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Driving performance at lateral system limits during partially automated driving

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ABSTRACT

This study investigated driver performance during system limits of partially automated driving. Using a motion-based driving simulator, drivers encountered different situations in which a partially automated vehicle could no longer safely keep the lateral guidance. Drivers were distracted by a non-driving related task on a touch display or driving without an additional secondary task. While driving in partially automated mode drivers could either take their hands off the steering wheel for only a short period of time (10 s, so-called 'Hands-on' variant) or for an extended period of time (120 s, so-called 'Hands-off' variant). When the system limit was reached (e.g., when entering a work zone with temporary lines), the lateral vehicle control by the automation was suddenly discontinued and a take-over request was issued to the drivers. Regardless of the hands-off interval and the availability of a secondary task, all drivers managed the transition to manual driving safely. No lane exceedances were observed and the situations were rated as 'harmless' by the drivers. The lack of difference between the hands-off intervals can be partly attributed to the fact that most of the drivers kept contact to the steering wheel, even in the hands-off condition. Although all drivers were able to control the system limits, most of them could not explain why exactly the take-over request was issued. The average helpfulness of the take-over request was rated on an intermediate level. Consequently, providing drivers with information about the reason for a system limit can be recommended.

1. Introduction

Just recently, several automobile manufacturers have introduced advanced driver assistance systems that are capable of supporting the driver in the longitudinal and lateral vehicle guidance, while she/he still has to be continuously ready to take over manual vehicle control if necessary. This type of vehicle automation has therefore been classified as 'partial automation' (Gasser and Westhoff, 2012; NHTSA, 2013). While partial automation can already be found in certain vehicles, further technological advancements and human factors research is currently being directed towards an automation level that allows the driver to even permanently disengage from the driving task, so called 'highly automated driving' (Gasser and Westhoff, 2012; NHTSA, 2013). In both automation levels, the driver will have to take over manual control in case of automation failures (e.g., sensor malfunctions) and in case of functional system limits (e.g., in case of missing lane markings; Gold et al., 2017). Thus, driving performance in these so-called 'take-over situations' has attracted a considerable body of research (e.g., Damböck et al., 2013; Gold et al., 2013; Gold et al., 2015; Hergeth et al., 2015; Louw et al., 2015; Naujoks et al., 2014; Radlmayr et al., 2014; Wiedemann et al., 2015).

However, most of these studies have dealt with highly automated driving, while driving in partially automated mode has not been investigated this extensively yet even though the market introduction is set earlier than the one of highly automated driving (Kircher et al., 2014; Larsson et al., 2014; Naujoks et al., 2016b; Naujoks et al., 2015b; Strand et al., 2014). The objective of this study on partial automation is to extend existing knowledge in several ways. First, the impact of the possibility to take the hands off the steering wheel for a considerable amount of time on the drivers' ability to safely manage transitions from partially automated driving to manual driving will be investigated. The focus of the study is on situations in which a system limit is recognized and a take-over request is issued to the driver. Second, the study aims at extending prior findings on driving performance during system limits of

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partially automated driving that have not been investigated extensively, namely lateral guidance boundaries. Third, the influence of secondary tasks will be taken into account as prior research suggests that partially automating the driving task will lead to an increase in the drivers' willingness to process secondary tasks during driving (e.g., Llaneras et al., 2013; Naujoks et al., 2016b).

1.1. Performance deficits caused by vehicle automation

Studies on driving performance at system limits of partial vehicle automation have already been conducted in the context of Adaptive Cruise Control (ACC) with additional steering assistance (SA). Due to sensor limitations, ACC might fail to detect vehicles in front of the host vehicle (Larsson et al., 2014; Park et al., 2006; Neukum et al., 2008; Young and Stanton, 2007) or fail to decelerate sufficiently to avoid collisions with vehicles in front (Lee et al., 2006; Nilsson et al., 2013; Strand et al., 2014). From a human factors perspective, such system limits have to be considered problematic as drivers may fail to react timely enough to fully compensate these automation deficiencies (Larsson et al., 2014; Park et al., 2006; Piccinini et al., 2015). This deficit has been attributed to poor system understanding (Beggiato and Krems, 2013; Piccinini et al., 2015), reduced situation awareness (Casner et al., 2016; Strand et al., 2014) or overreliance on the capability of the automation (Rajaonah et al., 2006). Consequently, some studies report that drivers are slower to respond to traffic conflicts compared with manual driving conditions (Larsson et al., 2014; Strand et al., 2014; Vollrath et al., 2011), and that these situations can ultimately result in accidents or near misses (Park et al., 2006; Stanton et al., 2001). In comparison to assisted driving, partial automation relieves the driver from the task of driving altogether, but it requires continuous monitoring of the driving environment. This changed role of the driver may increase drowsiness (Schömig et al., 2015a) caused by so-called 'passive fatigue' (May and Baldwin, 2009) and eventually further impair the driver's ability to react to system limits (Saxby et al., 2013).

1.2. Studies on system failures of partially automated driving

Recent studies have consequently dealt with the question whether additionally automating lateral vehicle control will worsen the criticality of situations that require manual intervention. Stanton et al. (2001) compared driver performance in a situation in which a lead vehicle unexpectedly started emergency braking and found no difference in the frequency of rear-end collisions between driving with ACC and ACC with Automated Steering (AS), but both assisted conditions had a higher incident rate compared to non-assisted driving. Strand et al. (2014) report a higher frequency of safety-critical events resulting from a sudden brake intervention of the lead vehicle to which the automation failed to brake sufficiently when driving with partial automation compared to driving with ACC alone. However, the level of automation did not influence brake reaction times on a statistically significant level. Larsson et al. (2014) also report no difference in brake reaction times in response to a cut-in situation (i.e., another vehicle changes to the lane of the participant's vehicle, which necessitates a braking intervention of the driver) that is detected late by the automation between ACC and partial automation. The authors also report no difference in the criticality of the situations, as measured by the minimum time to collision. However, ACC and partial automation increased brake reaction times and criticality of the situations compared with non-assisted driving. In both of the latter studies (Larsson et al., 2014; Strand et al., 2014), drivers were explicitly instructed to keep their hands on the steering wheel, which might explain that no differences between ACC and partial automation in brake reaction times were found. Damböck et al. (2013) investigated system limits in two scenarios, a lead vehicle braking scenario and an animal-crossing scenario. The authors compared driving without assistance to driving with ACC and driving with partial automation. In the partial automation condition, the instruction was either to keep the hands on the steering wheel or to keep the hands off the steering wheel. Compared to non-assisted driving, only partial automation with the instruction to keep the hands off the steering wheel led to an increase in brake reaction times in both scenarios. It appears that explicitly instructing drivers to take their hands off the steering wheel for an extended period of time decreases the drivers' ability to react to system failures during partially automated driving to an even greater extent.

At this point, it is important to emphasize that existing partially automated vehicle functions usually allow hands-free driving only for a limited amount of time (Casner et al., 2016). For example, the commercially available 'Distronic Plus with Steering Assistance' by Mercedes Benz didn't allow hands-free driving for longer than 10 s at higher speeds at its initial release. From a practical point of view, the question may thus not be if drivers are allowed to take their hands off the steering wheel or not, but rather for how long they are allowed to do so. Naujoks et al. (2015b) compared driver performance at a system limit in which a standing vehicle suddenly became visible and the partial automation failed to brake sufficiently enough to avoid a collision. The drivers could either take their hands off the steering wheel for only a short time interval of 10 s, which practically affords hands-on driving, or they could take their hands off the steering wheel for 120 s, which practically allows hands-free driving. Brake reaction times and the criticality of the situation, as measured by the frequency of safety-critical events, were not affected negatively by the possibility of extended periods of hands-free driving. However, the study also revealed that most of the drivers kept their hands on the steering wheel, even in the condition with the long hands-off interval.

1.3. Supporting the driver in taking over manual control

Another distinction of the study reported by Naujoks et al. (2015a,b) is that drivers were supported in taking back manual vehicle control by a take-over request (TOR) that was presented as soon as the need for intervention was detected by the partially automated vehicle. Assisting drivers during transitions to manual driving by supporting monitoring of the driving situation and reactions to system limits (van den Beukel et al., 2016) may counteract performance deficits found in studies in which drivers were required to react to hazards that were *not* detected by the automation (Damböck et al., 2013; Larsson et al., 2014; Strand et al., 2014). In the context of partially automated driving, visual-auditory TORs consisting of a warning sound and an additional depiction of a warning symbol have been used in different studies (Dogan et al., 2017; Naujoks et al., 2015b; van den Beukel et al., 2016). The multimodal presentation of warning signals usually speeds up the cognitive processes involved in the selection and execution of an appropriate response, such as braking or steering (Ho et al., 2007; Kramer et al., 2007; Naujoks et al., 2016a,b), which is called *redundancy gain* in cognitive psychology (Kiesel and Miller, 2007; Miller et al., 1999). Initiating an automated avoidance maneuver, such as braking, can further assist drivers during the take-over process (Blommer et al., 2017). In sum, the system limits that are recognized by the partial automation (e.g., temporary lane markings or missing lane markings) make it possible to assist drivers in taking over manual control, which can mitigate criticality of these situations, especially in comparison to non-recognized system failures.

1.4. Test situations used in studies on partially automated driving

The driver's ability to safely handle transitions from partially automated to manual driving might not only be influenced by whether she/he can take the hands off the steering wheel and whether a TOR is provided or not, but also depends on the specific driving situation (e.g., type of required reaction, available time budget, etc., cf. Marberger et al., 2017). Most of the studies on partial automation have focused on longitudinal rather than lateral guidance boundaries (Blommer et al., 2017; ck et al., 2013; Larsson et al., 2014; Naujoks et al., 2015b; Strand et al., 2014). However, it is precisely the ability of the automation to continuously handle lane keeping that extends partial automation compared to ACC. Consequently, these system limits might be both experienced frequently (e.g., when passing work zones) and unfamiliar to drivers, even when they have previous experience with ACC. System limits of lateral vehicle guidance have been investigated so far mainly in the context of highly automated driving in which the system limit is usually announced several seconds before the respective road section (e.g., missing lane markings, high road curvature, etc.) is reached. For example, Larsson et al. (2015) investigated lateral control failures during fully automated driving in which the lateral vehicle guidance was discontinued during a straight or curved road segment. System limits due to temporary lines have been included in the studies by Melcher et al. (2015) and Kerschbaum et al. (2014). Mok et al. (2015) and Walch et al. (2015) report findings on driver performance during take-over situations that are caused by high road curvature. Naujoks et al. (2014) investigated three different lateral guidance boundaries in which the lateral vehicle guidance could no longer be controlled by the automation during highly automated driving: (1) missing lane markings, (2) temporary lines due to a work zone and (3) high curvature.

