Highly automated driving with a decoupled steering wheel

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Future cars will almost certainly provide an increasing level of automation. Under certain conditions, they will allow the driver to withdraw from the control loop and deal with non-driving related tasks. To provide a convenient and safe user interface for this case, it can be advantageous to have the steering wheel decoupled from the steering link and stationary. In this study, we evaluated two alternative steering wheel concepts. The first concept represents a state of the art steering wheel that decouples from the steering link and remains stationary at an angle of 0° during highly automated driving. In the second concept, the steering wheel shows the same behavior but does not have visible spokes. Hence, it does not display its physical orientation to the driver. Using a dynamic driving simulator, we evaluated the concepts in a comparison drive and a take-over scenario in a curve. A permanently coupled state of the art steering wheel served as control condition. Results show that the decoupling was only noticed by a small number of participants. Further, no negative impacts on the take-over process could be determined. The steering wheel with no visible spokes led to an even better performance compared to the control condition.

INTRODUCTION

Driver assistance systems, especially with machine perception of the cars surroundings, have an increasing impact on traffic today. The advanced systems are able to take over longitudinal and lateral guidance (Schaller et al., 2008) with the objective of increasing traffic safety and driver comfort. The systems available today have one thing in common: the driver has to remain in the driving loop and monitor the automation. With technological progress, future cars will most probably allow the driver to completely withdraw from the driving task under certain driving conditions. This is referred to as highly automated driving (Gasser et al., 2012). As long as the automation cannot handle *every* driving condition, there will be situations in which the driver has to be requested to take over the control by means of a take-over request ("TOR"). Around this transition of control, critical problems for the driver can occur. Examples are the loss of manual and cognitive skills (Bainbridge, 1983) and lack of situation awareness (Endsley, 1995; Endsley & Kiris, 1995).

Consequently, future car interfaces will most probably have to support three different use-cases: Manual driving, highly automated driving and the corresponding transition process. The steering wheel plays a different role in each use-case.

- During manual driving, it is used for the lateral guidance of the car. Therefore, it must be coupled to the steering link.
- During highly automated driving, the driver uses the car interface for non-driving related tasks. Therefore, the steering wheel does not necessarily have to be coupled to the steering link. On the contrary, it would be advantageous if it remained stationary, because this is a good precondition to optimize the car interface for non-driving related tasks.
- Third, the steering wheel has to be easy to reach and grasp for the take-over process. If it has been decoupled before, the steering wheel has then to re-couple.

Regarding the steering wheel behavior in this context, relatively little research has been done in the past. Brunken et al. (2012) raise the topic of decoupling the steering wheel to demonstrate different interaction patterns for highly automated vehicles. Heesen et al. (2014) propose the brief decoupling of the steering wheel in manual driving mode with the objective of making automated emergency turns possible.

In order to satisfy the three use-cases of manual driving, highly automated driving and the take-over process, we developed and evaluated two concepts in this study.

Concept "Stationary". During highly automated driving, the steering wheel decouples from the steering link and automatically turns into the neutral orientation. There it remains stationary. The driver still has the possibility to override the automation by applying steering force. Then the steering lock is adjusted to the steering wheel orientation within a short recoupling phase. In the case of a TOR, the steering wheel recouples to the steering link. If this happens in a curve, the steering wheel quickly turns into the orientation that correlates to the actual steering lock. We assumed that this abrupt onset of motion might capture the drivers attention (Abrams & Christ, 2003), which could cost valuable reaction time in the take-over process.

Concept "Rim". The aim of this concept was to improve "Stationary" regarding the take-over process. The steering wheel behaves as in "Stationary" but does not display its orientation to the driver. The steering wheel movement is not particularly noticeable. Thus the possible attention capture effect at TOR should be precluded. Furthermore, the steering wheel has no spokes that could prohibit the thumb from reaching around the rim from inside. Thereby, it should be easier to grasp and should provoke less post-contact adjustments of the fingers (Fu et al., 2013).

Both concepts intend to take advantage of the automated driving mode with the driver out of the loop. However, the takeover process is one of the most critical aspects of highly automated driving and therefore had to be adduced for the concepts' evaluation. Consequently, the main questions to be answered were as follows.

- Is there any influence on the take-over process if the steering wheel is stationary during highly automated driving (concept "Stationary")?

