Controllability of lateral drift failures while driving with SAE Level 2 Advanced Driver Assistance Systems

Norbert Schneider, Lenne Ahrens and Achim Pruksch*

Abstract: SAE Level 2 systems, which allow the driver to drive hands-off while monitoring visual attention, raise the question whether the driver is still able to fulfill his allocated responsibility (object and event detection and response). We developed a setup to evaluate the driver's ability to detect and respond to silent lateral system failures. The results indicate that an attentive driver can perceive and handle lateral system failures, but a cognitive misattribution of the systems capabilities might occur even for attentive drivers. This differentiation of causal factors allows developers to focus on adequate countermeasures to increase safety of SAE Level 2 systems.

Keywords: controllability, SAE Level 2, safety, SOTIF

1 Introduction

SAE Level 2 systems, which can continuously take over lateral and longitudinal control while the driver is still responsible for the dynamic driving task and the supervision of the function, are becoming more prevalent in series vehicles. This responsibility is summarized under the term "object and event detection and response" [1]. Various studies raise concerns about the ability of the driver to fulfill this responsibility and provide a fallback in case of system errors, especially when the system is used for an extended time [2] [3]. A potential cause could be a decrease in driver vigilance associated with the monotonous monitoring task (see [4]), but additional cognitive and behavioral aspects e.g., the development of automation complacency [5] and the potential for misuse in the form of non-driving related tasks (NDRT) should be considered as well. Currently, the UNECE R 79 allows only SAE Level 2 systems designed for hands-on use, which include hands-on monitoring [6]. However, system concepts in the U.S., China and Japan also include SAE Level 2 systems which allow the driver to take his hands off the steering wheel (e.g., Cadillac Super Cruise, Ford Blue Cruise, Nissan Pro Pilot). To ensure that the driver is still fulfilling his responsibility according to the SAE Level 2, a driver monitoring camera is used, which monitors the driver's visual attention. From a human factors perspective, this design decision brings these SAE Level 2 systems closer to a SAE Level 3 system, although the basic requirements towards the driver remain the same as for a SAE Level 2 hands-on system. However, only a few studies analyzed the driver's ability to perceive and compensate silent failures when driving with combined longitudinal and

*Cross-Domain Computing Solutions, Human Centered Advanced Delopment (XC/ENA1), Robert Bosch GmbH, Postfach 13 55, 74003 Heilbronn, Germany (norbert schneider4@de.bosch.com, lenne-ahrens@de.bosch.com, achim.pruksch@de.bosch.com)

lateral control (e.g., [7] [8] [9] [10]). Commonly accepted controllability thresholds for lateral failures have been derived almost exclusively from manual driving [11]. This raises the question, whether results can be transferred to systems with continuous lateral and longitudinal guidance where the driver only has a monitoring task. Most publicly available studies combining longitudinal and lateral control have been conducted with SAE Level 3 systems in mind. These SAE Level 3 systems are assumed to provide a notification to the driver in case of a system failure or hazardous situation. However, it is a common misconception that an SAE Level 3 system will provide a take-over notification in all cases [12]. Nonetheless, it is assumed to be unfeasible for SAE Level 3 systems to not provide a notification, especially if they allow the driver to attend to non-driving related activities. This might also transfer to SAE Level 2 systems which allow the driver to take his/her hands off the wheel (see [9]). The available literature offers only limited insights regarding the capabilities of drivers to handle silent system failures, which require action within a short time-frame, when driving hands-off. This limited focus of human factors research on take-over scenarios in the automotive domain and its drawbacks have also been addressed by [13]. Previous studies looking at the controllability of system failures while driving hands-on can only provide general boundaries for the driver's capability to handle system failures even when driving hands-off. However, the results cannot be directly transferred to hands-free driving because the haptic feedback loop, which allows for very fast reflex-like counter-reactions, is missing. Internal studies indicate that the established test method for controllability, which evaluates whether drivers can stay in a driving lane with limited width, that drivers are not able to control limited failure dynamics while driving hands-off. Further, explorative studies revealed that this could be a consequence of the experimental setup, which utilized traffic cones positioned at the lane boundaries to increase pressure for the driver to act. Therefore, we created a new experimental setup to analyze the drivers' ability to handle lateral system failures while driving with continuous longitudinal and lateral control. The experimental setup allows lane deviations and lane departures without resulting in an objective fail (in contrast to the traffic cone setup) and provides a clear and adaptable pressure to act for the driver. In addition, it can be used with naïve participants at higher vehicle speeds (up to 120 km/h) to provide a clear pass/fail criterion without compromising safety; a clear improvement compared to method proposed by [14].

