Prediction of take-over time demand in conditionally automated driving - results of a real world driving study

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Abstract

In conditionally automated vehicles the driver still functions as a fall-back, responsible to take back manual vehicle control at any time. This study examines how driver's behaviour and characteristics may influence the time required for such a take-over. 34 participants took part in the study. During conditionally automated driving (SAE L3) in real traffic that was simulated using a Wizard-of-Oz vehicle, drivers engaged in Non-Driving Related Tasks (NDRTs) until a Request to Intervene (RtI) was issued. The assessed driver characteristics were: type of visual behaviour, self-rated sleepiness right before the RtI, attitude towards automated driving, previous experience with Adaptive Cruise Control (ACC) systems, individual reaction speed, as well as age and gender. Based on their visual behaviour, drivers could be classified into four groups with distinct visual gaze patterns. Further analysis indicated that a "medium off-road" visual behaviour was associated with increased take-over times. Additionally, individual reaction speeds and previous experience with ACC systems influence the take-over time. Sleepiness, as it occurred in the study, did not affect take-over time. Although further research is needed to verify the influence of driver characteristics on take-over times the current study gives important insights. Furthermore, the chosen Wizard-of-Oz approach extends previous research and helps to bridge the gap between simulator studies and naturalistic driving.

Introduction

Automation in automobiles improved greatly in recent decades. However, at the moment and in the near future, the driver will still need to take back manual vehicle control at system limits. It is therefore important to take a closer look at the take-over process and to examine possible factors involved.

The process of taking back manual vehicle control

The process of manual vehicle take-over after a period auf automated driving can be subdivided into several phases (see Figure 1). While driving with a conditionally automated driving system, the driver's state needs to remain compatible with system requirements determined by the system limits. That is, for example, the driver is

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allowed to engage in Non-Driving Related Tasks (NDRT) such as reading a book or using a smartphone but needs to be receptive for a Request to Intervene (RtI). In this case the driver has to switch from the NDRT to the driving task, which is described as the “driver state transition”. In this phase, depending on previous activities before the RtI, the driver may need to redirect his or her attention back to the driving scene, may need to free his or her hands and put them back on the steering wheel and place the feet on the pedals. For these reasons, this transition may elicit varying demands regarding the sensory, motoric and cognitive state of the driver. Time demand for the driver state transition is expected to vary with the number and complexity of the underlying sub-processes. After the automated driving function is deactivated by the user the driver performs the required intervention, such as keeping the lane, initiating a lane change or braking. Take-over time is defined as the duration of the transition phase, that is, the time between RtI and the driver’s intervention (Marberger et al., 2017).

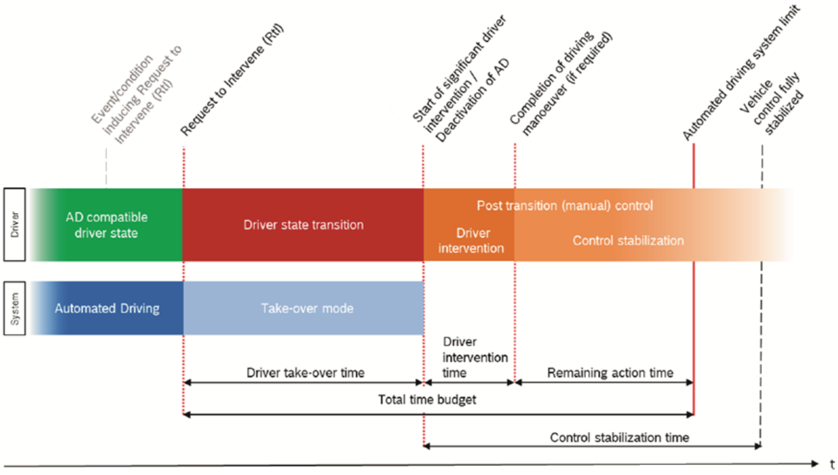


Figure 1. Model of the transition process from automated driving to manual control (Marberger et al., 2017).