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- In addition, is there any further influence if the steering wheel does not make its orientation transparent (concept “Rim”)?
- Does the driver notice that the steering wheel is stationary during highly automated driving? If so, what subjective impact does it have, if any?

To answer these questions, we conducted an experiment using a dynamic driving simulator. As control condition, we used a permanently coupled state of the art steering wheel.

METHOD

Experimental setup and participants

Driving Simulator. The dynamic driving simulator provides kinesthetic feedback while driving. It is equipped with a full vehicle mockup, projections give a 220° field of view and allow use of all mirrors. While driving, participants’ hands were filmed and all relevant data regarding the car’s status, movement, input and output devices were recorded. We used a head mounted eye tracking system (Dikablis) to record the participants’ gaze behavior.

Participants. The group consisted of 48 employees of the BMW Group, 7 females (15 %) and 41 males (85 %). They were between 21 and 54 years old (M=33,6 years; SD=9,3 years). 17 were wearing glasses (35%), 20 had driving simulator experience (42%).

Automation. We implemented an automated driving mode for the driving simulator. It could be switched on and off using a button on the dashboard. The automation was able to perform the longitudinal and lateral guidance of the car. The automated driving speed was set to 120km/h (default) and complied with speed limits on the simulated freeway. As long as the automation was active, a green icon was visible in the instrument cluster. Braking or applying more than 1Nm of steering momentum shut down the automation. The TOR was characterized by a visual (red icon in instrument cluster) and acoustical (warning tone) signal.

Non-driving related task. To evaluate the steering wheel concepts in a take-over scenario, participants had to be completely out of the loop while highly automated driving (Damböck et al., 2012). For this purpose, they had to engage in the Surrogate Reference Task (SuRT; ISO/TS14198). It required the participants to detect a target among similar distracters and then select the section of the screen containing the target. In contrast to ISO/TS14198, SuRT was implemented on a tablet computer placed in the center directly in front of the steering wheel. Using this setup, participants could still see the steering wheel in their peripheral field of view while dealing with the SuRT. Furthermore, they all had their hands in the same area at TOR.

Implementation of concepts. A BMW 5-Series multifunctional steering wheel was used for “Stationary” and the control condition concept. It has three spokes, two in the 3- and 9-o’clock position. The tablet computer for the SuRT was attached to a supporting structure underneath the steering wheel. The decoupling and re-coupling of the steering wheel was implemented in the driving simulator software framework.

For the concept “Rim”, the steering wheel had no spokes in the upper 280° sector, but one spoke centered at the 6-o’clock position. The supporting structure of the SuRT tablet was further equipped with an opaque plastic plate. This plate covered the steering wheel’s bottom 70° sector, including the single spoke and the impact absorber. Furthermore, the steering wheel rim was exactly concentric to the center of rotation and covered with leather of a homogeneous texture. As a consequence, the steering wheel movement was not visible to the driver within a steering wheel angle of +/- 35°.

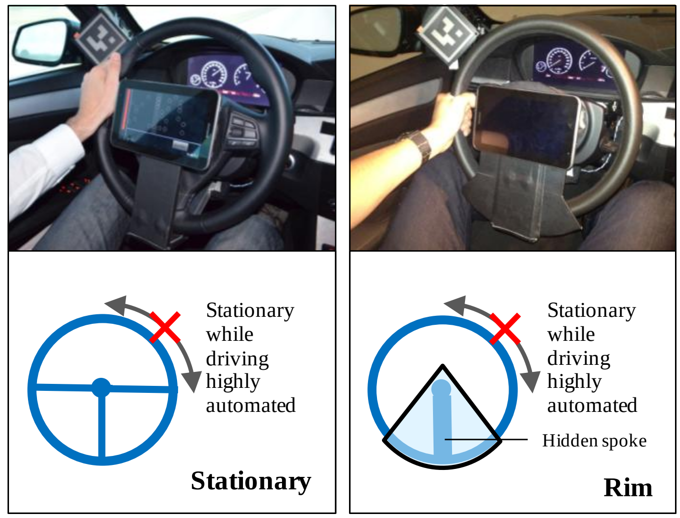

Figure 1: Implemenation of the concepts “Stationary” (left) and “Rim” (right).