One goal of this study was to assess the viability of the proposed experimental setup. The other goal was to evaluate whether attentive drivers, driving hands-off with combined longitudinal and lateral control by a SAE Level 2 system, can handle silent lateral failures with limited failure dynamics.

2 Methods

2.1 Setup

The study was conducted on the TRIWO test track in Pferdsfeld, Germany. A round course with a length of 5km was used for the tests, including a straight highway section with 3 driving lanes and an additional part with two driving lanes and variable speed limits (Figure 1).

To simulate a SAE Level 2 capable vehicle with hands-free driving abilities, we used

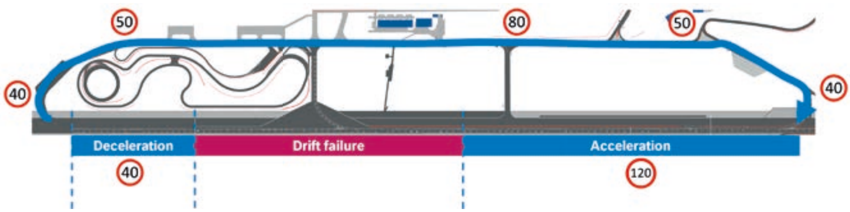


Figure 1: Round course for testing on the test track in Pferdsfeld.

a functional prototype vehicle from the Robert Bosch GmbH. Basis for this functional prototype was a VW Golf VII equipped with a DGPS system (iMAR iTraceRT-F402/7), programmable cluster display, capacitive steering wheel, driver monitoring camera, dual pedal controls for the safety driver, control switches for the experimenter and data recording equipment. A safety co-driver (passenger seat) and an experimenter (rear seat) accompanied the participant.

The prototype SAE Level 2 hands-free system included longitudinal and lateral guidance, intelligent speed adaption for curves and on/off-ramps to the highway section and automatic lane change capabilities. Longitudinal and lateral control could be activated simultaneously by pressing a button on the steering wheel. Before transitioning to hands-free driving, the driver had to drive hands-on for a limited time and was informed about the availability of the hands-free mode. To activate hands-free driving the driver had to take his hands off the steering wheel. The system could always be overruled or deactivated by turning the steering wheel (lateral guidance temporarily deactivated), applying the brake pedal, or press a button on the steering wheel (longitudinal and lateral control deactivated). All driving modes were displayed via a prototype human machine interface (HMI) in the programmable cluster display. The prototype HMI included a multi-stage warning concept (cf. [15]), which visually and acoustically warned the driver after 3 seconds eyes-off road (EOR) time (stage 1), followed by a visual-acoustic warning after additional 5 seconds, asking the driver to put his hands on the steering wheel (stage 2). Finally the driver is asked to take over manual control while the vehicle is decelerating, and visual and acoustic warnings are presented continuously (stage 3).

2.2 Test scenario

The test scenarios were set up on the highway section of the round course and consisted of 5 obstacles, positioned on left and right side of the driving lane (Figure 2). In both test scenarios a lateral drift with a defined maximum lateral velocity (0.2 m/s vs. 0.6 m/s) was triggered at pre-defined GPS positions after the experimenter enabled the failure activation via the safety control switch. The GPS position for the trigger was chosen based on the distance to the second obstacle on right side, the lateral drift velocity, the targeted overlap with the obstacle (25%) and the test speed of 120 km/h. This resulted in two different GPS trigger positions, depending on the maximum lateral drift velocity (TTC = 2.8 seconds for a drift velocity of 0.6 m/s and TTC = 5.8 seconds for 0.2 m/s). The lateral drift was initiated without any further notifications to the driver or changes in the HMI. In addition, the build-up of the lateral drift did not occur abruptly but was build-up gradually to avoid noticeable lateral jerks of the vehicle. In both scenarios a crash with the objects would occur if the driver did not react e.g., by steering back into the driving lane.