With few exceptions, lateral guidance boundaries of partially automated driving have been a non-issue so far. Körber et al. (2015) investigated a malfunction of lateral control that was not indicated by a TOR when entering a curve and found average reaction times of about 4 s. However, it was not reported whether drivers were able to keep the vehicle in the lane after the system malfunction. Wulf et al. (2013) also investigated a non-recognized error in lateral control and found mean reaction times of approximately 9 s. All drivers were able to keep the vehicle in the lane. In this study, the situations investigated by Naujoks et al. (2014) will be used to investigate driver performance during partially automated driving in order to extend existing knowledge to this kind of automation level.

1.5. Distraction conditions

Another aim of the study was to investigate the influence of making a secondary task available to drivers during the partially automated drive. Secondary task engagement has been shown to impair several aspects of driving performance and is thus expected to contribute to the difficulty of handling system limits of automated driving functions (Naujoks et al., 2017). For example, cognitive load by secondary tasks narrows the area that is visually scanned by the driver (Harbluk et al., 2007; Recarte and Nunes, 2000), impairs the ability to estimate safe time gaps (e.g., for overtaking or crossing intersections, see Cooper et al., 2009; Cooper and Zheng, 2002) and ultimately increases the reaction time to road hazards (Alm and Nilsson, 1995; Parkes and Hooijmeijer, 2001; Strayer et al., 2003). During partially automated driving, this might be especially the case when processing of the secondary task interferes with monitoring the automated driving system and driving environment (Spiessl and Hussmann, 2011). Consequently, performing secondary tasks during the partially automated drive may lower the drivers' ability to safely handle system limits (Merat et al., 2012; Payre et al., 2017) such as the ones investigated in this study. For example, in a study by Dogan et al. (2017), drivers that were allowed to read a magazine or interact with a smartphone were slower to respond to TORs that were issued because a partially automated vehicle reached its maximum operating speed. This concern is especially important as recent research suggests that increased vehicle automation may go along with an increase in the willingness to engage in secondary tasks while the vehicle is in motion (de Winter et al., 2014; Jamson et al., 2013; Naujoks et al., 2016b; Naujoks and Totzke, 2014). For this reason, providing drivers with the opportunity to engage in a secondary task during the partially automated drive was included in the experimental setup of this study.

1.6. Research questions

The objective of this study was to evaluate driving performance at functional system boundaries of partially automated driving and to extend the above cited findings on the controllability of such system limits. It was investigated if previous findings (Naujoks et al., 2015b), in which the controllability of a system limit of longitudinal vehicle guidance was assessed, can be transferred to other driving situations in which the automation's lateral control reaches its limits. Specifically, the study aimed at assessing whether the result from the previous study, that the allowed hands-off interval (10 s vs. 120 s) does not influence the driver's ability to safely manage transitions from partially automated driving to manual driving, would hold true for lateral guidance boundaries. In addition, it was investigated whether engaging in a non-driving related task during the partially automated drive would influence drivers' performance when required to suddenly regain manual control over the vehicle. Studies investigating distracted driving would suggest such a worsening of driver performance. The study was conducted in a driving simulator with a sample of naive drivers that were familiarized with the automated driving function. In a subsequent drive, participants were confronted with the mentioned system boundaries that required a transition from partially automated to manual driving. The presentation of a TOR indicated the need for manual control.

2. Method

2.1. System description

The partial automation investigated in the study took over longitudinal and lateral vehicle control up to a velocity of 50 km/h. When driving with the system, drivers still had to monitor the driving environment and had to be ready to resume control immediately whenever a system limit was encountered. Prior to the drive, they were thus explicitly instructed that they are still fully responsible for driving safety even when the automation is activated.

The automation was activated via pushing a button on the steering wheel and could be deactivated by either braking (threshold: pressing the brake pedal more than 10%) or by pushing the same button that activated the system once again. Deactivation by steering was also possible but afforded a considerable deviation from the center of the lane by the drivers. Drivers could place their hands on the steering wheel and override the automation's lateral vehicle guidance to a certain extent without deactivating the system. Overriding by gas pedal was also possible, which led to a temporary deactivation of the automated longitudinal guidance.

When activated, the system kept the host vehicle in the middle of the lane with a target speed of 50 km/h and a following distance (Time headway, THW) of two seconds. The maximum deceleration of the system was set to 4 m/s^2. Thus, the drivers could take their feet off the pedal when driving in partially automated mode. Regarding lateral vehicle control, two different variants of the partial automation were implemented and tested in this study. The drivers could either take their hands off the steering wheel for 10 s ('Hands-on' variant) or for 120 s ('Hands-off' variant). If no hands-on signal was detected for a longer time period than the respective threshold, the system issued a visual hands-off warning (see Fig. 1). When no hands-on signal was detected within the following five seconds, a visual-auditory take-over request (TOR, see Fig. 2) was issued and the vehicle started to decelerate with a constant deceleration of 0.08 m/s^2. This take-over mode could be deactivated by either pressing the gas or brake pedal more than 10%, or by pressing the button on the steering wheel that was also used for activating the system. A TOR was also issued when system limits were reached (see next chapter).

The visual Human-Machine Interface (HMI) was positioned at the top of the instrument cluster and displayed the status of the automation

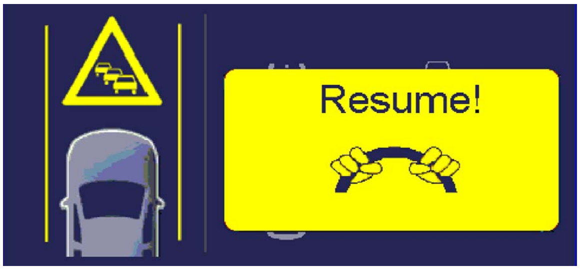


Fig. 1. Hands-off warning.

to the driver continuously. The displayed information consisted of the following elements (see Fig. 3):

- Indication of the mode (element 1 in Fig. 3) of the automation by showing a grey (mode: automation available), green (mode: automation active), white (mode: override) or red (mode: take-over request) symbol on the left side of the HMI that resembled the traffic jam road sign.
- Indication whether the preconditions for safe vehicle operation by the partial automation are fulfilled, or not (element 2–5 in Fig. 3). The automation could only be activated when driving on freeways, when a front vehicle as well as lane markings were identified correctly, and when both the host vehicle and the vehicle in front had a velocity below 50 km/h. If these preconditions were fulfilled, this was communicated to the driver on the right side of the HMI by showing the respective indicator in green. A more thorough description of the HMI screen can be found in Naujoks et al. (2015b).

2.2. Test scenarios

This study focuses particularly on system limits pertaining to the lateral vehicle guidance, during which the lateral control by the partial vehicle automation can no longer be ensured, for example because of missing or unclear lane markings. Three prototypical scenarios that may lead to failures of the lateral guidance functionality were implemented (see Table 1): (1) Missing lane markings ('Lines end/no lines'), (2) temporary lines because of a work zone ('Temporary lines'), and (3) high road curvature ('High curvature').

These situations were chosen on the basis of field tests and parameterized according to naturalistic conditions. Furthermore, similar situations have already been assessed in a prior study during highly automated driving (Naujoks et al., 2014) and were thus chosen to enable comparability to related research. At the beginning of each situation, the host vehicle drove on the right lane of a three-lane freeway (lane width: 3.75 m) in congested traffic with a velocity of 50 km/h and a set following distance of two seconds. A lead vehicle was always present. The neighboring lane was always occupied by other vehicles, so that the drivers would have to avoid letting the host vehicle drift to the left lane as a consequence of the loss of automated lateral control (see Fig. 4).

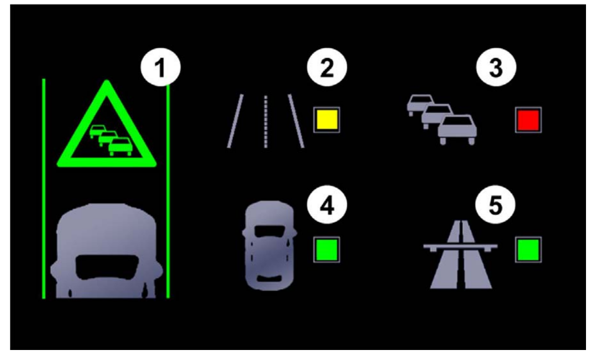
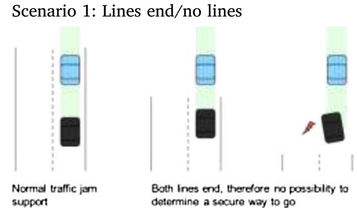
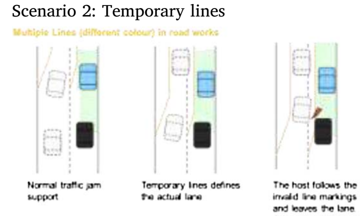
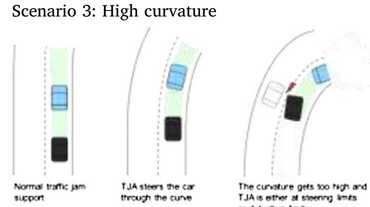


Fig. 3. HMI screen: (1) System activity/availability indicator; (2) Lane markings detection indicator; (3) Preceding vehicle and traffic jam indicator; (4) Ego vehicle condition indicator; (5) Road type indicator. Checkbox colors: Green = Conditions for activation fulfilled; Yellow = Transition condition; Red = Conditions for activation not fulfilled.

Table 1
Scenario schematics (left) and condition for TOR (right).

