CHALMERS
UNIVERSITY OF TECHNOLOGY

Analysis of drivers' reaction to automation failures in a curve scenario

Master thesis in Mechanical Engineering

Laura Wörns

Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

MASTER'S THESIS IN TECHNOLOGY MANAGEMENT

Analysis of drivers' reaction to automation failures in a curve scenario

Laura Wörns

Department of Mechanics and Maritime Sciences
Division of Vehicle Safety
Accident Prevention Group
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2018

Analysis of drivers' reaction to automation failures in a curve scenario

Laura Wörns

Master's Thesis 2018:05
Department of Mechanics and Maritime Sciences
Division of Vehicle Safety
Accident Prevention Group
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Chalmers / Department of Mechanics and Maritime Sciences
Göteborg, Sweden 2018-03-01

Analysis of drivers' reaction to automation failures in a curve scenario

Master's thesis in Technology Management
Laura Wörns
Department of Mechanics and Maritime Sciences
Division of Vehicle Safety
Accident Prevention Group
Chalmers University of Technology

Abstract

The last years the automotive industry experienced an enormous increase of Advanced Driving Assistance Systems installed in vehicles, moving the driver's role into a more passive. Previous studies have shown delays during the takeover in case of automation failures and related them to the out of the loop performance. So far, though, the research focused on rear end collision scenarios whereas curve scenarios received little attention. The purpose of this study was to examine the drivers' reaction and performance to an automation failure of SAE level 2 occurring in a curve scenario. The analysed data set stem from a moving based driving simulator study with 18 participants within the project SHADES. The findings of this thesis showed that the initial response to automation failures in curves is steering, however not all participants performed in the same manner. Two groups were identified who differed significantly in their reaction time and their following steering performance. The slow responding group with an average reaction time of 2.97 s showed a maximum lane deviation of 1.11 m and spent 39% of the time outside of the lane, resulting in an insufficient take over performance. The fast responding group in contrast, with a reaction time of 1.30 s drifted from the lane center only 0.52 m and therefore managed to stay in the lane. The steering wheel input and the maximum lateral jerk reached by the slow responding group showed higher values compared to the slow responding group (14 m/s^3 vs. 7 m/s^3). On the other hand, the participants of the fast responding group maintained significantly higher steering wheel control before the failure, compared to the slow responding group. Altogether, those results seem to indicate that the fast responding group executed rather lane correction whereas the slow responding group showed collision prevention performance and out of the loop behaviour. Besides, this study showed that the lateral position and the heading angle at the start of driver's steering response is highly correlated to the maximum lane deviation reached by each participant during the takeover. Significant correlations between the drivers' performance and age, gender, trust or technique interest could not be found so further research with a larger sample would be required to investigate if any of those variables could influence driver's reaction. The findings from this study can be used for modelling the drivers' reaction in the specific scenario and to provide information for the design of automated driving functions in critical scenarios.

Key words: automation failure, curve scenario, take over, steering response, out of the loop

Contents

Preface

This thesis is part of my master program Technology Management at University of Stuttgart. It has been carried out in cooperation between Chalmers University, VTI and University Stuttgart.

The thesis is based on a data set, collected 2013 as part of the project SHADES in a moving based driving simulator of VTI. Analyses of kinematic data, gaze data, interviews, questionnaires and video logs were executed.

I would like to thank Giulio Piccinini my supervisor and examiner from Chalmers and Niklas Strand my supervisor of VTI for their guiding and support. I also would like to thank my supervisors from University Stuttgart Tobias Miunske and Dan Keilhoff for their cooperation.

Göteborg March 2018-03-01

Laura Wörns

Notations

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistant Systems
ICM	Initial Correction Manoeuvre
LKA	Lane Keep Assist
SAE	Society of Automotive Engineering
TJA	Traffic Jam Assist
d	Euclidian distance
m	Meter(s)
n_A	Number of elements in data set A
p	Significance
r	Pearson correlation coefficient
s	Second(s)
μ_A	Mean of data set A
σ_A	Standard deviation of data set A
ρ	Spearman's rho

Figures

Tables

1 Introduction

In the last years, the automotive industry has experienced an enormous increase of automated driving functions installed in cars. Through Advanced Driver Assistance Systems (ADAS), the driver receives support like maintaining a determined headway to a lead vehicle with Adaptive Cruise Control (ACC) or staying in lane with the Lane Keeping Assist (LKA) (Louw & Merat, 2017). The degree of automation for on-road vehicles is classified by the Society of Automotive Engineers (SAE) into 6 levels, in which SAE level 0 and 1 define respectively no automation and driver assistance only. The next two levels represent semi-automation where the ADAS execute the driving tasks of steering and accelerating/decelerating, but the driver needs to monitor the driving environment and take over the system if necessary (SAE level 2) or when requested by the system (SAE level 3). High and Full Automation (SAE level 4 and 5) are characterized by the vehicle being capable of performing all driving functions without drivers' intervention and differ in the limitation where the automation systems can be used (Reimer et al., 2016; Shen & Neyens, 2017). The six levels of automation are pictured in Figure 1.

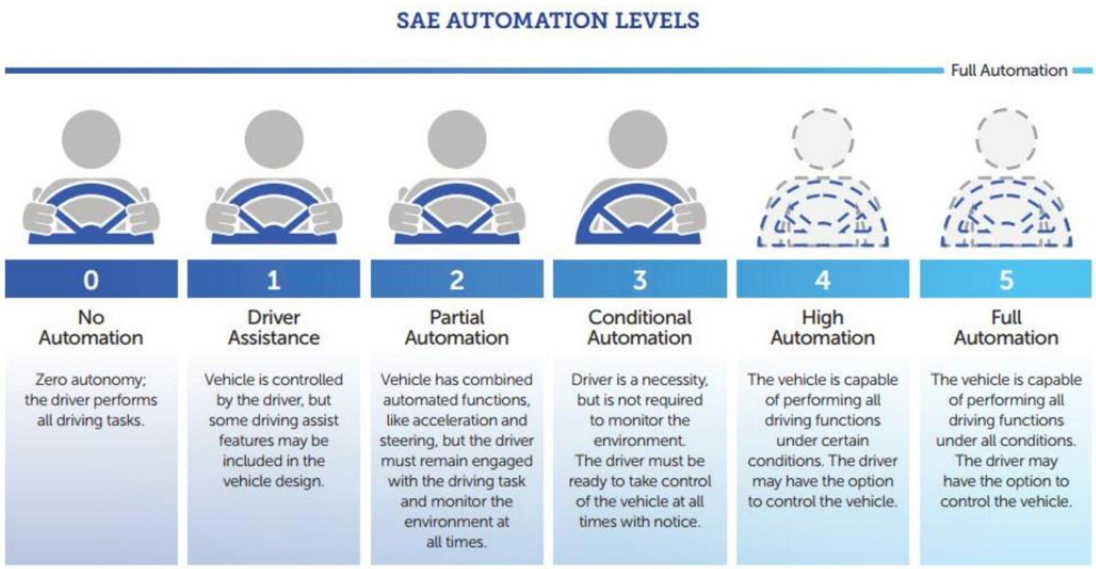


Figure 1: SAE automation levels from 0 (no automation) to 5 (full automation) (Federal Transit Administration 2018).

The future goal might be to implement high/full automation, releasing the driver completely from his tasks and offering him the possibility to work, rest or enjoy entertainment during driving: not only the possibility of social and individual benefits but as well the increase of mobility for people who are not able to drive, fewer emissions and improved safety are expected benefits of full automation (Reimer et al., 2016). However, before the realization of fully automated cars on roads, the laws, the technical aspects, and the drivers' understanding of these systems still needs to be improved.

Looking at the legal restrictions, driverless cars are not permitted yet and ADAS must be controllable by the driver, therefore an intervention of the driver in the support systems must be possible at any time (Vienna Convention of 2016).

From the technical point of view, fully automated cars with no crash guarantee are not developed yet either (Merat et al., 2014). However, previous studies show that, for example, the use of ACC in real traffic can decrease the number of crashes and create a smoother traffic flow (Davis, 2004). At the same time as advantages of automated driving functions are recorded, errors and limitations of these systems in traffic exist too. Automation limitations represent known limited capacity of the hardware like camera or sensor limits and software boundaries and are defined in the user manual of the system. Sensors, for example cannot detect dirty lane markers and can be limited by poor visibility or heavy rainfall. The software of ADAS are not programmed for all situations yet, the ACC for example is not able to react to stationary objects on the road and can be used only in a determined environment, like on highways. Additionally, many ADAS till SAE level 2 require driver support in case of hard braking or in other critical situations (Reimer et al., 2016; Dikmen & Burns, 2016; Merat et al., 2014). Automation errors however do not belong to the intended design and therefore their appearance is hard to predict (Strand et al., 2014). Errors can be divided into failures, when the automation is not working but it shows that the system is active, and false alarms which appear when the system indicates a problem, but it is actually working properly (Johnson et al., 2004). Dikmen & Burns (2016) presented in a survey with Tesla drivers who use regularly ACC and LKA that the participants emphasize, that the automation mode is not faultless and that it is necessary to maintain hands on the steering wheel and to stay focused. Additionally, the importance of the drivers' understanding of the systems and their limitations is underlined for safe driving (Shen & Neyens, 2017). These examples show that today's vehicles equipped with ADAS are still far away from allowing the drivers to allocate his attention to secondary tasks but they rather require full supervision in case of failures or critical events (Dikmen & Burns, 2016).

Finally, regarding the drivers' understanding of ADAS, human errors can occur as well. Human errors can be divided in omission and commission errors. Commission errors occur when the driver is responding wrongly to the ADAS, like overriding the system during a crash prevention. Omission errors appear when a driver does not respond to a system error although an engagement of the driver was necessary, and those types of errors can be caused by inattention or ignorance of the automation limitations (Johnson et al., 2004). Intervention failures of the driver can be attributed to the out-of-the-loop performance problem, a negative consequence of automation, which reduces the ability of the operator of the automated system to take back control in case of automation failure (Endsley & Kiris 1995; Lee et al. 2017).

The out of the loop performance can worsen driving performance, like longer reaction times to critical situations or failures (Strand et al., 2014; Shen & Neyens, 2017; Reimer et al., 2016) and cause issues in the human-automation interaction such as lack of detection, loss of situation awareness and skill loss. Being out of the loop will likely lead to a slower detection of automation failure, simply because the detection of the area where the failure can appear is reduced or lacking (Lee et al. 2017). Observations of the off-road glances showed that drivers dare to remove their eyes for a longer duration from the road with higher automation modes (Reimer et al. 2016). The situation awareness describes the perception of the dynamic state of the system and the assumed future trends and events (Lee et al. 2017; Endsley & Kiris 1995). Using automotive functions, the driver's role shifts into a more passive monitoring position and in addition the driver is released from the physical tasks of driving which leads to a lack of haptic feedback (e.g. lack of steering torque) and therefore reduces situation awareness (Louw & Merat, 2017). Skill loss is a long-term consequence of being out of the loop and reduces the ability to operate the vehicle manually due to the fact that the task is normally executed by the automated system. In the long term, drivers may feel less confident in manual driving and overloaded when takeover is required (Lee et al. 2017).

The transition from automated driving functions to manual driving in emergency situations has been addressed by previous studies. The driving scenarios investigated seem to be mostly rear end collisions and lane change scenarios with and without secondary tasks engagement of the drivers. Young and Stanton (2007) studied brake reaction times after an automation failure in rear end situations with automation level SAE 2. Eriksson et al. (2017) investigated in a driving simulator study steering and brake reaction times according to different human machine interfaces during takeover requests in lane change and rear end scenarios. Strand et al. (2014) found in a driving simulator study that about a third of the drivers were not able to react to an automation failure in a rear end situation in time. In a merge in scenario where drivers with automated functions needed to brake to avoid a collision, De Waard et al. (1999) found that 65% of the drivers performed a late response with insufficient quality or no take over response at all. Louw et al. (2015) found when drivers regained control of automated vehicles to prevent a crash with a stationary object by changing the lane that lack of steering wheel feedback is strongly correlated with the out of the loop behaviour and that out of the loop drivers showed aggressive vehicle control, measured by lateral acceleration. Curve scenarios in contrast, are less explored: Kircher et al. (2014) observed higher lateral jerks for drivers using automated driving functions SAE level 2 in an automation failure compared to the reference group of manual drivers and Dinparastdjadid (2017) found a correlation between the situation at drivers' response start (regarding steering angle, heading angle and lateral lane position) and the overall performance measured by the maximum lane deviation.

Summarizing, ADAS present a first big step towards full automation and have a high potential to improve safety (e.g. fewer crashes) and comfort (e.g. smoother traffic). However, their introduction could also originate negative consequences such as delayed responses to takeover situations. Therefore, it is important to further examine the interaction between the driver and automated systems to improve the design of ADAS and guarantee their safe use especially for curve scenarios which received less attention compared to rear end and lane change scenarios.

The aim of this master thesis is the analysis of the drivers' reaction to automation failures (SAE level 2) in a curve scenario. The detailed research questions are the following:

- What is the initial response to automation failure in a curve scenario?
- How long does it take for drivers to react to automation failures?
- How long does it take for drivers to take back control from the automation failure?

1.1 Driving simulator study

This section describes the data collection method, the participants, the used ADAS and the collected dataset which was used for the analysis.

The data was collected in a driving simulator study within the project System Safety through the Combination of Dependable Systems and human-machine interaction (SHADES) in 2013. The SHADES project was financed by SAFER and pursued the goal to improve system safety in vehicles (Strand 2014).

Participants and driving simulator

Eighteen participants (14 men, 4 women) in the age range between 25 and 64 years old (Mean = 44,39 years, SD = 10,71) joined voluntarily the driving simulator study and met the following requirements:

· No previous experience of driving with ACC
· Valid driver’s licence
· At least 5 years of driving experience
· Between 24 and 65 years of age
· No reported tendency of simulator sickness
· Annual mileage exceeding 10,000 km

The experiment took place in the simulator SIM IV, located at the VTI office in Gothenburg (Figure 2). The SIM IV is a moving based driving simulator allowing rotations around all axes as well as lateral and longitudinal movements. The software of SIM IV, consists of CORE software managing the simulation kernel and of VISIR software providing the graphics for an 180° field of view (Jansson at al. 2014). Eight projectors create a front view, showing the surrounding of the car including the road, the landscape and the on-going traffic. LCD screens were installed in the rear-view mirror and in the two side view mirrors to enable the driver to observe the environment on the sides and behind the car. For this study, a Volvo XC60 cabin was mounted in the simulator since the experiment addressed car drivers. The simulator car, was equipped with an automatic gear for this experiment, so the participants did not need to shift manually.

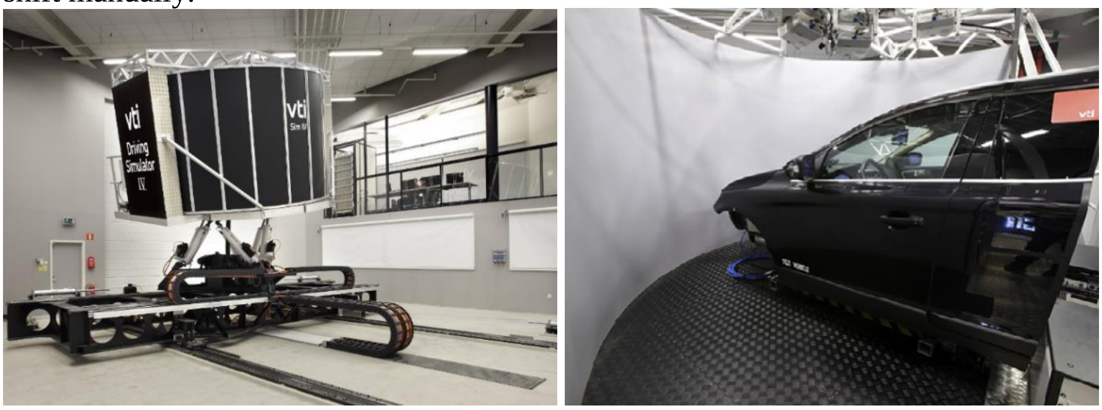


Figure 2: Moving based driving simulator Sim IV (left) with a vehicle driver cabin (right).

During the experiment, three camera views as well as gaze data and kinematic data were recorded (Figure 3). One camera recorded the side view of the driver, so that the head and the upper body movements as well as the steering wheel were visible. The second camera recorded the drivers' feet with the pedals and the third camera recorded the front view through the windshield. On top of the video logs, many kinematic parameters of the car were measured, such as the lateral and longitudinal lane position, acceleration and speed, the activation mode of the used advanced driver assistant system, the time elapsed since the start of the simulation and the driven distance.

Figure 3: Three recorded camera perspectives: driver from the side (left), foot and pedals (middle), and front view through the windshield (right).

The point used to identify the position of the vehicle in the simulator, hereafter named subject vehicle (SV), was located 0.82 m from the front end of the car and 0.80 m from the right and the left side of the SV and is marked with a red cross in Figure 4. The SV had width of 1.60 m and length of 4.71 m and drove on a 3 m wide lane with a 1 m wide paved stipe on the right side. During the use of the ADAS, the SV was driving in the middle of the lane.