Experimental design

Before the experiment started, the participants were instructed about the experiment procedure and the automation features. They had the opportunity to take a 10-minute test drive to familiarize themselves with the dynamic driving simulator and experience the automated driving mode, a take-over request and the SuRT. We conducted the experiment on a simulated freeway with three lanes and a hard shoulder. It consisted of the two following parts, a comparison drive and a take-over drive.

Comparison drive. We conducted the comparison drive to investigate whether the driver notices the decoupling of the steering wheel if its orientation is visible. We chose the within-subjects design to decrease error variance due to individual differences. 32 participants went through two 10-minute drives in the highly automated driving mode, one with “Stationary” and one with the control condition concept. The chronological order was permutated to eliminate associated effects. Participants were not instructed about the different behavior of the steering wheel in advance. They did not perform any specific task in this drive. We removed the tablet computer so the participants were able to notice the steering wheel orientation clearly.

Take-over drive. We conducted the take-over drive to investigate influences of the different concepts on the take-over process. “Stationary”, “Rim” as well as the control condition concept were evaluated with 16 participants each (between-subjects design). We assumed that differences between the concepts regarding the steering wheel orientation would emerge especially if the TOR occurred in a curve. Therefore,

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the system boundary was represented by an s-bend that guided the traffic around a construction site. The guidance was marked by yellow sidelines and deviated from the usual freeway lanes. At the top of the first curve, the automation requested take-over by the driver. Hence, the participants had to take over the control when there was considerable steering lock and manually guide the car through the rest of the s-bend (Figure 2). As soon as the driver applied more than 1Nm steering momentum, the automation shut off completely. The SuRT was activated 1km before the s-bend for the reasons mentioned above.

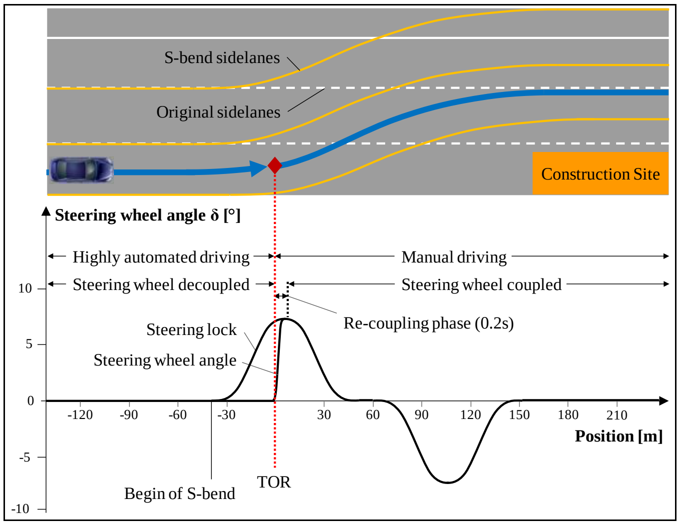

Figure 2: Take-over scenario in the s-bend.

Dependent Variables

Comparison drive. After the comparison drive, we asked the participants if they noticed any difference between the two drives in regard to the behavior of the controls (*noticed/ not noticed*). If they were not aware of any difference, we informed them about the decoupling of the steering wheel at "Stationary" and asked if they could remember this different steering wheel behavior (*upon request*). Subsequently we asked them to fill in a short questionnaire. Besides demographical data, we asked for their preferred coupling mode during highly automated driving on a 5-point scale with values "decoupled strongly preferred" (1) to "coupled strongly preferred" (5). Furthermore, participants had the opportunity to state the advantages and disadvantages of both concepts.

Take-over drive. We investigated two different aspects of the take-over process: timing aspects and the take-over quality. The corresponding measured values are listed in Table 1.

