Tiredness and level 3 – automated driving

Compact accident research

Unfallforschung der Versicherer
GDV

Content

Introduction

This UDV compact accident research report summarizes the second part of the project on takeover times and highly automated (level 3) driving. The summary of the first part has already been published as compact accident research report no. 57.

Up to now there have been only a few studies that have shown how the duration of the drive and tiredness affect how drivers interact with vehicles with high levels of automation. It is suspected that the effects of tiredness do not lose their relevance to safety on the roads in partially (level 2) or highly automated (level 3) vehicles [1], [2]. Until drivers are no longer considered to be a fallback option, there will be times when control of the vehicle is returned to them. In such situations, the driver is required not only to take back control of the vehicle as quickly as possible but also to gain a full awareness of both the situation on the road and the state of the vehicle as quickly as possible. Tiredness or fatigue could be just as detrimental to drivers taking over after an automated driving phase as it is to tired or fatigued drivers of conventional cars, possibly even more so.

How the tiredness of the driver develops when interacting with an automated vehicle is also of interest. The initial indications are that drivers get tired sooner when interacting with an automated vehicle and that having to continuously remain attentive in a monotonous driving environment may even be more of a strain than driving a conventional car. Tired drivers may behave differently from alert drivers when interacting with level 3 vehicles and neglect to monitor the situation properly or miss certain cues indicating potentially dangerous situations. The driving simulator study presented below was carried out against this background at the Technische Universität Braunschweig (TU Braunschweig) in 2016 in order to examine closely some of the parameters identified as relevant. The aim of the study was to quantify the tiredness of drivers in level 3 vehicles compared to those in conventional vehicles. Tiredness was systematically measured and recorded both for drivers with a slight sleep deficit and for those without a sleep deficit. In addition, takeover requests were issued to the drivers, and their reaction times and the quality of their reactions to these takeover requests and to subsequent critical events were analyzed.

Experimental design

The aim of the study was to estimate the time taken by tired drivers to safely assume control of a vehicle after a level 3 drive and long driving times. In addition, their initial reactions were analyzed in a typical complex scenario following a takeover request. This scenario was preceded by a level 3 drive during which the tiredness of the drivers was rated at regular intervals by trained assessors on the basis of valid tiredness indicators (how long eyelids are closed for, eye movements, yawning and other behavioral indicators). The drivers were not given any secondary tasks to distract them during the drive.

Half of the subjects were asked to sleep no more than five hours the night before the experiment and not to have any drinks containing caffeine beforehand. This group of subjects was also invited to take part between 8 p.m. and midnight in order to simulate a late drive home after a day at work. Subjects in this group had slept an average of 4 hours and 52 minutes the night before. The other group of subjects were asked to sleep normally the night before the experiment. This group of subjects was invited to take part between 9 a.m. and 11 a.m. or between 3 p.m. and 5 p.m. Subjects in this group had slept an average of 7 hours and 52 minutes the night before.

Half of the drivers in each of these two groups drove in a vehicle with an automation system and received a takeover request (an audible warning signal plus a visual warning) before the complex scenario. The other half remained in manual control of the vehicle the whole time and also received an audible warning signal before the scenario (see table 1). The complex scenario was triggered by the trained tiredness assessors at different points in time, depending on the group involved, in order to examine the reactions of the drivers when they were in comparable states. For the drivers with a sleep deficit (with/without automation), the scenario was triggered when they reached a "moderate" level of tiredness (indicated by them keeping their eyelids closed for around a second, adopting a fixed gaze, or stretching). For the drivers who had slept normally (with/without automation), the scenario was triggered after around an hour of driving regardless of their level of tiredness.

Table 1: Experimental design and random sample planning

Random samples/ cause of tiredness	Experimental condition	Number of subjects
Population 1: Tiredness (sleep deficit + negative effect of circadian rhythms)	Non-automated drive	15
	Automated drive	15
Population 2: Long driving time (constant attentiveness + positive effect of circadian rhythms)	Non-automated drive	15
	Automated drive	15

Takeover scenarios

The study was conducted in TU Braunschweig's driving simulator. The driving data was obtained in Version 5 of the driving simulation software SILAB [3]. The driving simulator used consisted of a seat box with a driver's seat and passenger's 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 noises, engine noises and the sound of traffic were output over a surround sound system. Figure 1 shows the configuration of the simulator room.

