Takeover times in highly automated driving

Compact accident research

Unfallforschung
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GDV

Contents

Introduction

This UDV compact research report describes part of an extensive research project and summarizes the first part of this two-part study focusing on takeover times and highly automated driving.

Automated vehicles in which the driver can allow the vehicle to do all the work on certain parts of the trip and no longer has to monitor anything are currently being developed by many automotive manufacturers. When there are driving tasks that these highly automated vehicles can no longer handle, control must be returned to the driver. The driver must have sufficient time to take over manual control of the vehicle safely and easily. To find out the time required for the safe takeover of manual control by a driver, takeover scenarios and secondary tasks of varying complexity were developed and tested in a static driving simulator with 60 subjects aged from 20 to 76.

An empirical study was designed and conducted to find out when full physical and cognitive control over a vehicle was reestablished after a phase of highly automated driving. The effect of a driver being "out of the loop" was analyzed, in particular. In some experimental conditions, the driver was thus completely uninvolved in the task of driving, and distracted by a secondary task, at the time of the takeover request.

It should be noted here that the times were ascertained in a driving simulator and thus can only be understood as an approximation of the time required for a takeover in a real vehicle. However, more recent studies do indicate that times ascertained in a simulator correlate well with those in a real vehicle. It should also be emphasized that the takeover time alone cannot be an adequate measure of the quality of a takeover. The times must always be seen in connection with other measures of the quality of the takeover. This include the quality of the safety of the takeover and the fullness of the driver's awareness of the situation during the takeover.

In order to be able to interpret the results correctly, it is necessary to know the definitions of the automation levels. According to Gasser et al. (2012), highly automated driving refers to functionality that involves the vehicle taking control of both longitudinal and lateral guidance for a certain period. The driver does not have to continuously monitor the situation. Instead, the driver must take over control again with a certain amount of time to spare when requested to do so. The aim of this study was to ascertain how much time there is to spare. Highly automated driving is thus clearly different from partially automated driving. In partially automated driving, the vehicle also takes control of longitudinal and lateral guidance, but the driver has to monitor the situation continuously and be able to take back control at any time. The next step up from highly automated driving is fully automated driving, in which the vehicle handles longitudinal and lateral guidance completely and continuously. The driver is no longer required as a fallback option, since in the absence of a driver takeover the system can put the vehicle in a status in which the risk of an accident is minimized.

Experimental design

The experimental design involved the independent variables "type of secondary task" and "type of takeover situation". The secondary tasks were subdivided into four groups: The drivers in the "manual" group had to drive in all situations without any automation or secondary tasks. The "monitored" group had to drive with automation enabled and without a secondary task but had to monitor the the situation during automated driving. The two other groups had to drive with automation enabled and handle secondary tasks. These differed in terms of the extent to which they motivated the subjects to continue with them.

Each subject in the experimental groups experienced five driving scenarios in which takeover situations occurred. A drive lasted around five minutes. The scenarios differed in terms of their complexity, but the course they took was as comparable as possible in the interests of facilitating analysis. A mixed 4x5 experimental design was developed for the groups and scenarios (Table 1)

Table 1: Experimental design with the factors "type of secondary task" and "type of takeover situation"

Factor A: Type of secondary task	Factor B: Type of takeover situation				
	Scenario M01	Scenario M02	Scenario M03	Scenario M04	Scenario M05
Manual driving (n=15)	✓	✓	✓	✓	✓
Automated driving without secondary task (n=15)	✓	✓	✓	✓	✓
Automated driving with secondary task 1 (n=15)	✓	✓	✓	✓	✓
Automated driving with secondary task 2 (n=15)	✓	✓	✓	✓	✓

Takeover scenarios implemented in the driving simulator

The experiments were carried out in the static driving simulator of the department of engineering and transport psychology at the Technische Universität Braunschweig.

The driving simulation was implemented using the software environment SILAB Version 4.0 (Krueger et al. 2005). The driving simulator used consisted of a seat box with a driver seat, a passenger seat, a steering wheel and pedals. The simulation was projected onto screens by three projectors. The simulation also included four small monitors that served as the wing mirrors, rear-view mirror and speedometer. Driving noise, engine noise and noise from the surrounding traffic was output by a surround-sound system. Figure 1 shows the configuration of the simulator rooms.