- Timing aspects of take-over process*:* Influences on the gaze reaction time are critical in a take-over process. The sooner the driver glances on the road after the TOR ("road fixation", Gold et al., 2013), the earlier he or she can start gathering information to improve situation awareness. Furthermore, the point of time when the driver has full manual control over the car is critical to the take-over process. Therefore, the "grasp time" value is defined. It includes the time needed for transport, grip and post-contact adjustments of the hand (Jeannerod, 1981). The value t_{grasp} was evaluated via analyzing the videos frame by frame (cycle time: 20ms).
- Take-over quality: The take-over quality provides information about the level of supremacy of the driver and the danger potential during the take-over process. Therefore, we investigated the maximum current acceleration. It is calculated from the longitudinal and lateral acceleration using the following formula (Pacejka, 2006):

$$a_{cur} = \sqrt{a_x^{\,2} + a_y^{\,2}}$$

If the current acceleration of the car increases, it more likely becomes unstable. That is because the force transmission between the tires and the road is limited. In addition, we analyzed the maximum steering wheel angle because it directly influences the current acceleration. Furthermore, we adduced the standard deviation of lateral position to characterize the take-over quality.

We defined the point in time when the TOR occurs as the starting point for all measurements. For the take-over quality values, we considered a timeframe of eight seconds after the TOR in the analysis, because eight seconds completely covered the s-bend at the given speed and the values were relatively steady afterwards.

Aspect	Variable	Definition	
Timing aspects of take-over process	Gaze reaction	Time until the first saccade stirs from the SuRT	t_{gaze} [s]
	Road fixation	Time until the first glance is at the scenery	t_{road} [s]
	Grasp time	Time until the driver's hands have adopted the pose on the steering wheel that they maintain for manual steering	t_{grasp} [s]
Take-over quality	Maximum acceleration		a_{cur} [m/s^2]
	Maximum steering wheel angle		δmax [°]
	Standard deviation of lateral position (SDLP)		SDLP [m]

Table 1: Dependent variables and measured values.

RESULTS

Regarding the take-over drive, seven participants had to be excluded due to simulation errors.

Comparison drive

From the participants that experienced "Stationary" and control condition, 15 participants (47%) stated that they did not notice the difference in steering wheel behavior (Figure 3, left chart). Participants who did not notice the difference mostly stated that they simply did not look at the steering wheel while driving highly automated.

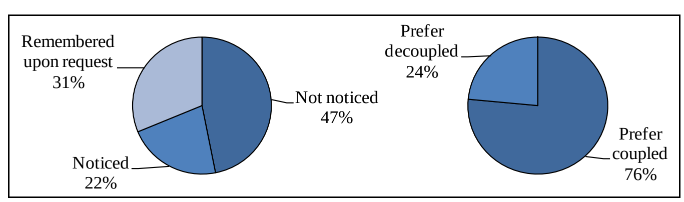

Figure 3: Results of comparison drive.

Participants who noticed the difference predominantly prefer a permanently coupled steering wheel (Mdn=4), which is illustrated in Figure 3 (right chart). They considered the lack of system transparency and the lack of potential to detect failure

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as downsides of the steering wheel being decoupled. An advantage of concept “Stationary” that was occasionally mentioned was the calm atmosphere during highly automated driving.

Take-over drive

Trajectories. Figure 4 shows the driven trajectories. Their deviation at “Rim” appears considerably lower compared to control condition and “Stationary”, which indicates a lower accident risk.

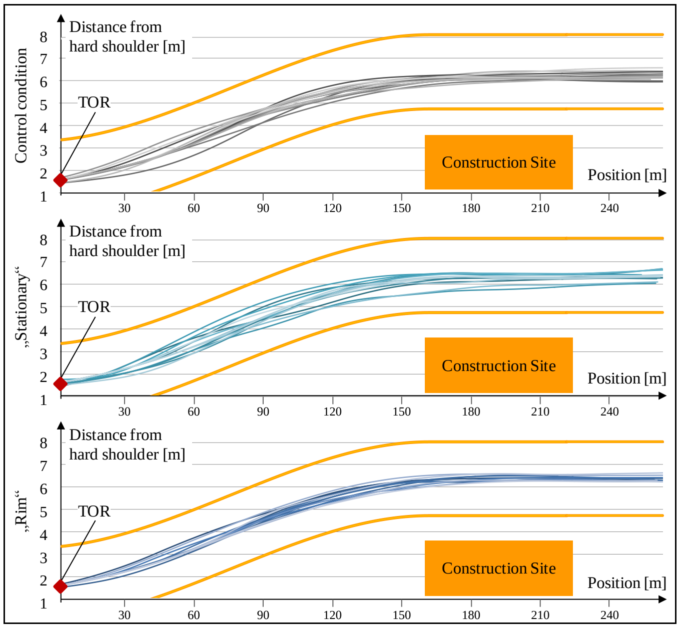

Figure 4: Driven trajectories after Take-over request.