Scenario 1: Lines end/no lines 	Condition for TOR The TOR is issued approx. 20 m after the host vehicle has entered the road section with missing line markings. The road geometry is slightly bent (curvature: 0.000125 m^{-1}). In case the driver does not respond to the TOR, the vehicle's center of mass crosses the lane after 9.3 s.
Scenario 2: Temporary lines 	The TOR is issued approx. 20 m after the host vehicle has entered the road section with temporary line markings. In case the driver does not respond to the TOR, the vehicle's center of mass crosses the lane after 3.5 s.
Scenario 3: High curvature 	The TOR is issued approx. 20 m after the host vehicle has entered the road section with high curvature (curvature: 0.005 m^{-1}). In case the driver does not respond to the TOR the vehicle's center of mass crosses the lane after 4.2 s.

The loss of guidance scenarios build up from the traffic scenery without specific announcements like traffic signs that hint towards the upcoming event. Approximately 20 m after the host vehicle entered the respective scenario (i.e., missing lines section, temporary lines section,

Fig. 2. Take-over request presented on the HMI screen. The position of the HMI screen can be seen in the right part of the figure on top of the instrument panel.

Fig. 4. Driver's view of the congested traffic situations.

or high curvature section) a visual-auditory TOR was issued, the automated lateral vehicle control was discontinued and the host vehicle started to decelerate with a constant deceleration of 0.08 m/s^2. The TOR was only issued after the host vehicle had already entered the situation assuming that it would take the host vehicle's sensors a moment to recognize the respective system limit. The TOR consisted of a depiction of the pedal and steering wheel as well as the indication to 'take over' driving (see Fig. 2). A warning tone was presented together with the visual HMI.

2.3. Secondary task

The secondary task used in this study consisted of retrieving weather related information within a 1 × 4 × 4 × 4-task menu (see Fig. A1). The task was presented on a touch display that was installed in a fixed position at the upper part of the central information display. Performing the task did not afford to take both hands off the steering wheel. Engaging in the task was voluntary for the participants. The task itself was originally developed for a study on the distraction effects of different visual-manual and visual-auditory tasks funded by the German Federal Highway Research Institute (Schömig et al., 2015b). In a study on the distraction effects of this task (see Schömig et al., 2015b), it turned out that total glance time and single glance durations generally were within the acceptable tolerance range according to the visual-manual NHTSA driver distraction guidelines for in-vehicle electronic devices (NHTSA, 2012). The task was selected because we expected that the drivers would be able to engage in the secondary task during the partially automated drive. This is particularly important as drivers normally show situation-adaptive behavior in the sense that they adapt their level of task engagement to the demands of the traffic situation (see e.g., Jamson et al., 2013; Metz et al., 2014; Naujoks et al., 2016b; Naujoks and Totzke, 2014). During a prior on-road study, Naujoks et al. (2016b) showed that drivers readily engage in this task while driving, and that partial automation of the driving task leads to an increase in the frequency of performing this secondary task compared to non-assisted driving. Additional information on the secondary task can be found in the Appendix A.

2.4. Experimental design

The study was carried out in a 3 × 3 × 2 mixed between-within design with the between-subjects factor 'Automation level' ('Hands-on' vs. 'Hands-off' vs. 'Baseline') and the within-subject factors 'Situation' ('Temporary lines' vs. 'High curvature' vs. 'Lines end/no lines') and 'Secondary task' ('with secondary task' vs. 'without secondary task').

The drivers encountered the driving scenarios while driving with one of the two automation levels (Hands-off vs. Hands-on) or while driving in the manual control condition (Baseline). Within the test session, every driver completed two drives with the secondary task being either available or not to the participants while driving through the situations. The order of the two drives was randomized. Participants were given the opportunity to rest for some minutes between the drives. During each of the drives, the three test scenarios were presented to the participants in randomized order to control for potential order effects. In total, every driver completed six situations.

2.5. Driving simulator

The study was conducted using the dynamic driving simulator at the Würzburg Institute for Traffic Sciences (WIVW GmbH, see Fig. 5). The driving simulation software SILAB developed at WIVW was used for environment visualization as well as for simulation of assistance systems, traffic and vehicle dynamics. The integrated vehicle's console contains all the necessary instrumentation and is identical with a production type BMW 520i with automatic transmission. In order to simulate a realistic steering torque, a servo motor based on a steering model is used. The motion system uses six degrees of freedom and can briefly display a linear acceleration up to 5 m/s^2 or 100°/s^2 on a rotary scale. It consists of six electro-pneumatic actuators (stroke +/− 60 cm; inclination +/− 10°). Three LCD projectors are installed in the dome of the simulator and provide the projection. Three channels provide a 180° screen image. LCD displays serve as exterior and interior mirrors.

2.6. Procedure and instructions

At the beginning of the experimental session, drivers were told a cover story, i.e., that they would drive with a newly developed driver assistance system and that their task was to assess its usability. The drivers were not told that the goal of the study was to assess the controllability of the partial automation and that they would encounter critical driving situations. Prior to the test drives, all of the drivers were familiarized with the automated driving system. During this training drive, activation and deactivation as well as the possibilities to override the longitudinal and lateral control were explained to the participants and practiced (i.e., all participants knew how to activate, deactivate and override the system). The drivers were also instructed to drive with their hands off the steering wheel until a hands-off warning was issued by the automation during the training drive. An initial system boundary

Fig. A1. Secondary task (example task: looking up the rain probability on the evening of the same day). First screen: task presentation, second screen: selection of day, third screen: selection of time of day, final screen: selection of specific information.

Fig. 5. The WIVW dynamic driving simulator. Hexapod movement system (left) and simulator interior with vehicle mock-up and video projection (right).

was also experienced in a cut-out situation in which a front vehicle suddenly changed lanes uncovering a vehicle in stand-still. Here, a TOR was presented and the participants had to take over manual control and initiate emergency braking which all drivers managed successfully. The results of this study part are reported in Naujoks et al. (2015b).

In the subsequent main part of the study, the drivers were instructed to stick to the Traffic Code and to always drive on the right lane of the road. They were also told to use the partial automation during the drive. Depending on the system variant, the drivers were instructed that they could take their hands off the steering wheel for either 10 s or 120 s. However, they were not explicitly instructed to take their hands off the steering wheel; instead they were told to drive as they would if they would use such a system in daily traffic. They were also explicitly instructed that they were still fully responsible for driving safety. Regarding situations with secondary task availability, the participants were told to work on the task whenever they felt that the driving situation would be safe enough to do so. In order to encourage them to engage in the secondary task, they were also told that they could earn extra financial compensation of 30 Euros if they complete more tasks than the other participants. However, they were also told that they would lose any points earned in the secondary task if they endangered themselves or other road users.

During the drive, the surrounding traffic was programmed to create a relatively stable traffic flow in low speed driving conditions. A maximum velocity of 50 km/h was never exceeded. After approximately 10 min of driving in congested traffic without interruption, the first test situation was encountered. Directly following the situation, a short on-road questionnaire was completed before the drivers continued driving in congested traffic until they experienced the next situation. This procedure was followed until all drivers had completed all situations. The time in-between the test situations varied between 10 and 15 min. To mimic real-world driving with partial automation in which the longitudinal vehicle control (and not only the lateral control) also has to be monitored by the driver, additional non-critical take-over situations were introduced to the drive. The aim of introducing these distractor events was also to mitigate learning effects with regard to a stimulus-response association between TOR and the need to steer the vehicle. The distractor scenarios occurred in randomized order between the three test situations and consisted of a cut-in situation, a cut-out situation with a vehicle in standstill and a lead vehicle braking scenario. In these scenarios, the partial automation carried out the brake reaction but still requested the driver to take over. Taken together, the test drive lasted about one and a half hours. The drivers received financial compensation of 50 Euros for participation in the study.

2.7. Sample

The participant sample consisted of 34 drivers (10 females). All drivers were recruited from an existing driver panel at the WIVW. The drivers had participated in a standardized simulator training that aims at familiarizing the drivers with the handling of the simulated vehicle and at reducing the occurrence of simulator sickness. During the training procedure, all participants completed two consecutive training sessions, each lasting about two hours, in which they were trained in handling the simulated vehicle correctly. Details of this training can be found in Hoffmann and Buld (2006) and Naujoks et al. (2015a).

Characteristics of the sample are presented in Table 2. Age and previous experience with ACC are taken into account, as these variables have been discussed to be relevant in the context of human factors studies on automated driving (e.g., Larsson, 2012; Larsson, 2014; Naujoks et al., 2016b; Naujoks et al., 2015b). Previous experience with ACC is defined by having already participated in prior studies involving driving with ACC. The drivers were assigned randomly to the automation levels. The subsamples assigned to the experimental conditions did not differ significantly with regard to age ($F(2,31) = 0.55$, $p = 0.580$). The two partial automation conditions did also not differ significantly with regard to frequency of participants with prior ACC experience ($\chi^2 = 0.18$, $df = 1$, $p = 0.673$).

2.8. Dependent measures

Using pressure sensors in the steering wheel, it was continuously assessed whether drivers kept contact with the steering wheel (i.e., having at least one hand on the steering wheel). The primary measures for assessing the driver's reactions to the take-over requests when encountering the system limits as well as the resulting criticality of the situations are listed and explained in Table 3. First, it was analyzed how (i.e., by pressing the brake pedal, gas pedal or the steering wheel button) and when drivers deactivated the take-over mode. The quality of lateral vehicle control was measured by the standard deviation of lateral position in the time interval between the presentation of the TOR up to 10 s after the TOR was issued. Note that lateral vehicle guidance was discontinued at the same time as the TOR was presented. In the manual condition, the parameter was measured during the corresponding time interval (i.e., when the TOR would have been issued up to 10 s after this point). The driver's velocity during this time

Table 2
Sample characteristics.

Automation level	ACC-experience		Age			
	n	$n_{ACC\ experience}$	Mean	Min	Max	SD
Hands-off	12	8/12	45.50	24	66	14.85
Hands-on	12	7/12	40.83	24	63	14.86
Baseline	10		39.10	22	61	15.14

Table 3
Objective and subjective dependent measures employed in the simulator study.