In order to design technically feasible scenarios for a takeover, interviews were conducted with experts on the basis of the latest literature on the capabilities and limits of automated driving systems (Maurer et al. 2015; Meyer and Beiker, 2014; Ziegler et al., 2014; Aeberhardt et al. 2012; Hillel et al. 2014). Particular emphasis was placed on the question of the situations in which an automated vehicle could take over control of the vehicle and in which situations the driver would be requested to take over. Based on the replies given in the interviews, a typical automated vehicle was created with specific capabilities and limitations. According to these replies, in the near future automated vehicles in Germany will…

- Drive on the autobahn (freeway)
- Drive in mixed traffic with automated and non-automated vehicles
- Only be linked to other vehicles or the infrastructure to a limited extent (GPS, Mobile Data, Car-to-X)
- Drive at a maximum speed of 100-130 km/h (also includes traffic jam assistants with lower speeds)

*Figure 1:
Configuration of the seat box and simulator room*

- Drive regardless of traffic density
- Recognize all road signs
- Recognize all other road users found on the auto-bahn
- Be able to keep in lane and to some extent overtake
- Work in good to moderate weather and road conditions
- Permit to some extent the use of external devices and internal vehicle convenience functions during the drive
- Drive in automated mode for an unlimited period of time (no return of control after a fixed period of time)
- Reliably recognize all system limits
- Initiate the return of control to the driver with a time buffer
- Inform the driver about an imminent transfer multi-modally
- Bring about a risk-minimizing status (e.g. an emergency stop) at any time

On the basis of the responses in the interviews and the literature, five takeover scenarios were developed that reflected the current system limits of an automated vehicle as well as possible and, at the same time, demonstrated different levels of complexity. Since the systems that will become available in Germany in the near future are initially to be used primarily on autobahns, a multi-lane autobahn was used as the basis of the simulation in all scenarios. The scenarios implemented for the driving simulator are outlined in Table 2. In scenarios M01, M02, M03 and M05, the

takeover of control was simulated on an autobahn with three lanes in each direction. In scenario M04 there were only two lanes.

Perfect automation was assumed for this study (as opposed to imperfect automation as described, for example, in Skitka et al. 2000). This means an automated system that neither issues false alarms nor categorizes critical

situations as uncritical. The purpose of this study was not to investigate the influence of the reliability of automated systems on users' behavior. Consequently, the automated system implemented issued a takeover request correctly in 100 percent of cases and recognized all system limits correctly.

In addition, it was specified that the automated system was able to make use of the full range of vehicle dynamics in longitudinal guidance. The automated system was thus able to use 100% of the vehicle's possible acceleration and 100% of its possible deceleration to cope with situations. On the other hand, a function that would have allowed situations to be defused by changing lane or by means of an evasive maneuver was not implemented. The automated system was set to drive at 120 km/h. During automated driving, the automated system kept to a distance of 60 meters behind any vehicles in front before a takeover request (TOR). In addition, a minimum distance between the vehicle and the vehicle in front was defined that was comparable to the point of no return defined by Strand et al. (2014). The automated system adhered to this for as long as it remained activated. The automated system implemented here braked hard shortly before reaching the minimum distance to the vehicle in front and thus avoided a collision. Based on the existing classifications for automated driving systems, the most suitable category for the system defined here is "highly automated" (as defined by Gasser et al., 2012).

The automated system reported its readiness to take over control by means of a simple symbol consisting of green hands and a steering wheel. If the automated system was active, a blue and green symbol of a vehicle was displayed with an ellipse around it. The takeover request was symbolized by red hands and a red steering wheel accompanied by an audible warning signal, thus meeting the requirement to use a multimodal warning. The symbols appeared in the driving simulator's head-up display. The pictograms used are explained in brief in Table 3.

