Accident Analysis and Prevention 108 (2017) 147–162

Contents lists available at ScienceDirect

Accident Analysis and Prevention

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

Driving performance at lateral system limits during partially automated driving

Frederik Naujoks[a,*], Christian Purucker[a], Katharina Wiedemann[a], Alexandra Neukum[a], Stefan Wolter[b], Reid Steiger[c]

[a] Würzburg Institute for Traffic Sciences (WIVW), Robert-Bosch-Straße 4, 97209 Veitshöchheim, Germany
[b] Ford Werke GmbH Research & Innovation Center Aachen, Süsterfeldstraße 200, 52072 Aachen, Germany
[c] Ford Werke GmbH, Spessartstrasse Tor 54, 50725 Cologne, Germany

ARTICLE INFO

Keywords:
Automated driving
Partial automation
Controllability
Lateral scenarios

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

* Corresponding author.
E-mail addresses: naujoks@wivw.de (F. Naujoks), purucker@wivw.de (C. Purucker), wiedemann@wivw.de (K. Wiedemann), neukum@wivw.de (A. Neukum), swolter3@ford.com (S. Wolter), rsteige3@ford.com (R. Steiger).

http://dx.doi.org/10.1016/j.aap.2017.08.027
Received 13 September 2016; Received in revised form 24 August 2017; Accepted 26 August 2017
0001-4575/

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