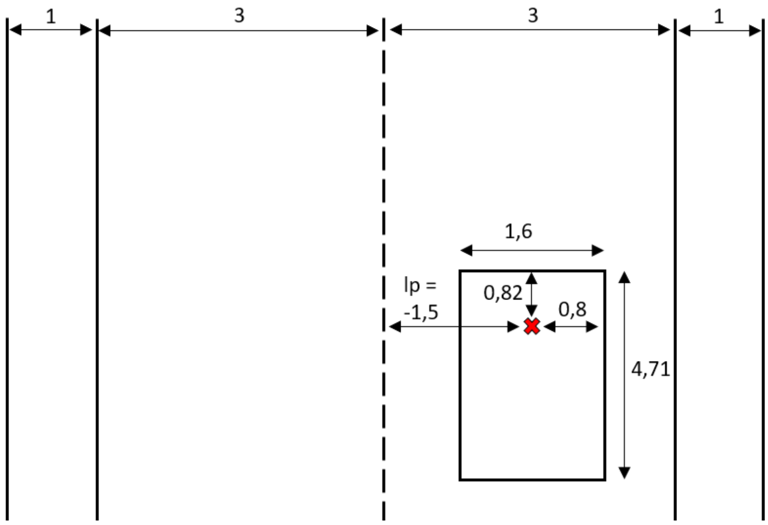


Figure 4: Dimensions of the road and the simulator car with its measurement point, marked with a red cross, from where the kinematic data of the car was measured.

Additionally, the participants eye gaze was recorded by five cameras placed within the vehicle cockpit. Each participant went through a gaze calibration procedure, performed against known features in the surrounding physical environment. The gaze data was collected and processed at 50 Hz by a SmartEye system, which continuously streamed information to the driving simulation kernel for synchronization and storage.

The kinematic data was sampled at 100 Hz whereas the gaze data was collected with 50 Hz.

Advanced Driver Assistance System

The SV was equipped with a prototype - called Traffic Jam Assistant (TJA) - of the current Pilot Assist and was provided by Volvo Car Corporation. The TJA takes over longitudinal and lateral movements of the SV and it is therefore a system acting at SAE level 2. The TJA combines the longitudinal functionalities of ACC system with the automatic steering and it is designed for driving in traffic jam scenarios. The TJA takes overs the drivers' accelerating and decelerating tasks, which means that if the lead vehicle slows down, the TJA decreases the vehicle’s speed to maintain the set time interval – 1 second in this study – to the front car. On the other hand, if the lead vehicle increases its speed, the TJA also accelerates to keep the set time interval as long as the set speed value is not reached. With respect to the automatic steering, the TJA keeps the SV in the lane by following the path of the front vehicle and considering the side lane markers and therefore releases the driver from the steering task. The automatic steering function of the TJA was active only if there is a lead vehicle to follow in front of the SV.

To activate the TJA, the driver needed to press a button located on the steering wheel. The system could be deactivated by the driver at any time, by pressing the same button as for the activation or by depressing the brake pedal or by steering. If the driver depressed the gas pedal, the TJA was temporarily overridden but the system took over control again as soon as the driver released the gas pedal. In the dashboard, a symbol inside the tachometer showed to the driver if the TJA was activated or in standby mode (Figure 5). When the TJA was activated, 3 different icons were presented in the tachometer (Figure 5, left):

- The digital indication of the speed set by the driver appeared in the centre of the tachometer
- A green steering wheel within a green circle and the sign ‘ON’ appeared below the digital indication of the speed
- A traffic lane with an approaching traffic jam appeared above the digital indication of the speed.

When the system was not active but available for activation, a car with a grey sign ‘AVAILABLE’ appeared in the tachometer to remind the driver that the TJA was in standby mode and available for activation (Figure 5, right).

Figure 5: TJA symbol in the dashboard, indicating if the TJA is active (left) or in standby mode (right).

It is important to notice that the TJA supports the drivers but does not replace him/her and, hence, despite the TJA takes over the physical driving task from the driver when requested, he/she is always responsible for the driving task. Therefore, the driver needs to supervise the system and decide if it is necessary to take back manual control.

The TJA has some functional limitations and cannot recognise or respond to all various traffic situations and environment conditions correctly. Limitations of the TJA can appear due to many reasons based on the hardware as the cameras and sensors or the software, which are defined in the user manual of the ADAS. The TJA will go into standby mode when the sensors are not able to capture the needed information as the lane markers or the vehicle ahead. Additionally, the TJA is not able to identify people or animals, small vehicles as bicycles or motorcycles, low trailers and slow moving or not moving objects. The TJA is not recommended to use in the city or in heavy traffic situations, in slippery road conditions, during heavy rain-/snowfall or poor visibility and in curvy roads or highway on-/off ramps. Besides, the user manual mentions that in situations of fast braking, the driver is requested to brake, and that the steering capacity of the system is limited which might demand the driver's engagement to maintain the vehicle in its travel path. Steering force support might be especially needed in curves and the driver should not wait for automatic steering action but steer himself when necessary (Volvo Cars 2016). During the experiment, in case the driver deactivated the TJA, a yellow message 'aktivera systemet' ('activate the system', in English) appeared in the projected landscape to remind the driver to turn on the TJA again.

Procedure

The procedure was the same for every participant and took about one and a half hour per person. After arriving at the driving simulator at the office of VTI in Gothenburg, the participant received verbal information about the driving experiment and an information sheet with a consent form to sign. Then, the participant was requested to fill out a questionnaire with demographic information and questions regarding his/her driving experience and his/her interest and trust in technique. Afterwards, the experiment leader led the participant to the driving simulator car where he took a seat and was told how to change the basics settings of the car like seat and steering wheel position. Additionally, the participant was shown the button on the steering wheel for activating and deactivating the TJA, and he/she was given a manual about the driver assistance system. Then, the participant underwent a training drive in the simulator, in which he/she had the chance to get accustomed to the driving in the simulator and to practice changing from manual driving into the automatic mode and vice versa. The participant was requested to deactivate the TJA in all possible ways to understand how to intervene – if required – during the drive. After the training session, the participant was provided with the following written description about the scenario occurring in the next drive: the participant was told that he/she visited friends in Becken during his/her second vacation week and left their house earlier than planned and therefore had a lot of time to drive back to his/her home in Gödal, located 50 km away and reachable through highway drive. Before the drive started, the participant was instructed to keep at least one hand on the steering wheel also while driving with TJA activated and to drive as naturally as he/she would normally do.

The virtual route in the driving simulator was a rural road through forest with one lane in each direction. The speed limit of the road was 70 km/h but the vehicles in front of the SV were travelling in average at 50 km/h. The oncoming traffic was travelling in the opposite lane at an average speed of 70 km/h and the frequency of the oncoming vehicles was high to hamper the participant to overtake the slower lead vehicles. After some minutes of driving a traffic radio message occurred announcing that queues were going to appear on the route where the participant was driving on, to make the situation as realistic as possible. The participant drove for about 40 minutes in which no further instructions were given. In the first two thirds of the drive, three deceleration failures of the TJA appeared in which the driver needed to brake to avoid a collision with the lead vehicle, as described in Strand et al. (2014).

The automatic steering of the TJA worked properly during the whole experiment but after 25 minutes, in the last curve, a failure of the system occurred, which is the focus of this study. The scenario is schematically represented in Figure 6: the driver approached a curve towards right following the lead vehicle which was driving closely to the middle lane instead of in the centre of its lane. Before entering the curve, the TJA stopped working while the symbol in the dashboard still showed that the TJA was activated. As a consequence of the TJA deactivation, the lateral and longitudinal movement of the SV was not controlled by the TJA anymore and, if the participant did not take over control from the system, the SV continued straight towards the oncoming lane (no lateral control active) and reduced its speed (no longitudinal control active). Then, a lack of the participant's intervention would have resulted into a collision with the oncoming traffic. Besides, as soon as the participant took over control by steering or/and braking, the TJA went into standby mode and the earlier described yellow message 'aktivera systemet' appeared on the projected landscape.

After the drive, the participant was led into another room and an interview followed to discuss the critical situations of the drive. The video log of the participant's reaction during the TJA failures was shown to the driver to support the recall and reflection about the situations. Finally, the participant received two cinema tickets as a reward for the time and support to the research project and the test leader explained to the participants the overall aim of the driving simulator study.

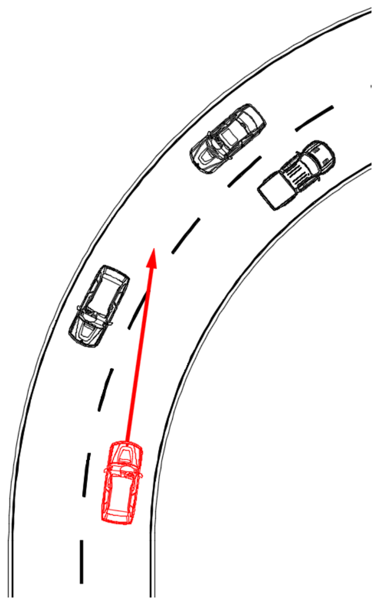


Figure 6: Curve scenario with automation failure.

2 Methods

To analyse the drivers' behaviour, qualitative data and quantitative data was examined. In Section 2.1, the quantitative analysis methods are presented which are on the one hand focusing on the examination of the lateral control and therefore on the drivers' steering response to the event and on the other hand on the gaze behaviour of the participants. In Section 2.2, the qualitative analysis methods of the thesis are described, which are investigating interviews and questionnaires from the driver simulator study as well as video logs of the participants to score their hand positions.

2.1 Quantitative analysis

The goal of the quantitative analysis is to investigate the reaction of the participants during the failure of TJA through kinematic data and gaze data. Since the automation failure happened in a curve scenario, the lateral control of the SV is of high interest. The next sections explain the methods to investigate the lateral control and all variables which were calculated within this analysis as well as the method to examine the gaze behaviour of the participants.

2.1.1 Analysis of lateral control

For the analysis of the drivers steering behaviour, different performance measures were calculated from the kinematic data set. The SAE international standard 'Operational Definitions of Driving Performance Measures and Statistics' specifies different steering performance measures - the steering reaction time, the steering movement time and the steering response time, which are defined by corrective steering actions and are measured in seconds or milliseconds (SAE J2944, 2015). The steering performance measures, which are used for the analysis are marked in red in Figure 7 and described below.

<u>Steering reaction time</u>
The steering reaction time is defined as the time interval from the beginning of an initiating event to the first steering wheel response. The steering reaction time is an extension of the more general reaction time which is defined as time lapse from the start of a certain event to the first response, such as a movement of the drivers' hands on the steering wheel or a foot movement or a voice reaction for voice activated controls. In this driving simulator study, the failure of the TJA is considered as the initiating event of the steering reaction time. For the steering wheel response, a threshold must be set to distinguish between unintentional movements on the steering wheel and an evasive manoeuvre of the driver. A limit of two degrees steering wheel angle was chosen to determine the start of the steering wheel response (Gold et al. 2013). Hence, for this driving simulator study, the steering reaction time is the time elapsed from the time of the TJA failure until the first time for which the steering wheel angle is bigger than two degrees, measured in absolute value.

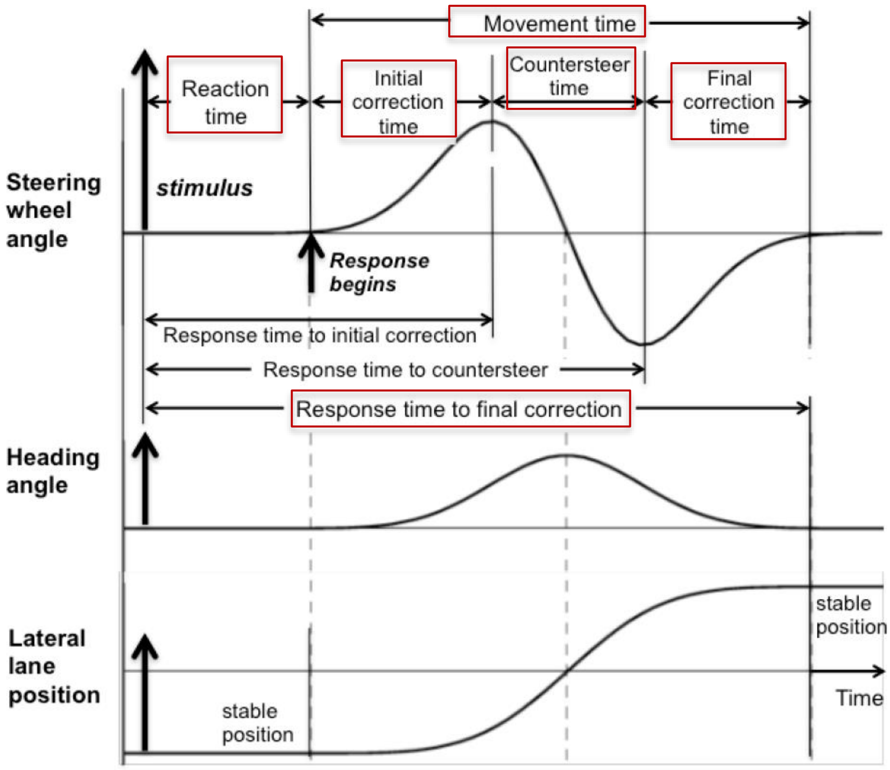


Figure 7: Steering wheel angle, heading angle and lateral lane position for a lane change situation are plotted over time; the reaction time, movement times and response times, used in this thesis are marked in the graph (SAE J2944, 2015).

Steering movement time

The steering movement time is the time period between the first response and the final correction of the driver. In this study the final correction is executed by reactivating the TJA. The steering movement time can be split into several time periods connected to steering movements. After the first response, an initial correction movement follows and the ensuing event is a countersteer movement which serves as a second compensatory correction to bring the vehicle back into its desired path. After these movements, further corrections can follow until the final correction takes place, which aligns the vehicle with its original path. The steering movements times - included in the overall steering movement time and used in this thesis - are described below:

- Initial correction time
  The initial correction time starts with the drivers' first response, which was determined above with an absolute steering angle bigger than two degrees and ends with the initial correction point which is represented by the first maximum or minimum in the steering wheel angle.
- Countersteer time
  The countersteer time is defined from the initial correction point, which means the first maximum or minimum in the steering wheel angle plot, until the countersteer point which is recognized by the second maximum/minimum in the steering wheel angle plot. If the initial correction point is indicated by a maximum, the countersteer point is indicated by a minimum and vice versa.
- Final response time

The final response time is defined from the countersteer point, which means the second maximum or minimum in the steering wheel angle plot, until the final correction of the driver which equals in this study the reactivation of the TJA.

The initial correction point and the countersteer point are defined respectively by maxima and minima in the steering wheel angle plot. Since real steering wheel signals are characterized by noise and minor oscillations and are not consequently as smooth as in Figure 8, a methodology is required to identify minima and maxima in the steering wheel angle data, as shown in Figure 9. The methodology used in this work considers thresholds both for the amplitude change and for the time window to define a steering reversal by filtering out sudden minor changes in the steering wheel angle signal:

- Threshold for amplitude change: the threshold was set to two degrees as for the identification of the first steering wheel response.
- Threshold for time window: the threshold was set to 0.65 seconds after various trials.

Then, if the steering wheel angle is changing with a minimum amplitude of two degrees in the determined time window it is identified as minimum/maximum.

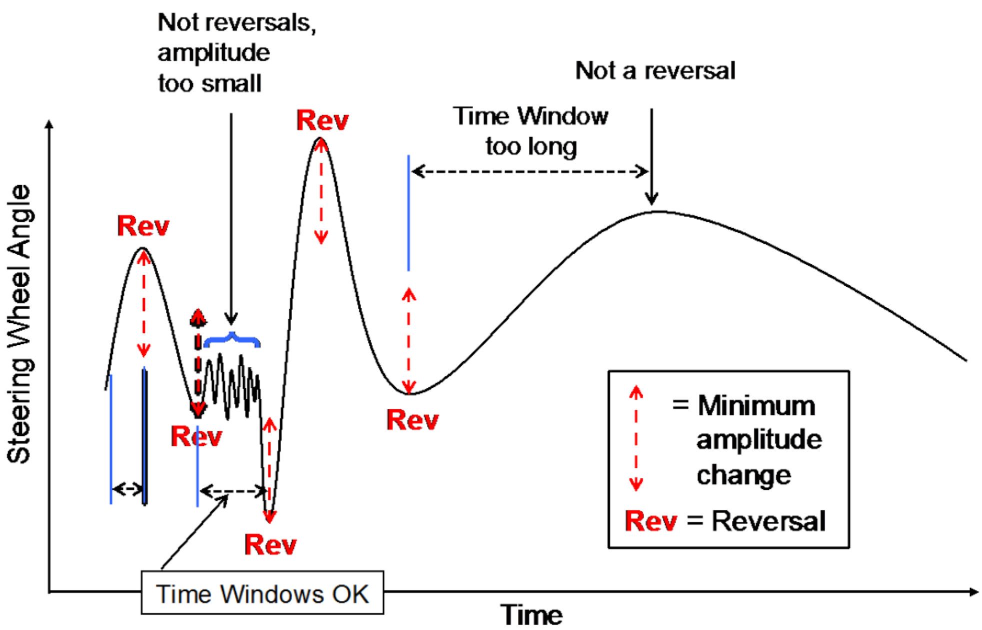


Figure 8: Determined thresholds for minimum amplitude change and time window to identify steering wheel reversals, which equals maxima and minima in the steering wheel angle plot.