Takeover scenarios implemented in the driving simulator

Table 2: The takeover scenarios implemented in the driving simulator

Scenario	Image of the takeover situation	Description of the takeover situation
M01		This describes a takeover situation in which the driver is requested to take over control in order to select a particular route or leave the autobahn. There are no other vehicles around. 5.25 seconds after the takeover request, a navigation arrow appears on the head-up display, prompting the driver to change lane.
M02		This describes a takeover situation in which, due to the absence of road markings, the vehicle is no longer able to steer safely enough and therefore passes control to the driver. There is a vehicle in front of the driver's vehicle driving at the same speed and in the same lane. Moderate traffic density is simulated in the overtaking lane. At the time of the takeover request, the vehicle in front of the driver's vehicle is around 250 meters ahead and initially maintains a speed of 120 km/h. After 5.25 seconds, the vehicle in front brakes hard until it has reached a speed of 80 km/h, which it then maintains..
M03		This describes a takeover situation in which, due to the failure of a sensor or a software error, the vehicle is no longer able to steer safely enough and therefore passes control to the driver. This scenario plays out similarly to scenario M02. The only difference is that there is no absence of road markings..
M04		This describes a takeover situation in which, due to roadworks, the vehicle is no longer able to steer safely enough and therefore passes control to the driver. High traffic density is simulated in the overtaking lane. As of the point at which the takeover request is issued, the automated system decelerates the driver's vehicle in accordance with the speed limits shown on the road signs from the original 120 km/h to 60 km/h. In addition to the roadworks at a distance of 300 meters from the point at which the takeover request is issued, a stationary vehicle is simulated, part of which is in the driver's vehicle's lane. The distance of the driver's vehicle from the stationary vehicle at the time of the takeover request is 175 meters.
M05		This describes a takeover situation in which, due to extreme weather conditions, the vehicle is no longer able to steer safely enough and therefore passes control to the driver. This scenario plays out similarly to scenarios M02 and M03. In addition, at the time of the takeover request, the sudden onset of heavy rain is simulated. This continues until the end of the scenario.

Table 3: Pictograms indicating the status of the automated system

The assistance system is ready to take over control (steering, acceleration, braking).	The assistance system is active and takes over the monitoring of the surroundings and the control of the vehicle.	The assistance system has identified a situation that necessitates the intervention of the driver. Please take control of the vehicle.

Secondary tasks implemented in the driving simulator

In order to ascertain a realistic takeover time, it was stipulated that the driver must take over control after being out of the loop as completely and realistically as possible. The driver was thus engaged in a completely different task during the automated drive, and the driver's awareness of the situation at the time of the takeover request was very limited. In order to engage the drivers visually, cognitively and in terms of movement and distract them from the task of driving, two secondary tasks were developed that appear realistic in the context of automated driving.

A large number of secondary tasks have been used for this type of distraction during an automated drive. The most frequently used way of presenting the secondary task up to now has been on a tablet computer, a smartphone or a laptop. Another way of presenting it is on the vehicle's human-machine interface (HMI). In addition, purely linguistic tasks have been tested, and in some studies analog media such as newspapers have been used.

Two secondary tasks were defined for the study: The "reading" task involved reading newspaper articles on a tablet computer. The "playing" task involved playing a game on a table computer's touchscreen. Both tasks were categorized as engaging the driver visually, cognitively and in terms of motor activity. In the case of the "playing" task, it was also assumed that the game would be particularly engaging for the test drivers, thus making it more difficult for them to pull themselves away from it.

A game had to meet certain requirements to be selected for the task. The idea was for the game to be as motivating and immersive as possible, require motor skills and be both as difficult as possible to interrupt and easy to learn. Tetris turned out to be the game that was most suitable as a secondary task to distract the drivers. The basic principle of the game is that you have to stack the game pieces, which fall from the top of the screen in different geometric shapes, in as space-saving a way as possible by moving and rotating them and forming rows of these pieces at the bottom of the screen without any gaps. In this version of the game, the pieces are moved and rotated by tapping and swiping the tablet computer's touchscreen. Complete rows without any gaps are automatically removed and rewarded with points. Incomple

te rows remain. Each stacked piece is followed immediately by the next piece, increasingly filling the playing area and increasing the level of difficulty as the game progresses. Figure 2 shows the playing surface on the tablet computer during a typical game.

Abbildung 2: Screenshot eines typischen Spielverlaufs in der als Nebenaufgabe ausgewählten Version des Spiels Tetris.

Experimental procedure

The subjects were initially informed about the planned experiment and how to use the driving simulator. They were then informed about the objectives of the study and instructed as to what they had to do. Particular emphasis was placed on adhering to the rules of the road, which in this case were the German Road Traffic Regulations (StVO), keeping to the speed limits and ensuring safety. It was also explained to them how the automated assistance system worked. They learned that the system could take full control of the vehicle but that there were driving situations that the vehicle couldn't handle alone. In accordance with the defined capabilities of the automated system, they were told that the vehicle could identify these situations with 100% accuracy and notify the drivers about them accordingly with a time buffer before the situation occurred. The drivers were also informed that the system remained active until the driver switched it off.