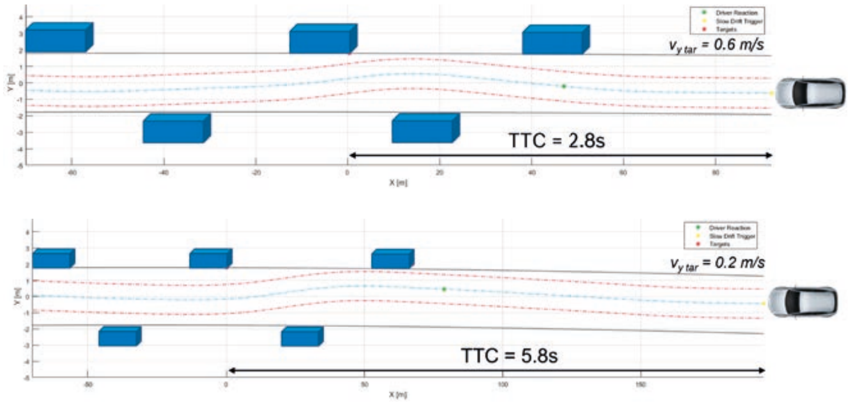


Figure 2: Schematical illustration of the test scenario setup. The trigger point was adapted based on lateral drift velocity which resulted in different TTCs.

2.3 Procedure

To conceal the true purpose of the study, participants were told that the test focused on user acceptance of a novel automation system, which allowed them to drive partially automated while taking their hands off the steering wheel under special conditions. Before the testing each participant received written information about the system's capabilities and potential system boundaries. This included the explicit information about the necessity for the driver to take over control of the vehicle e.g., if the system departed from the current driving lane. Afterwards the participants started with manual drive to familiarize themselves with the test track and test vehicle. The manual drive was continued until participants reported that they were familiar with the vehicle and the test track (5-10 minutes). After completing the manual drive, combined longitudinal and lateral control were activated for the first time but restricted to hands-on driving only. The participants were asked to explore the system and the experimenter noted their comments. During this exploration phase, the participants were instructed to try out all options to activate/deactivate and overrule the system (e.g., pressing the button on the steering wheel, applying the accelerator, applying the brake pedal, turning the steering wheel). After a short pause and filling out a questionnaire about the hands-on system, the hands-free system was activated, and participants were asked again to explore the system. Participants were instructed to overrule the system including putting the hands on the steering wheel to adjust the lane position. If participants asked about their responsibility, we reminded them verbally that they are responsible for the driving task and encouraged to take over control whenever they wanted. Before activating the GPS trigger and initiating the lateral drift towards the obstacle, the experimenter made sure that the participant was attentive but not in a hyper-vigilant state (e.g., constantly trying to take over the system without an apparent reason, not taking the hands off the steering wheel on the straight section of the highway, keeping the hands up and close to the steering wheel). After the test a semi-structured interview was conducted, and participants filled out additional questionnaires.

2.4 Sample

In total N=61 (40 male / 21 female) participants between 20 and 72 years of age and an average annual mileage of 19.778 km took part in the study. Out of the N=61 participants only N=54 filled out the demographic questionnaire completely. 26% (N=14) reported to be experienced with adaptive cruise control (ACC), 30% (N=19) reported to be experienced with lane keeping assistance and 4% (N=2) reported to be experienced with assistance systems with combined longitudinal and lateral guidance.