Timing aspects of take-over process. In addition to the cases mentioned above, we had to exclude the results from thirteen further participants from the glance behavior investigation either because the eye tracking failed temporarily during the experiment or due to technical issues. It turned out that the mean gaze reaction time at “Stationary” (M=0.34s, SD=0.06s) and “Rim” (M=0.36s, SD=0.12s) was just about equal to the mean value at the control condition (M=0.34s, SD=0.08s). The mean road fixation time at “Stationary” (M=0.56s, SD=0.20s) was slightly longer than at the control condition (M=0.48s, SD=0.10s) and at “Rim” (M=0.50s, SD=0.14s). A one-way analysis of variance (ANOVA) revealed no significant main effect (F(2,25)=0.049, p=0.952). Four participants experienced a simulation error when grasping the steering wheel and therefore we had to exclude their results from grasp time and take-over quality evaluation, in addition to the cases mentioned above. The mean grasp time at “Stationary” (M=1.96s, SD=0.66s) was slightly shorter than at the control condition (M=2.27s, SD=0.58s). At “Rim”, the mean grasp time was 1.47s (SD=0.76s). A one-way analysis of variance (ANOVA) indicated a significant main effect (F(2,33)=4.368, p=0.021, r=0.458). A Games-Howell post-hoc test revealed a significant difference between control condition and “Rim” (p=0,020). Figure 5 shows diagrams for the timing aspects of the take-over process.

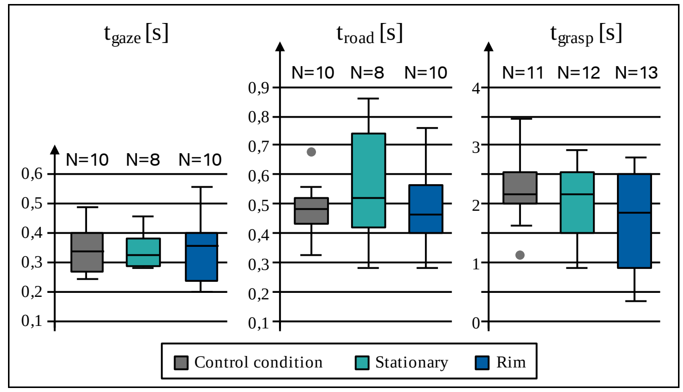

Figure 5: Box-whisker diagrams of t_{gaze}, t_{road} *and* t_{grasp}.

Take-over quality. The mean value of maximum acceleration was 1.10m/s^2 (SD=0.18m/s^2) at the control condition, 1.22m/s^2 (SD=0.28m/s^2) at “Stationary” and 1.03m/s^2 (SD=0.14m/s^2) at “Rim”. An analysis of variances revealed no significant main effect (F(2,32)=2.329, p=0.114).

The mean of the maximum steering wheel angle at “Stationary” (M=12.45°, SD=3.42°) is quite minor, at “Rim” (M=10.52°, SD=1.94°) considerably minor compared to control condition (M=13.34°, SD=1.30°). As Levene’s test indicated, the assumption of homogeneity of variance was violated (F(2,33)=3.656, p=0.037) which could not be rectified by transformation. The data indicate a significant main effect (F(2,33)=4.353, p=0.021, r=0.456) between the control condition and “Rim” (Games Howell post-hoc test, p=0.001).

The mean of the standard deviations of lateral position (SDLP) at “Stationary” (M=0.17m, SD=0.06m) and at “Rim” (M=0.15m, SD=0.05m) are considerably minor compared to the control condition (M=0.21m, SD=0.05m). A Kruskal-Wallis test revealed a significant effect regarding the SDLP between the three concepts (H(2)=6.262, p=0.044). Considering the Bonferroni correction, the Mann-Whitney test revealed a significant difference between the control condition (Mdn=0.20) and ”Rim”(Mdn=0.12; U=30.00, p=0.015). Results regarding take-over quality are illustrated in Figure 6.