ZIn addition, the subjects were told how to operate the system (switch it on and off), and the system's status indicators were explained. A lever behind the steering wheel was used to switch the automated system on. It worked in a similar way to current cruise control and ACC systems. It was explained that the automatic control of the vehicle was terminated as soon as the driver either operated this lever behind the steering wheel again or, alternatively, the brake pedal. All this information was provided in preparation for an initial training drive with the automated system.

On completion of the training drive, the subjects were given the instructions they needed, depending on which experimental group they were in, their secondary task was explained to them, and they were able to practice it. The instructions defined the three automated experimental groups: the monitored, reading and playing groups. All of the groups with the automated system were to only take over control when the vehicle issued a takeover request. The manual group did not have an automated system available. The subjects in this group were told that there was an assistance system that recognized difficult situations and issued warnings about them. The warnings were issued in all situations at the exact point at which the takeover request was issued in the automated groups.

Definition of the objective parameters measured

It is essential to define the parameters to be measured in order to make the results comparable and understand how the results were obtained. The objective parameters in this study are all of the measured values obtained on the basis of times, driving data, simulator data, eye-tracking data and video data. The definitions are particularly important for the purpose of reporting reaction times, since even a slight difference in the understanding of when to measure these reactions can lead to deviations in the interpretation of the results.

Times of measurement and reaction times

The existing literature was studied before setting the times at which the reaction times were to be measured. The time for starting the measurement period is the same in almost all studies. It is the moment when the takeover request is presented. The end of the measurement period and thus the critical time for the definition of the reaction time can be identified by means of a number of criteria indicating that the driver has taken over control or is ready to react. Petermann-Stock et al. (2015) define four classes of reactions during the takeover. These classes are used here to arrange the times of measurement operationalized in the previous studies: orientation reaction, readiness to act, action and vehicle stabilization.

The most frequent operationalizations for the orientation reaction are looking up from the secondary task after an automated drive (e.g. Petermann-Stock et al., 2015) and looking at the road (e.g. Damböck, 2013; Gold et al., 2013a). For the purpose of this study, the reaction time for "looking at the road" was defined as the period between the presentation of the takeover request and the first glance at the middle of the vehicle's lane. The eye move-

ments in the study were tracked using the Dikablis eye-tracking system (Lange, 2005), which has a tracking frequency of 50 Hz.

The reaction time for "readiness to act" has most often been defined on the basis of either touching or grasping the vehicle's controls (e.g. initial contact with the steering wheel (Petermann-Stock et al., 2015; Zeeb et al., 2015); hands on the steering wheel (Damböck, 2013; Lorenz et al., 2014; Naujoks et al., 2014)). In accordance with these definitions of readiness to act, it was assumed in this study that drivers were able to intervene in the situation or take over control as soon as they grasped the steering wheel with at least one hand. An additional measure used to indicate readiness to act in this study was the time at which the driver's foot touched the accelerator or brake pedal. Both hand and foot movements were recorded using cameras (25 frames per second).

There were bigger differences between the previous studies in terms of how they defined the time of measurement to indicate that action had been taken. Accordingly, criteria were defined in this study for an initial action after a takeover request. The time at which the automated system was switched off was defined as the operation of the lever to switch it off or the initial reaction on the brake pedal (brake pedal position > 0). A brake reaction was defined as operating the brake pedal by more than 10 percent in order to distinguish this reaction from merely tapping the brake pedal to switch the automated system off after a takeover request. For the eye reactions in this class of reactions, the times at which the driver looked at the wing mirror or the speedometer for the first time were recorded. These values were recorded analogously to the glance at the road using the eye-tracking system. In order, like Lorenz et al. (2014) to get indications of the behavior of the drivers after a takeover request, the types of reactions to the takeover request were classified as "no reaction", "braking", "steering and braking", "switching off the automated system using the lever" and "steering only".

Driving data

A number of different measures have also been used in previously published studies for vehicle stabilization. These are described below. A wide range of driving data that can indicate the behavior of the drivers during and after a takeover is often used to describe the stabilization of the vehicle after a takeover request.