3 Experimental design and data analysis

3.1 Experimental design

The experiment was conducted as a between-subject design with the experimental factor lateral drift velocity (0.2 m/s vs. 0.6 m/s), meaning that each participant only experienced one drift scenario (either with 0.2 m/s or with 0.6 m/s). To fulfill the requirements according to ISO 26262 and the Response Code of Practice regarding required sample sizes for a controllability assessment of C2, (C2 = 90% of drivers are able to control the failure) a valid sample size of at least N=20 per experimental group was targeted. In total, N=61 took part in the study. N=7 cases had to be rated as invalid either due to the participants having the hands at the steering wheel (N=3) or missing data recordings (N=4). No crash was observed in any of the invalidated cases. For the analyses N=34 participants were considered with a lateral drift velocity of 0.6 m/s and N=20 with a lateral drift velocity of 0.2 m/s.

3.2 Data analysis

Data analysis was based on the number of passed/failed test cases. In addition, vehicle dynamic parameters, video recordings of the driver, lane position and distance to the targets and questionnaire and interview data were considered for descriptive and exploratory analysis. Perception time and hands-on time were estimated based on video labeling; the steering reaction time was estimated on the first increase of steering torque after the failure was triggered. Time to collision (TTC) to the obstacle and time to lane crossing (TLC) were estimated based on the vehicle dynamics parameters and the GPS position of the vehicle, the lane markings, and the target.

4 Results

Four participants failed to control the situation. Three with a drift velocity of 0.6 m/s and one with a drift velocity of 0.2 m/s. All other participants (N=50) were able to avoid a collision with the target and control the vehicle safely after the evasive maneuver.

4.1 Driver behavior in failed cases

A detailed video analysis revealed the same behavioral pattern in all failed cases (see Figure 3). At first, the participants moved their hands close to the steering wheel (Figure 3, middle), indicating that they perceived the lateral drift and considered taking over the control of the vehicle. This initial reaction was followed by putting the hands down again (Figure 3, right).

Figure 3: Sequence of driver reactions in the cases with observed collisions. Approaching obstacle with hands on lap (left), hands close to steering wheel (middle), hands put down shortly before collision (right).

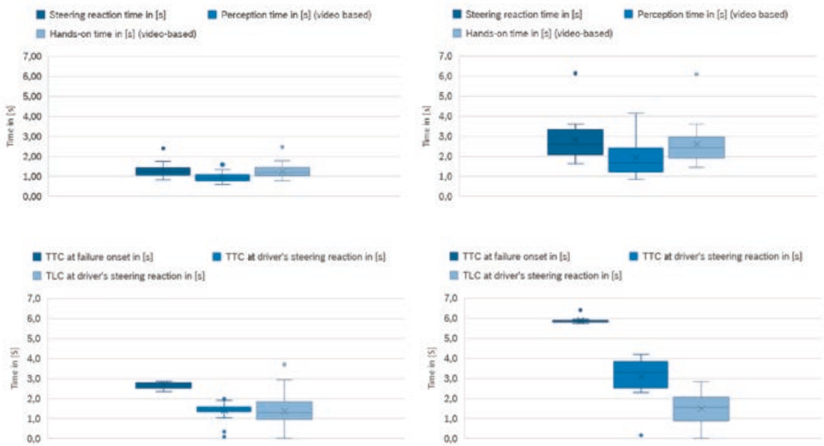
4.2 Reaction and perception time

The pattern observed in the failed cases is also reflected in the perception time (see Figure 4). Based on the video labeling, every participant perceived the lateral failure before the crash (range between 1,05 and 1,59 s for a drift velocity of 0.6 m/s and up to 4.16 s for a drift velocity of 0.2 m/s). Although participants showed a steering reaction at a different time to collision (TTC) depending on the drift velocity, the steering reaction occurred at a similar time to lane crossing (TLC). However, not all participants responeded before departing from the lane. In some cases departing from the lane was observed although no collision occured with the target (see Figure 5). In addition, the semi-structured interview revealed the following exemplary responses from the participants to the question why they did not take over control in the situation:[1]