Factors influencing the take-over process

Several factors are assumed to affect the take-over process. These include the complexity and criticality of the situation as well as the state of the driver right before an RtI is issued. Previous research for example reported a reduced level of take-over performance when the driver previously engaged in NDRTs (Radlmayr et al., 2014; Zeeb et al., 2016). Also sleepiness or fatigue are generally associated with poor vehicle guidance (Matthews & Desmond, 2002; Philip et al., 2005) which may also deteriorate take-over performance. Besides the state of the driver, various individual driver characteristics may also influence the take-over. Just a few studies considered such individual driver characteristics like trust in automation (Hergeth et al., 2016), individual reaction time (Körber et al., 2015), age (Körber et al., 2016; Warshawsky-Livne & Shinar, 2002), or gender (Warshawsky-Livne & Shinar, 2002). Another study by Zeeb et al. found that driver’s gaze behaviour with respect to NDRTs can be considered as a stable factor as it revealed classified groups of gaze patterns. These gaze patterns in turn affected specific aspects of the take-over performance (Zeeb et al., 2015). As a limitation, most of the studies were conducted in driving simulators and just very few examined take-over situations in the real world. Moreover, the NDRTs used in automated driving studies often consist of standardized tasks, which are either cognitively or visually demanding, but often lack ecological validity.

The purpose of this study is to examine drivers' behaviour in take-over situations in conditionally automated driving on the real road. Of particular interest are the effects of naturalistic non-driving related tasks on take-over time and the prediction of take-over time by the drivers' gaze behaviour pattern and other driver characteristics.

Method

Test vehicle and automated driving system

To simulate a conditionally L3-automated system (SAE, 2014) on the real road, a Wizard-of-Oz setting was used in the study (Figure 2). When the driver activated the system, the co-driver (driver wizard) took over full longitudinal and lateral vehicle guidance via dedicated control units on the armrest, the seat and secondary foot pedals. The Human Machine Interface (HMI) was managed by the experimenter on the backseat (HMI wizard). The participants were fully informed about the characteristics of the simulated L3 system and the role of the driver wizard before the drive.

Figure 2. Automation related HMI (left); co-driver as driver wizard (middle); experimenter as HMI wizard on the back seat (right). Figure adopted from Naujoks et al. (2018).

The automation system could be activated and deactivated with two levers on both sides of the steering wheel. The participants were instructed to use only those two levers and not the steering wheel or the pedals for deactivation. The actual state (available, active, off) and the RtI were displayed on the cluster display and the Head-up Display (HUD), and were accompanied by acoustic signals. The displayed information for activation and deactivation of the system can be seen in Figure 3.

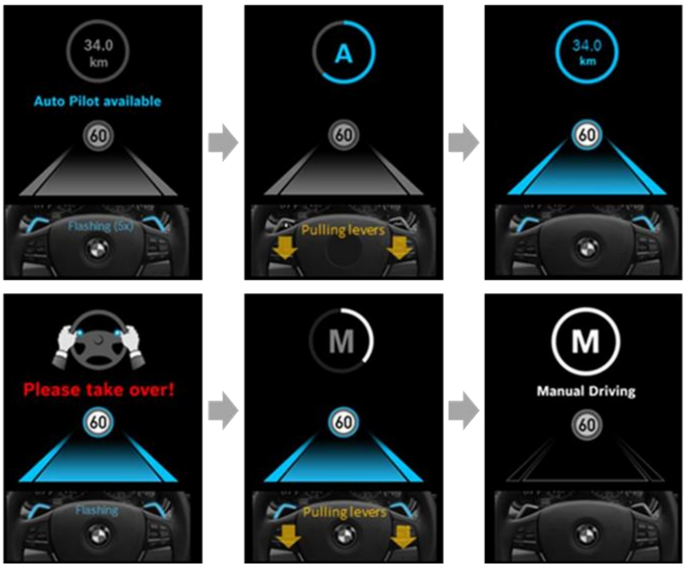


Figure 3. Visual HMI display for activation (top) and deactivation after RtI (bottom). Control transitions were generally signaled by acoustic signals with dedicated speech messages. Figure adopted from Naujoks et al. (2018).