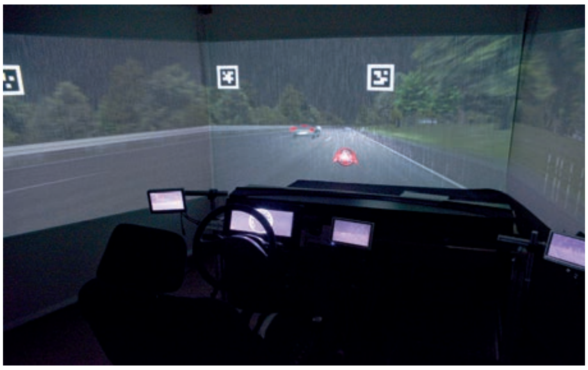

Figure 1: Configuration of the seat box and simulator room (photo: Matthias Powelleit)

To test the effects of tiredness and long driving times on the ability of drivers to take control following a request to do so, a number of different scenarios were developed in the first study in this series. All of the scenarios were based on the assumption that only takeover situations that can be planned for by the vehicle's system are relevant at the high automation level. Sudden interventions by the driver, such as when a vehicle in front suddenly pulls in, are no longer expected at this level of automation. The vehicle has to handle this.

Against this background, interviews were conducted with experts in order to come up with realistic scenarios for plannable takeover situations [4]. These included changing from a section of freeway where automation is available to a section in which it is not available, the failure of a (redundant) sensor system, missing or barely visible road markings, a roadworks site and weather conditions that interfere with the functioning of the vehicle's sensors. Based on what was learned in the first study in the series, the scenario M05 was selected for this study, in which the weather conditions (the onset of heavy rain) impair the functioning of the sensors. In order to make the scenario of driving home from work after a night with too little sleep more realistic for the "tired" group, the simulation for this group was switched to night-time driving in both conditions: with and without automation. This changed the lighting for the simulation, and all vehicles were shown with their headlights switched on.
When the heavy rain started in the groups with automation, the drivers received an audible and visual takeover request. The design of the takeover request was similar to that of takeover requests in recent studies and current production vehicles with partially automated functions. The symbols used for the different statuses of the automation system are shown in table 2.

Table 2: Possible statuses of the automation system and the symbols used for them

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

The aim of the study was not just to ascertain how long it takes for drivers to assume control after a takeover request but to assess their ability to react to critical situations on the road following a takeover. To this end, a realistic, critical incident was implemented in each scenario shortly after the drivers had assumed control. The takeover scenario took the same course as the one in the first study so that the reactions of the drivers in the two studies could be compared.

For the weather scenario used in this study, the vehicle in front braked heavily from 120 km/h to 80 km/h 175 meters (around 5 seconds) after the takeover request. At the time of the takeover request, the vehicle in front was around 250 meters ahead. The intention was to simulate the braking of vehicles in front in response to the onset of rain. The delay of 5 seconds after the takeover request was chosen following a review of the available literature because, by that time, most of the drivers would have switched off the automation system [4].

The capabilities of the simulated automation system were similar to the capabilities of automation systems described in interviews with experts [4]. The automation system corresponded largely to the high automation level described in [1] or level 3, conditional automation [2]. The automation system was set to a speed of 120 km/h and was thus programmed to maintain this speed while taking into account speed limits and traffic.

The vehicle simulator was able to stay in lane and maintain its distance from the vehicles in front of it, respond to speed limits and overtake autonomously when a vehicle in front of it was driving more slowly. In the takeover scenario described above, the vehicle issued a takeover request. If a driver had not switched the automation system off within 10 seconds of a takeover request, the vehicle switched to a risk-minimizing status, staying in lane, braking and coming to a standstill or following a vehicle in front at a safe distance.