<u>Steering response time</u>
The steering response time begins with the initiating event and ends with one of the above described steering wheel movements: initial correction, countersteer or final correction. Therefore, the steering response time can be subdivided into the response time to initial correction, the response time to countersteer and the response time to final correction, although only the last measurement is used for this research. The initiating event with which all response times begin is, as noted before, the start of the TJA failure. The steering response time to final correction is defined below:

- The response time to final correction is defined from the TJA failure to the final correction movement and can be calculated by the sum of the steering reaction time, the initial correction time, the countersteer time and the final correction time. The response time to final correction represents the time from the initial event, here the automation failure to the vehicle being back on its desired path. In this driving simulator study, the response time to final correction equals the time without automation, since the TJA is managing the driving tasks before the failure start and after the reactivation.

Heading angle

The heading angle measures the angle between the direction of the SV and the desired direction of the SV, which is following the road in its center, as shown in Figure 9. A positive heading angle describes a shift of the SV counterclockwise to the ideal path and a negative heading angle signalises that the SV is shifting clockwise to the desired travel path.

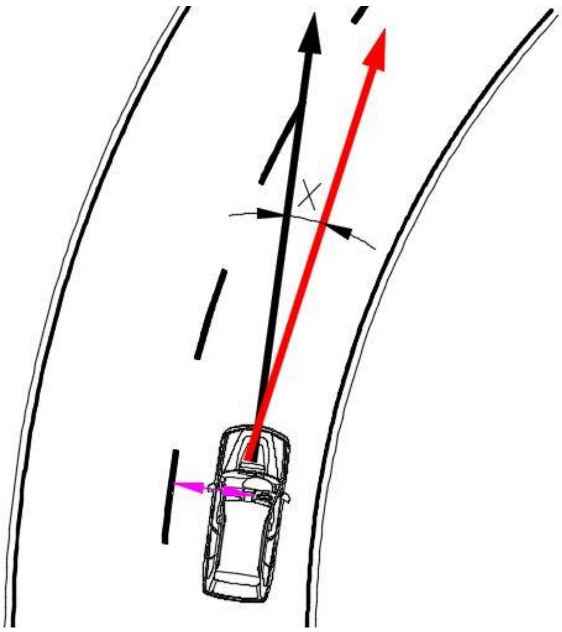


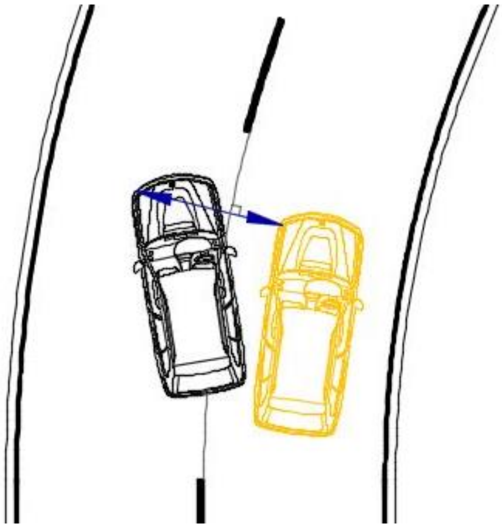
Figure 9: The red line marks the ideal travel path while the black line shows the orientation of the SV. The angle between these lines describes the heading angle of the SV. A positive angle, as shown here, appears by the SV shifting counter clockwise to the ideal path. The purple mark, perpendicular from the center line to the lateral center of the SV, measures the lateral lane position in meters.

Lateral lane position

The lateral lane position measures the orthogonal distance of the SV center from the center line (Figure 9). The lateral position is given in meters and if the SV is placed in the center of the lane, its lateral position is -1.5 m. If the SV centre lays in the center line, the lateral position is 0 m.

Lane deviation

The lane deviation is in this thesis defined as the distance between the SV travelling in its desired position in the middle of the lane to the SV's real position, measured in the SV's corner, furthest away from the lane center (Figure 11 left). Therefore, the corner points of the vehicle were calculated for every time point by using the heading angle and the SV's position. Through rotating the corners of the SV with a rotation matrix around the heading angle and afterwards vector addition the SV's corners for each moment were calculated, which is shown in Figure 10 (right). For simplicity, the extreme edges of the vehicles were limited to the body structure, not taking into account the wheels.



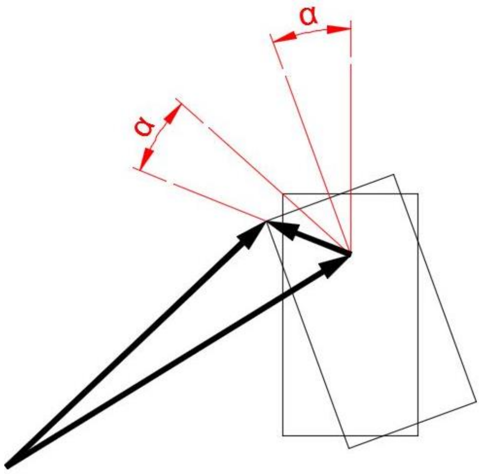


Figure 10: Lane deviation of the back SV to its centered position (yellow vehicle) measured from the SV's corner which is furthest away from the lane center (left). Calculation of the SV's corner points with its heading angle and lane position, to enable the determination the SV's lane deviation (right).

In the analysis the maximum lane deviation was examined, which is a performance measurement for a smooth transition from automation to manual. High values can expose a steering control fault or oversteering (Dinparastdjadid, 2017).

<u>Lateral jerk</u>
The lateral jerk is the derivative of the lateral acceleration and it is reported in m/s^3. The lateral acceleration, recorded in the simulator at a sample rate of 100 Hz, is differentiated and afterwards filtered with a five point moving average filter method which is consequently representing the jerk. The jerk measures the change rate of the acceleration/deceleration and is strongly connected to riding comfort. To identify near crash situations or unplanned/surprising driving manoeuvres the jerk represents an important parameter (Hayafune & Yoshida 1990; Kircher et al. 2014; Bagdadi & Várhelyi 2013).

2.1.2 Gaze behaviour

The raw gaze data is defined by a X, Y and Z vector, describing a unit direction vector of the gaze and measured at a sample rate of 50 Hz. For better visualisation, the data was transformed through trigonometrical calculation to angles describing the horizontal and vertical gaze direction per sample. Additionally, the smart eye system noted the dashboard gazes of the participants, which are analysed together with the vertical gaze eccentricity.

Participants with insufficient quality of raw gaze data were excluded. The quality of the raw data is scored by the smart eye system from 0 (bad quality) to 1 (very good quality) and a threshold of 0.6 identifies valid quality data. For the dataset it was determined that participants with 80 % valid gaze data over the examined time are included for the analysis. The time window is defined by five seconds before the failure to investigate where participants were looking during the use of the TJA and about seven seconds after the failure until the average reactivation of the TJA, to investigate the whole manual recovery driving period.

2.1.3 Exploratory analysis

During the analyses of the quantitative data set, indications for patterns in the data were found. After the visualisation of kinematic data like the reaction time, heading angles and lane deviations, clusters in each plot were recognized. To identify if these patterns/clusters in the data set are consistent which may divide the participants into groups the research questions got expanded. The analyses continued additionally to the existing research questions, to focus on the research if a significant difference between the participants' performance is given. Therefore, the following research questions were added:

- Is there a consistent clustering of drivers existing?
- If yes – what are the differences in the groups?

2.2 Qualitative analysis

The following sections describe the analysis of qualitative data. The methods to analyse interviews, questionnaires and to assess hand positions from video logs are presented respectively in Section 2.2.1, Section 2.2.2 and Section 2.2.3.

2.2.1 Thematic analysis

For the analysis of the interview data, only the interview parts regarding the TJA failure in the curve scenarios were considered. The questions which were asked while showing the video log of the curve scenario were how the participant would describe this situation and how he/she perceived the situation.

One of the foundational qualitative methods is the thematic analysis, which is used in this study to investigate the interviews of the participants and to interpret their explanations of their driving behaviour. The thematic analysis is a tool to investigate a qualitative data set with the goal of identifying, analysing and picturing patterns or so called 'themes'. The analysis starts with the researcher making himself/herself familiar with the interview material by reading it several times and by working systematically through the data to create initial codes to picture the content. Coding can be done by writing notes, highlighting, coping data extracts and comparing data sections. Afterwards themes need to be chosen, which should be connected to the research question(s). The amount of how often a theme appears in the dataset or that the theme mirrors the overall content of the data set is not of priority however the theme should offer information to the research question(s). Additionally, it is demanded to create a consistent way to count a theme. For example, a way to establish a consistent judgement of the occurrence of a theme in interview data is to examine if the interviewed person uses the theme's name (Braun & Clarke, 2006). The main research question of this thesis is how the driver reacts to automation failures and the interview data might provide insights to the driver's behaviour for the specific scenario.

Additionally, to the thematic analysis of the interviews, quotes of participants were used to explain special behaviour and reasoning outlier data.

2.2.2 Analysis of questionnaires

The analysis of the questionnaires, as the analysis of the interview data, aimed to answer the question why the participants were reacting to the automation limitation in a certain way. The questionnaire of the simulator driving study included two open questions regarding the age of the participants and the duration of drivers' licence ownership and four closed questions regarding the participants' interest in technique, which could be answered by choosing a number between 1 (not true) and 5 (true). An example questionnaire is attached in the appendix.

The answers to the questionnaires were summarised and compared to the participants' reaction time, to identify correlations between the quantitative data and the qualitative data.

2.2.3 Video log analysis

The analysis of the video logs aimed to assess the hand position on the steering wheel while driving into the curve and if the driver changed his/her hand/foot position before the curve.

For the assessment of hand position on the steering wheel, the measurement of De Waard et al. (2010) was used, which classifies it into low, medium and high control. The definition of De Waard et al. (2010) for the different levels of control on the steering wheel are described below:

- High control: The driver has high control over the steering wheel, when both hands are located in the high control area marked in blue in Figure 11. This means that the right hand should hold the steering wheel between 2 or 3 o'clock position while the left hand should hold it between the 9 or 10 o'clock area.

- Medium control: The driver has medium control over the steering wheel when one hand is located in the high control area of the steering wheel while the second hand is not in the high control area. Examples of medium control are if the left hand is located on the 9 o'clock position and the right hand is located on 5 o'clock or if the right hand is located on the 2 o'clock position and the left hand is holding the steering wheel on the 8 o'clock position.

- Low control: The driver has low control over the steering wheel, when both hands are located in the low control area between the 5 and 7 o'clock position, which is marked in red in Figure 11. Additionally, the hand position is judged as low control when either only one or no hand is located on the steering wheel.

For the analysis described in the results section, the last hand position of each participant before the failure was assessed.

Figure 11: Categorising the steering wheel into high, medium and low control hand positions by De Waard et al. (2010). The blue area marks the high control hand position while the red area shows the low control area. For high control both hands need to be located in the blue area. Medium control of the vehicle is existing when the driver has one hand located in the blue area and the other hand is not in the blue area. Low control is scored when the driver's hands are in the red area or when only one hand or no hand is on the steering wheel.

To examine if the participant changed his/her hand/foot position before the curve, any change of the drivers' hand or foot position, was noted. It was not demanded that the driver improved his/her hand position to a higher control position after the definition of De Waard et al. (2010). A change of the number of fingers holding the steering wheel was judged as position change, like if the participant held the steering wheel with three fingers per hand and changed it to five fingers per hand without moving the hands. Also, a change from a loose grip to a stronger hand grip on the steering wheel or a change of the hand position on the steering wheel was judged as preparation for the curve. Regarding the feet movement, the participants were judged as changing their position before the curve if he/she moved the feet on top of a pedal or pressed any pedal. The change of feet/hand position was observed during the last 10 seconds before the participant started driving into the curve. A hypothesis was stated that with a change of hand/foot position the driver is 'preparing' for the curve.

2.3 Statistical analysis

For the statistical data analyses, the below methods were used to assess significance.

<u>Comparison of two means</u>

To compare if two samples have different means, various tests can be used. In this thesis, all datasets come from independent samples and the Lilliefors test for normality was used to examine if the data samples have normal distribution. The Lillifors test assumes the null hypothesis that the data comes from a distribution in the normal family and is calculated with

$$D = max_A |F * (A) - S_n(A)|$$

Being $F*(A)$, the cumulative normal distribution function of the data sample A, and $S_n(A)$ the sample cumulative distribution function (Marques de Sá, 2007).

When the populations of the two samples were normally distributed, the two-sample t-test was used with the null hypothesis stating that the two data samples come from independent samples with normal distribution and equal means and the alternative hypothesis stating that the two data samples come from independent samples with normal distribution and different means. The two-sample t-test is calculated as shown below (Marques de Sá, 2007):

$$t = \frac{\mu_A - \mu_B}{\sqrt{\frac{{\sigma_A}^2}{n_A} + \frac{{\sigma_B}^2}{n_B}}}$$

With $\mu_A =$ mean of A, $\sigma_A =$ standard deviation of A, $\mu_B =$ mean of B and $\sigma_B =$ standard deviation of B.

When the populations of the two samples were not normally distributed, the Mann-Whitney U test was used instead.

<u>Correlation between variables</u>
To determine the linear correlation between two continuous variables, the Pearson correlation coefficient r was used, which is calculated as below:

$$r = p(A,B) = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{A_i-\mu_A}{\sigma_A}\right)\left(\frac{B_i-\mu_B}{\sigma_B}\right)$$

With A and B containing n observations each, $\mu_A =$ mean of A, $\sigma_A =$ standard deviation of A, $\mu_B =$ mean of B and $\sigma_B =$ standard deviation of B.

The Pearson correlation coefficient r is dimensionless and takes values between -1 and 1, with r = 0 standing for no linear association, r = 1 representing total linear association with A and B changing in the same direction and r = -1 signalizing total linear association with A and B varying in the opposite direction (Marques de Sá, 2007). Cohen (1992) suggested to categorize the effect of r in three levels:

- Small effect (r = 0.1): 1% of the total variance is described (= a change of the dataset A describes the change of the dataset B with 1%)
- Medium effect (r = 0.3): 9% of the total variance is described
- Large effect (r = 0.5): 25% of the total variance is described

In addition to the effect size r, the significance value p was calculated: in case the significance level is p < 0.05, the determined size of correlation calculated by r is significant (Field, 2015).

For correlations between variables with ordinal level of measurement, the Spearman's test was used, which first ranks the data and uses afterwards the Pearson correlation equation. The Spearman test results in a Spearman correlation coefficient called Spearman rho (ρ), which should be interpreted together with the significance value, as described for the Pearson correlation (Field, 2015).

Clustering

For clustering the data, a centroid based k-mean algorithm was used which is based on the distance d between the objects of the data set (p, q) with the Euclidian distance measure:

$$d(p,q) = \sqrt{(q_i - p_i)^2}$$

Before the cluster process starts, a value k needs to be chosen which determines the number of clusters. Then, k centroids are identified and the distance d_i of the data points to the closest centroids are calculated. Lastly, in a repeated process, the mean of each cluster is calculated and new centroids are determined with less differences in the distance measures, until the convergence criteria is met (Uppada, 2014).

3 Results

In this chapter, the results of the quantitative and qualitative analysis of the simulator driving study are represented.

3.1 Outlier

From the data set of 18 participants, one participant needed to be excluded from the analysis of the curve scenario, since this participant did not have the TJA activated when the limitation of the TJA in the curve appeared. Figure 12 shows the TJA mode for the outlier participant 35 seconds before and after the failure, which is marked with a vertical red line. The participant was overriding and deactivating the TJA during the test drive even in non-critical situations.

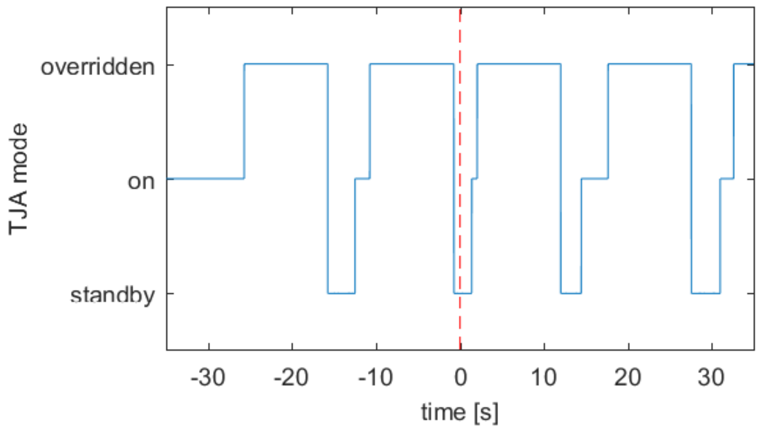


Figure 12: The TJA mode of the outlier participant is shown 35 s before and 35 s after the failure. During the failure start, which is marked in red, the TJA was deactivated and in standby mode. Therefore, the participant was excluded from the analysis.

3.2 Quantitative results

For the data analysis, 5 seconds before and 15 seconds after the failure of the TJA appeared, were examined. This timeframe was adequate to secure that the TJA was working properly before the failure and to observe the complete manual driving recovery of the situation for each participant. During the examined interval, no one of the participants braked, which results in approximately constant speeds during the timeframe, and therefore the section will include only the analysis of the lateral control. Additionally, the results of the gaze behaviour of the participants are presented.

3.2.1 Response times

Since no participant braked after the failure, the reaction time was assessed through the steering reaction time. The reaction times for the seventeen participants are shown in Figure 13 (left) and reach values from -0.01 s to 3.27 s. A negative reaction time of 0.01 s, is due to one participant deactivating the TJA just before the failure started. However, since this participant maintained the TJA activated when possible during the drive, he/she was not taken out for the analysis.