Procedure and NDRTs

At the beginning, the participant performed a familiarization drive to get used to the functions and the handling (e.g., the take-over procedure) of the automated driving system. The test drive on a German freeway was separated into six sections (see Figure 4). Every section started with the activation of the system. The participant was then instructed to engage in one of the five NDRTs. After approx. 5 or 15 minutes an RtI was issued and the driver had to take-over manual vehicle control. After a short interview the participant reactivated the system and started with the next NDRT block. Each test drive additionally consisted of a section of manual driving as an individual baseline. The order of the sections was pseudo-randomized and counterbalanced across the drivers. A more detailed detailed description of the study procedure can be found in Naujoks et al. (2018).

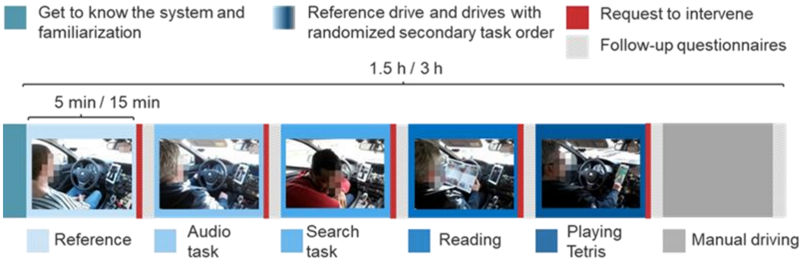
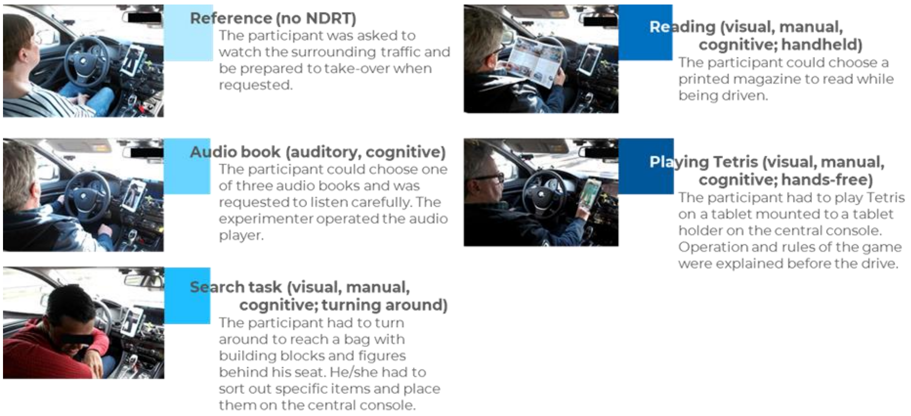


Figure 4. Procedure of the test drive. Figure adopted from Naujoks et al. (2018).

Subsequent to the whole test drive, participants went through a short simple reaction time task on a computer where they were instructed to press the space bar as fast as possible when a displayed red traffic light turned green.

The chosen NDRTs affected the sensory, motoric and cognitive state of the driver in different ways and consisted of an audio listening task, a reading task, a backseat-searching task, playing Tetris on an installed tablet and a reference task (supervision of the vehicle environment). See Figure 5 for a more detailed description of the tasks; a more detailed assessment of the workload demands of the task can be found in Purucker et al. (2018).



Reference (no NDRT)
The participant was asked to watch the surrounding traffic and be prepared to take-over when requested.

Reading (visual, manual, cognitive; handheld)
The participant could choose a printed magazine to read while being driven.

Audio book (auditory, cognitive)
The participant could choose one of three audio books and was requested to listen carefully. The experimenter operated the audio player.