In this study, both average values and absolute criteria were defined on the basis of which the quality of the takeover after a takeover request and after the event was to be evaluated in the different scenarios. The speeds selected during and after the takeover situation, the intensity of the braking reaction, the distance from the vehicle in front and the maximum acceleration in longitudinal and lateral directions were recorded in relation to average values over a period. Collisions with the surrounding traffic were analyzed and critical events defined as absolute criteria for the assessment of a takeover. Sharp braking, defined as a combination of high braking pressure and high deceleration, stopping the vehicle in a scenario (speed < 10 km/h) and interventions of the automated system to take control (initiating the risk-minimizing status) were counted as critical events.

Subjects

The driving simulator study was conducted in August 2015 with 60 subjects aged from 20 to 76. 22 of the people in this random sample were female, and 38 were male. The participants in the study had held a driving license for an average of 18 years. Half of the participants said they drove less than 9,000 kilometers a year. The other half said they drove more than that annually. 26 participants said they had experience of using assistance systems that provide longitudinal guidance (cruise control systems, ACC systems, emergency brake assist systems), and 17 people said they had experience of using

assistance systems that provide lateral guidance (lane-keeping assist systems, lane-departure warning systems, lane-change assist systems, blind-spot warning systems). 38 people in the sample had already used a driving simulator once (5 people) or more than once (33 people).

Results: reactions

The figures below show the reactions of the individual subjects to a takeover request (TOR). The x-axis represents the time that elapses after a takeover request. The y-axis shows the percentage of test drivers in this group who had shown the reactions displayed by the relevant point in time. Figure 4, for example, can be read as follows: About 2.5 seconds after the takeover request, about 90 percent of the test drivers in the "monitored" group had their hands on the steering wheel again. Some further descriptive statistical measures can be derived from these charts. The steepness of the curves represents the distribution of the reactions over time. A very steep curve thus means a low level of distribution, whereas a flat curve indicates a high level of distribution. Plateaus in the curves can be an indication that the sample is subdivided into different groups in terms of their behavior.

In some of the charts, time periods are highlighted. They show the periods within which 90% of the drivers distracted by a very engaging, motivating and challenging secondary task ("playing") showed the relevant reaction.
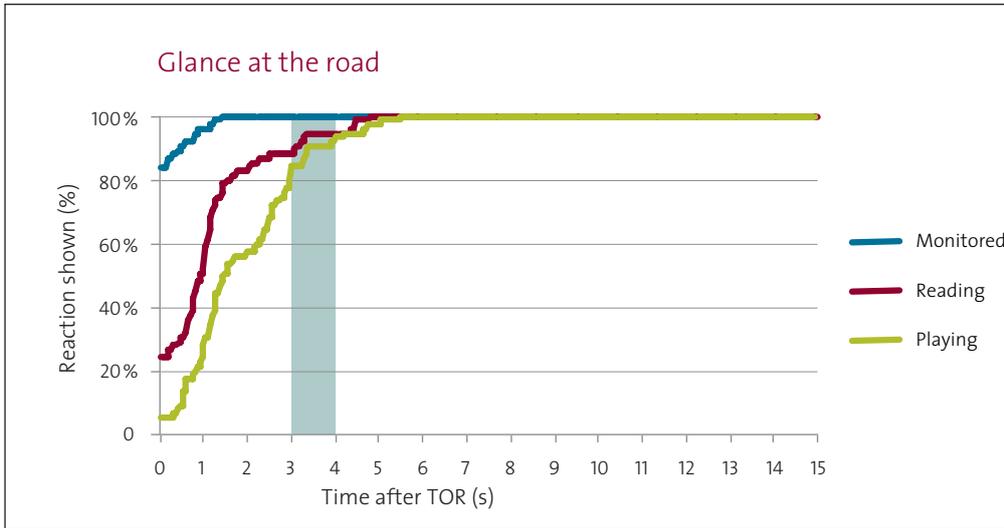
Glance at the road


