement ($M = 11.73$, $SD = 2.2$) were evaluated better by the drivers than the condition without steering wheel movement ($M = 8.94$, $SD = 4.2$; $p_{100\%\text{-}0\%} = .028$, $p_{50\%\text{-}0\%} < .001$). The comparison of full and 50% reduced steering wheel movement showed no significant difference in piloted driving ($p_{100\%\text{-}50\%} = .267$). In the take-over situation the drivers evaluated the full steering wheel movement as best (*M* = 11.60, *SD* = 2.91) compared to the strategy with 50 % reduced steering wheel movement (*M* = 10.32, *SD* = 2.8; $p_{100\%\text{-}50\%} = .028$). The strategy without steering wheel movement were the least accepted by the drivers in the take-over situation (*M* = 7.27, *SD* = 3.82;$p_{100\%\text{-}0\%} < .001$, $p_{50\%\text{-}0\%} < .001$).

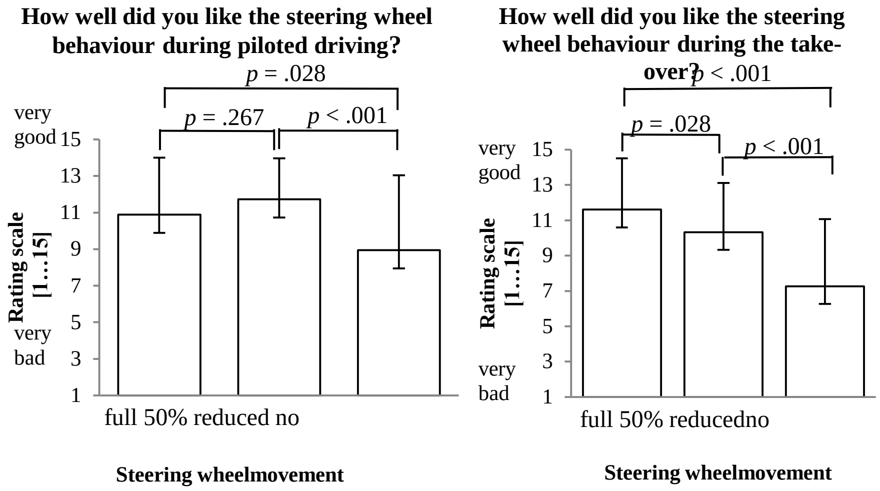

Figure 6. Mean and standard deviation of general evaluation of the three strategies of steering wheel movement during piloted driving (left) and in the take-over situation (right).

With regard to the evaluation of comfort the analysis showed a significant main effect of the steering wheel behaviour on the driver`s assessment of comfort during piloted driving ($F(1.6; 98.2) = 9.6$, $p < .001$) and in the take-over situation ($F(2; 122) = 24.1$, $p < .001$, figure 7). The strategy with 50% reduced steering wheel movement was rated as the most comfortable by the drivers during the piloted driving (*M* = 11.9, *SD* = 2.0, $p_{100\%\text{-}50\%} = .027$, $p_{50\%\text{-}0\%} < .001$) whereas the full steering wheel movement were rated as the most comfortable in the take-over situation (*M* = 11.6,*SD* = 2.8, $p_{100\%\text{-}50\%} = .038$; $p_{100\%\text{-}0\%} < .001$). During the piloted phase there was no significant difference in the evaluation of comfort between the full steering wheel movement (*M* = 10.76, *SD* = 3.0) and the condition without steering wheel movement (*M* = 9.42, *SD* = 4.2; $p_{100\%\text{-}0\%} = .167$). In the take-over situation the strategy without steering wheel movement (*M* = 7.47, *SD* = 4.11) was rated significantly less comfortable by the drivers than the other two strategies ($p_{100\%\text{-}0\%} < .001$, $p_{50\%\text{-}0\%} = .001$).

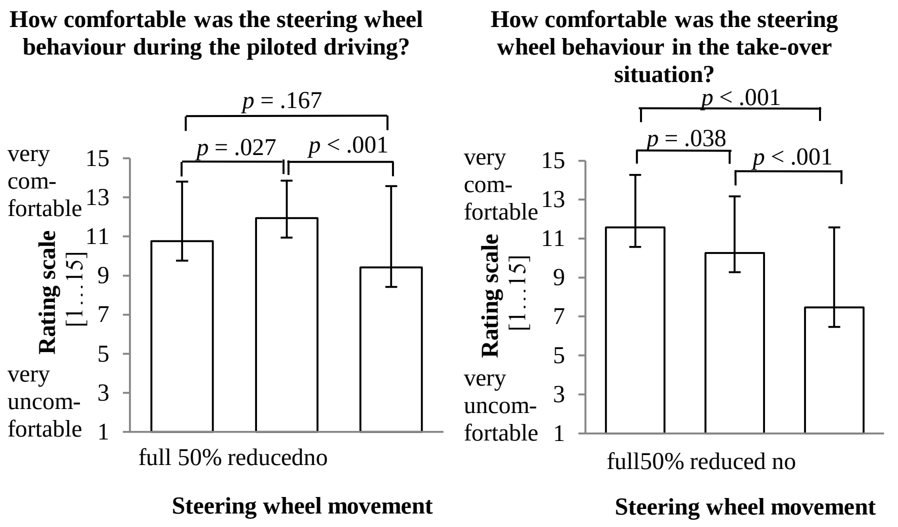

Figure 7.Mean and standard deviation of comfort rating per steering wheel strategy during piloted driving (left) and in take-over situation (right).