Playing Tetris (visual, manual, cognitive; hands-free)
The participant had to play Tetris on a tablet mounted to a tablet holder on the central console. Operation and rules of the game were explained before the drive.

Search task (visual, manual, cognitive; turning around)
The participant had to turn around to reach a bag with building blocks and figures behind his seat. He/she had to sort out specific items and place them on the central console.

Figure 5. NDRTs used in the study. Figure adopted from Naujoks et al. (2018). For a more detailed assessment of the workload demands see Purucker et al. (2018).

Variables

For a general overview of the take-over time, several time components were measured such as the time to the first gaze to front, the time to free the hands, the time to turn the body to front, the time to pull and release the levers as well as the time the vehicle control is handed over by the driver wizard. For classification and regression analysis the take-over time (TOT) as dependent variable was then defined as time between start of the RtI message and start of deactivation procedure (pulling of both steering wheel levers). Furthermore, to assess the drivers' gaze behaviour, the driver was recorded on video during the drives, and off-road glances were coded after the study. Off-road glances include glances at the NDRT, at other passengers or glances inside the vehicle within an interval of 60 s before the RtI. From the video coding, number and duration of off-road gazes were used as metric independent variables. For modelling the TOT, the drivers' sleepiness shortly before the RtI, the attitude towards highly automated driving (HAD), previous experiences with ACC-systems, results of a simple reaction time task, as well as age and gender of the drivers were used as predictor variables. The driver's sleepiness in a time interval of 10 s before the RtI was rated by trained observers using the 5-point rating scale for observer ratings, ranging from "0 – Not Drowsy" to "4 – Extremely Drowsy" (Appendix A; Höfling, 2017; Wierwille & Ellsworth, 1994). The attitude towards highly automated driving (HAD) was assessed via a questionnaire with 7-point likert scales. The given ratings were averaged for each driver and were contributed to the multiple regression as a metric variable. The items of the questionnaire can be seen in Appendix B. The individual reaction time was measured by a simple reaction time task in seconds. Results from five trials were averaged, outliers excluded. Sleepiness, attitude and individual reaction time were used as metric variables. Previous experience with ACC-systems, age and gender of the drivers were assessed also via a questionnaire and were handled as categorical independent variables.

Results

Sample

34 participants (6 females) with a mean age of 54 years (SD = 14 years) took part in the study. Of those, 21 had previous experience with ACC. Each drive consisted of 5 take-over situations. In one case, only 2 take-over situations were recorded due to technical problems, resulting in 167 take-over trials.

Effects of NDRT on take-over

Figure 6 shows the effects of specific NDRTs on different take-over time components. The values for “lever pulled” correspond to the definition of take-over time (TOT). The average TOT is the longest for the search and the reading task (~ 5 s), shortest for the reference task, and a bit longer for the audio book task (~ 3 s). The average TOT after playing Tetris is in between (~ 4 s). The mean time for the “first gaze to front” component is roughly equally long for the search task, the reading task as well as the Tetris task, whereas the time to free the hands is the longest for the reading task an the shortest for the Tetris task.