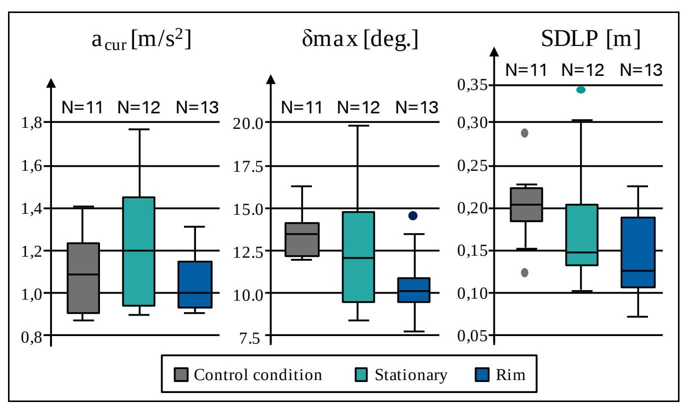

Figure 6: Box-whisker diagrams of a_{cur}, *δmax and SDLP.*

DISCUSSION

One key result of this study was that nearly half of the participants (47%) did not notice that the steering wheel was decoupled during highly automated driving. We did not expect this,

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because cars available today provide a permanently coupled steering wheel. However, it has to be noted that the difference between "Stationary" and the control condition would be more obvious at higher steering wheel angles (+/-6° at maximum on the simulated test track). The disadvantages of "Stationary" stated by participants who noticed the difference indicate a lack of mode awareness (Sarter & Woods, 1995).

Concept "Stationary". With the assumption that the re-coupling of the steering wheel captures the participants' attention, we expected two effects. First, the gaze reaction time would be shorter compared to the control condition, as the abrupt steering wheel motion intensifies the take-over request signal. As the results show, this is not true. Possibly, the reaction time at control condition was already as short as it can get. Secondly, we expected the road fixation time to be longer, because the eyes "rest" on the steering wheel shortly while participants glance up to the road. Results slightly indicate this effect. Even so, the re-coupling phase in "Stationary" happened just shortly after the usual steering at the beginning of the curve in the control condition concept. Therefore we assumed that the effect could emerge more clearly if the curve were longer and TOR happened later in the curve. Regarding the grasp time, concept "Stationary" leads to a greater variance of the value compared to the control condition, but the mean values do not differ significantly. The same pattern applies to the values for maximum acceleration, maximum steering wheel angle and the SDLP. Apparently, "Stationary" has positive and negative influence on the take-over process highly depending on the individual participant. Furthermore, the steering wheel would probably be more difficult to grasp if the TOR appeared in a sharper curve.

Concept "Rim". As expected, the concept "Rim" did not cause any significant gaze behavior differences compared to the control condition. It could not be proven for sure whether the attention capture effect could be avoided, because "Stationary" did not significantly cause this effect either. However, results show that the concept "Rim" was indeed significantly easier to grasp than the control condition concept. Participants seemed to be very confident while grasping the steering wheel. The post-contact adjustments were marginal (Fu et al., 2013), which is presumably due to the missing spokes. For the aspect of take-over quality, the maximum of the steering wheel angle as well as the SDLP showed a significantly lower mean value at "Rim" compared to the control condition. In summary, participants were able to handle the car significantly better compared to the control condition concept. Potentially this is an effect of the easier grasp process, because the gaze behavior is not different from the control condition.

Generally we assumed that the SuRT tablet position had a substantial influence on the results of the experiment. Furthermore it was observed that some participants tried to counteract the automation after the TOR in a way that was not justified by the s-bend. This can be referred to as one consequence of mode confusion during the take-over process (Sarter & Woods, 1995).

SUMMARY

Three key aspects can be derived from this study. Firstly, the decoupling of the steering wheel seems not to cause any negative effects on the take-over process ("Stationary") under the chosen circumstances. Consequently, preassuming curve radiuses as high as in this study, it should be relatively unproblematic to design car interfaces for the automated driving mode that require a stationary steering wheel. Secondly, a steering wheel with no visible physical spokes ("Rim") can even improve performance in the take-over process in curves. This is a valuable fundamental piece of knowledge when designing the interface for highly automated cars. Third, results indicate that people prefer a permanently coupled steering wheel, but only a small portion actually realizes the difference between the two coupling modes under the chosen conditions. We assume that the effects revealed depend on the curve radius and the timing of the TOR in the test scenario. Further studies should be conducted to investigate these influences.

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