Parameter	Description	Unit
Deactivation of take-over mode		
Deactivation method	Method used for system deactivation after the TOR was issued (gas pedal, brake pedal or steering wheel button)	[n]
Time-to-deactivate	Time elapsed between TOR and deactivation of take-over mode	[s]
Longitudinal control		
Velocity	Velocity driven during time interval after TOR	[km/h]
Quality of lateral vehicle control		
Standard deviation of lateral position	Standard deviation of lateral displacement from lane center	[m]
Criticality		
Maximum lateral deviation	Maximum deviation from lane center	[m]
Lane exceedances	Frequency of lane exceedances	[n]
Subjective rating of situation criticality	Rating of situation criticality (Neukum et al., 2008)	Rating [0…10]
Helpfulness of TOR		
Subjective rating of Helpfulness	Rating: How helpful was the TOR?	Rating [0…15]
Understanding of TOR	Question: Why was the TOR issued?	Explanation correct/incorrect

interval was also compared between the experimental groups.

The criticality of the take-over situations was measured by the maximum lateral deviation, recorded in the same time interval as the standard deviation of lateral position, and by the frequency of lane exceedances. Additionally, the drivers were asked to rate the criticality of the situations directly after they had completed them using the ‘Scale of criticality assessment of driving and traffic situations’ (see Fig. 6 left). This scale was originally developed in order to assess the controllability of erroneous interventions of driver assistance systems (e.g., ESP; Neukum and Krüger, 2003) and later extended to the assessment of the criticality of driving situations (Neukum et al., 2008). A clear advantage of the scale is the definition of a threshold value that defines critical situations from the driver’s perspective (rating as ‘dangerous’ or ‘not controllable’). In addition, the drivers were asked to rate the helpfulness of the TOR using a 15-point scale (see Fig. 6 right). In order to assess the participant’s understanding of the TORs, they were also asked to explain why, in their own words, the TOR was issued when they encountered the system limit for the first time. No information about the system limits were given to the drivers prior to the test drive. The answers were classified into correct and incorrect answers.

2.9. Inferential statistics

The dependent measures presented in Table 3 were subject to full-factorial mixed between-within 3 × 3 × 2-ANOVAs with the between-subjects factor ‘Automation level’ (‘Hands-on’ vs. ‘Hands-off’ vs. ‘Baseline’) and the within-subject factors ‘Situation’ (‘Temporary lines’ vs. ‘High curvature’ vs. ‘Lines end/no lines’) and ‘Secondary task’ (‘with’ vs. ‘without secondary task’). Every participant contributed six data points to the analysis, three per ‘Situation’ and two per ‘Secondary task’ condition.

Regarding the within-subject factors, multivariate statistics are reported. Main effects of the factor ‘Situation’ are not reported, as they would show the particular effect of the traffic scenario on all the investigated automation levels. As the focus of the paper is on the driver’s performance during the take-over situations when driving with partial automation, this would unnecessarily lengthen the results section. Partial η^2 is reported as a measure of effect size. If an interaction effect between the independent variables was found, additional ANOVAs were conducted separately for the respective factor levels (i.e., separate ANOVAs for each of the test situations). To avoid inflation of the alpha level of these ANOVAs, it was divided by the number of post-hoc tests according to the Bonferroni adjustment procedure.

3. Results

3.1. Hands-on detection

As a first step, it is analyzed whether drivers make use of the possibility to take their hands off the steering wheel. Fig. 7 depicts the percentage of drivers that have at least one hand on the steering wheel as a function of time until the control is given back to the driver in the three driving situations. One important finding from this analysis is that drivers tend to keep contact with the steering wheel, even if they have the opportunity to take their hands off the steering wheel for longer time periods (i.e., in the Hands-off condition). After the TOR is presented, the remaining drivers quickly place their hands back on the steering wheel. After approximately one second, all drivers have their

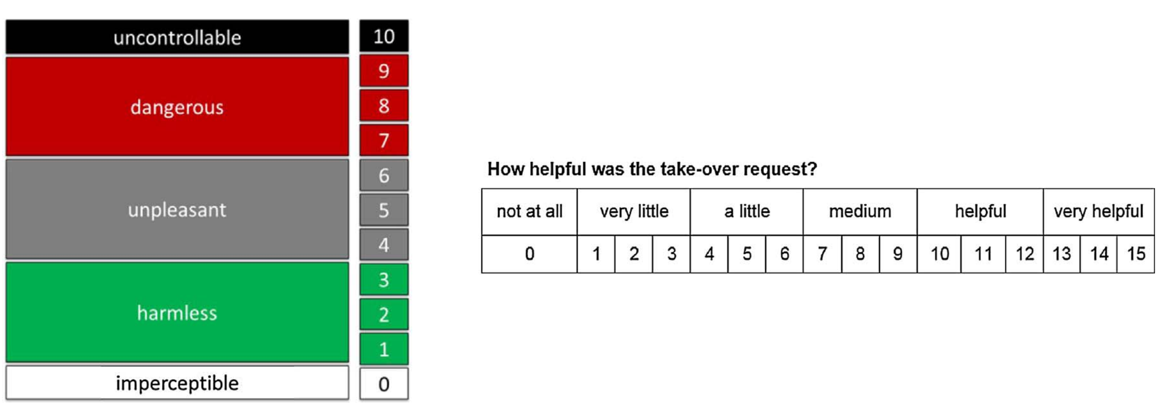


Fig. 6. Scale for criticality assessment of driving and traffic scenarios (left) and rating scale for helpfulness assessment (right).

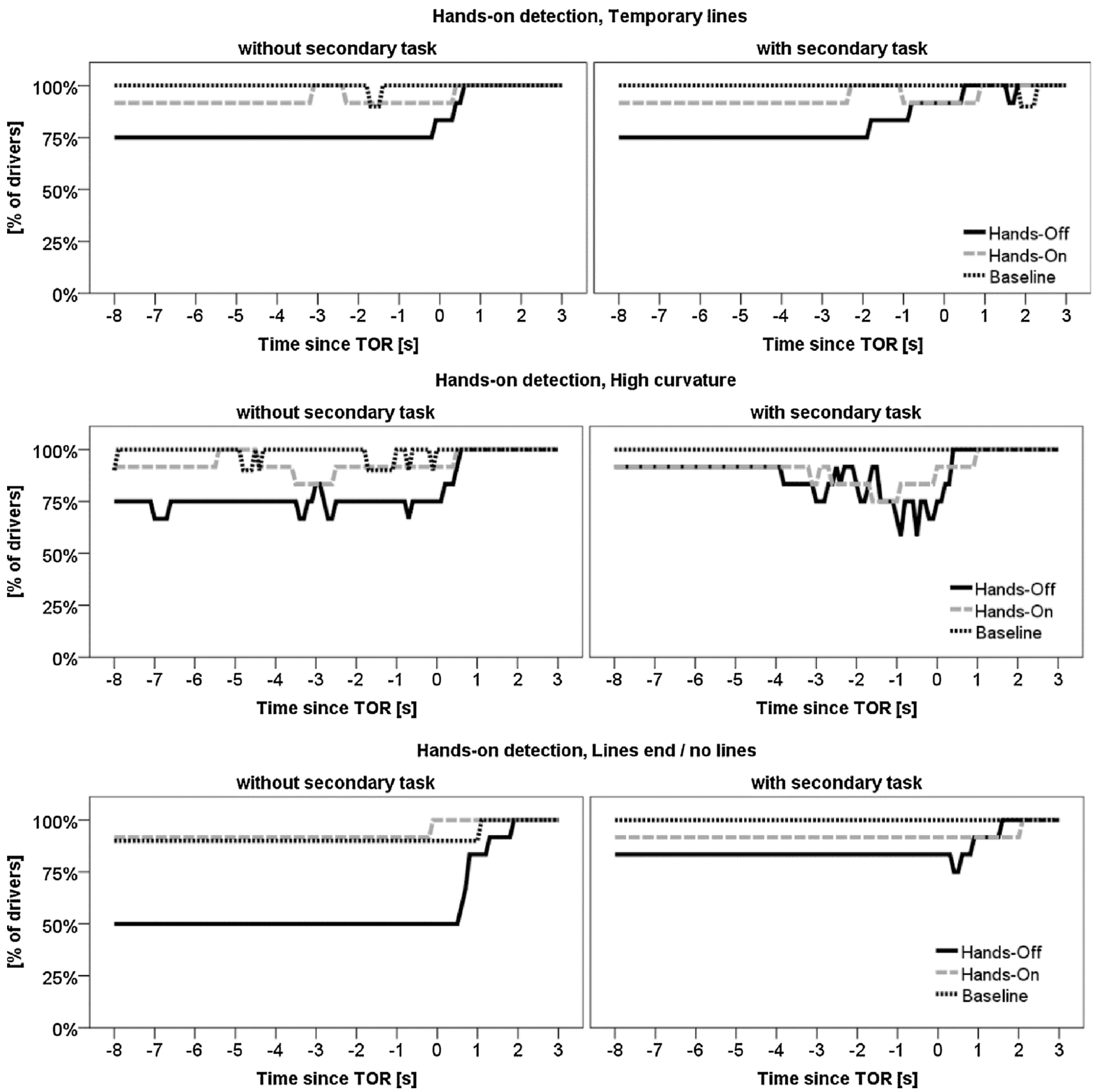


Fig. 7. Hands-on detection: The figures depict the percentage of drivers having contact to the steering wheel as recognized by sensors in the steering wheel with a sampling rate of 10 Hz.

hands back on the steering wheel.

When looking at the manual reference drives (Baseline) in which all drivers had to have their hands on the steering wheel, it can also be seen from the figure that the hands-on detection by the pressure sensor was not perfectly reliable. It may thus be that the results based on these values could slightly underestimate how quickly drivers took back their hands on the steering wheel, as only gently touching it might not have been detected.

3.2. Deactivation of take-over mode and velocity distribution

As described in Section 2.1, the host vehicle decelerated slightly until the take-over mode was deactivated by pressing the gas or brake pedal, or by pressing the button which was previously used for activation. As can be seen in Table 4, the drivers deactivate the take-over mode most often by using the gas pedal (53% of the cases) or by pressing the brake pedal (41% of the cases). The button on the steering wheel is only rarely used (6% of the cases). χ^2-tests show that the frequency of reactions does not vary between 'Automation levels' ($\chi^2 = 0.27$, $df = 2$, $p = 0.874$), but between 'Secondary task' conditions ($\chi^2 = 5.92$, $df = 2$, $p = 0.052$). When the secondary task is available to the drivers, they deactivate the take-over mode less often

Table 4
Deactivation of take-over mode.