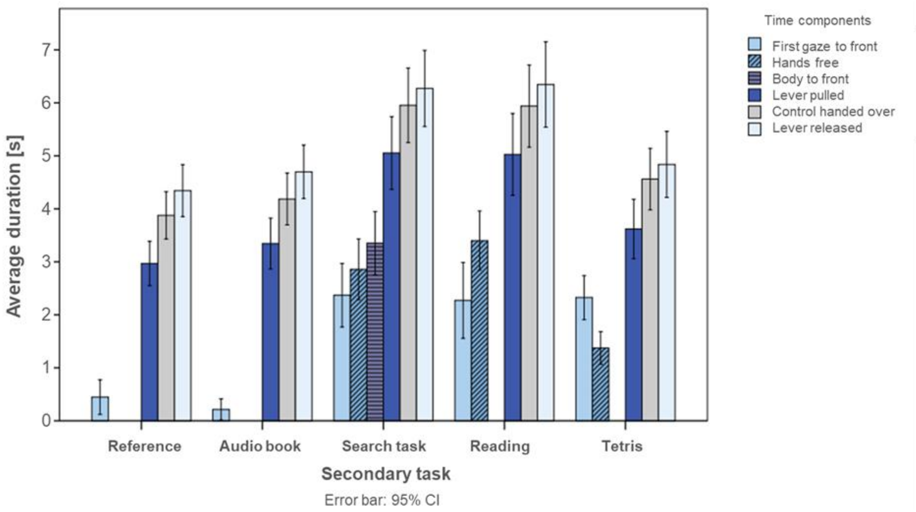


Figure 6. Average duration of different take-over time components in combination with specific NDRTs.

Classification of drivers’ gaze behaviour

To classify the drivers’ visual gaze behaviour a hierarchical cluster analysis with Ward’s minimum variance method (Ward, 1963) was conducted using the maximum duration of off-road glances in combination with the number of off-road glances for each trial and for each driver 60 s before the RtI. Figure 7 shows the results of the analysis. Considering the total number of trials the analysis revealed four groups with different gaze patterns described as “long off-road”, “medium off-road”, “short and often off-road” and “short and seldom off-road” (Figure 7 left panel). When TOTs are averaged across all NDRTs in a separate analysis, still four groups emerge, but with less variance (Figure 7, right panel). To examine whether the gaze behaviour is indeed an individual driver characteristic and not just determined by the specific NDRT, the results from the initial cluster analysis were plotted separately for each NDRT in Figure 8. It can be seen that specific NDRTs influence the driver’s gaze behaviour and, therefore, the classification based on maximum duration of off-road glances and number of off-road glances. While the reference and the listening (audio book) task provoke mainly “short and seldom off-road” glances, the search task, the reading task and the Tetris task tend to involve at least three of the classified groups. Note that this pattern seems to relate to the observed TOTs.

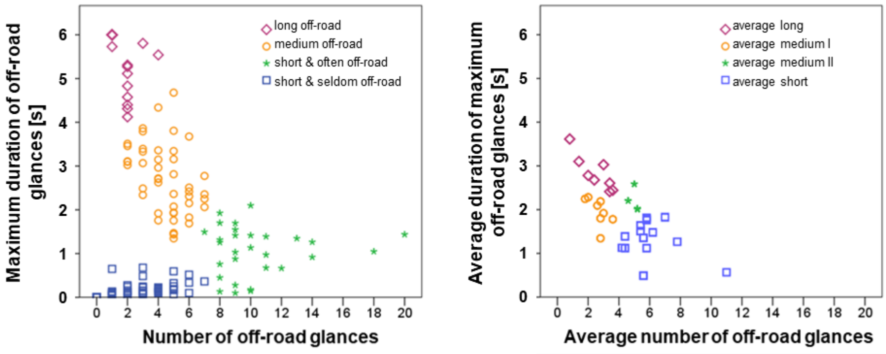


Figure 7. Results of the cluster analysis of the driver's gaze behavior for each trial (left) and an additional analysis averaged over the total drive for each driver (right).

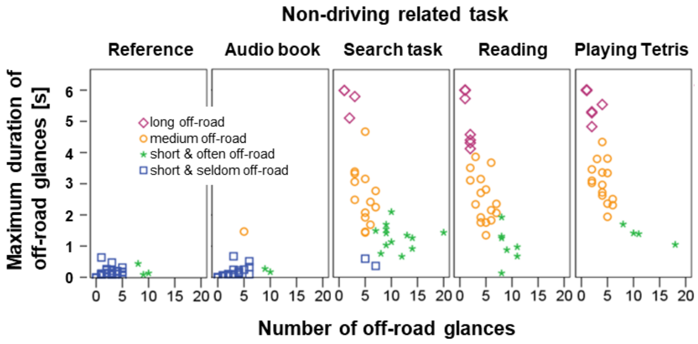


Figure 8. Results of the cluster analysis separated by NDRTs.