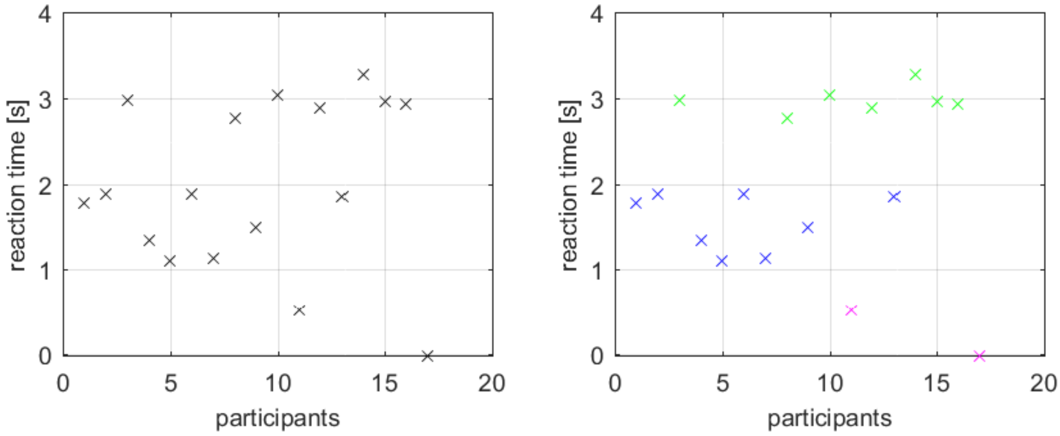


Figure 13: The reaction times of 18 participants (left), which are clustered into three groups by centroid based mean method (right) are shown. Due to the small sample size of the purple group, the group with the shortest and the second shortest reaction time were considered together for the further analysis.

By visual observation, the reaction times can be divided into three groups, which is confirmed by a centroid based k-mean method, clustering the reaction times with a chosen k = 3 into three clusters, as shown in Figure 13 (right). The purple group with the shortest reaction times, contains only two participant which is statistically not reliable to draw conclusions according to Taylor (1997). For higher accuracy, the exclusion of these two participants from the analysis was considered but, due to the small total sample size, it was of interest to examine as many participants as possible. Therefore, the two participants from the purple group were merged into the second shortest reaction time group, which is marked in blue. In the following analysis the participants are clustered into two groups:

- Group 1 (hereafter marked in blue): consists of 10 participants with minimum reaction time of -0.01 s and maximum reaction time of 1.89 s.
- Group 2 (hereafter marked in green): consists of 7 participants with minimum reaction time of 2.76 s and maximum reaction time of 3.27 s.

The results of the t-test ($t(15) = -6.73$, $p < 0.001$) report that the mean of the reaction times of group 1 ($M = 1.30$ s, $SD = 0.64$) is significant lower than the mean of group 2 ($M = 2.97$ s, $SD = 0.16$).

In the next paragraph, the results of the initial correction time and the countersteer time are reported. Some participants reactivated the TJA without executing an initial correction or a countersteer movement and, for this reason, not for all participants an initial correction time and/or countersteer time could be assessed. Hence, the following results include only 15 participants for the initial correction time and 10 participants for the countersteer time.

By plotting the initial correction time over the reaction time, a significant negative correlation ($r = -0,89$, $p < 0.001$) is reported, as seen in Figure 14. A longer reaction time results in a shorter initial correction time and a shorter reaction time leads to a longer initial correction time. The mean of the initial correction time of group 1 ($M = 2.14$ s, $SD = 0.72$) is due to the t-test significantly higher ($t(13) = 4.49$, $p < 0.001$) than the mean of group 2 ($M = 0.78$ s, $SD = 0.35$).

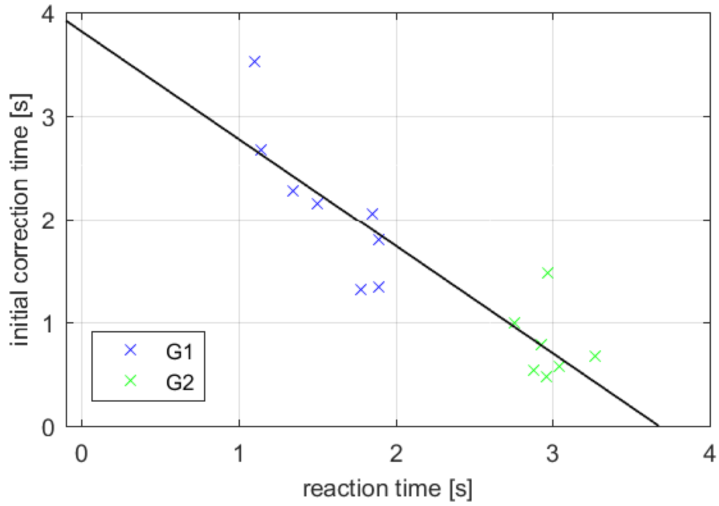


Figure 14: Linear correlation between the reaction time and the initial correction time is found: with a longer reaction time the initial correction time decreases and vice versa.

The participants' countersteer time is pictured over the reaction time in Figure 15 (left) and over the initial reaction time in Figure 15 (right). No significant relationship could be determined (left: r = -0.23 and p = 0.52 right: r = 0.48 and p = 0.16). Between the mean of the countersteer time of group 1 (M = 0.86 s, SD = 0.13) and the mean of group 2 (M = 0.76 s, SD = 0.26) no significant difference was found (t (8) = 0.32, p = 0.76). The duration of the countersteer time seems to be independent from the duration of the initial correction time and of the reaction time.

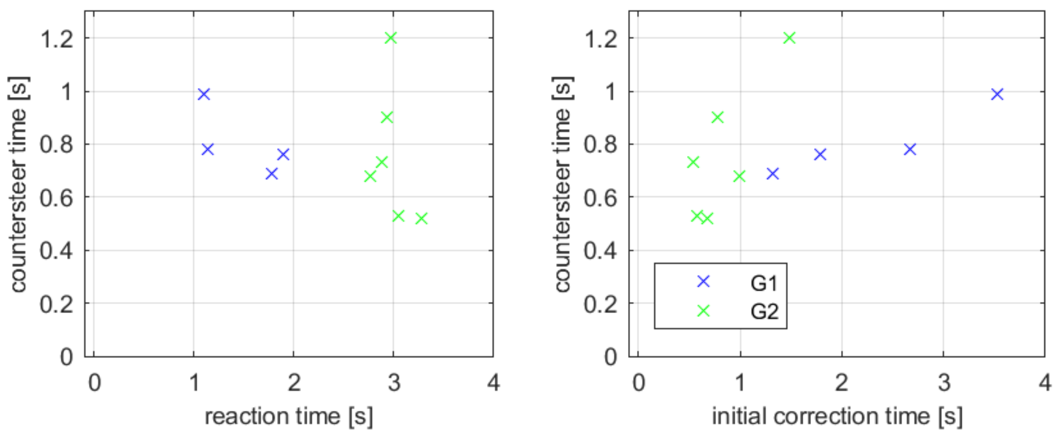


Figure 15: No significant correlation between the initial correction time and the reaction time (left) and the initial correction time and countersteer time (right) is reported.

In Figure 16 (left) the movement time (time interval from response begin to TJA reactivation) is plotted over the reaction time, but no significant correlation is found (r = -0.07, p = 0.79). The mean of the movement time of group 1 (M = 5.54 s, SD = 2.42) does not differ significantly (t (15) = 0.9539, p = 0.3553) to the mean movement time of group 2 (M = 4.50 s, SD = 1.89). Also, no correlation between the reaction time and the response time to final correction (time interval from failure start to TJA reactivation) can be stated (r = -0.07, p = 0.79, Figure 15 right). The average response time to final correction for all participants is 7.10 s (SD=2.36). Consequently, no dependency is found between the participant's reaction time and his/her movement time and his/her recovery time from the automation failure.

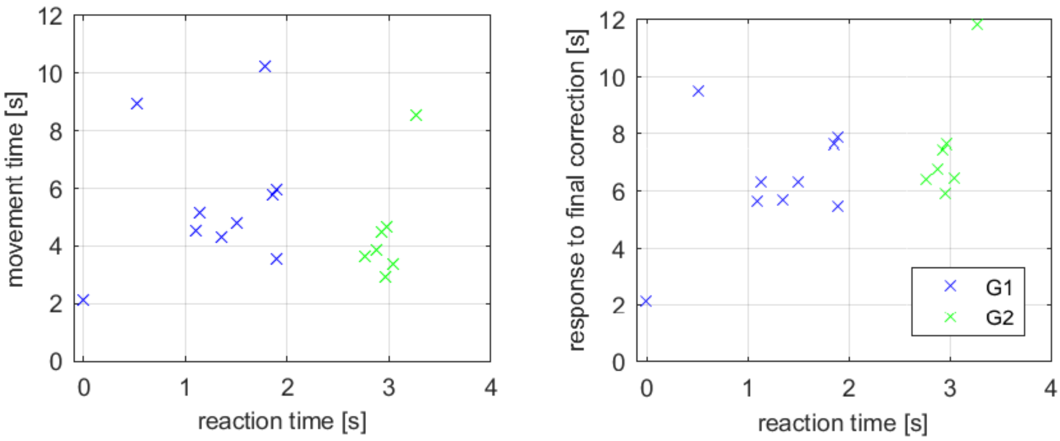


Figure 16: No significant correlation between the reaction time and the movement time (left) and the reaction time and the response time to final correction (right) is reported.

Table 1 summarizes the descriptive statistics (e.g. mean and standard deviation) for the performance times of the two groups.

Table 1: Mean steering performance times of group 1 and group 2 as well as the overall average with the standard deviation are represented as well as the results of the significance test which report if a difference in the means of group 1 and 2 is found.

	Mean Group 1	Mean Group 2	Significant difference	Mean of all participants
Reaction time [s]	1.30 +/- 0.64	2.97 +/- 0.16	Yes	1.99 +/- 0.98
Initial correction time [s]	2.14 +/- 0.72	0.78 +/- 0.35	Yes	1.51 +/- 0.90
Countersteer time [s]	0.85 +/- 0.13	0.76 +/- 0.26	No	0.78 +/- 0.21
Movement time [s]	5.54 +/- 2.42	4.50 +/- 1.89	No	5.10 +/- 2.21
Response time to final correction [s]	6.84 +/- 2.65	7.47 +/- 2.00	No	7.10 +/- 2.36

3.2.2 Steering wheel angle, heading angle and lateral position

After examining the relationships between the reaction time, movement times and the response time to final correction, the next analysis focus is on the steering wheel angle, the heading angle and the lateral lane position of all 17 participants over a time period of 5 seconds before and 15 seconds after the failure (Figure 17). All variables are measured from the lateral centred measurement point, located 0.82 m from the front of the SV, which was introduced in Section 1.1. Each participant and additionally the average values for each group and the overall average are shown. The vertical lines mark the mean steering performance times of all participants: looking from left to the right, the first red line refers to the start of the failure of the TJA. The three following dotted grey lines signalize the response start, the initial correction point and the countersteer point. The red line to the right symbolizes the reactivation of the TJA which equals the final correction.

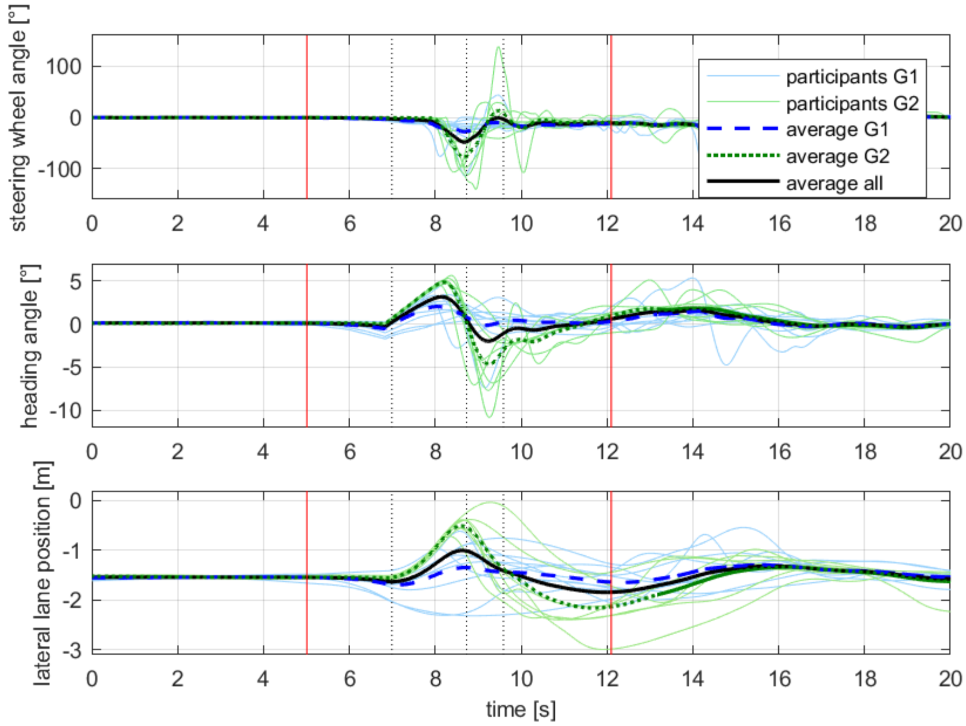


Figure 17: The steering wheel angle, heading angle and lateral lane position is shown over time for the average of all participants and the average of the two groups.

The TJA is responsible for the lateral control of the SV before the failure line and after the reactivation line. However, some participants overrode or deactivated the TJA after the reactivation again by accelerating or steering against the TJA, which will not be further investigated in this thesis.

The vertical lines, symbolizing the average initial correction point and the average countersteer point, show a slight delay compared to the minima and the maxima of the average steering wheel plot. This shift appears due to the fact that not all participants were executing an initial correction and/or a countersteer movement which is why only 10 to 15 participants are considered, whereas all 17 participants influence the average values of the steering wheel angle plot.

Comparing the average values of group 1 and 2, differences in the steering wheel values, the heading angle and the lateral position are visible. Group 2 reaches in all three subplots larger absolute values than group 1. To examine the behaviour of the two groups further the three subplots for steering wheel angle, heading angle and lateral lane position are investigated separately to assess any significant difference between the means of the two groups, by using the t-test (Figure 18 to Figure 20). The significance values are reported frame by frame as negative base 10 logarithm which results in large values standing for small p values. Since the significance is tested at every data point, the t-test is evaluated in the 12 s interval around 600 times for small bin sizes and consequently a conservative significance threshold of p = 0.01 - which equals $log_{10}(p) = 2$ - is used. The results should be regarded as indicative and the significance threshold is plotted in a grey horizontal line. The vertical lines in Figure 18 represent again the average failure start, the average response start, the average initial correction point, the average countersteer point and the final correction. The time interval of interest ends with the average reactivation. In addition to the average lines of the two groups, their standard deviation is plotted shaded in blue for group 1 and in green for group 2.

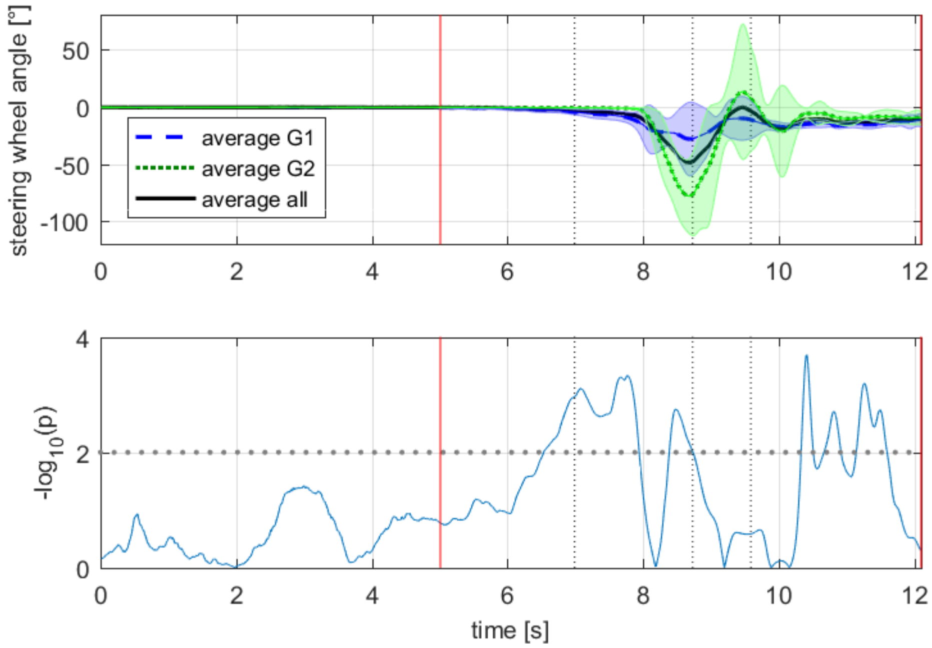


Figure 18: Steering wheel angle in degrees over time of group 1 and 2 with the standard deviation and the significance value p regarding the difference in means of the two groups is shown. In addition, the average steering wheel angle of all participants is plotted in black.