- ”I trusted the vehicle and hoped, that it would react.” (crashed participant 1)
- ”I expected the system to intervene.”(crashed participant 2)
- ”The system did not tell me to take over.” (crashed participant 3)

[1]similar responses have been reported by [16]

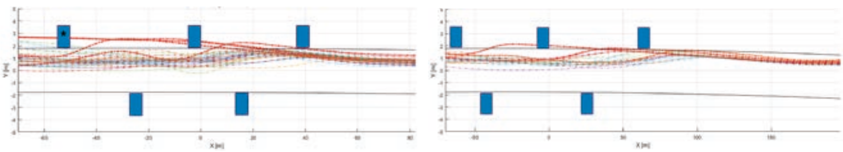
- "I perceived the system to be autonomous, because I could drive without any input." (crashed participant 4).



(a) Drift velocity 0.6 m/s

(b) Drift velocity 0.2 m/s

Figure 4: Steering reaction time, perception time and hands-on time (top) and TTC at failure onset as well as TTC and TLC at the time of the steering reaction (bottom) for both test cases.



(a) Drift velocity 0.6 m/s

(b) Drift velocity 0.6 m/s

Figure 5: Lateral position of the right corner of the car for all test-cases. Red lines indicate cases in which the vehicle crossed the lane boundary.

5 Summary and discussion

The main goal of this study was to evaluate whether an attentive driver (who is using the SAE Level 2 system with hands-free driving capabilities according to the driver manual) can perceive lateral drift failures and avoid a collision without losing control of the vehicle. The study was conducted on a closed test track with the help of a prototype vehicle and a SAE Level 2 hands-free system with a gaze-based driver monitoring system and a staged warning design.

The results indicate that all participants were able to perceive the lateral drift failure (irrespective of its dynamics) in time and even before departing from the driving lane. However, four participants did not intervene which led to a collision. The observed behavior as well the verbal responses of participants indicate that this behavioral pattern is mainly a result of an overtrust in the system's capabilities, despite explicit information that they are required to take over control in cases where the vehicle is departing from the lane. Interestingly, the participants reacted at a comparable time to lane crossing (TLC) irrespective of the intial drift velocity. This could indicate that the TLC is a relevant cue for participants to intervene although not all participants, which avoided a collision, stayed within the lane boundaries. This strengthens our inital assumption that departing from the lane does not necessarily indicate that drivers cannot react adequately. However, this also indicates that a reaction might only occur if an imminent hazard is perceived by the driver. Although this finding seems to be trivial it highlights the necessity to ensure an adequate situational awareness of the driver when driving with an SAE Level 2 hands-free system.

Based on these results, we conclude that the problem is not the driver's ability to handle limited lateral failure dynamics when driving hands-free but rather a cognitive misattribution of the systems capability which is build up by experience of the system and user expectations. This phenomenon has been described before as "automation expectation mismatch" [17], "mode confusion" or "automation complacency" [5] and several causal factors are discussed in the literature (e.g., perceived system performance or the out-of-the-loop concept [18]). Although the solution to this problem might not be trivial, being able to differentiate between "driver ability" and "cognitive misattribution" is important for the safety evaluation of SAE Level 2 hands-free systems. The driver's ability to handle system failures is an integral part of the functional safety evaluation of driver assistance system (e.g., for the assessment of controllability). If a failure is rated to be uncontrollable, one possible solution is to limit the failure dynamics. Our study clearly indicates that limiting the failure dynamics of a lateral drift does not solve the problem (that drivers will depart from the lane in case of lateral failure or even collide with an obstacle in the neighboring lane). However, it also demonstrates that attentive drivers can perceive and compensate lateral failures with limited dynamics. Therefore, we assume that the analyzed lateral failures are controllable for at least 90% of the population (corresponding to a controllability level of C2) if the driver is visually attentive and has adequate situational awareness. Nonetheless, the shown cognitive misattribution of the system's capabilities must be addressed. This problem is covered in the ISO 21448 [19] and could be attributed to the aspect foreseeable misuse. Due to this differentiation, it is possible to focus on adequate counter measures e.g., better driver training and information about the system's capabilities [20], and the driver's responsibilities when driving with a hands-free system.