Experimental procedure

The instructions given to the subjects were largely the same as those given in the first study in the series [4]. Consequently, the instructions are merely summarized here. Any differences from or additions to the instructions provided in the previous study are indicated. The subjects were informed of the capabilities of the simulated automation system and told that it would correctly identify all situations in which a takeover was necessary and issue a warning. During a training drive lasting around 12 minutes, the subjects learned how to drive without automation in the simulator and what to do when the automation system was on. A takeover situation was also included, in which the subjects received an audible and visual warning and were able to go through the process of taking control.

The automation system was activated by means of a control stalk on the steering column. In the event of a takeover request, the drivers were able to deactivate the automation system either by applying the brakes or by using the control stalk. The automation system remained active after a takeover request until the subjects deactivated it.

The subjects were asked not to take their mobile phones or any other devices into the simulator. The subjects in the groups with the automation system were told that they didn't have to constantly monitor the automation system, since a takeover request would always be issued whenever there was a takeover situation. However, the subjects were given nothing else to do or distract them except for observing the unfolding situation on the road. Drivers in the group driving without automation were told a "story" to make the warning plausible. They were told that their vehicle had an assistance system that could identify potentially critical systems and issue an audible warning.

The subjects in all groups were asked not to use the intercom system to speak to the researchers conducting the experiment during the drive, except in emergencies or if they felt sick. They were told to imagine that they were alone in the vehicle. The idea was to prevent them being distracted or combating tiredness by entering into conversations. The subjects' consent to the recording of driving and video data was obtained before the experiment. However, it was not explicitly explained to them that their level of tiredness during the drive would be assessed by the researchers by means of a camera pointed at their head and upper body. It was also not explained to the subjects that the takeover situation was initiated dynamically by the researchers depending on the level of tiredness measured. Instead, the subjects were told that the number of takeover situations and the time of their occurrence was randomly generated by the computer and not subject to influence by the researchers. The idea was to prevent subjects from feigning tiredness in order to bring the experiment to an end earlier. In addition, the subjects were supposed to feel unobserved, just as they would feel in these situations in their own cars. The researchers explained the purpose of the experiment to the subjects after the end of their drive.

Subjects

60 subjects aged from 18 to 87 (M = 41.3, SD = 21.1) took part in the study. 48 percent of this random sample were younger drivers aged from 18 to 35, 25 percent were in the middle age range of 36 to 55, and 27 percent were older drivers (55+). 38 people in the random sample were male (63 percent), and 22 of them were female (37 percent). Around 75 percent of the participants had already had experience of assistance systems for longitudinal and/or lateral guidance. Just over half of the participants had already taken part in a driving simulator study at least once. None of the participants had taken part in the driving experiments in the first study in this series, so the takeover scenario used was new to all of them.

Data acquisition

The data acquired in the study was similar to what was recorded and analyzed in the first study in the series [4]. In addition to the reaction times, driving data and eye movement data, trained assessors monitored tiredness indicators at regular intervals during the drive.

Measuring tiredness

In order to record the tiredness and fatigue of the drivers during the drive, all of the researchers were trained in tiredness assessment methods. This training was based on the template provided by Wierwille and Ellsworth [5] and further developed by Wiegand [6]. It included written documents with descriptions of the objective indicators of tiredness and video clips from naturalistic driving studies. The video clips showed examples of all the possible tiredness indicators, as portrayed by a number of different people.

Drivers' tiredness was monitored by the assessors during the drive by means of a high-resolution infrared camera pointing at the subject's face and upper body. The indicators of tiredness (e.g. eyelids closed for a relatively long time, yawning, rubbing of the face) were counted for a minute at intervals of 5 minutes and recorded on an observation sheet. The level of tiredness was then rated on a scale from 0 (alert) to 8 (extremely tired) on the basis of the weighted number of counted indicators for this period. Table 3 lists the tiredness indicators recorded by the assessors for the different levels of tiredness in this study.