Situation	Distraction	Automation level	Type of reaction			
			N	Button press	Gas pedal	Brake pedal
Temporary lines	without secondary task	Hands-Off	12	1	8	3
		Hands-On	12	1	7	4
	with secondary task	Hands-Off	12	0	5	7
		Hands-On	12	0	5	7
High curvature	without secondary task	Hands-Off	12	1	7	4
		Hands-On	12	2	7	3
	with secondary task	Hands-Off	12	1	5	6
		Hands-On	12	0	7	5
Lines end / no lines	without secondary task	Hands-Off	12	0	6	6
		Hands-On	12	1	8	3
	with secondary task	Hands-Off	12	1	6	5
		Hands-On	12	0	6	6

Table 5
ANOVA results, Time-to-deactivate take-over mode. Full-factorial tests with the within-subject factors 'Situation' and 'Secondary task' as well as the between-subjects factor 'Automation level' were conducted.

Effect	Time-to-deactivate				
	F	df_1	df_2	p	η^2
Situation	1.05	2	21	0.366	0.09
Situation * Automation level	0.72	2	21	0.500	0.06
Secondary task	1.93	1	22	0.179	0.08
Secondary task * Automation level	0.01	1	22	0.939	0.00
Situation * Secondary task	0.47	2	21	0.632	0.04
Situation*Secondary task*Automation level	0.95	2	21	0.401	0.08
Automation level	0.43	1	22	0.518	0.02

by using the gas pedal (without secondary task: 59% of cases, with secondary task: 47% of cases) and more often by pressing the brake pedal (without secondary task: 40% of cases, with secondary task: 50% of cases).

On average, it takes approximately four seconds for the drivers to deactivate the take-over mode (M = 3.82, SE = 0.45). There is no effect of 'Automation level', 'Secondary task' and driving 'Situation' on the time-to-deactivate the take-over mode (see Table 5).

Fig. 8 shows the time-series of the drivers' velocity in the interval of 10 s after the TOR which is analyzed in this study. It becomes evident from the figure that the participants drive with a lower velocity after control has been transferred back to them compared with the manual reference condition. On a descriptive level, it appears that this is even more the case in the condition with the longer hands-off interval.

The lower velocity can be explained by the slight deceleration of the host vehicle during the take-over mode as well as the fact that the frequency of usage of the accelerator pedal stays below that of the manual reference condition during the following interval of 10 s after the TOR (see Fig. 9). Taken together these data can be interpreted in a way that, in terms of velocity, a more cautious driving style is observed right after the control transitions from partially automated to manual driving.

3.3. Lateral control

Next, the time-series of the drivers' lateral deviation from the lane center are analyzed on a descriptive level. It becomes apparent from Fig. 10 that participants in the manual driving condition choose to drive with a greater lateral deviation from the road center at the onset of the

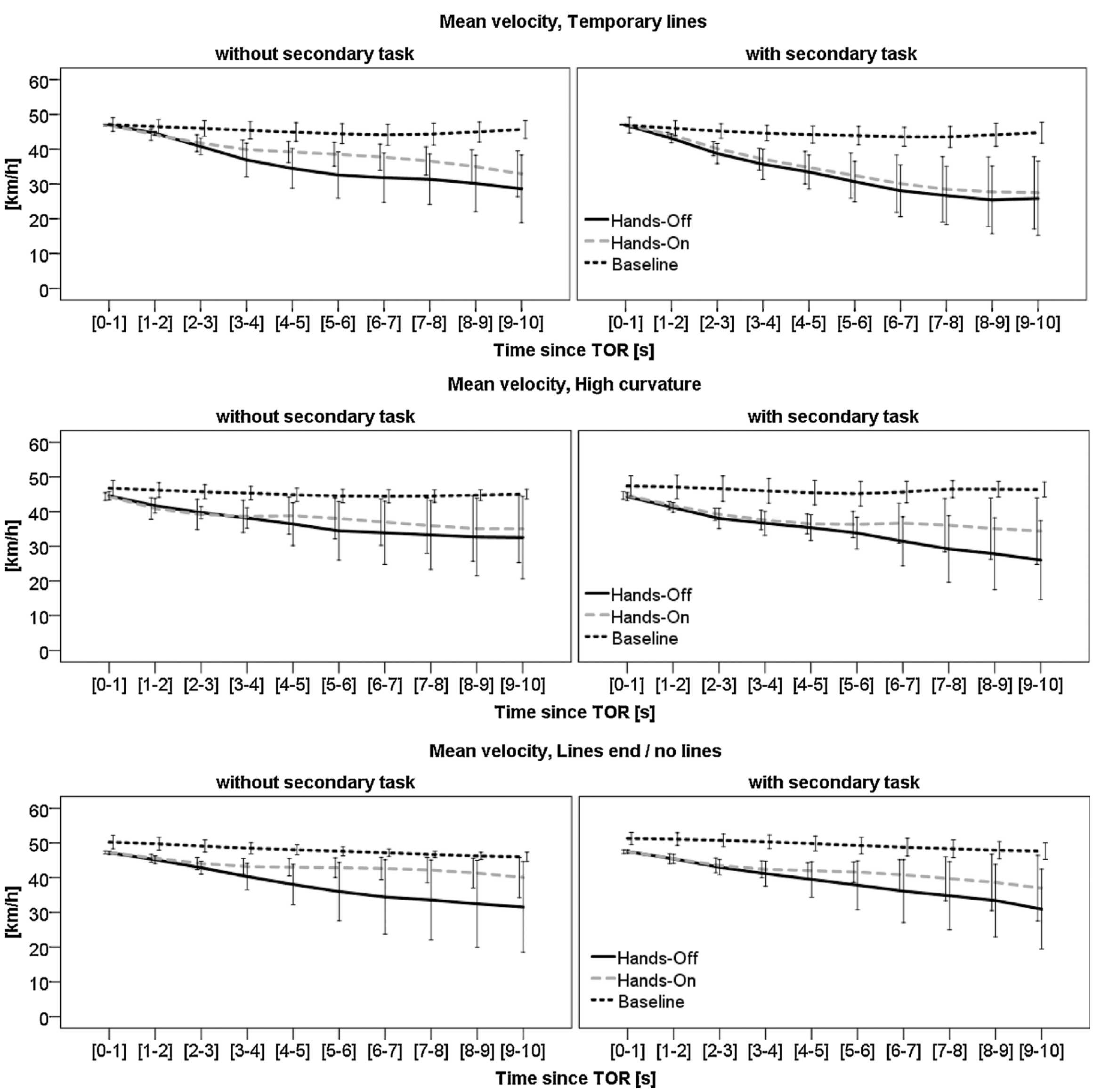


Fig. 8. Mean velocity, means and 95%-confidence limits for moving time windows of one second are depicted.

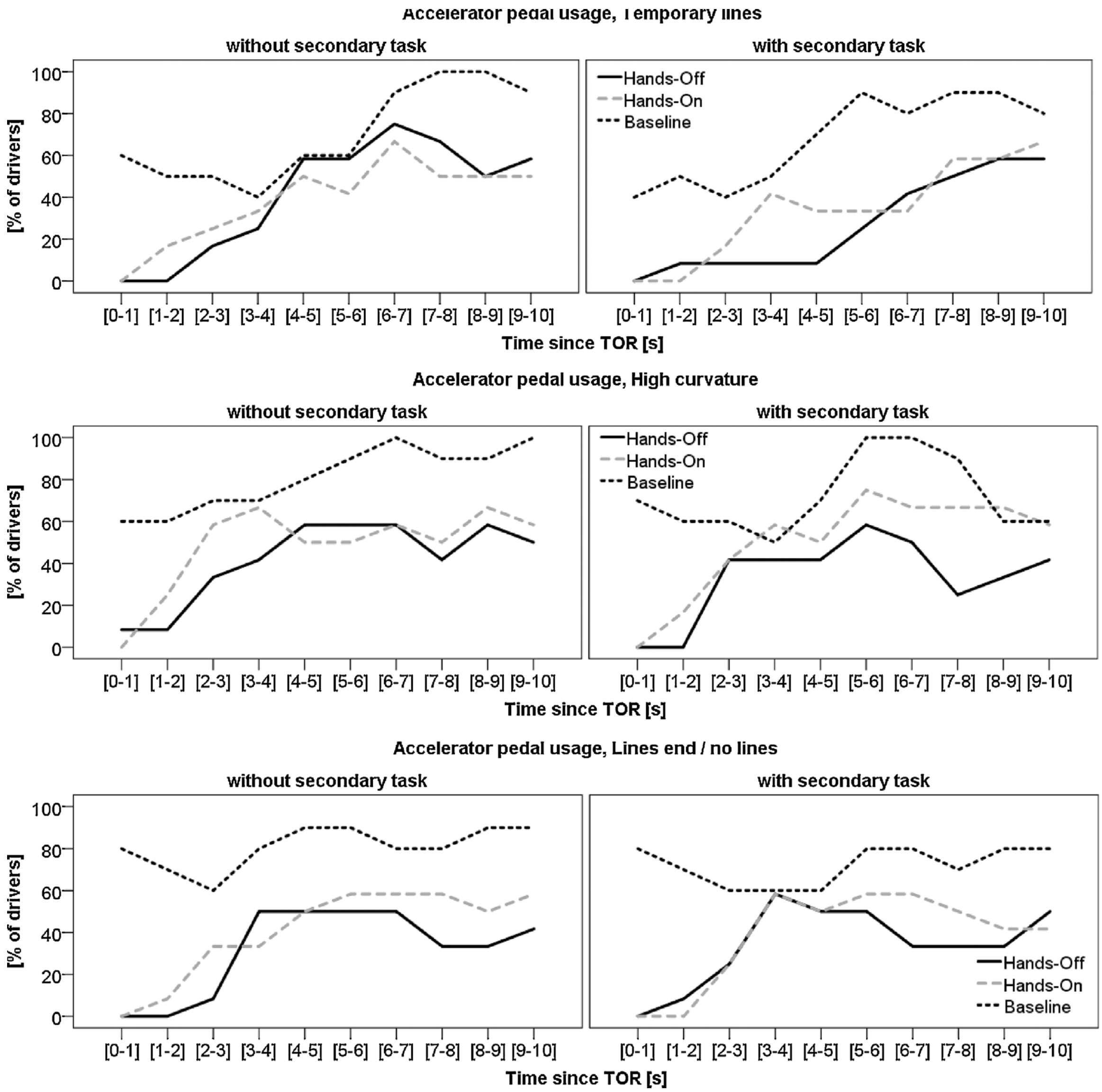


Fig. 9. Accelerator pedal usage, the percentage of drivers having pressed the gas pedal for more than 10% during moving time windows of one second are depicted.

events (i.e., when the TOR is presented in the partially automated conditions) than those in the partial automation conditions because of the simulated automated vehicle's lane centering. After the vehicle control has been handed over to the driver, the difference to the manual driving condition gradually decreases and the time series appear to converge. As apparent from Fig. 11, this process of re-engaging in the driving task seems to go along with an increase in the standard deviation of lateral position in the first seconds after the TOR.