Prediction of take-over time

To examine how the TOT can be predicted from the observed gaze patterns and the obtained driver characteristics, a first multiple regression model was calculated with the classified gaze behaviour. For a second model, the observer-rated sleepiness, the attitude towards automated driving systems, previous experiences with ACC-systems, the individual reaction time as well as age and gender of the drivers were additionally used as predictors. 18 take-over trials were excluded because drivers were not engaged in NDRTs at the time of the RtI, resulting in 149 valid take-over trials. Results are shown in Table 1. The total model produces an adjusted $R^2 = .182$, ($F(9,148) = 4.669$, $p < .001$). Significant predictors are medium off-road gaze patterns, the result of a simple reaction time test and previous experience with ACC systems. Neither the rated sleepiness, nor the attitude towards highly automated driving, age and gender reach significance. Concerning the β-weights of the significant predictors, only previous experience with ACC systems has negative impact on take-over time, indicating that drivers with experience in ACC systems need shorter time to take back manual control than drivers without previous experience. Average reaction time and medium off-road gaze behaviour, however, show positive β-weights, that is, longer individual reaction times and medium off-road gaze behaviour lead to longer take-over times. Among those three significant predictors, medium off-road gaze behaviour shows the largest β-weight and thus, the strongest impact.

Table 1. Result of the multiple regression with take-over time as dependent variable.

Coefficients

DV: Take-over time	Non-standardized coefficients		Standardised coefficients	T	*p*
	Regression-coefficient B	Standard error	Beta		
(Constant)	1.319	.034		39.162	<.001
Short & often off-road gazes	.037	.066	.063	.566	.572
Medium off-road gazes	.205	.055	.394	3.751	<.001
Long off-road gazes	-.024	.062	-.042	-.385	.701
(Constant)	.775	.360		2.151	.033

Short & often off-road gazes	.030	.067	.051	.450	.653
Medium off-road gazes	.192	.055	.368	3.516	.001
Long off-road gazes	-.011	.063	-.019	-.175	.861
Rated Sleepiness	-.173	.146	-.092	-1.182	.239
Attitude to HAD	.057	.065	.067	.873	.384
Individual reaction time [s]	1.025	.462	.175	2.218	.028
Experience with ACC systems [no; yes]	-.084	.036	-.195	-2.318	.022
Age [years]	-.001	.002	-.026	-.323	.747
Gender [male; female]	-.030	.043	-.055	-.694	.489

Reference: short and seldom off-road gazes

Discussion

The aim of the study was to measure the effect of specific NDRTs when human drivers are requested to take-over manual control from conditionally automated driving. This was pursued by classifying the drivers' gaze behaviour and by examining, which of various specific driver characteristics additionally influenced TOTs in a multiple regression.

In a first step, the measured time components of the control transition were regarded separately for each NDRT. The TOT was the longest for the search task and the reading task and the shortest for the reference task. The time the drivers needed to redirect their gaze back on the road was comparable for searching, reading and playing Tetris. Regarding the time the drivers needed to free their hands, it was the longest for the reading task, followed by the search task and the Tetris task.

In a second step, we analysed a predictive model that (by intention) does not contain the NDRTs themselves but rather stable driver characteristics or measurable criteria of driver behaviour. To this end, a cluster analysis was conducted for the analysis of gaze behaviour, indicating four groups of gaze patterns from "long off-road" to "short and seldom off-road". As opposed to Zeeb et al. (2015), the results here revealed a forth group of "short and seldom off-road glances" probably due to the audio listening task we used as a non-visual demanding NDRT. Further analysis showed that the found gaze patterns are also determined by the NDRT the driver performed during automated drive. "Short and seldom off-road" glances primarily occurred in the reference and audio listening task as those two tasks require little visual attention.