Table 3: Levels of tiredness and objective tiredness indicators recorded for each level

Level of tiredness	Tiredness indicators
0 – Alert	Eyelids closed only for a short period, normal blinking, continual shifts of gaze, upright sitting position, fast saccades (eye movements), steering wheel held at "10 to 2"
1 – A little tired (-)	Eyelids closed for up to half a second, tired facial expression, yawning, rubbing/scratching of face, grimacing, supporting/resting of the head
2 – A little tired (+)	
3 – Moderately tired (-)	Eyelids closed for longer (approx. 0.5-1 second), glazed look without blinking (duration > 3 seconds), stretching/lolling, eyes half open
4 – Moderately tired (0)	
5 – Moderately tired (+)	
6 – Very tired (-)	Eyelids closed for much longer (1-2 seconds), involuntary rolling of the eyes, involuntary nodding of the head
7 – Very tired (+)	
8 – Extremely tired	Eyelids closed for > 2 seconds, momentary nodding off, waking with a jolt

Note: The fine gradations of tiredness (+/0/-) were created for the basic categories of tiredness based on the frequency of occurrence of the different indicators within the observation period of a minute.

If drivers in the experimental condition where they had a sleep deficit reached tiredness level 3, a takeover request was triggered. In contrast to the experimental condition in which drivers had enough sleep the night before, tiredness was thus recorded in some cases for shorter periods. Drivers who brought the drive to an end because the researchers had triggered the takeover request were categorized in the data as having "dropped out". In all of the experimental conditions, the takeover request was triggered after a drive of 15 minutes at the earliest and 60 minutes at the latest (long drive).

Reaction times

The reaction times of the drivers were recorded to ascertain how long it took them to take control after a takeover request. Some of these reaction times were obtained from video observations and some from the driving data recorded in the driving simulator. In addition, reaction times were obtained from the eye movement data recorded by an eye tracker. The end times for the reaction times and the measurement criteria used are shown in table 4. The time of the takeover request was selected as the starting point for measuring reaction times. This point in time was also used for the drivers without the automation system, since the drivers in this experimental condition received a warning at the same time as the drivers with the automation system. The timing of the warning or takeover request was thus the same for all of the subjects. The start and end points for the reaction time measurements were defined in the first report in the series on the basis of the available literature, and described in detail there [4]. The criteria for the reaction time measurements used in this study were adopted in full from the first report [4].

Table 4: Defined reaction times and end times of the reaction time measurements

Reaction time	End time for reaction time measurement
Eyes on Road	Eyes clearly focused on the middle of the road (as revealed by eye movement measurements)
Hands On	At least one hand fully on the wheel (derived from video observation)
Feet On	The right foot is touching the accelerator or brake pedal, or the right foot remains poised over the brake pedal ready to react (derived from video observation)
Automation Off	The automation system has been deactivated by the driver through the use of the brake pedal or the control stalk on the steering column
Brake Reaction	The brake pedal has been pressed to at least 10 percent of its full range following the occurrence of the critical incident
Gaze Side Mirror	The first glance at the wing mirror on the driver's side after the takeover request
Gaze Speed	The first glance at the speedometer after the takeover request

Driving data

In addition to the reaction times, driving data from the driving simulator system was recorded in this study in order to measure the quality of driving after the driver had taken over control. The data collected and analyzed here was obtained in the same way as the driving data in the first study in this series [4]. The driving data included the distance from the vehicle in front following the takeover request, the minimum distance from the vehicle in front during the takeover situation and the speed driven during the takeover situation. In addition, lateral guidance and lane-keeping quality parameters were analyzed: the mean deviation from the ideal driving line, the maximum lateral acceleration forces and the timing of a lane switch. Any collisions with traffic in the vicinity and the number of interventions of the automation system in the event of the driver failing to react and takeover were also recorded.

Results

After a drive in which they had reached a moderate level of tiredness and were not distracted, 90 percent of the drivers with the automation system looked at the road again for the first time after 1 second, had their hands on the steering wheel and their feet on the pedals after 3-4 seconds (see Figure 2) and had switched off the automation system after 6-7 seconds (see Figure 3). However, if the first glance at the mirror and the glance at the speedometer are taken as indicators of awareness of the situation, you see that 12-15 seconds were required (see Figure 4). These reactions, which are required in order to understand the current traffic situation, were thus delayed by up to 6 seconds compared to the reactions of drivers with control of the vehicle in the same situation. Except for the first glance at the road, the values of tired drivers with an automation system are comparable to those of alert drivers on a short, automated drive in which they are strongly distracted visually, cognitively and in terms of motor activity by an engaging secondary task [4].