Fig. 12, left panel, shows the standard deviation of lateral position during the time interval of 10 s beginning from the TOR. The degree of automation influences the stability of lane keeping when the drivers are forced to continue driving manually (main effect 'Automation level', see Table 6). However, this effect is depending on the type of situation (interaction effect 'Situation' * 'Automation level'). Separate ANOVAs per driving situation show that an increased variability of the lateral vehicle position is only found in the situation with 'High curvature' (main effect 'Automation level'; 'High curvature': $F(2,31) = 5.11$, $p = 0.012$, $\eta^2 = 0.25$; 'Temporary lines': $F(2,31) = 1.28$, $p = 0.293$, $\eta^2 = 0.08$; 'Lines end/no lines': $F(2,31) = 0.19$, $p = 0.830$, $\eta^2 = 0.01$; adjusted alpha level: $\alpha = 0.017$). Planned comparisons to the manual driving condition show that the variability of the lane position increases in the 'High curvature' situation both with longer ($p = 0.011$) and shorter hands-off interval ($p = 0.007$). There is no difference in the standard deviation of lateral position between the experimental conditions with and without secondary task (effect 'Secondary task').

The right panel of Fig. 12 depicts the average maximum deviation from the lane center collapsed across all situations. As evident from the figure, the maximum lateral deviation in both automated drives (Hands-off: $p = 0.040$; Hands-on: $p = 0.035$) is actually lower compared to manual driving (effect 'Automation level', see Table 6), which might be explained by the fact that the vehicle is centered to the middle of the lane when the TOR is issued and the lane centering is discontinued (see Fig. 10). Furthermore, none of the drivers exceeds the lane when regaining control from the automation.

3.4. Subjective data

Due to a technical logging failure, subjective data of one driver are missing. The drivers' criticality ratings are shown in Figs. 13 and 14. As evident from the figures, the ratings are distributed on a low level of the rating scale. On average, the situations are rated to be 'harmless' in all automation levels (Baseline: $M = 1.27$, $SE = 0.38$; Hands-on: $M = 2.44$, $SE = 0.34$; Hands-off: $M = 2.61$, $SE = 0.36$). None of the drivers rates the situation to be 'dangerous' or even 'non-controllable'.

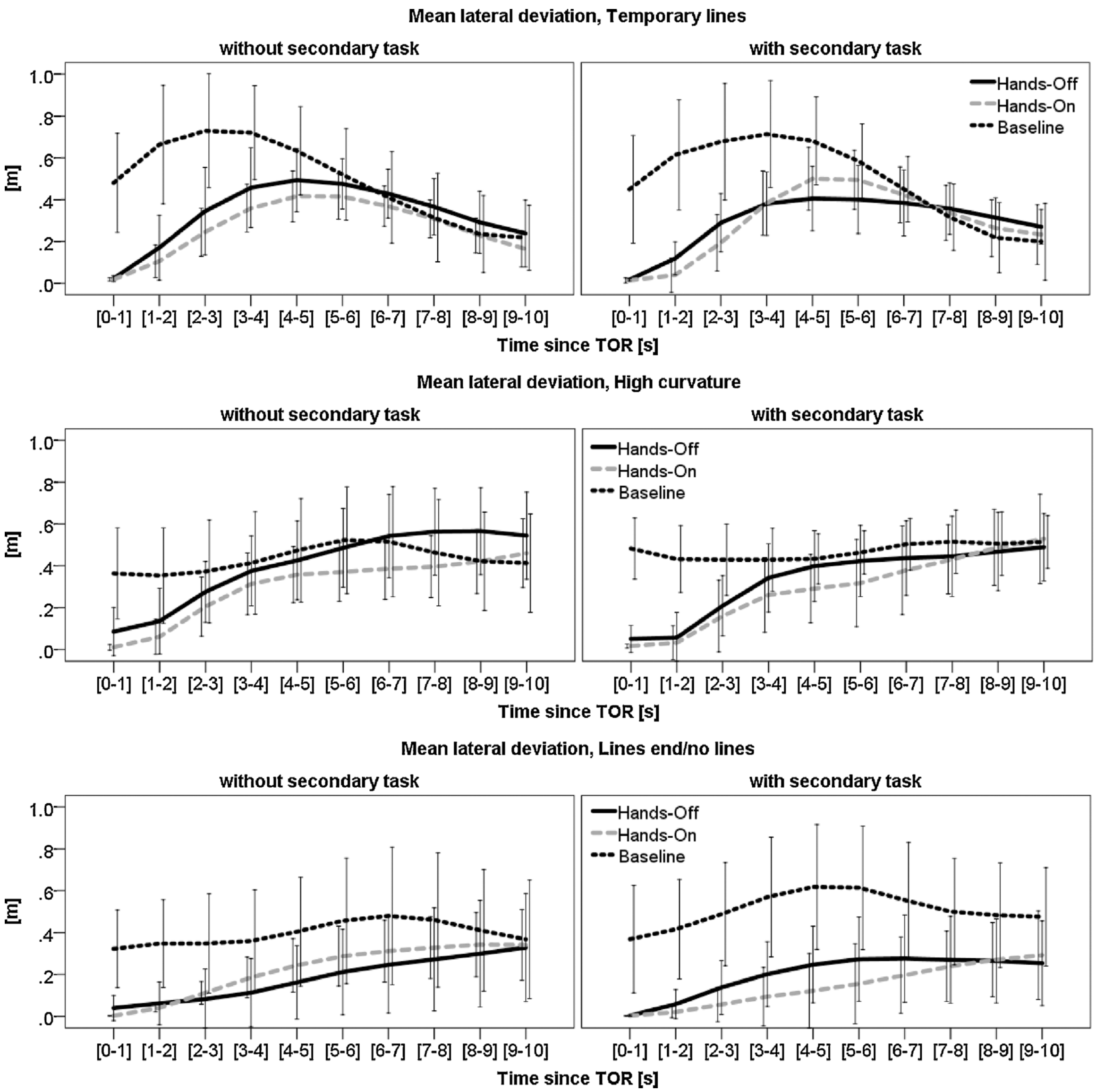


Fig. 10. Mean deviation from lane center, means and 95%-confidence intervals for moving time windows of one second are depicted. Positive values represent deviations to the right side of the lane. Note that positive and negative values were not transferred to absolute values.

Both driving 'Situation' and 'Automation level' influence these ratings, as both main effects and the interaction between 'Automation level' and 'Situation' are statistically significant (see Table 7). Separated ANOVAs within the three driving situations show that the criticality ratings differ between automation levels only in the 'High curvature' situation (main effect of 'Automation level', 'High curvature': $F(2,30) = 7.88$, $p = 0.002$, $\eta^2 = 0.34$; 'Temporary lines': $F(2,30) = 1.07$, $p = 0.355$, $\eta^2 = 0.07$; 'Lines end/no lines': $F(2,30) = 2.13$, $p = 0.137$, $\eta^2 = 0.12$; adjusted alpha level: $\alpha = 0.017$). Here, planned comparisons reveal that the drivers rate the situations to be more critical both in the hands-off ($p = 0.001$) and hands-on condition ($p = 0.005$). However, on an absolute level, they still rate the situation with 'High curvature' to be 'harmless' (Hands-off: $M = 2.96$, $SE = 0.41$; Hands-on: $M = 2.46$, $SE = 0.39$).

As can be seen in Fig. 14, the drivers' criticality ratings are also depending on the 'Secondary task' condition in one of the investigated situations (interaction effect 'Situation' * 'Secondary task', see Table 7). Drivers rate the situation to be more critical (with secondary task: $M = 2.89$, $SE = 0.28$; without: $M = 1.98$, $SE = 0.27$) when asked to engage with the secondary task only in the situation with 'Temporary lines' (main effect of 'Secondary task', 'Temporary lines': $F(1,30) = 9.36$, $p = 0.005$, $\eta^2 = 0.24$; 'High curvature': $F(1,30) = 0.00$, $p = 0.958$, $\eta^2 = 0.00$; 'Lines end/no lines': $F(1,30) = 0.19$, $p = 0.665$, $\eta^2 = 0.01$; adjusted alpha level: $\alpha = 0.017$). This applies to manual driving as well as the conditions with partial automation.

The drivers' helpfulness ratings regarding the TOR are shown in Fig. 15. The average ratings fall within the medium range of the rating scale ($M = 7.09$, $SE = 0.76$). The ratings do not differ between the hands-off and the hands-on condition. The 'Secondary task' condition only influences the ratings when the driving situation is also considered (interaction effect 'Situation' * 'Secondary task'). Separate ANOVAs per situation reveal that the TOR is rated to be more useful when drivers are asked to engage in the secondary task (without secondary task: $M = 6.44$, $SE = 0.86$; with: $M = 8.64$, $SE = 0.86$) only in the situation with 'Temporary lines' (main effect of 'Secondary task', 'Temporary lines': $F(1,21) = 7.10$, $p = 0.014$, $\eta^2 = 0.25$; 'High curvature': $F(1,21) = 0.21$, $p = 0.648$, $\eta^2 = 0.01$; 'Lines end/no lines': $F(1,21) = 0.84$, $p = 0.370$, $\eta^2 = 0.04$; adjusted alpha level: $\alpha = 0.017$).