Figure 3:
Reactions of the sub-
jects in terms of their
first glance at the roa

— Monitored
— Reading
— Playing

Hands on the steering wheel
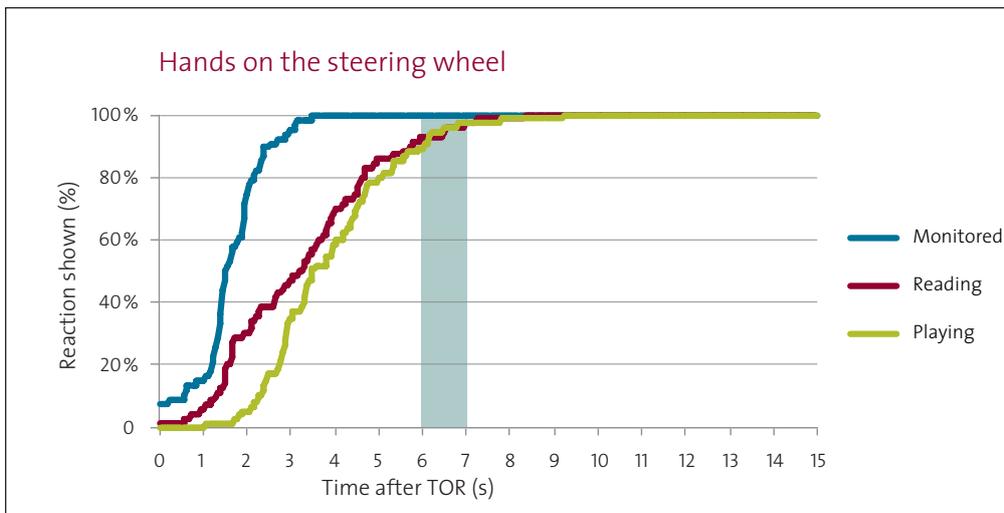
Figure 4:
Reactions of the sub-
jects in terms of "hands
on the steering wheel"

— Monitored
— Reading
— Playing
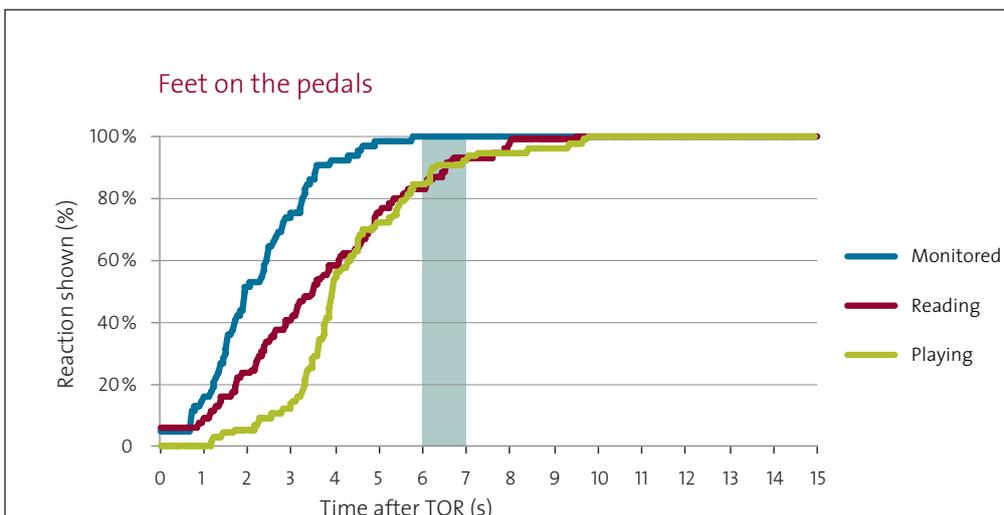
Feet on the pedals

Fiigure 5:
Reactions of the sub-
jects in terms of "feet
on the pedals"