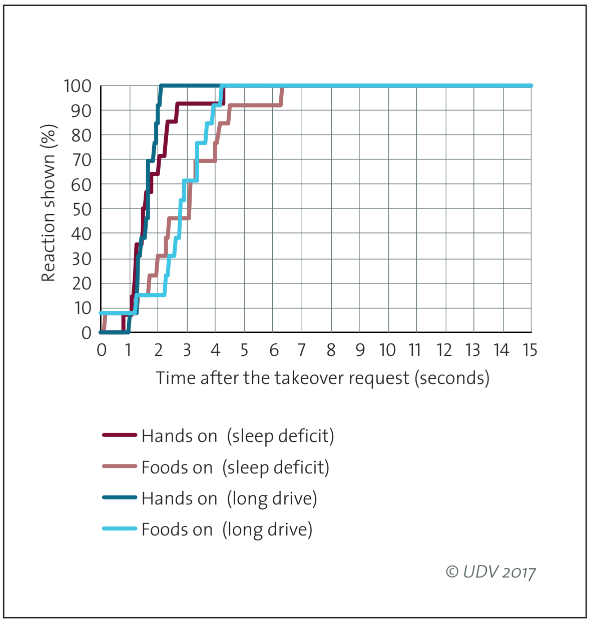

Figure 2: Time taken to put hands on the steering wheel and feet on the pedals following a takeover request

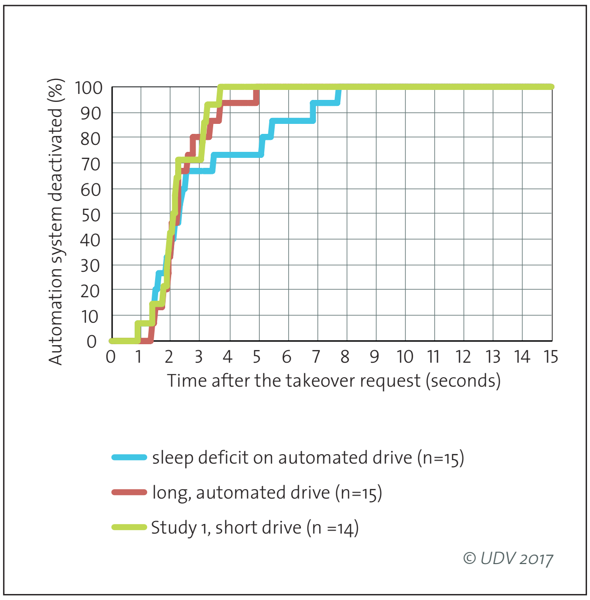

Figure 3: Reaction times taken to deactivate the automation system following a takeover request

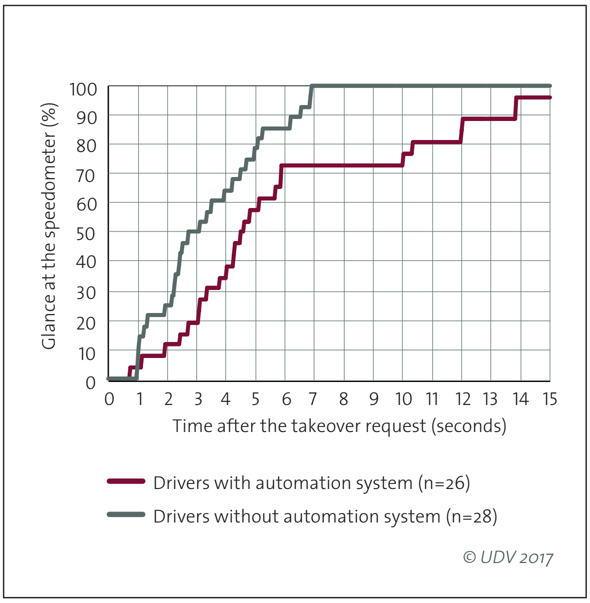

Figure 4: Reaction times taken to glance at the speedometer for the first time following a takeover request/warning