It has yet to be clarified whether the same behavior would have been observed outside of this experimental context. Although similar results can be observed in test track studies [9] [10] [21] [17] as well as simulator studies [8] the question remains: Would the participants have behaved differently on-road? Due to the safety constraints, a trade-off between a realistic hazard scenario and the safety of the participants had to be accepted for the experimental setup. Naturalistic driving studies and field observations with already available SAE Level 2 hands-free capable vehicles could provide further information regarding whether or not drivers show similar behavioral patterns on the road.

References

[1] SAE On-Road Automated Vehicle Standards Committee. *J3016 Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. Warrandale, USA, Apr. 2021. DOI: `https://doi.org/10.4271/J3016_202104`.

[2] Victoria A. Banks, Alexander Eriksson, Jim O'Donoghue, and Neville A. Stanton. "Is partially automated driving a bad idea? Observations from an on-road study". In: *Applied Ergonomics* 68 (2018), pp. 138–145. ISSN: 0003-6870. DOI: `https://doi.org/10.1016/j.apergo.2017.11.010`. URL: `https://www.sciencedirect.com/science/article/pii/S0003687017302594`.

[3] Alexander Frey. "Müdigkeit und Vigilanz in einer automatisierten Realfahrt". In: *Mensch-Maschine-Mobilität 2019*. Der (Mit-)Fahrer im 21. Jahrhundert!? Vol. 2360. Düsseldorf: VDI Verlag, 2019, pp. 121–132. DOI: `https://doi.org/10.51202/9783181023600-121`.

[4] Robert Molloy and Raja Parasuraman. "Monitoring an automated system for a single failure: Vigilance and task complexity effects". In: *Human Factors* 38.2 (1996), pp. 311–322.

[5] Raja Parasuraman and Dietrich H Manzey. "Complacency and bias in human use of automation: An attentional integration". In: *Human factors* 52.3 (2010), pp. 381–410.

[6] United Nations. *Regulation No 79 of the Economic Commission for Europe of the United Nations Uniform provisions concerning the approval of vehicles with regard to steering equipment*. Standard. UN/ECE, Oct. 2018. URL: `https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=uriserv:OJ.L_.2018.318.01.0001.01.ENG`.

[7] Giulio Bianchi Piccinini, Esko Lehtonen, Fabio Forcolin, Johan Engström, Deike Albers, Gustav Markkula, Johan Lodin, and Jesper Sandin. "How do drivers respond to silent automation failures? Driving simulator study and comparison of computational driver braking models". In: *Human factors* 20 (7 May 2019), pp. 1212–1229. DOI: `10.1177/0018720819875347`.

[8] Laura Wörns. "Analysis of drivers' reaction to automation failures in a curve scenario". Master Thesis. Sweden: Chalmers University of Technology / Department of Mechanics and Maritime Sciences, 2018. URL: `https://odr.chalmers.se/handle/20.500.12380/254961`.

[9] Myra Blanco, Jon Atwood, Holland Vasquez, Tammy Trimble, Vikki Fitchett, Joshua Radlbeck, Gregory Fitch, Sheldon Russell, Charles Green, Brian Cullinane, and Justin Morgan. *Human Factors Evaluation of Level 2 and Level 3 Automated Driving Concepts*. Report No. DOT HS 812 182. Washington, DC: National Highway Traffic Safety Administration, Aug. 2015. DOI: 10.13140/RG.2.1.1874.7361. URL: https://www.nhtsa.gov/sites/nhtsa.gov/files/812182_humanfactorseval-l2l3-automdrivingconcepts.pdf.

[10] Robert E. Llaneras, Brad R. Cannon, and Charles A. Green. "Strategies to Assist Drivers in Remaining Attentive While Under Partially Automated Driving: Verification of HumanMachine Interface Concepts". In: *Transportation Research Record* 2663.1 (2017), pp. 20–26. DOI: 10.3141/2663-03. eprint: https://doi.org/10.3141/2663-03. URL: https://doi.org/10.3141/2663-03.