Figure 18 shows the recovery steering profile of the two groups and reports a significant difference in the steering wheel input in the time interval between the failure start and the time of reactivation. In the first 3.5 s after the failure, group 2 shows a quite consistent behaviour whereas group 1 has more variance in the steering input. From the initial correction point until the reactivation group 2 shows higher variance. Overall, participants in group 1 apply significant smaller steering wheel angles compared to group 2. The highest steering wheel angles - in absolute value - are reached at the initial correction point and differ significantly ($t (15) = -2.41$, $p = 0.03$) between group 1 ($M = 48.69°$, $SD = 36.85$) and group 2 ($M = 91.82°$, $SD = 35.56$). The second highest steering wheel angles are reached at the countersteer point, however no significant difference ($t (15) = -0.38$, $p = 0.14$) between group 1 ($M = 11.19°$, $SD = 13.82$) and group 2 ($M = 32.81°$, $SD = 47.63$) can be found. The highest steering wheel angels at the initial correction point differ significantly to the second highest steering wheel angles reached at the countersteering point ($t (32) = -2.77$, $p = 0.03$).

The heading angle plot shows as well significant differences between the two groups after the TJA failure (Figure 19). Similar to the steering angle plot, group 1 shows earlier a higher standard deviation than group 2, due to the fact that participants of group 1 react earlier compared to participants of group 2. Higher heading angles are reached by group 2 and a significant difference between the two groups can be found during the initial correction time ($t (15) = -4.87$, $p = 0.01$, group 1: $M = 2.99°$, $SD = 1.21$, group2: $M = 5.04°$, $SD = 0.36$) and during the initial correction time and the final reaction time ($t (15) = -3.66$, $p = 0.02$, group 1: $M = -2.51°$, $SD = 2.14$, group 2: $M = -6.05°$, $SD =$

2.93). Compared to the two absolute steering wheel angle maxima, the absolute heading angles maxima, before and after the initial correction, do not show a significant difference and change per group by only maximal 1 degree.

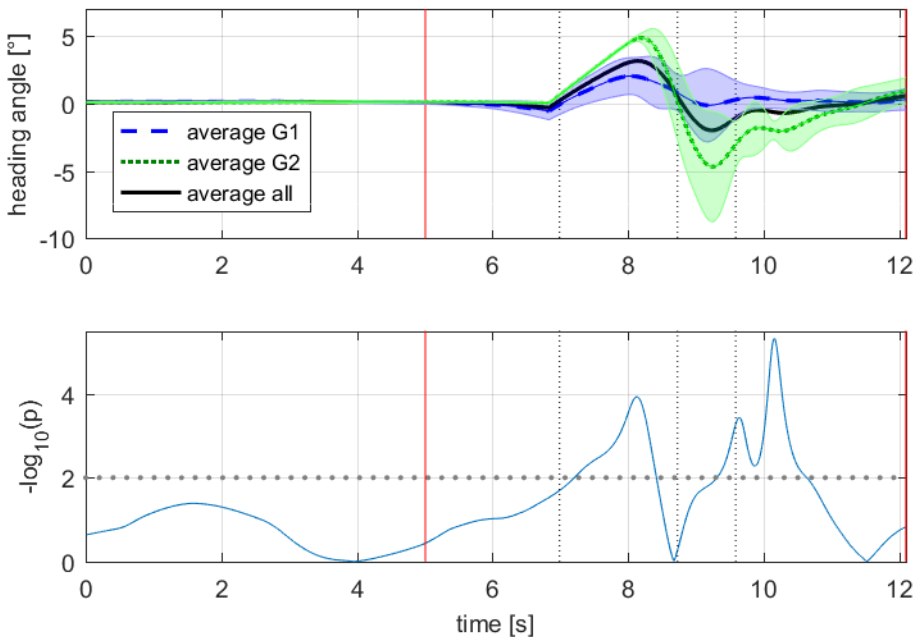


Figure 19: Heading angle in degrees of group 1 and 2 with the standard deviation and the significance value p regarding the difference in means of the two groups is shown. In addition, the average heading angle of all participants is plotted in black.

Figure 20 visualizes the lateral lane position of the two groups with their standard deviation and the significance values based on t-test. The lateral lane position with a value of -1.5 stands for the SV being in the middle of the lane. During the initial correction time point group 1 shows more variation compared to group 2 but overall the values of the lateral lane position are never as extreme as for group 2. A significant difference ($t(15) = -2.28$, $p = 0.04$) between the means of the two groups can be noticed around the time of initial correction point, where group 1 reaches a maximum lateral position of -1.89 m (SD = 0.25) to the left and group 2 drifts to a maximum lateral position of - 2.27 m (SD = 0.43) to the left.

The lateral position was further examined to investigate the maximal lateral lane position reached, measured on the corners instead of the center of the SV. Figure 21 shows the average of the left corner points and the average of the right corner points of the SV for each group and for all participants. The horizontal dashed line at the lane position 0 represents the middle lane and the two grey lines represent the left and right boundaries of the road where the SV is travelling. The two vertical red lines signalize the start of the failure and the time of reactivation of the TJA.

The average of group 2 exceeded the middle line into the lane of the oncoming traffic whereas the average of group 1 did not. Also, group 2 gets close to exceeding the right line.

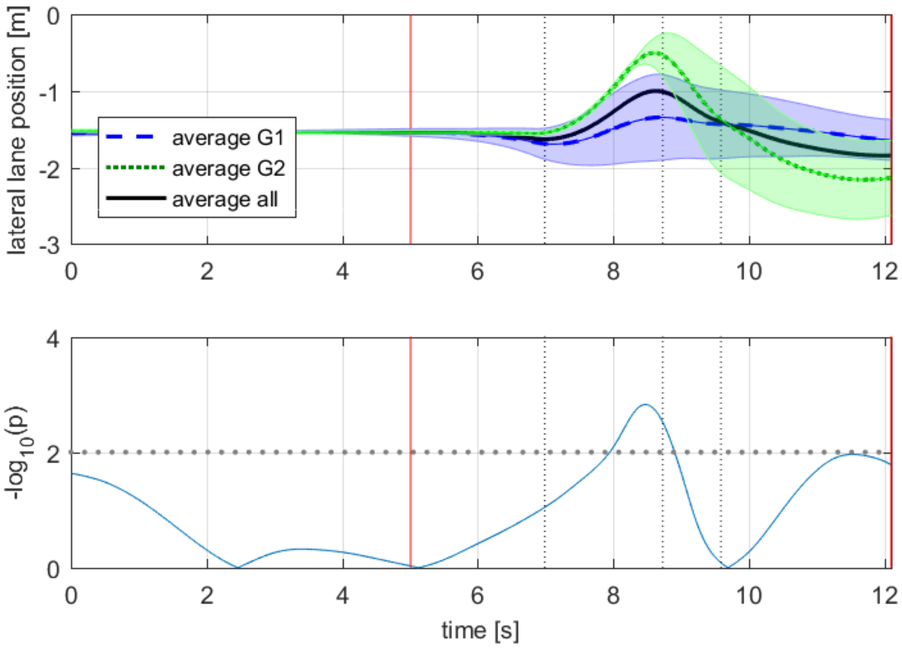


Figure 20: Lateral lane position of group 1 and 2 with the standard deviation and the significance value p regarding the difference in means of the two groups is shown. In addition, the average lateral position of all participants is plotted in black.

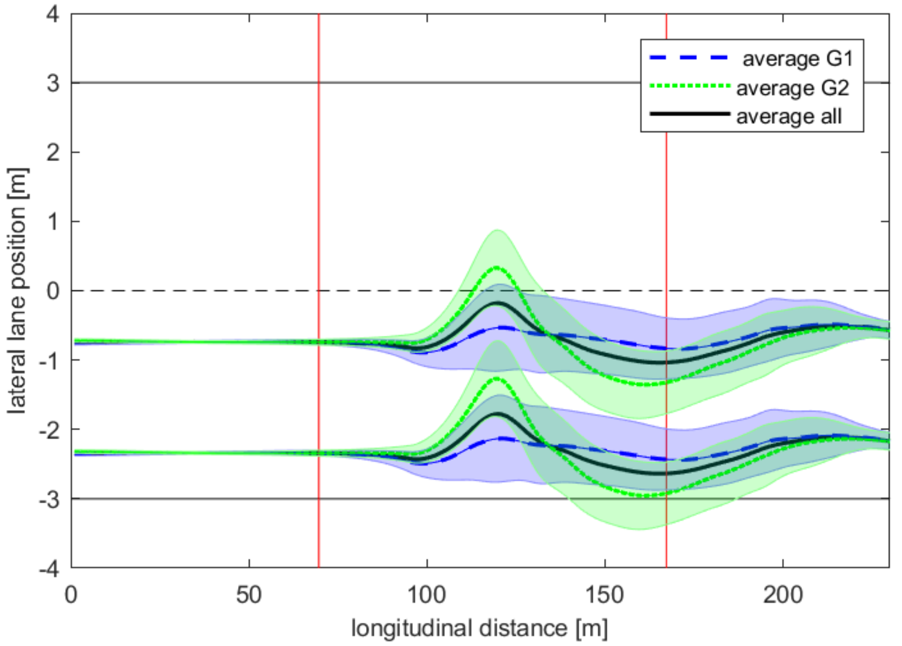


Figure 21: Lateral lane position, measured at the corner points of the SV, over the driven distance with the road in the background is shown for the two groups and for all participants.

3.2.3 Lane deviation

Figure 22 reports the maximum lane deviation towards the reaction time for each participant. The maximum lane deviation measures the maximum distance the corners of the SV drift from the lane center position to the left, in the time interval defined from the failure start to the TJA reactivation. The horizontal dashed line shows the value of lane deviation for which the SVs reach the middle line. Two participants of group 1 and all participants of group 2 cross the middle line and drift into the other lane. A linear correlation between the maximum lane deviation and the reaction time was found with a high significance ($p < 0.001$) and a high correlation coefficient of $r = 0,89$. Consequently, a longer reaction time leads to a greater lane deviation into the lane of the oncoming traffic. Group 1 reaches an average lane deviation of 0.52 m (SD = 0.31), which is significantly lower ($t(15) = -5.17$, $p < 0.001$) than the average of group 2, equal to 1.11 m (SD = 0.21). Based on the maximum lane deviation values, the distance how far the SV drift into the other lane can be calculated. Consequently, group 1 stays in average in the lane with an average distance to the middle lane of 0.18 m whereas group 2 in average exceeds the middle lane and drifts 0.41 m into the other lane. Overall, out of the 17 participants, one crash was reported during the manual driving after TJA failure, being the participant of group 2 with the highest lane deviation of 1.5 m and a reaction time of 2.97 s.

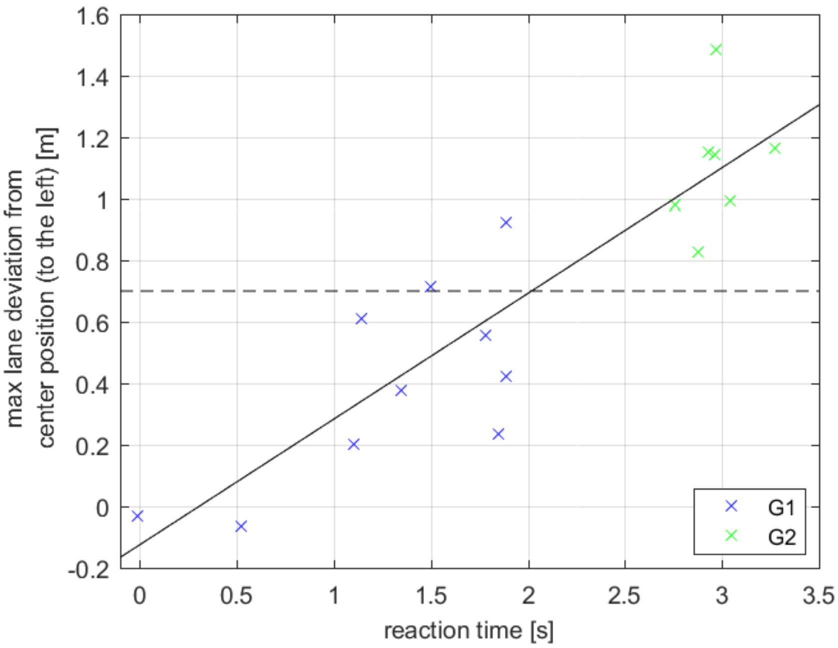


Figure 22: A linear correlation between the maximal lane deviation to the left and the reaction time is noted. The participant with a lane deviation of 1.5 m crashes into the oncoming traffic.

In addition to the maximum lateral deviation, the time which the participants spent outside of the road lane was investigated for group 1 and group 2 (Figure 23). The time spent outside of the lane during the curve scenario was measured in absolute time and relatively in comparison to the response time to final correction of each participant in the curve scenario and therefore is given in seconds and in percentage. The time spent outside of the lane to the right is marked in turquoise whereas the time spent outside to the left of the lane - into the lane of the oncoming traffic - is marked in red. The percentages show per participant the absolute time spent outside of the lane to the left and to the right.

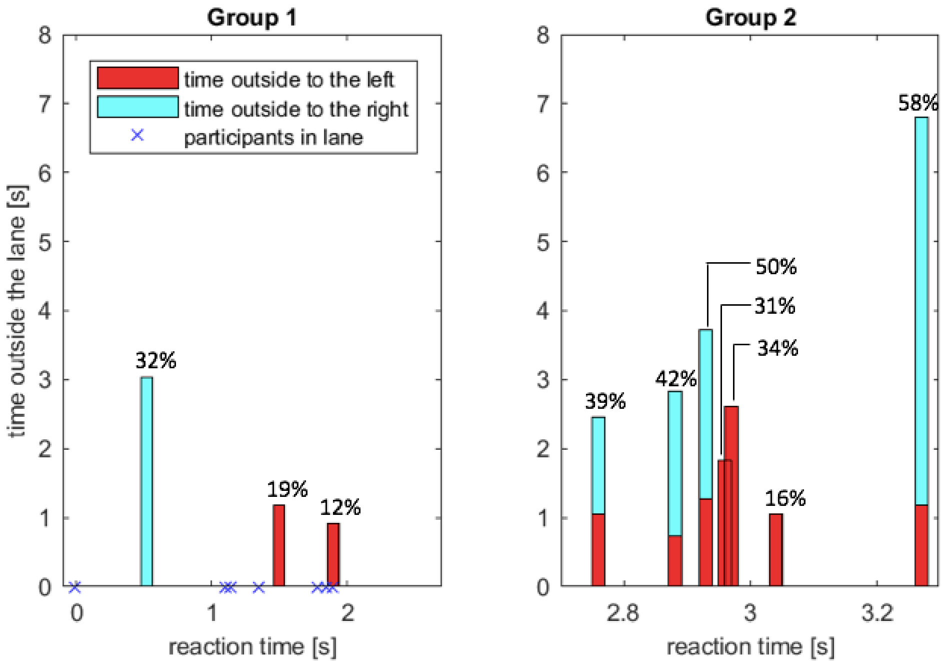


Figure 23: Time spent outside of the lane to the left and to the right measured in absolute values over the reaction time is shown per participant. The total time spent outside of the lane is additionally measured relatively to the response time to final correction and given in percentages.

In Group 1 one participant is leaving the lane towards the right for 32% of his/her manual driving time and two participants are 12% and 19% of their manual driving time outside to the right of the lane. The other seven participants of group 1 were always staying in their lane.

As noticed above, all participants of group 2 left the lane towards the left side into the oncoming traffic lane and four participants additionally drifted outside to the right of their lane. The participant with the highest reaction time spent 58% of the manual driving time outside of his/her lane and reached the maximum time outside the lane of all participants.

Group 1 spent in average 6.25% of the considered time interval with a part of the SV outside of the lane which equals in absolute time 0.51 seconds and is significantly lower ($t(15) = -3.67$, $p = 0.002$) than the time spent outside the lane for group 2 with 38.57% of their manual driving time and a mean of 3.04 seconds. Distinguishing the sides to which the participants left their lane, group 1 reached an average value of 3.05% to the left (= 0.21 s) and 3.20% (= 0.3 s) to the right. On the other hand, group 2 was in average 19.44% (= 1.39 s) of the time in the oncoming traffic lane to the left and 9.12% (= 1.65 sec) to the right.

The described values of lane deviation and time outside of the lane per groups and the values considering all participants are summarized in Table 2.

Table 2: Maximum lane deviation and time spent outside of the lane (to the left, to the right and in total) per group and for all participants.

		Group 1	Group 2	All participants
Max lane deviation	To the left	0.52 m ± 0.32	1.11 m ± 0.21	0.69 m ± 0.45
Time outside the lane	To the left	3.05% (=0.21 s ± 0.45)	19.44% (= 1.39 s ± 0.63)	9.80% (= 0.70 s ± 0.79)
	To the right	3.20% (=0.3 s ± 0.96)	9.12% (= 1.65 s ± 1.03)	9.76% (= 0.86 s ± 1.59)
	In total	6.25% (=0.51 s ± 0.99)	38.57% (= 3.04 s ± 1.85)	19.56% (= 1.55 s ± 1.87)

After examining the lateral steering profile and the maximum lane deviation, a correlation between the situation at response begin and the maximum lane deviation is analysed. Since the steering wheel angle is for all participants 2° at response begin, only the heading angle and the lateral lane position at response begin is compared with the maximal reached lateral lane deviation (Figure 24). The horizontal, grey line symbolizes the middle line and shows that with a maximum lane deviation value of 0.7 m the SV enters the other lane. For both variables a significant high linear correlation is found: the greater the heading angle at the time of the first reaction, the greater is the maximum lane deviation during the manual driving ($r = 0.82$, $p < 0.001$). At response start, group 1 showed in average a heading angle of -0.02° (SD = 0.14), which is significantly smaller ($t(15) = -22.62$ $p < 0.001$) than the mean heading angle of group 2 with 4.47° (SD = 0.61). Observing the lateral lane position at response start (measured in the lateral centered measurement point of the SV), a strong correlation to the maximum lane deviation (measured from the SVs' corners) was determined ($r = 0.89$, $p < 0.001$). The closer the participants are to the lane center (at lateral position = -1.5 m, marked with a grey vertical line) at the moment of the first response, the smaller is their lane deviation during the manual recovery from the automation failure. Group 1 is located in average at a lateral lane position of -1.57 m (SD = 0.08) whereas group 2 drifted significantly ($t(2) = -9.69$, $p < 0.001$) further into the direction of the middle line with a mean lateral lane position of -0.96 m (SD = 0.18). The SVs of group 1 are consequently located in average slightly to the right of the lane center and the SVs of group 2 have their left corners in average at a distance of 0.16 m to the middle line.