— Monitored
— Reading
— Playing

Results: reactions
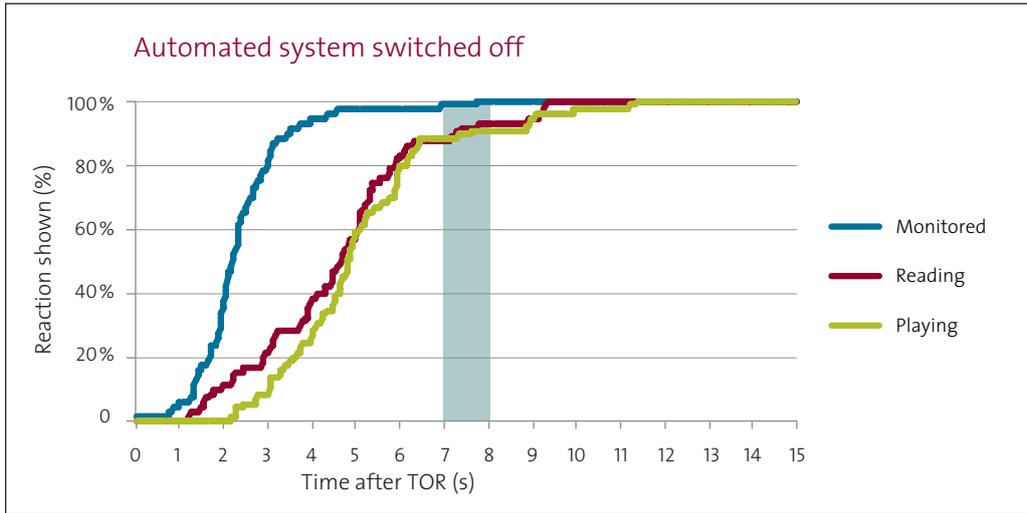
Figure 6:
Reactions of the
subjects in terms of
switching off the
automated system
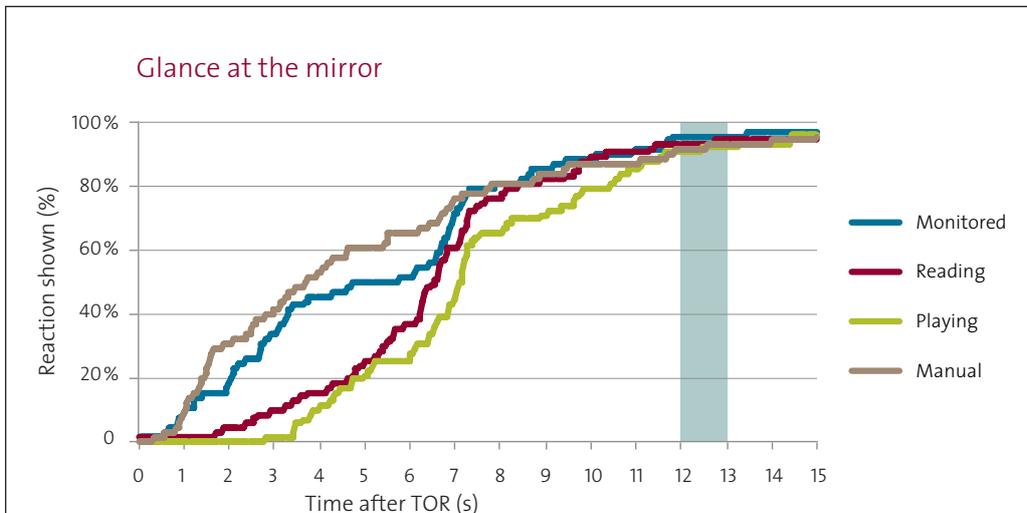
Figure 7:
Reactions of the
subjects in terms of
their first glance at
the mirror
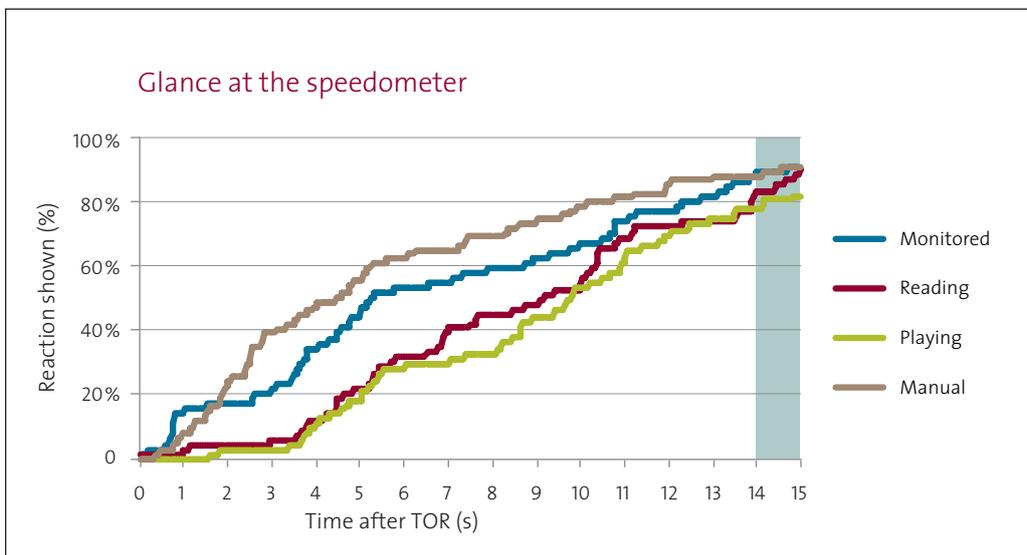
Figure 8:
Reactions of the
subjects in terms of
their first glance at
the speedometer