Progression of tiredness

It is particularly critical in this context that drivers with the automation system who had slept normally the night before taking part in the study were found by the assessors to be about as tired after a drive of about an hour as drivers who had not had enough sleep the night before. These drivers who had slept too little the night before reached a comparable level of tiredness after around 15-20 minutes. In contrast, even after a drive of an hour, the drivers driving without an automation system and without a sleep deficit were rated as either only a little tired or not tired at all. Drivers driving without an automation system but with a sleep deficit reached a comparable level of tiredness after around 35-40 minutes. Generally speaking, the drivers in the groups with the automation system were thus more tired than those without an automation system, and they also reached this level of tiredness earlier (see figures 5 and 6). Some of these drivers with the automation system closed their eyes for extended periods or even fell asleep. In the figures below, the category “dropped out” refers to those participants with a sleep deficit who had reached at least tiredness level 3 (moderately tired), and to whom the researchers had therefore triggered the takeover request.

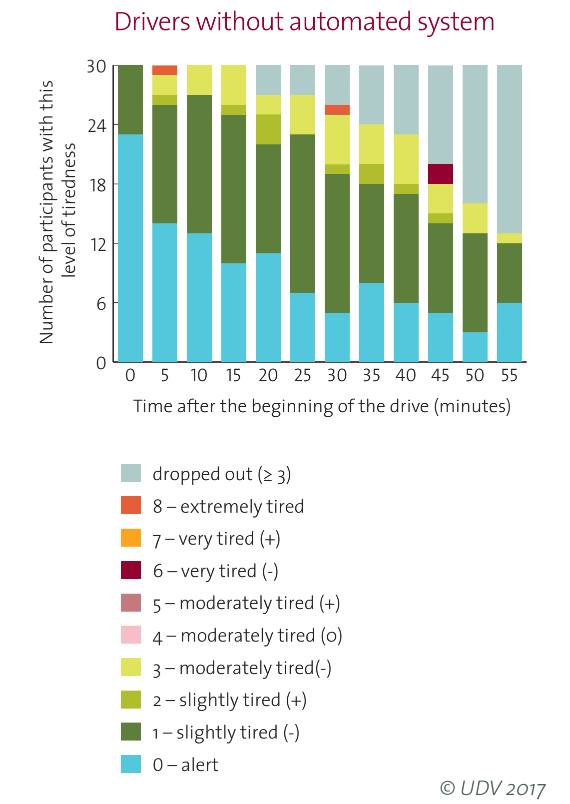

Figure 5: Tiredness ratings of the test drivers in the experimental condition of non-automated driving (with and without a sleep deficit) over the course of the drive

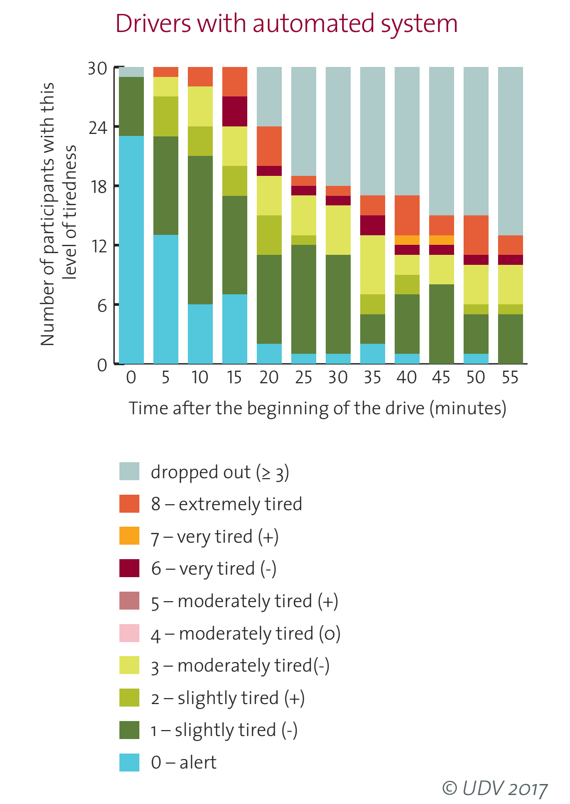

Figure 6: Tiredness ratings of the test drivers in the experimental condition of automated driving (with and without a sleep deficit) over the course of the drive