With a maximum lane deviation of 0.7 m the SV is crossing the middle line and entering the oncoming traffic lane. According to the correlation between the variables heading angle/lateral lane position and the maximum lane deviation, the SV will cross the middle line when a heading angle of 1.88° and a lateral position of -1.32 m is reached at the situation of response begin.

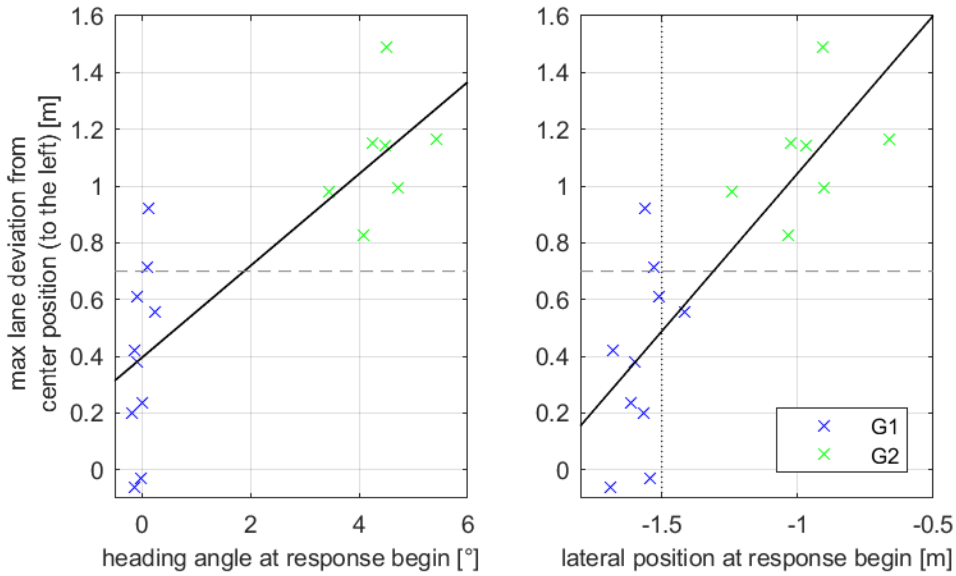


Figure 24: High correlation between heading angle and lane position at response begin to the maximal lane deviation from the center position to the left is found.

3.2.4 Lateral jerk

During the driver simulator study the lateral acceleration of the SV was recorded, from which the lateral jerk was calculated and filtered. The absolute maximum of the lateral jerk during the critical curve scenario of each participant is plotted over the participants' reaction times in Figure 25. A significant correlation between the reaction time and the absolute maximum jerk was found (r= 0.65, p=0.01) which shows that a longer reaction times results in a higher absolute maximum of the lateral jerk. Comparing the two groups, the maximum absolute lateral jerk of group 1 is significantly lower (Whitney U Mann test: U = 65, p = 0.01) with a mean of 6.55 m/s^3, whereas group 2 reached a mean of 18.74 m/s^3.

The absolute maximum lateral jerk value of 42.08 m/s^3 of the participant with the slowest reaction time was investigated in more detail. By examining the steering wheel angle plot, the lateral acceleration and the video log of the participant, a rapid steering behaviour was noted: during 1.1 sec, three steering angle peaks (-140°, -138° and -113°) were reached. Since the maximum lateral jerk of this participants stood out from the other values, the results were additionally examined excluding this participant, reducing then group 2 to six participants. By doing so, group 2 reaches a mean of 14.37 m/s^3 which is according to the Witney U Mann test significantly higher (U = 65, $p < 0.03$) to the mean of group 1 with 6.55 m/s^3. A significant correlation between the absolute maximum lateral jerk and the reaction times of the participants is determined (r=0.6498, p=0.0048).

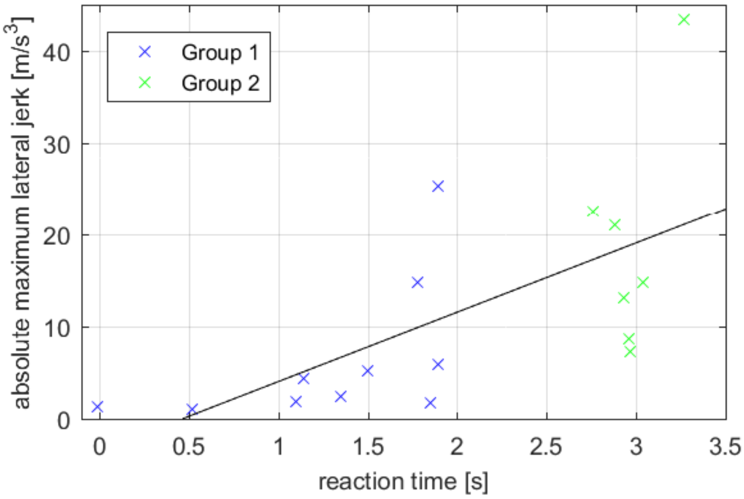


Figure 25: Significant correlation between absolute maximum lateral jerk in m/s^3 and the reaction time of all 18 participants is found.

Two absolute maximum lateral jerk values are found in the recovery manoeuvre of each participant: one between the response start and the initial correction and one between the initial correction movement and the countersteer movement. The values of theses absolute maxima of the lateral jerk before and after the initial correction manoeuvre (ICM) are compared in Figure 26. No significant difference (U = 306, p = 0.7829) between the means of the maximum lateral jerk before (M = 8.78 30 m/s^3) and after (M = 10.29 30 m/s^3) the initial correction movement was found but a significant correlation between these variables can be reported (r = 0.92, $p < 0.001$). A smaller lateral jerk before the initial correction results as well in a smaller lateral jerk afterwards. Group 1 reaches a mean of 5.11 m/s^3 before and 5.30 m/s^3 after the initial correction whereas group 2 shows a mean of 11.89 m/s^3 before and 12.73 m/s^3 after the initial correction movement.

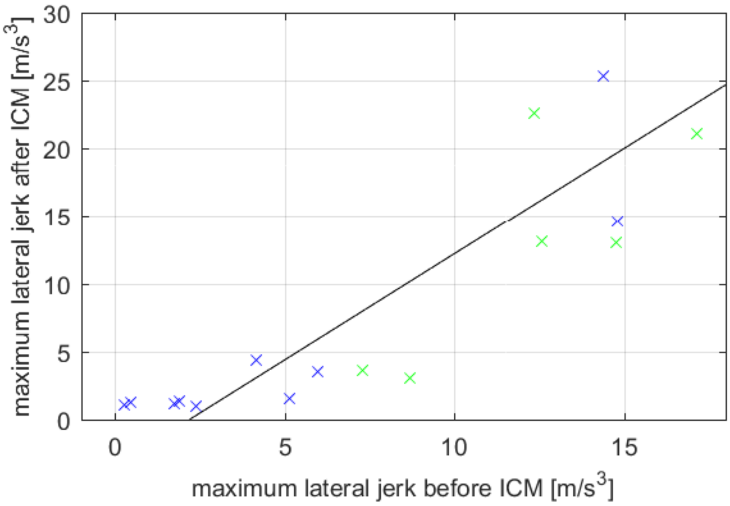


Figure 26: Absolute maximum lateral jerk before and after the initial correction point with a significant correlation to each other.

3.2.5 Gaze

Due to the quality of the raw gaze data, two participants with only 0% and 27.4% valid gaze data over the examined time interval were excluded from the analysis. Hence, for the gaze data analysis, group 1 is reduced to nine participants and group 2 decreases to six participants. For the remaining participants, a valid gaze data mean of 97,45% (SD = 1.89) for group 1 and a mean of 92.60% (SD = 7.50) for group 2 of the considered time were found. The gaze data is sampled at 50 Hz.

To investigate if the fast responding group (group 1) and the slow responding group (group 2) differ in their gaze eccentricity, the groups are analysed separately. The vertical raw gaze eccentricity of each group (positive angles gazes upwards and vice versa) and the dashboard gazes per group are visualized in Figure 27. The average of each group is filtered with a moving three point average and marked in black. The vertical red line shows the start of the failure, the first blue and green line symbolizes the average first response of group 1 (blue) and group 2 (green) and the second blue/green line represents the average reactivation of group 1 (blue) and group 2 (green). Over the observed time frame, the vertical gazes of the participants are recorded mainly between 0° and -5° with some gazes reaching down to -30° for dashboard gazes and even lower gazes before the reactivation of the TJA. During the pre failure period group 1 and group 2 show about the same amount of dashboard gazes, but those gazes almost disappear for both groups in the first 5 seconds after the failure start. In the last 2.5 seconds before the groups' average reactivation of the TJA, an increase of dashboard gazes is found again. The vertical gazes before the reactivation reach higher absolute angles than the values before the failure, which could indicate fixations to the TJA reactivation button, located on the steering wheel.

Figure 28 shows the horizontal gaze eccentricity of the two groups and their median gaze angles, which are smoothened with a moving three point average filter and marked in black. The vertical lines show as in the figure above the failure begin, the average response begin and the average reactivation of group 1 and 2. A positive angle symbolizes a gaze to the left while a negative value stands for a gaze to the right. Comparing the average gazes from the two groups, both groups stay mostly around 0° and therefore maintain a straight look forward. However, the median of group 2 shows higher variation, shifting from a minimum angle of -6.13° to a maximum angle of 15.62° whereas the average gaze of group 2 stays between -3.67° and 3.81°. By visual analysis, group 2 shows overall more gazes to the left. Looking at the time interval between failure start and response begin, group 1 maintains its gazes mainly in a ±10° angle while group 2 shows higher horizontal angles to the left.

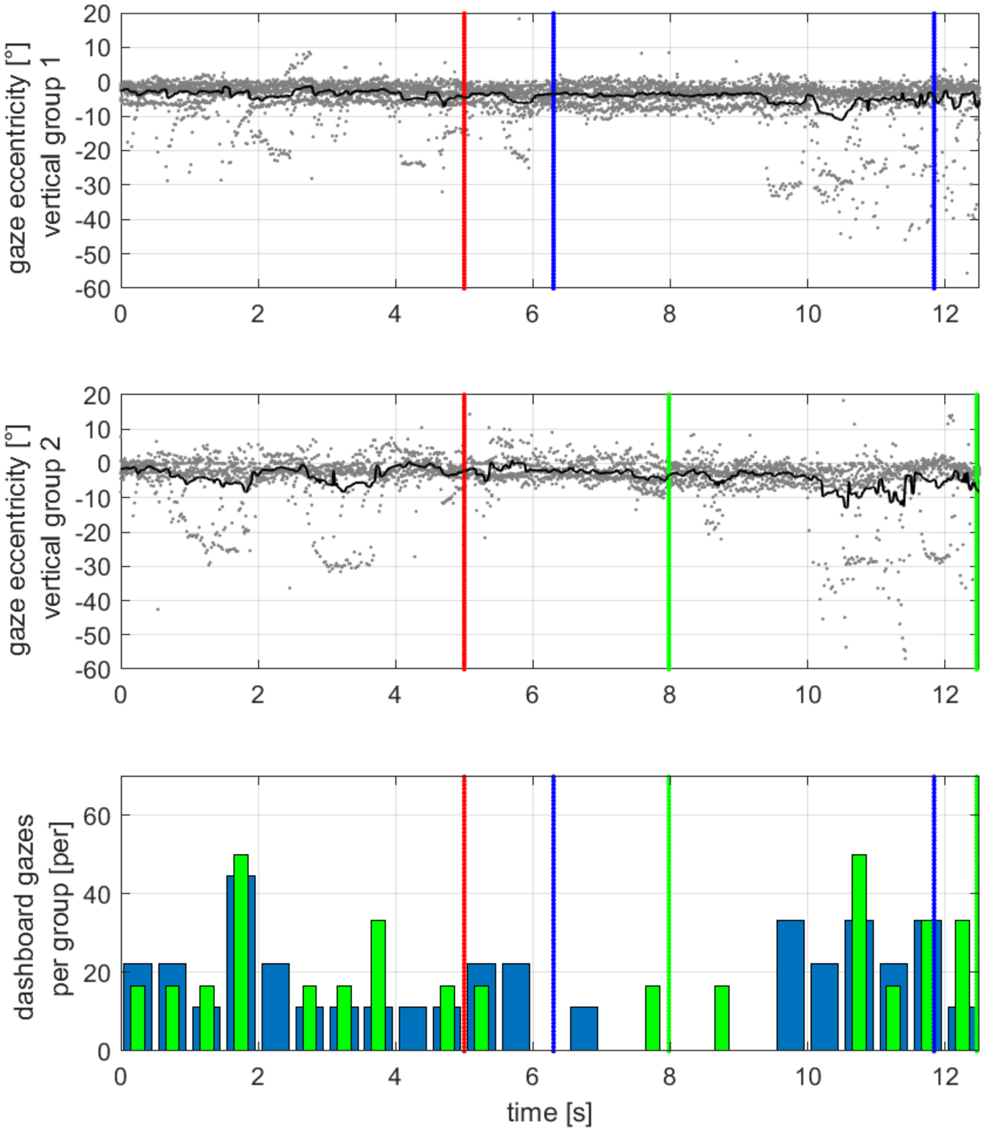


Figure 27: The first and the second subplot show the vertical gaze eccentricity of group 1 and group 2 in degrees over a 12.5 s time interval (5 s before and 6.5 s after the failure). The average horizontal gaze per group is filtered and pictured by black lines. The vertical red line symbolizes the failure start, the first blue/green line represents the average response begin of group 1/group 2 and the second blue/green line indicates the reactivation of the TJA of group 1/group 2. The third subplot presents in percentage how many participants of group 1 (blue) and group 2 (green) looked on the dashboard measured in 0.5 s steps.

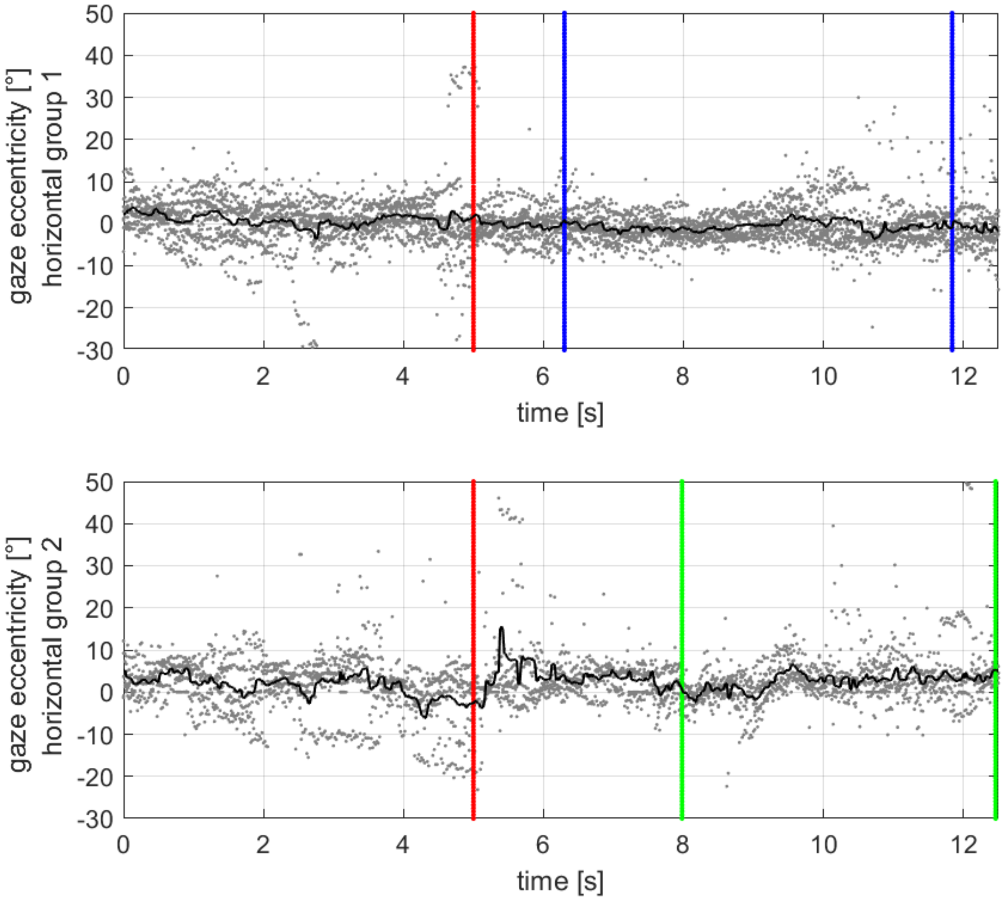


Figure 28: Horizontal gaze eccentricity of group 1 and group 2 in degrees over 12.5 s time interval (5 s before and 6.5 s after the failure) with the average gaze per group, marked with a black line. The vertical red line symbolizes the failure start, the first blue/green line represents the average response begin of group 1/group 2 and the second blue/green line indicates the reactivation of the TJA of group 1/group 2.