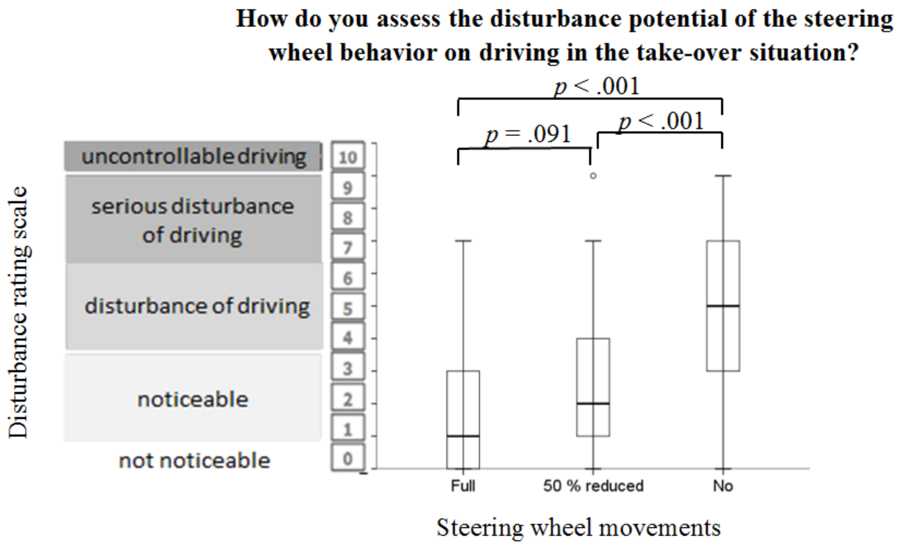

Figure 8. Disturbance rating (Neukum & Krüger, 2003) per steering wheel strategy in the take-over situation shown as boxplot diagrams.

An ANOVA was conducted to evaluate the disturbance rating scale (Neukum & Krüger, 2003) regarding the steering wheel behaviour. Driver`s disturbance ratings differed significantly between the three types of steering wheel behaviour (F(2; 122)

= 28.6, p < .001, figure 8). The rating of full steering wheel movement ranged from not noticeable to serious disturbance of driving (Range 0-7) whereas 50% reduced and no steering wheel movement ranged up to 9. Nevertheless disturbance ratings did not differ significantly between full and 50 % reduced steering wheel movement ($p_{100\%-50\%}$ = .091). Drivers tend to feel more disturbed when there was no steering wheel movement ($p_{100\%-0\%} < .001$, $p_{50\%-0\%} < .001$).

Discussion

The aim of the driving simulator study presented here was to examine the influence of different steering wheel strategies on controllability of vehicle guidance and driver acceptance in conditional automated driving. The results give a first insight into the question, how the steering wheel should behave in hands-off piloted driving and in a safety-critical take-over situation in a curve.

In the take-over situation the full steering wheel strategy resulted in the slightest deviation of steering wheel angles from the autopilot steering reference. This indicates that the continued rotation of the steering wheel enables the driver to take back control over the vehicle in the take-over situations due to a coupling of steering wheel angle and wheel angle. This result is supported by the driver`s subjective rating. The full steering strategy was explicitly preferred by the drivers in the take-over situation.

With the 50 % reduced steering wheel movement the number of drivers exceeding the left road marking in the take-over situation was smaller than with the other two strategies. A possible explanation for this effect could be that drivers overestimated the steering wheel angle of the autopilot in the condition with 50 % reduced steering wheel angles and therefore steered slighter. Especially during piloted driving the 50 % reduced steering wheel movement was evaluated as most comfortable by the drivers.

The no steering strategy caused the highest deviation of the steering wheel angle from the autopilot`s reference in the curve. This result is supported by the lower rating of comfort and higher disturbance potential of the no steering strategy in the take-over situation compared to the other two strategies.

In conclusion, there were strong differences in the effect of the three steering wheel strategies on vehicle controllability and driver acceptance. Overall, the analysis showed a preference of the full steering wheel behaviour in the take-over situation, whereas the 50 % reduced steering wheel movement was preferred during piloted driving. In contrast to the other two strategies, the waiver of steering wheel movement was not well accepted by the drivers, especially in the take-over situation. Thus, a complete waiver of steering wheel movement cannot be recommended. However the results indicate that a reduction of the steering wheel movements could be considered in future conditional automated vehicles, though an adjustment of the take-over process is necessary to improve vehicle control and comfort while resuming control in a take-over situation. This could be done by an enhanced assistance of the autopilot in the take-over situation. Another question that remains unanswered covers the effect of the fadeout of the autopilot in the take-over situation. Further research is needed to examine the influence of different types and lengths of fadeouts on the controllability of vehicle guidance.

The results of the study should be considered with caution because the study was conducted in a static driving simulator. As Schmidt (2009) and Neukum et al. (2009) showed, lateral acceleration and gear rate of the vehicle are important predictors of the subjective rating of steering wheel functions. Therefore, further research in on-road driving studies is required to examine the functions of the steering wheel in conditional automated driving in a more realistic context to validate the results.

In conclusion, it is not possible to already recommend the use of one of these steering wheel behaviours for future conditional automated vehicles. However, the driving simulator study enables first insight into the role of the steering wheel in conditional automated driving. Paying attention to the restrictions of the study the research question "Should the steering wheel rotate" should be *yes*, but *how* remains as an open question.

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