A multiple regression model was calculated based on the found gaze patterns and further driver characteristics in order to examine their influence on TOT. Results showed three significant predictors: "Medium off-road" gaze behaviour, individual reaction speed and previous experiences with ACC systems. Drivers showing this type of gaze behaviour and drivers with lower individual reaction speeds needed longer to take-over manual vehicle control. Previous experience with ACC systems, by contrast, resulted in decreased take-over times. All in all, the goodness-of-fit of the regression model (adjusted $R^2 = .182$) is rather low, making it difficult to use the model for prediction purposes.

The data did not reveal significant effects of attitude to highly automated driving, sleepiness, age or gender of the driver. Two results are particular interesting and call for further research. First, although the group of medium off-road gaze behaviour leads to increased TOTs, the group with long off-road gazes does not. According to the data of this study the link between off-road gazes and TOTs does not seem to be linear as opposed to the findings of Zeeb et al. (2015). This observation may result from behavioural compensation: Drivers who do not look at the road for prolonged periods of time may try to compensate this gaze behaviour by showing faster responses to the RtI. At the same time, drivers with medium off-road gaze behaviour may not yet perceive the need to compensate. The second observation result refers to the sleepiness of the drivers. The variance of the observer ratings was rather low which makes it difficult to find significant effects. Generally, the study design does not seem to be appropriate to provoke sleepiness. So, more research is needed to examine the influence of sleepiness and to further verify the influence of other driver characteristics on TOTs.

The results of this study refer to low demand take-over scenarios. Drivers were not required to act under time pressure or in safety-critical scenarios. Although this type of test scenario may be representative for most take-over scenarios in real life it may not be suitable to investigate the human performance limits to safely take-over. Still, the current study gives important insight in individual driver aspects and, hence, individual TOTs. Furthermore, the naturalistic design used here extends previous research and help to bridge simulator studies and real-world driving.

Acknowledgements

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Appendix

A) Rating scheme for the trained raters to evaluate drowsiness of the drivers (according to Höfling, 2017; Wierwille & Ellsworth, 1994).

How drowsy is the driver?				
0 **Not Drowsy**	**1** **Slightly Drowsy**	**2** **Moderately Drowsy**	**3** **Very Drowsy**	**4** **Extremely Drowsy**
- Appearance of alertness - E.g., normal face tone, normal fast aye blinks, short ordinary glances - Occasional body movements or gestures	- E.g., prolonged glances at a fixed position, slower eyelid closures - Still, alert enough to be fit to drive	- Behaviour against drowsiness: - E.g., Rubbing the face/eyes, scratching, facial contortions, moving restlessly in the seat - Signs of drowsiness: e.g., slower eyelid closures, decreased facial tone, glassy-eyed appearance, staring at a fixed position.	- E.g., eye lid closures of 2-3 s, rolling movement of the eyes, no focusing, decreased face tone - Lack of apparent activity or large isolated movements, e.g., large correction to steering or reorienting the head from a leaning or tilting position.	- E.g., falling asleep, very long eye lid closures (at least 4 s) - Prolonged periods of lack of activity, large punctuated movements as a transition in and out of intervals of dozing.

B) Items of the questionnaire to assess the attitude towards automated driving.

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree	Don´t know
I am generally positive about such automated vehicles described above	☐	☐	☐	☐	☐	☐	☐	☐
Automated driving will increase driving safety of the driver.	☐	☐	☐	☐	☐	☐	☐	☐
Automated driving will increase traffic safety.	☐	☐	☐	☐	☐	☐	☐	☐
Automated driving is a meaningful and useful development.	☐	☐	☐	☐	☐	☐	☐	☐
I would hand over control to the automated vehicle.	☐	☐	☐	☐	☐	☐	☐	☐
I think, automated vehicles that actively intervene in driving are prone to errors and are dangerous.	☐	☐	☐	☐	☐	☐	☐	☐
I would not like to drive such an automated vehicle.	☐	☐	☐	☐	☐	☐	☐	☐