3.3 Results of qualitative analysis

The results of the thematic analysis of the interview data, the analysis of the questionnaires and the analysis of the video logs are presented respectively in Section 3.3.1, Section 3.3.2 and Section 3.3.3.

3.3.1 Interviews

The interviews were examined with the thematic analysis. To find appropriate themes, the question 'what could the drivers' reaction be based on?', was investigated by looking for results in the themes 'trust', 'tiredness' and 'discomfort with the lane position'. A participant was counted into a theme as soon as he/she was using the theme name during the interview. However, for the theme 'trust' it appeared that some participants talked about trust in a positive fashion while some mentioned it in a negative form, which led to splitting the overall theme 'trust' into sub-two themes: 'trust' and 'no trust'.

Since not every participant mentioned each theme, information of some participants about themes were missing. Table 3 shows the overall results of the thematic analysis.

Table 3: Results of the thematic analysis of the interviews.

	Group 1	Group 2
Trust	1	4
No trust	3	0
Tiredness	2	3
Discomfort with lane position	6	3

Regarding the theme trust four participants of group 2 mentioned that they trusted the automatic system. In group 1 however, only one participant trusted the system and three participants mentioned that they did not trust the system. The theme "tiredness" was found for two participants of group 1 and three participants of group 2. Discomfort with the lane position of the TJA regarded six participants of group 1 and three participants of group 3.

Summarizing, it could be noticed that group 2 trusted the TJA more than group 1 and group 1 experienced more discomfort with the lateral lane position of the TJA than group 2. However, even if differences between the two groups can be recognized, significant conclusion cannot be drawn since the numbers of participants who talked about the themes are too few.

Additionally, the interview data was examined to try to find explanations of the extreme values in the reaction time with some quotes of the participants. Quotes were picked from the two participants with the shortest reaction times, the participant with the longest reaction time and the participant who crashed into the oncoming traffic.

The participant with the shortest reaction time, who deactivated the system 0.01 seconds before the failure started, said 'the car in front felt too close to me and it felt unnecessary to be so close to the middle line if you don't need to. Therefore, I never let go of the steering wheel and never trusted it […] I wanted to take the curve straighter […] if only the ACC was turned on I would have trusted the system more.' The participant with the second fastest steering reaction time stated also a very close control behaviour to the steering wheel: 'I didn't expect that I need to reactivate the system there again. Maybe I followed the steering wheel too much there?'. Both participants were unsure if a failure of the system appeared or if they were steering too much and therefore a request of a reactivation appeared.

The participant who crashed into the oncoming traffic in the other lane explained his/her behaviour with the statement: 'The car just continued to drive, it was scary. […] the curve was so obvious, even an automatic system should not crash with the cars of the other lane.' The participant with the slowest reaction time stated some discomfort with the simulator ride: 'when it is braking and accelerating it feels weird in the head, not sea sick but weird' and mentioned a different behaviour of him/her due to being in a simulator: 'You have in mind that you are sitting in a simulator and that the system will brake for you, so you should not brake but in the last moment you can't stop yourself and then you need to brake.' The last quote does not refer to the curve scenario but rather the braking scenarios in the simulator drive, but it gives a hint about the thoughts of the participant during the simulator experience, which influences the behaviour in the steering failure situation.

3.3.2 Questionnaires

The answers of the questionnaires are plotted against the reaction time of the participants and shown in Figure 29 and Figure 30.

To determine if a correlation between the information asked to the participant and his/her reaction time, the Pearson's correlation coefficient *r* was calculated. The statistical results are shown in Table 4.

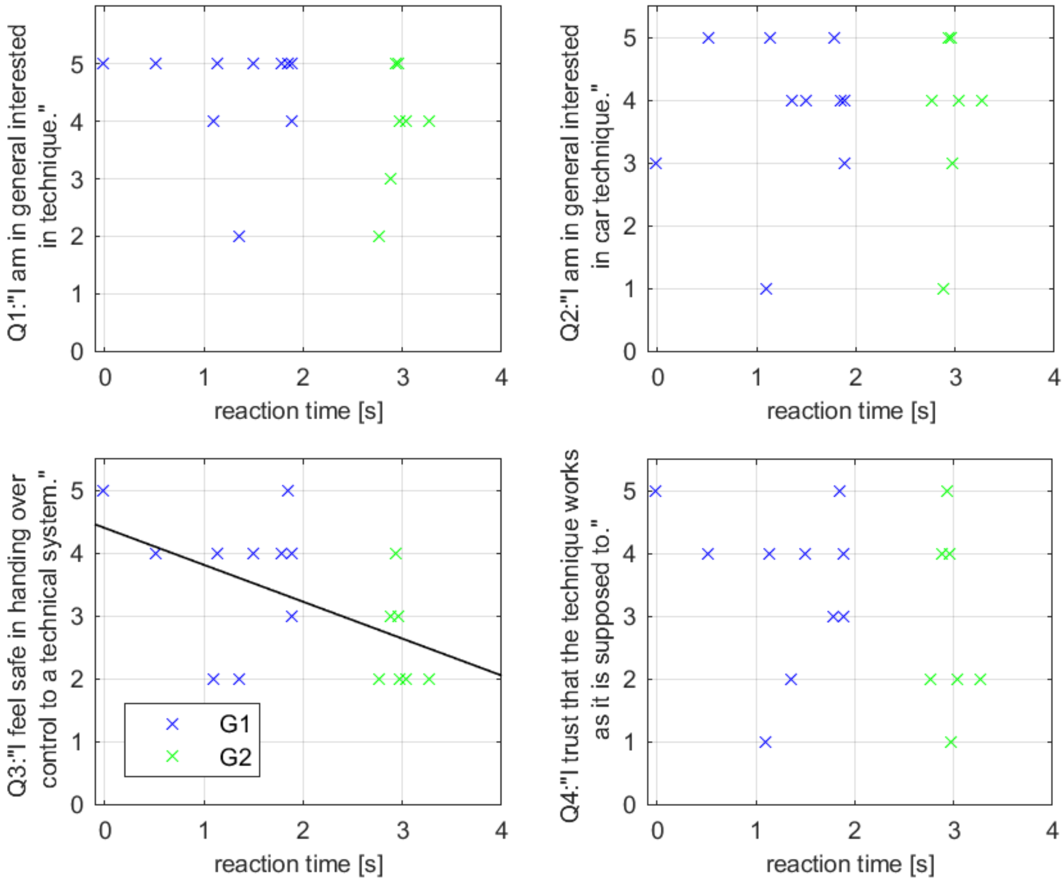


Figure 29: The participants' answers of four closed questions (question 1 to question 4), given before the simulator ride with the possibility to choose between 0 (not true) and 5 (true), are plotted of the reaction time of the participants.

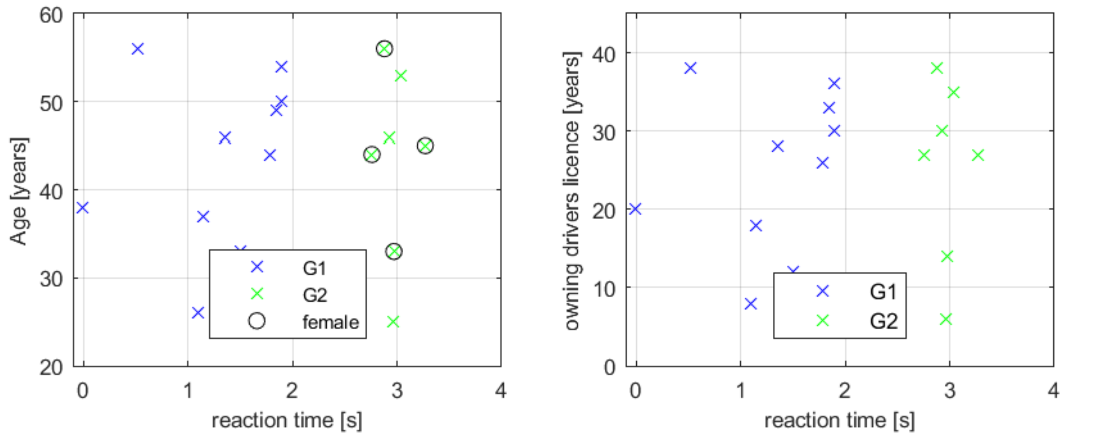


Figure 30: The participants' answers of two open question (question 5 and question 6) about age, gender and the years of ownership of a driver licence, are plotted over the reaction time of the participants.

Table 4: Results of the statistical analysis of the answers of the questionnaires to the reaction times of the participants. The t-test reports for h=1 a significant difference in the answers between group 1 and group 2 regarding a specific question.

	Significance *p*	Correlation coefficient *r*	Significant difference between two groups
Question 1	0.2796	- 0.2782	No (U = 104.5, p = 0.175)
Question 2	0.9229	0.0254	No (t (15) = 0.135, p = 0.895)
Question 3	0.0297	- 0.5272	Yes (t (15) = 2.386, p = 0.031)
Question 4	0.2614	- 0.2885	No (t (15) = 0.966, p = 0.349)
Question 5	0.7617	0.0795	No (t (15) = 0.032, p = 0.975)
Question 6	0.7204	0.0937	No (t (15) = -1.301 p = 0.211)

The results of the questionnaires show that only for the answers of question 3: 'I feel safe in handing over control to a technical system' a significant correlation to the participants' reaction times was found: the more the drivers felt safe, the quicker they reacted to the TJA failure. For the same question, a significant difference between the means of the answers of the two groups was identified.

In question 5 not only the age but as well the gender of each participant is displayed. All four women participating in the driving simulator study are part of the slow responding group 2. However due to the small sample of women no significant conclusions can be drawn.

3.3.3 Video logs

The video logs of each participants were investigated regarding two topics:

- Hand position on the steering wheel while driving into the curve
- Change of hand/foot position before the curve

The hand position, in which the participants enter the curve, was judged after the measurement of De Waard et al. (2010), which categories different hand positions on the steering wheel in low, medium and high control. Any change in the position of hands, fingers or feet, was interpreted as a sign that the participant recognizes the curve as a more critical situation and prepares for.

The results of the hand position scoring were compared with the reaction time of the participants (Figure 31). In group 1, three participants had a high control position, two participants had medium control position and four participants had low control of the steering wheel. All participants with low steering wheel control of group 1 changed their hand/foot position before the curve as well as one participant with medium and one with high steering wheel control. In group 2 however, all participants had low control of the steering wheel and only one participant of group 2 changed the physical position before the curve. All other participants of group 2 remained in their hand/feet position before entering the curve.

It is worth noticing that not every change of hand position does result in an improved performance. In the case of the participant of group 2 mentioned above, he/she had his/her right hand located on the steering wheel before the curve and removed the hand just before entering the curve. At the time the participant realized that manual takeover was required, the participant demanded extra time to put his/her hand back to the steering wheel and react to the critical scenario.

With the Spearman test a significant linear correlation between the reaction time and the steering wheel control was found (ρ = -0.4854, p < 0.0483). With a lower steering wheel control the reaction time increases.

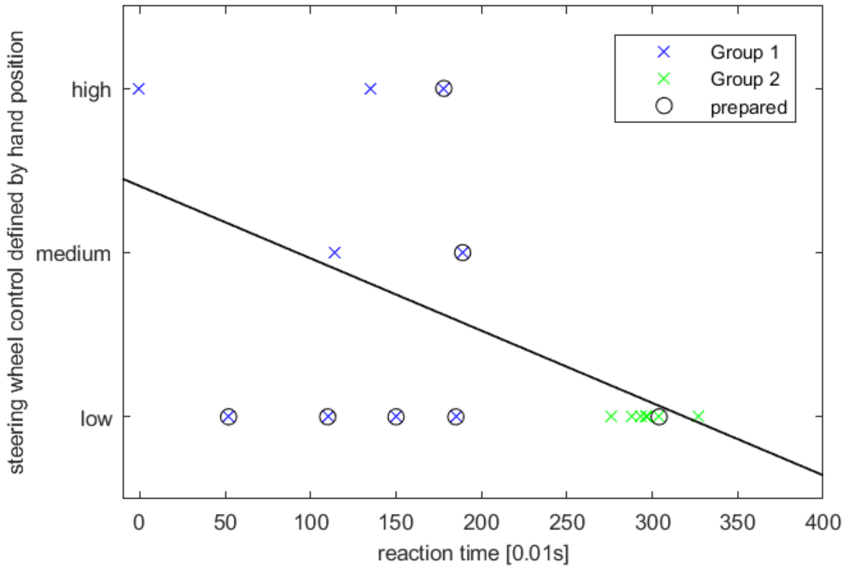


Figure 31: The steering wheel control and the preparedness of each participant while entering the curve scenario is shown.

4 Discussion

The present thesis analysed drivers' reaction to a failure of TJA occurring in a curve. Quantitative analyses of time-series data (e.g. steering wheel angle, heading angle, lateral jerk) and qualitative analyses of interviews, questionnaires and video data were performed.

The results show that all participants reacted to the critical scenario by steering and not by braking. The same response to an analogous scenario was found by Dinparastdjadid (2017), who performed a driving simulator study with 44 participants. This finding answers the first research question regarding what response follows the automation failure in a curve scenario.

The results of the lateral control analysis showed that the corrective steering actions (response begin, initial correction, countersteering, final correction) do not show similar behaviour for all participants. By examining the participants' reaction times, an average reaction time of 1.99 s was found, which is comparable to the steering reaction time of 2.01 s to a takeover request (warning is given) in lane change scenarios found by Eriksson et al. (2017). Due to the appearance of clusters during the visualisation of the quantitative data, two groups were identified, one fast responding group (group 1) with a mean reaction time of 1.30 s and one slow responding group (group 2) with a mean reaction times of 2.97 s. The stated reaction times answer the second research question regarding the response begin to automation failure. The slow responding group 2 is presenting around 40 percent of all participants. Strand et al. (2014) found that around 30% of the participants could not respond in time to a level 2 SAE automation failure in a rear end scenario and collided with the front vehicle. Finally, De Waard et al. (1999) reported, in a merge in scenario where drivers with automated functions needed to brake to avoid a collision, 65% of participants with late break response and insufficient take over performance. Based on these studies and the findings of this master thesis, there is evidence to state that not all drivers react in the same manner to the system failure.

The slow responding group reached significantly higher absolute maxima values in the steering wheel angle, the heading angle and the lateral lane position compared to the fast responding group. Looking at the maximum lane deviation reached by the two groups during manual driving, the slow responding group drifted 1.11 m to the left whereas group 1 stayed in lane and went less than half the distance (0.52 m) towards the middle line. One crash with the oncoming traffic of a participant of the slow responding group was reported. The maximum lane deviation, used in Dinparastdjadid (2017) as a performance measurement of a smooth transition from automation to manual, shows that the performance of the two groups differ significantly. While the fast responding group performed a safe transition to manual, all participants of the slow responding group entered the other lane where oncoming traffic was travelling with high frequency. As well, the time spent outside of the SV's lane, measured relatively to the participants' response times to failure (time from failure start to reactivation of the TJA), is for group 2 higher than for group 1 (39% vs. 6%). The maximum lane deviation and the time spent outside the lane in curve scenarios is hard compare to other studies due to different speed and different curve radius. In the specific scenario analysed in this thesis, the significantly worse performance of the slow responding group might indicate that the participants were out of the loop when the failure occurred.

Furthermore, the process leading the participants to exceed the lane was analysed more in detail by looking at the maximum lateral jerk. The maximum absolute lateral jerk can be an indicator to explain if the lane was exceeded by the driver intentionally or unintentionally. The assumption is that a higher later jerk signalises a higher likelihood for an unplanned line crossing (Kircher et al. 2014). The results of the jerk show significant differences between the groups, being the absolute maximum lateral jerk of 6.55 m/s^3 for group 1 and of 14.37 m/s^3 for group 2 (excluding the participant with the very high jerk value). Kircher et al. (2014) found in a similar curve scenario in a driving simulator study, a maximum lateral jerk of about 10 m/s^3 for the participants reacting to a steering failure of a system similar to TJA while a reference group with manual driving experienced a jerk around 5 m/s^3. The lower jerk of the participants driving with automation in Kircher's study compared to group 2 can be explained due to a warning which was given about the failure of the system while this was not the case in the driving simulator study analysed in this thesis. However, group 1 has lower values of lateral jerk compared to the participants using automation driving functions in Kircher's study being the results of group 1 and the participants driving manually in Kircher's study are comparable. Looking at the overall results in the two studies, it can be assumed that group 1 seemed in control of the situation and therefore reacted to the failure similar as the manual driving participants in Kircher's study. Group 2 however, was surprised by leaving the lane which resulted in unplanned, rapid driving manoeuvres. Considering further that the slow responding group was in the other lane with high frequently opposing traffic, the steering performance of group 2 aimed to avoid a crash. According to Dingus et al. (2006) who defined near crash situations as any scenarios which demand prompt, evasive manoeuvre to prevent a collision by the subject vehicle or any other road user, the slow responding group was experiencing near crash scenarios and one participant even a crash. The maximum lateral jerk values seem to strengthen the hypothesis that the slow responding group 2 was out of the loop when the failure occurred.