Fig. 16 shows the drivers' explanations on why a TOR has been issued. These qualitative statements have been collected after each test situation and were categorized into 'correct' and 'incorrect' answers. As can be seen from the distribution of the answers, there is a considerable

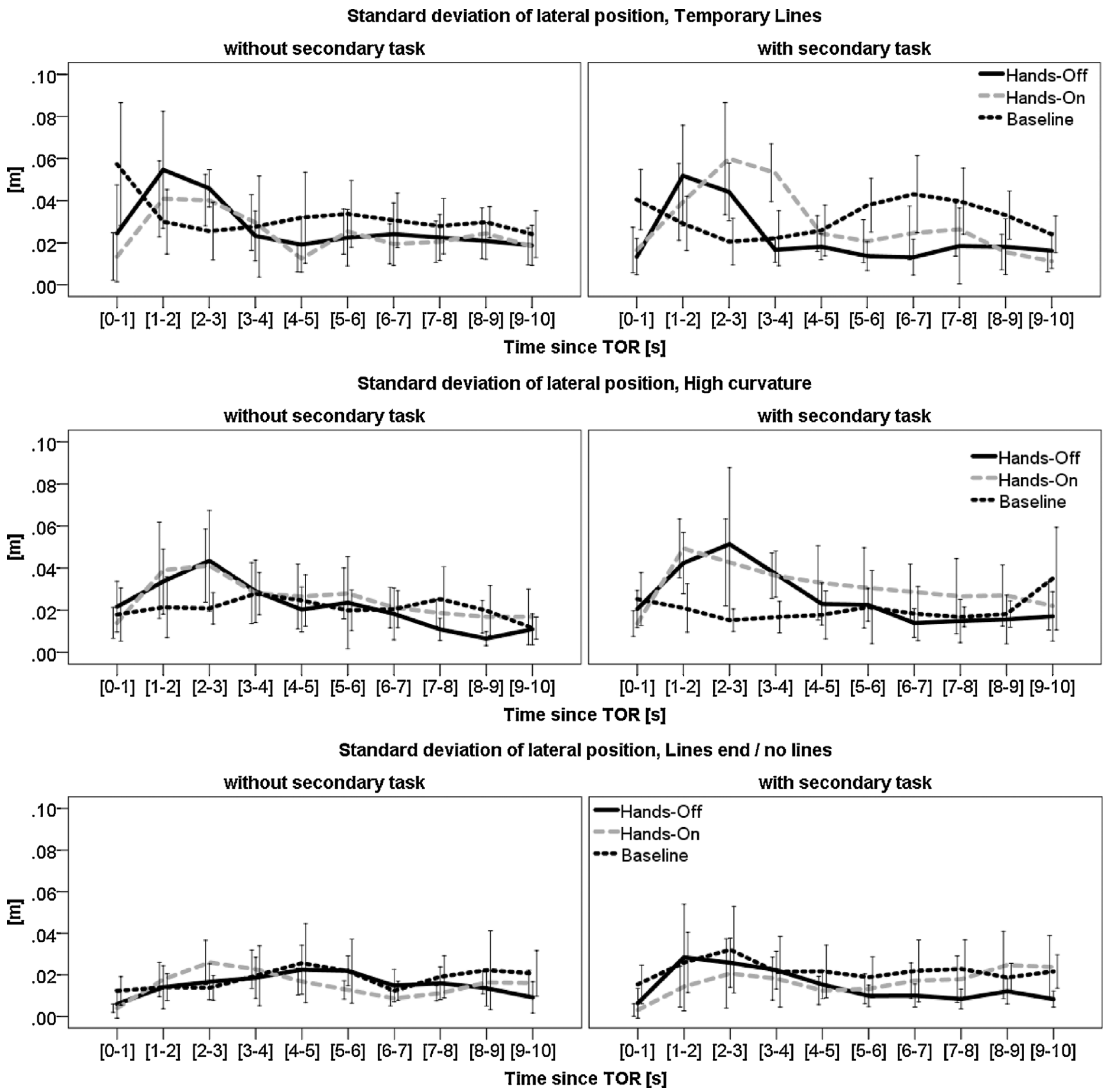


Fig. 11. Mean standard deviation of lateral position, means and 95%-confidence limits for moving time windows of one second are depicted.

number of drivers that do not state the correct reason for the TOR during these situations. χ^2-tests show that the frequency of correct answers varies between the driving situations ($\chi^2 = 8.44$, $df = 2$, $p = 0.015$), but not between the automation levels ($\chi^2 = 0.00$, $df = 1$, $p = 1.000$). As can be seen from Fig. 16, a considerable part of the participants are not able to state the correct reason for the TOR in the situations 'Lines end/no lines' and 'High curvature', whereas most drivers correctly stated that the TOR was issued because of the 'Temporary lines'.

4. Summary and discussion

This study investigated driver performance at transitions from partially automated driving to manual driving because the partial automation could no longer maintain the lateral vehicle control. Drivers were warned about the loss of lateral control by a visual-auditory takeover request either with or without a secondary task being available. Driving performance was evaluated in three distinct driving situations ('Temporary lines': temporary lines because of a work zone; 'Lines end/ no lines': missing lane markings; 'High curvature': road curvature

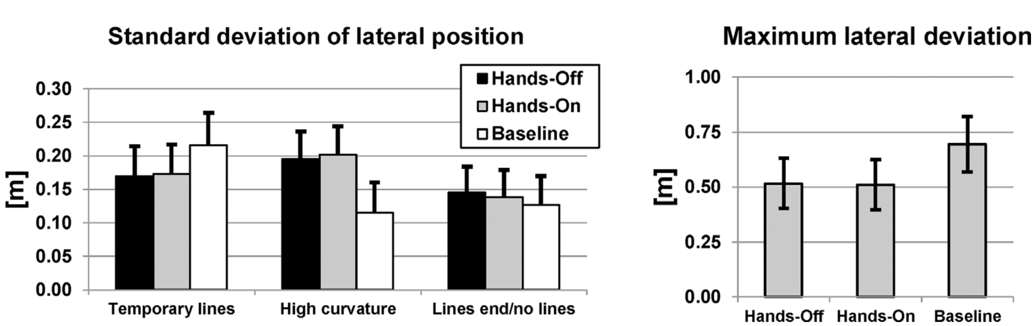


Fig. 12. Standard deviation of lateral position (left) and maximum deviation from lane center (right). Mean and 95% confidence interval are depicted. The maximum deviation from the lane center represents the maximum absolute deviation during the analyzed 10 s-time interval after the TOR.

Table 6
ANOVA results, standard deviation of lateral position and maximum lateral deviation. Full-factorial tests with the within-subject factors 'Situation' and 'Secondary task' as well as the between-subjects factor 'Automation level' were conducted.

Effect	Standard deviation of lateral position					Maximum lateral deviation				
	F	df_1	df_2	p	η^2	F	df_1	df_2	p	η^2
Situation	9.81	2	30	0.001	0.40	3.80	2	30	0.034	0.20
Situation * Automation level	3.06	4	62	0.023	0.17	1.83	4	62	0.134	0.11
Secondary task	0.18	1	31	0.679	0.01	0.09	1	31	0.761	0.00
Secondary task * Automation level	1.73	2	31	0.194	0.10	1.01	2	31	0.376	0.06
Situation * Secondary task	0.15	2	30	0.860	0.01	0.25	2	30	0.781	0.02
Situation*Secondary task*Automation level	0.66	4	62	0.621	0.04	0.55	4	62	0.697	0.04
Automation level	0.39	2	31	0.683	0.02	3.06	2	31	0.061	0.17

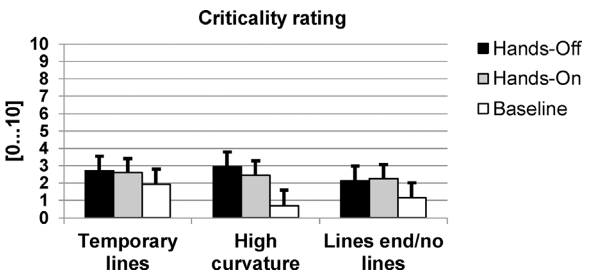


Fig. 13. Criticality rating separated by 'Automation level' and 'Situation'. Mean and 95% confidence interval are depicted. Item: 'How critical was the situation?'.

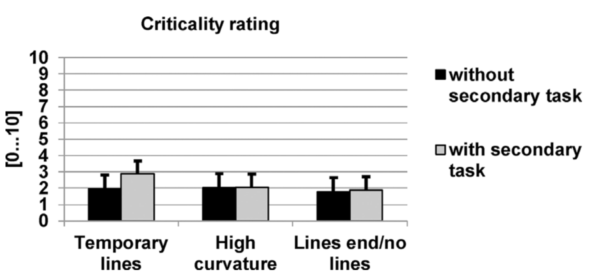


Fig. 14. Criticality rating separated by 'Automation level' and 'Secondary task' condition. Mean and 95% confidence interval are depicted. Item: 'How critical was the situation?'.

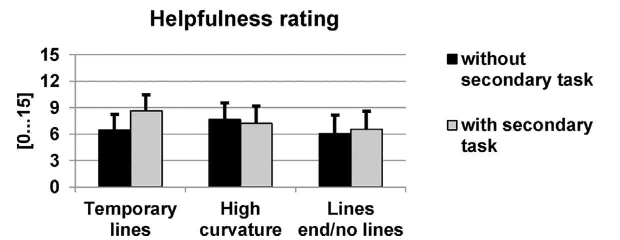


Fig. 15. Helpfulness rating of the TOR. Mean and 95% confidence interval are depicted. Item: 'How helpful was the take-over request?'.