[11] Alexandra Neukum and Hans Peter Krüger. "Fahrerreaktionen bei Lenksystemstörunge Untersuchungsmethodik und Bewertungskriterien". In: *VDI Berichte* 1791 (2003), pp. 297–318.

[12] Philip Koopman. *SAE J3016 User Guide*. Carnegie Mellon University. Sept. 2021. URL: https://users.ece.cmu.edu/~koopman/j3016/.

[13] Joost de Winter, Neville Stanton, and Yke Bauke Eisma. "Is the take-over paradigm a mere convenience?" In: *Transportation Research Interdisciplinary Perspectives* 10 (2021), p. 100370. ISSN: 2590-1982. DOI: https://doi.org/10.1016/j.trip.2021.100370. URL: https://www.sciencedirect.com/science/article/pii/S2590198221000774.

[14] Nadja Schömig, Katharina Wiedemann, Ruth Julier, Alexandra Neukum, Andre Wiggerich, and Heike Hoffmann. *Methoden für die Bewertung der Mensch-Maschine-Interaktion beim teilautomatisierten Fahren*. 2021. ISBN: 978-3-95606-591-0.

[15] Alexandra S. Mueller, Ian J. Reagan, and Jessica B. Cicchino. "Addressing Driver Disengagement and Proper System Use: Human Factors Recommendations for Level 2 Driving Automation Design". In: *Journal of Cognitive Engineering and Decision Making* 15.1 (2021), pp. 3–27. DOI: 10.1177/1555343420983126. eprint: https://doi.org/10.1177/1555343420983126. URL: https://doi.org/10.1177/1555343420983126.

[16] Pär Gustavsson, Trent Victor, Joel Johansson, Emma Tivesten, Regina Johansson, and Mikael Ljung Aust. "What were they thinking? Subjective experiences associated with automation expectation mismatch". In: Oct. 2018.

[17] Trent W. Victor, Emma Tivesten, Pär Gustavsson, Joel Johansson, Fredrik Sangberg, and Mikael Ljung Aust. "Automation Expectation Mismatch: Incorrect Prediction Despite Eyes on Threat and Hands on Wheel". In: *Human Factors* 60.8 (2018). PMID: 30096002, pp. 1095–1116. DOI: 10.1177/0018720818788164. eprint: https://doi.org/10.1177/0018720818788164. URL: https://doi.org/10.1177/0018720818788164.

[18] Natasha Merat, Bobbie Seppelt, Tyron Louw, Johan Engström, John Lee, Emma Johansson, Charles Green, Satoshi Kitazaki, Chris Monk, Makoto Itoh, Daniel McGehee, Takashi Sunda, Kiyozumi Unoura, Trent Victor, Anna Schieben, and Andreas Keinath. "The Out-of-the-Loop concept in automated driving: proposed definition, measures and implications". In: *Cognition, Technology Work* 21 (Feb. 2019). DOI: 10.1007/s10111-018-0525-8.

[19] International Organization for Standardization. *ISO/PAS 21448:2019 Road vehicles Safety of the intended functionality*. Standard. Geneva, CH: International Organization for Standardization, Jan. 2019.

[20] Annika Boos, Birte Emmermann, Bianca Biebl, Anna Feldhütter, Martin Fröhlich, and Klaus Bengler. "Information Depth in a Video Tutorial on the Intended Use of Automated Driving". In: May 2021, pp. 575–582. ISBN: 978-3-030-74607-0. DOI: 10.1007/978-3-030-74608-7_70.

[21] Linda Pipkorn, Trent Victor, Marco Dozza, and Emma Tivesten. "Driver conflict response during supervised automation: Do hands on wheel matter?" In: *Transportation Research Part F: Traffic Psychology and Behaviour* 76 (Jan. 2021), pp. 14–25. DOI: 10.1016/j.trf.2020.10.001.