Taking into account the results of the video log analysis regarding the hand position judgement after De Waard et al. (2010) and the scoring if participants changed their hand/foot position before the curve, a high concordance with the drivers' reaction times was found. The fast responding group had either higher steering wheel control during driving into the curve or the participants had low steering wheel control but changed their hand/foot position before the curve whereas the slow responding group maintained their physical position with low steering wheel control while entering the curve. De Waard et al. (2010) who defined the categorization of the steering wheel control used in this thesis, found a correlation between mental workload of the driver and the drivers' hand position. In addition, De Waard stated that swapping the steering wheel control, reflects a change in workload and control demand. Although in this thesis not the change of the steering wheel control level was examined, but the general change of hand/foot placement, a hypothesis can be stated that with changing the physical position on the steering wheel/pedals, the drivers recognised the curve as situation with higher control requirement and 'prepared' physically for it. However, since previous research did not investigate this matter, future studies should look if changes in hand/feet position might be an indicator of a better situation awareness and a preparation for the curve. Louw et al. (2015) found strong connections between lacking vehicle feedback (no hands on the steering wheel) and out of the loop behaviour. Group 1, with low steering wheel control might have experienced very low haptic feedback from the vehicle which might have reduced their situation awareness. The higher steering wheel control of group 1 may provide stronger vehicle feedback and show higher workload of these participants. Altogether, these findings seem to support the hypothesis that the slow responding group 2 was out of the loop while the fast responding group 1 is focusing on the driving situation.

Regarding the monitoring of the situation before and during the failure, the results of the gaze behaviour present that both groups showed an even amount of dashboard gazes before the failure. After the failure, the dashboard gazes almost stopped until 2.5 seconds before the reactivation of the TJA, when both groups started glancing down at the dashboard or/and the reactivation button on the steering wheel again. Comparing the lateral gazes of the two groups, the gazes of the fast responding group are located in average between $\pm 3°$ which indicates straight forward looks while the slow responding group shows more variance, especially to the left side with average gazes up to 16°. Gazes to the left show no common gaze behaviour in a right curve, which might lead to the assumption that participants of group 2 were looking at the oncoming traffic instead of the road. Although the gaze data set was quite small due to insufficient gaze data quality of some participants, indications of the gaze eccentricity could be given and in context with the other found parameters, it could support the finding of group 2 being out of the loop.

The qualitative analyses were performed to find a possible explanation of the results obtained with the quantitative analyses. Looking at the results of the interview data more participants of the slow responding group 1 felt uncomfortable with the lane position of the SV. Complains about the distance to the lead vehicle or the distance to the middle line were stated, which might have increased their attention to the situation. Based on the interview analysis, the slow responding group 2 stated higher trust to the TJA compared to group 1. It might indicate over trust to the automated driving function which is supported by single quotes of the participants and could cause decrease of situation awareness. However, in the statement 'I trust that the technique works as it is supposed to' of the questionnaire, no correlation between the participants' answers and their driving performance was found. No correlation could be stated either between the participants' interest in technique, their age or the time of owning their driver license to the takeover performance. The only statement that revealed correlation to the reaction times was 'I feel safe in handing over control to a technical system'. Participants who felt safer in handing over control to a technical system reacted faster to the automation failure. This correlation might be based on that participants who felt safe in handing over control to automation, know and understand the ability and limitations of the system and therefore performed better. The slow responding group, who did not feel as safe in releasing control to the system might have not understood the system fully and therefore felt unsecure in using it. However, the qualitative analysis is not sufficient to draw conclusions about drivers' reaction to the failure so further research is suggested. Additionally, the questionnaires showed that all female participants were part of the slow responding group 2. However, only four women were included in the sample and therefore, further research should be conducted to define if gender could have an influence on the takeover performance.

Looking at the extended research question a consistent clustering of the participants could be found. The two identified groups differ significantly in their reaction time, steering input, maximum heading angles and maximum lane deviation, time spent outside of their lane and their maximum lateral jerk values. Additionally, different steering wheel control and changes of hand/foot position before the curve could be reported. The gaze eccentricity indicates differences between the groups although the gaze data are too few to draw conclusions. The qualitative analyses of questionnaires and interview data did not reveal great significant differences between the two groups. Overall, different takeover performances between the two groups were found, revealing evasive recovery performance to prevent crashes for the slow responding group 2 which let assume that these participants are out of the loop while participants from group 1 are responding safe and show rather a lane corrective performance.

In addition, this study showed that the initial situation at response begin regarding lateral position and heading angle of the participants, is highly correlated to the maximal lane deviation reached later during the recovery process. These results stand in line with the findings of Dinparastdjadid et al. (2017) and can offer information to the design of warning systems of ADAS for example. If certain heading angles and lateral lane positions are exceeded before the first driver's reaction takes place, the following driving performance, regarding maximum lane deviation, seems to be deteriorated with possible negative consequences (e.g. crash with oncoming traffic). In this thesis heading angles greater than 1.88° and a lateral position greater than -1.32 m at response begin resulted in the SV crossing the middle line and entering the opposing traffic lane. These stated values should be examined further with a bigger sample of participants and might change depending on the curve scenario. The values of the critical heading angle and lateral lane position at the first response situation, predicting a lane exceedance, are additionally dependent on the curve radius and the SV speed and would need to be studied in more detail to identify thresholds which are valid for different curve scenarios.

Also, the fact that participants from the fast responding group 1 are located slightly to the right of the lane center during response begin, is interesting for the design of automated driving. Some participants of group 1 want to take the curve straighter instead of following the lane center. This is supported by one participant taking over the manual driving just before the failure happened and another participant reacting after only 0.5 seconds from the failure start and their interview statements 'I wanted to take the curve straighter.' These findings are in line with (Treffner at al. 2002) who stated that instructor drivers tend to straighten out the corner of curves. For the design of automated driving, the mimic of human behaviour during driving is extremely important and, therefore, consideration about straightening the trajectory in curves should be taken into account for some drivers.

Observing the steering response closer, a correlation between the reaction time and the initial correction time was found. A long reaction time forces the driver to a very quick initial correction probably caused by the close distance to the other lane with the oncoming traffic during the response start. Drivers who responded early to the TJA failure and therefore showed a short reaction time and a fairly centred lateral lane position at response begin, took more time for the following initial correction to ensure a higher stability of the vehicle. The correlation of reaction time and initial correction time could be used for the design of automated driving functions in critical scenarios, to make automated driving's reaction as similar as possible to humans' reactions. However, no correlation was found between the reaction time and the countersteer time: the duration of the countersteer movement seems to be independent of the reaction time and the initial reaction time. As well, the recovery time (response time to final correction) seems to be independent from the reaction time of the participant. The average movement time is 7.10 s: the slow responding group shows a mean movement time of 7.47 s which does not differ significantly from the reached value of the fast responding with 6.84 s. This latter remark also answers the third research question regarding how long it takes the driver to recover from the automation failure. It needs to be noted that the message which appeared in the landscape to remind the participants to reactivate the system could have influenced the drivers to reactivate the TJA earlier as they would have done it without reminder.

4.1 Limitations

The present study has some limitations like the analysed data set is collected in a driving simulator, which can show differences to naturalistic driving data and tend to provide relative validity rather than absolute validity. For example, during the occurring crash, the colliding vehicles were just driving through each other and no lateral acceleration was measured which effected the lateral jerk results. Besides the message, which appears in the landscape to remind the participants to reactive the TJA might have influenced the driving performance and pushed the participant to reactivate the system and therefore reduced the response time to final correction. As well, the lead vehicle driving in the curve very closely to the center line, could have influenced the participants reaction in the curve scenario. Additionally, not every participant felt comfortable with the standardized time to the lead vehicle of 1 s, which represents according to the society of automotive engineers the minimum time interval which must be given if no additional safety features are included (SAE J2399, 2014). The short time to the lead vehicle might have changed the natural driving behaviour of participants. Automation failures are quite unlikely to appear, but in this simulator study the participants experienced three longitudinal failures and one automation failure in a curve in a time interval of 45 minutes which might have prepared the participants to the takeover situations. In naturalistic data drivers might be more surprised and show a different response performance since they have never experienced an automation failure before. In addition, the uncommon environment and the feeling of being observed might have affected the driving performance. Lastly, the analysed sample with 17 useable participants was quite small, especially for analyses where a part of the participants needed to be excluded, like the gaze analysis.

4.2 Future research

The finding of this thesis might build a base for modelling the drivers' reaction in emergency situations in curve scenarios. For that, the high dependency of the initial correction time to the reaction time might be considered, while this correlation might be as well interesting for the improvement of the design of ADAS in critical scenarios. In addition, the heading angle and the lateral lane position of the vehicle, seem to be highly correlated to the lane deviation and therefore present important variables to implement warning systems for the driver. To identify exact thresholds for critical heading angles and lateral lane positions, which can predict lane exceedance of the vehicle, further research must be performed with bigger sample sizes and under consideration of the SV's speed and the curve radius. Additionally, future research might examine deeper the relationship between the steering wheel control and the two identified driver behaviours. If high steering wheel control improves significantly resuming control in case of automation failure, the requirements or advices for hand position on the steering wheel while using the ADAS (SAE level 2) should be adapted.

To erase the limitations of a driver simulator study, an analysis of naturalistic data with a bigger sample size could progress research in this field.

5 Conclusions

In this thesis work the drivers' reaction to automation failure of a SAE level 2 system in curve scenarios was examined. Data of 17 participants, measured in a moving based driving simulator, was analysed and provided three key results.

First, during the analysis consistent cluster were found, which showed that not all participants were responding to the automation failure in the same way. Two groups, defined by clustering the reaction time, were identified which differed significantly in their recovery performance. The slow responding group showed late first responses resulting for all participants in unplanned lane exceedance followed by strong steering manoeuvres with high lateral jerks. In this group one crash with the oncoming traffic was reported while all other participants experienced near crash scenarios. Together with the low steering wheel control and no recorded 'preparation' for the curve and higher scattered lateral gazes, the results seem to show that the slow responding group was out of the loop when the failure appeared. The fast responding group in contrast, shows milder steering wheel input with less than half of the lane deviation reached by the slow responding group. The lateral jerks are more comparable to manual driving performances and as well the steering wheel control reminds with higher controlled hand positions on manual driving. Compared to the slow responding group, the fast responding group showed rather lane correction performance than evasive manoeuvres to prevent crashes. These conclusions show that during the analysis of drivers using automated driving functions, not only one reaction time value and one lane deviation value can be used to assess the overall performance. Rather clusters for similar driving performances should be observed to describe a detailed transition to manual. Second, a high correlation between the maximum lane deviation and the situation at response begin, regarding heading angle and lateral lane position was found. This finding might provide important information for the design of warning systems and for automated driving functions in critical situations. To identify concrete thresholds for the heading angle and the lateral lane position, valid for different curve scenarios, further research is required. Third, the reaction time and the initial correction time are highly correlated, whereas no correlation to the response time to final correction was found. Also, this finding can be applied for the design of advanced driver assistant systems and automated driving to mimic a response similar to the human performance.

6 References

Bagdadi, O., & Várhelyi, A. (2013). Development of a method for detecting jerks in safety critical events. *Accident Analysis & Prevention*, *50*, 83-91.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative research in psychology*, *3*, 77-101.

Cohen, J. (1992). A power primer. *Psychological bulletin*, *112*, 155-159.

Davis, L.C. (2004). Effect of adaptive cruise control systems on traffic flow. *Physical Review E*, *69*, 066110.

De Waard, D., Van den Bold, T.G., & Lewis-Evans, B. (2010). Driver hand position on the steering wheel while merging into motorway traffic. *Transportation research part F: traffic psychology and behaviour*, *13*, 129-140.

De Waard, D., Van der Hulst, M., Hoedemaeker, M., & Brookhuis, K. A. (1999). Driver behavior in an emergency situation in the Automated Highway System. *Transportation human factors*, *1*, 67-82.

Dikmen, M., & Burns, C.M. (2016). Autonomous driving in the real world: Experiences with tesla autopilot and summon. In *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 225-228). New York, NY, USA: ACM.

Dingus, T.A., Klauer, S.G., Neale, V.L., Petersen, A., Lee, S.E., Sudweeks, J.D., Perez, M.A, Hankey, J., Ramsey, D.J., Gupta, S., Bucher, C., Doerzaph, Z.R., Jermeland, J. & Knipling, R.R. (2006). The 100-car naturalistic driving study, Phase II-results of the 100-car field experiment. Washington, DC, USA: National Academy of Science.

Dinparastdjadid, A., Lee, J.D., Schwarz, C., Venkatraman, V., Brown, T.L., Gasper, J., Gunaratne, P. (2017). After the fail: How far will drivers drift after a sudden transition of control. In *Proceedings of the Fourth International Symposium on Future Active Safety Technology – Towards zero traffic accidents*, Nara, Japan: SAE of Japan.

Endsley, M.R., & Kiris, E.O. (1995). The out-of-the-loop performance problem and level of control in automation. *Human factors*, 37, 381-394.

Eriksson, A., Petermeijer, S.M., Zimmerman, M., De Winter, J.C.F., Bengler, K.J., & Stanton, N.A. (2017). Rolling out the red (and green) carpet: supporting driver decision making in automation-to-manual transitions. *IEEE Transactions on Human Machine Systems*, under review.

Federal Transit Administration (2018): Transit Automation Research. Available online at https://www.transit.dot.gov/automation-research.

Field, A. (2015): Correlation. In *Discovering statistics using IBM SPSS statistics. 4th Edition* (pp. 262-292). Los Angeles, CA, USA: SAGE.

Gold, C., Damböck, D., Lorenz, L., Bengler, K. (2013). "Take over!" How long does it take to get the driver back into the loop?. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Volume 57* (pp. 1938-1942). Los Angeles, CA, USA: SAGE.

Jansson, J., Sandin, J., Augusto, B., Fischer, M., Blissing, B., Källgren, L. (2014). Design and performance of the VTI Sim IV. Poster session presented at *Driving Simulation Conference* (pp. 128-138). Paris, France.

Johnson, J.D., Sanchez, J., Fisk, A.D., Rogers, W.A. (2004). Type of automation failure: The effects on trust and reliance in automation. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Volume 48* (pp. 2163-2167). Los Angeles, CA, USA: SAGE.

Hayafune, K., & Yoshida, H. (1990). Control method of autonomous vehicle considering compatibility of riding comfort and vehicle controllability. SAE Technical Paper 901486.

Kircher, K., Larsson, A., & Hultgren, J.A. (2014). Tactical driving behavior with different levels of automation. *IEEE Transactions on Intelligent Transportation Systems, 15*, 158-167.

Lee, J.D., Wickens, C.D., Liu, Y., Boyle, L.N. (2017): Human-Automation Interaction. In *Designing for people. An introduction to human factors engineering. 3rd Edition* (pp. 357-387). Charleston, S.C., USA: CreateSpace.

Louw, T., & Merat, N. (2017). Are you in the loop? Using gaze dispersion to understand driver visual attention during vehicle automation. *Transportation Research Part C: Emerging Technologies*, 76, 35-50.

Louw, T., Merat, N., & Jamson, H. (2015). Engaging with Highly Automated Driving: To be or Not to be in the Loop?. In *Eighth International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design* (pp.190-196). Iowa City, IA, USA: Public Policy Center, University of Iowa.

Marques de Sá, J.P.M. (2007). Parametric Tests of Hypotheses. In *Applied statistics using SPSS, Statistica, Matlab and R. 2nd Edition* (pp.111-218). Berlin, Heidelberg: Springer-Verlag.

Merat, N., Jamson, A.H., Lai, F.C., Daly, M., & Carsten, O.M. (2014). Transition to manual: Driver behaviour when resuming control from a highly automated vehicle. *Transportation research part F: traffic psychology and behaviour, 27,* 274-282.

Reimer, B., Pettinato, A., Fridman, L., Lee, J., Mehler, B., Seppelt, B., Park, J. & Iagnemma, K. (2016). Behavioral Impact of Drivers' Roles in Automated Driving. In *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 217-224). New York, NY, USA: ACM.

SAE J2399 (2014). Adaptive Cruise Control (ACC) Operating Characteristics and User Interface. In SAE J2399_201409: SAE International.

SAE J2944 (2015). Operational Definitions of Driving Performance Measures and Statistics. In SAE J2944_201506: SAE International.

Shen, S., & Neyens, D. M. (2017). Assessing drivers' response during automated driver support system failures with non-driving tasks. *Journal of safety research, 61*, 149-155.

Strand, N. (2014). *When Driving Automation Fails Drivers' Experiences and Interactions*. PhD thesis, Chalmers University of Technology. Göteborg, Sweden.

Strand, N., Nilsson, J., Karlsson, I.M., & Nilsson, L. (2014). Semi-automated versus highly automated driving in critical situations caused by automation failures. *Transportation research part F: traffic psychology and behaviour, 27,* 218-228.

Taylor, J.R (1997). Preliminary Description of Error Analysis. *Introduction to error analysis, the study of uncertainties in physical measurements. 2nd Edition* (pp.3-12). Mill Valley, CA, USA: University Science Books.

Treffner, P.J., Barrett, R.S., Petersen, A.J., & White, R. (2002). Active stabilisation and perceptual sensitivity in safe driving. In *Developing safer drivers and riders: Proceedings of Travelsafe - Australian College of Road Safety conference* (pp. 91-104). Mawson, ACT, USA: ACRS.

Uppada, S.K. (2014) Centroid Based Clustering Algorithms-A Clarion Study. *International Journal of Computer Science and Information Technologies*, 5, 7309-7313.

Volvo Cars (2016): XC 90: Owner's Manual. Gothenburg.

Young, M.S., & Stanton, N.A. (2007). Back to the future: Brake reaction times for manual and automated vehicles. *Ergonomics*, *50*, 46-58.