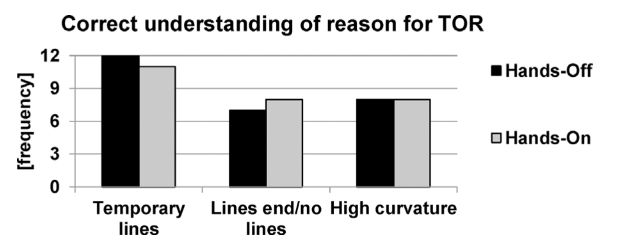


Fig. 16. System understanding. Frequency of correct answers is shown. Question: 'Why was the take-over request issued?'.

exceeds steering capabilities of partial automation) and with three levels of automation ('Hands-off': hands-free driving possible for 120 s; 'Hands-on': hands-free driving possible for 10 s; 'Baseline': manual reference drive). The main result of the assessment is that all participants managed to control the situations safely, regardless of the automation level. All participants kept the vehicle in the lane, even when they were able to take their hands off the steering wheel for extended time periods. Accordingly, the situations were mostly rated as 'harmless'. Under the conditions of this study, no negative influence of the secondary task availability on the collected measures of driving performance was observed.

At this point it should be clearly emphasized that the study focused on system limits in which an imminent TOR is issued to the drivers (e.g., because temporary lane markings are detected that possibly impair the automated vehicle's capability to reliably guide the vehicle). This focus inherently limits the generalizability of the results to system failures that are *not communicated* to the driver so that she/he needs to override the partial automation without being previously warned about the situation. It can be expected that handling such situations is much more difficult, especially when drivers are distracted. The results of this study are thus not transferable to system failures that are not announced by TORs. Another limiting factor is the use of the secondary task that consisted of a rather easily interruptible visual-manual task installed at a fixed position inside the vehicle. It has to be expected that more complex tasks that, for example, draw more heavily on the driver's cognitive or visual resources would impair the driver's ability to

Table 7
ANOVA results, criticality rating and helpfulness rating. Full-factorial tests with the within-subject factors 'Situation' and 'Secondary task' as well as the between-subjects factor 'Automation level' were conducted.

Effect	Criticality rating					Helpfulness rating				
	F	df_1	df_2	p	η^2	F	df_1	df_2	p	η^2
Situation	4.78	2	29	0.016	0.25	2.25	2	20	0.131	0.18
Situation * Automation level	2.67	4	60	0.041	0.15	0.58	2	20	0.569	0.06
Secondary task	2.20	1	30	0.148	0.07	1.75	1	21	0.200	0.08
Secondary task * Automation level	0.51	2	30	0.605	0.03	0.78	1	21	0.386	0.04
Situation * Secondary task	4.33	2	29	0.023	0.23	4.73	2	20	0.021	0.32
Situation*Secondary task*Automation level	1.88	4	60	0.126	0.11	1.65	2	20	0.217	0.14
Automation level	3.93	2	30	0.031	0.21	1.52	1	21	0.231	0.07

safely handle transitions from partially automated to manual driving more than the task used in this study (Marberger et al., 2017; Naujoks et al., 2017). With this in mind, significantly more research has to be conducted before definitive conclusions about driver performance and safety of lateral guidance boundaries of partially automated driving can be drawn.

Previous findings on the controllability of system limits of automated driving are extended by the study in several ways. Some studies have investigated driving performance at system limits of partially automated driving before, however, these studies (Damböck et al., 2013; Larsson et al., 2014; Strand et al., 2014; Young and Stanton, 2007) have so far mainly focused on longitudinal control boundaries of the automation (e.g., failure to brake sufficiently or failures to detect surrounding traffic). These kinds of failures have also been investigated by a broad body of literature that dealt with these system limits in the context of assisted driving with ACC (e.g., Neukum et al., 2008; Park et al., 2006; Piccinini et al., 2015; Rajaonah et al., 2006). This study extends previous findings to system limits that are specific to partial automation in the sense that the continuous lateral control provided by the system is suddenly interrupted. In the context of highly automated driving, in which the driver is usually given an advance warning about the upcoming system limit (e.g., Kerschbaum et al., 2014; Larsson et al., 2015; Melcher et al., 2015; Walch et al., 2015), these kind of situations have been extensively studied, but not particularly within the context of partially automated driving. Our findings support the view that drivers can manage lateral guidance boundaries during partially automated driving, even if they are provided with the possibility of extended periods of hands-free driving, given that the system limit is communicated via a take-over request. In contrast to the above-cited studies, drivers were only provided with the take-over request when the system limit was already reached (e.g., when they had already entered the work zone with temporary lines). Performing the described visual-manual secondary task during driving did not alter driver performance in these situations. These results are in line with findings of Wulf et al. (2013) who did not find an increase in reaction times to and criticality of a non-recognized failure of lateral control during partially automated driving as a result of performing a visual-manual menu task. The results may also lessen concerns expressed by potential end-users in a recently published survey (König and Neumayr, 2017) that using automated driving features will lead to safety consequences caused by technical error, provided that drivers are supported in managing these situations by suitable TORs.

Another important finding of this study is that some participants did not report the correct reason for the TORs in the situations ‘High curvature’ and ‘Lines end/No lines’, although they all managed the situation safely. They also rated the helpfulness of the TOR on an intermediate level. In a previous study, the helpfulness of the same take-over concept was rated higher in a situation in which a standing vehicle was detected late by the partial automation, so that the drivers had to bring the vehicle to a stop manually (Naujoks et al., 2015b). This result points out that the helpfulness of TORs could be enhanced by providing drivers with additional information on why the TOR has been issued to them. For example, research on C2X-based warnings (i.e., warnings based on communication of data between vehicles or infrastructure) has demonstrated that the perceived helpfulness of warnings can be increased if specific information about the type of hazard the driver is warned about is provided (e.g., Naujoks, 2015; Naujoks and Neukum, 2014; Zarife, 2014). On the other hand, given that the driver needs to react within a short timeframe to these TORs during partially automated driving, lengthening the time it takes the drivers to interpret and react to the TORs by displaying overly complex information also has to be avoided. The integration of this information into the take-over concept thus has to be carefully considered and merit further research.

The lack of differences between the automation levels may be due to several specifics of the test protocol. First, drivers were instructed that they are still responsible for driving safety. This is in accordance with the automation level under investigation, which affords drivers to continuously stay in the control loop while using the automation. Second, the automation was not designed to allow completely hands-free driving, as it was necessary to regularly touch the steering wheel even in the ‘Hands-off’ condition to avoid a discontinuation of the automated drive. Third, take-over situations were rather frequent events and drivers could not drive for longer time periods without needing to resume manual driving. These factors may have jointly produced the behavioral pattern observed in the experiment with regards to drivers’ usage of the partial automation. In the distracted driving condition, a secondary task was used that did not require taking the hands off the steering wheel because it was installed on a fixed position inside the vehicle. The specific task chosen in the study was selected because a prior field study had shown an increase in secondary task engagement with this specific secondary task when driving with partial automation (Naujoks et al., 2016b). However, it should be emphasized that it may well be possible that other types of secondary tasks, which would possibly afford taking the hands off the steering wheel for longer time periods or which would produce a higher cognitive workload, may well go along with greater impairments of the driver’s ability to take over manual control when partial automation fails. Indeed, several surveys suggest that drivers would possibly have the desire to engage in more complex tasks than the one investigated in this study. In a web-based survey on activities that drivers would like to do during automated driving, Pfleging et al. (2016) found that the most often mentioned activity were talking with passengers, watching out of the window, texting, eating/drinking and surfing the internet. Schoettle and Sivak (2014) also reported that drivers would like to spend their time during an automated ride on tasks like reading, texting/talking to friends, watching movies and working.

Another limitation of the study is the use of a driving simulator. As the test situation was expected to possibly result in critical situations, or even collisions, using a driving simulator can be seen as a necessary tool to conduct this kind of research. However, the generalizability of the results may be limited as the participants experience no real danger in this research environment. Just recently, a number of studies were conducted, comparing driver behavior in real traffic compared to driving behavior in the same simulator used in this study. Neukum et al. (2014) compared brake reaction times and criticality of unexpected brake interventions from the perspective of the following traffic both in everyday traffic with instrumented vehicles and when using the driving simulator at hand. The authors report a good match between the test environments. However, the driving simulator consistently resulted in longer brake reaction times with a mean difference of approximately 300 ms and, consequently, to more severe situations. Purucker et al. (2014) as well as Rüger et al. (2014) showed that subjective criticality ratings obtained in the driving simulator were comparable to those obtained on a test track when drivers were asked to rate different following distances during car-following and different lateral distances. Based on these studies, it may be concluded that, considering that safety of the participants can be ensured, the use of the driving simulator can be viewed as justified.

5. Conclusions

The study investigated driving performance at specific system limits of partially automated driving in lateral guidance scenarios. The following conclusions can be drawn from this study:

- The drivers managed to regain manual control of the vehicle safely, regardless of whether they could take their hands off the steering wheel only for a short (i.e., 10 s) or an extended time period (i.e., 120 s) and regardless of whether or not they were asked to engage in a secondary task while driving. The drivers were asked only to engage in the secondary task when they felt that the traffic situation was safe enough to do so.

- Take-over requests because of lateral guidance boundaries should provide the driver with information of why the lateral vehicle guidance was discontinued, as a considerable part of the sample was not able to correctly explain why the TORs were issued. Although it appears that this is not necessary from a safety perspective under the assessed conditions, it could enhance the subjective helpfulness of TORs. Consequently, future studies should investigate further how such information can be integrated into a comprehensive take-over concept.

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Appendix A

Secondary task description

Fig. A1 depicts the secondary task menu. The first screen indicated the type of information that had to be retrieved in order to complete the task. Interactions with the secondary task consisted of the following procedure: Within each task, participants were asked to either look up the minimum temperature, the maximum temperature, the rain probability or the wind velocity at different times of the day (in the morning, at noon, in the evening or at night) on different days (today, tomorrow, in two days or in three days). For example, the first screen would indicate a question such as: "*what is the rain probability in the evening in two days?*". After touching the screen, participants were required to select the day (second screen in Fig. A1), the time of the day (third screen in Fig. A1) and the type of weather information (fourth screen in Fig. A1). Subsequently, the next task was displayed on the screen, e.g., "*what is the minimal temperature in the morning in three days?*". The tasks were continuously presented while driving, however, performing the task was optional (i.e., drivers were asked to work on the task only when they felt that the driving situation would be safe enough to do so). The task order was generated randomly. There was no limit to the maximum number of tasks that could be processed.

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