Summary of the results and recommendations

After a drive with a high level of distraction, 90 percent of the drivers looked at the road again for the first time after 3-4 seconds, had their hands on the steering wheel and their feet on the pedals after 6-7 seconds and had switched off the automated system after 7-8 seconds (see Figure 3-6). However, if you look at the first glance at the mirror and the glance at the speedometer as indicators of awareness of the driving situation, you see that 12-15 seconds are required (see Figure 7 and 8). These reactions, which are required in order to understand the current traffic situation, are thus delayed by up to 5 seconds compared to the reactions of drivers in manual control in the same situation. Part of this period could be saved if drivers in a takeover situation did not have to put down an external device (e.g. a smartphone or tablet computer).

There were very large differences between the drivers for all these reactions. Some drivers showed much quicker reactions. However, there were also some drivers who took longer to react than the times specified above. After some drivers took over control again, collisions or critical driving situations occurred. However, this also occurred to a similar extent in purely manual driving. These situations could have been avoided by means of suitable assistance functions (e.g. an emergency brake assist system). Assistance functions should therefore also be available after takeover by the driver in order to help the driver and prevent incorrect reactions.

The braking reactions to a critical event immediately after the takeover request were not delayed in the groups with the automated system compared to the group of manual drivers. In addition, the distances from the vehicles in front were no shorter in the groups with the automated system than in the group of manual drivers. The somewhat lower speeds driven by strongly distracted people after the takeover request indicate a more cautious approach to driving after the takeover

The type of takeover situation itself seems to have only a slight impact on the reactions. On the other hand, stronger positive involvement in the secondary task, making it more difficult to interrupt, resulted in slight delays, particularly in the initial steps of the takeover.

The automated system used was able to control the vehicle safely even after issuing the takeover request until the driver took over control. This included correctly staying in lane, selecting the correct speed, keeping a minimum distance from the vehicle in front and, if necessary, stopping before an obstacle. If the driver did not take over within 10 seconds, the automated system stopped the car ("risk-minimizing status"). The fact that this was in some cases necessary shows that 10 seconds is not enough for some drivers to ensure a safe takeover and is a further indication of the necessity of supporting assistance systems after the takeover request as well.

When the reactions of monitoring drivers and drivers with the maximum level of distraction are compared with those of drivers in manual control, there are generally delays in all reactions. This was clearest in the case of distracted drivers. But even drivers who were monitoring the situation had delayed reactions compared to drivers in manual control. If you apply this finding about the behavior of the driver monitoring the situation to partially automated driving, it is clear even after an automated drive of five minutes that it is necessary to consider the findings when designing partially automated driving functions.

Prerequisites for a safe takeover

The following points summarize the prerequisites for the safe takeover of manual control after a highly automated drive:

• The driver is notified as early and clearly as possible of the necessity of taking over control.

Summary of the results and recommendations

- If at least 90 percent of drivers are to be able to react correctly, the takeover period must last longer than eight seconds. In this period, a vehicle moving at a speed of 120 km/h travels about 267 meters.

- The automated system must remain active during the takeover process until the driver has clearly signaled readiness to take over control.

- If the takeover doesn't happen, the automated system must be able to bring about a risk-minimizing status appropriate to the situation.

- The vehicle identifies 100 percent of all situations that result in transfer of control to the driver early enough to ensure the driver has time to take over.

Further recommendations for a safe takeover

A safe and convenient takeover of manual control after a highly automated drive by the driver could be facilitated by certain measures:

- The automated system should provide comprehensive but succinct information on the current situation to facilitate the development of an awareness of the situation after an automated drive.

- Increased readiness of the vehicle to assist after the driver takes over control could help prevent inappropriate reactions on the part of the driver (e.g. the prevention of unnecessary emergency braking or evasive maneuvers).

- A cascade of different types of warnings can indicate the urgency of the situation to the driver and ensure the warning is noticed.

- Drivers could be instructed specifically about the capabilities and limitations of automated driving systems, thus ensuring appropriate reactions in the event of a takeover and preventing the automated system from being switched off too early.

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