Figure 7: Tiredness of the test drivers in the experimental conditions of automated driving with a sleep deficit, automated driving without a sleep deficit, non-automated driving with a sleep deficit and non-automated driving without a sleep deficit (from the top left to bottom right) as the drive progressed

Figure 7 shows how the tiredness of the various experimental groups, as rated by the assessors, increased as time went on (see figure 7). The rate of increase was faster for the drivers with the automation system than for those without. In addition, the effect was amplified in the subjects with a sleep deficit. Drivers in the automated mode thus seem to be particularly susceptible to tiredness. Although drivers without an automation system but with a sleep deficit showed clear signs of tiredness as the drive went on, this tiredness set in more slowly than for the drivers with the automation system, at least in this random sample. It is particularly critical that even drivers using the automation system who did not have a sleep deficit became really quite tired after a relatively short time. By contrast, this happened only very rarely in the case of drivers without automation and without a sleep deficit.

The trend for the tiredness ratings allows an estimate to be made of the period for which an automated drive can actually be monitored: half of the drivers with automation and a sleep deficit reached a critical (moderate) tiredness level after around only 20 minutes compared to around 40 minutes for those without automation and with a sleep deficit. Half of the drivers with automation but without a sleep deficit reached a comparable level of tiredness after around 35 minutes of driving. On the other hand, the drivers without automation and without a sleep deficit showed few indications of tiredness even after the end of the maximum driving time of around an hour.

Tiredness and fatigue during the drive appear to occur significantly sooner in drivers with automation than in drivers without it. Based on the significant changes between the tiredness ratings after 15 minutes of driving compared to the ratings after 10 minutes, a level 3 drive of over around 15 minutes without anything else to do cannot be considered to be safe if the driver is required to monitor the automation system or react quickly to indications given by the automation system. Particularly drivers in automated vehicles who are tired as a result of a sleep deficit take about as long as drivers distracted by other activities to react and adjust to the driving situation.

Even if their driving after taking control does not appear to be clearly impaired by this, the vehicle should adjust the time available for a takeover process to suit the condition of the driver (tiredness, duration of the drive, secondary task) and provide the driver with situation-dependent support both in the period after the takeover request and in the period after the automation system is switched off. As a result of this support, a safe transition to driving without automation could be ensured, and critical situations after the takeover of control could be prevented.

Limitations and outstanding issues

The study on which these assessments are based was conducted in a static driving simulator with subjects aged from 18 to 87 (M = 41.3, SD = 21.1). The reactions could be different in a real vehicle or with significantly older or younger subjects. The sleep deprivation to which the subjects were subjected in this study did not induce the kind of extreme level of tiredness that involves, for example, momentary nodding off, involuntary rolling of the eyes or nodding of the head. The idea was to induce the sort of tiredness you might experience driving home one evening after too little sleep the night before. The results of this study do not exclude the possibility of more extreme reactions and longer reaction times or of drivers reaching the high level of tiredness sooner if they have had even less sleep or have accumulated a sleep deficit over several days. However, since shift workers or truck drivers, for example, often suffer from cumulative sleep deficits like this, future studies should also take into account greater sleep deficits.

Conclusion

A level 3 drive without secondary activities for the driver should not exceed 15 minutes. Longer drives without breaks have to be considered unsafe, since drivers are unable to monitor the situation during an automated drive for an extended period without getting tired, and the condition of the driver cannot be assessed with certainty by technical systems. When tired or fatigued, drivers require about the same amount of time to take control as drivers who have been seriously distracted by being engaged in a secondary activity that motivates them.

If drivers are given a sufficiently long advance warning period, even when tired or after a long drive, they are able to handle driving situations after a takeover request about as well as those driving without an automation system. 12 to 15 seconds is a sufficient warning time for the majority of drivers after a drive of more than 30 minutes, or for a tired driver after a drive of more than 15 minutes. Although drivers switched the automation system off significantly more quickly (after 6-7 seconds), and were able to react to critical situations about as well as drivers without an automation system, they needed an additional 6-7 seconds after switching the automation system off to gain a comprehensive understanding of the situation on the road.

It is thus essential that the driver's condition is monitored during the automated drive and taken into account when a decision is taken about how long it takes to resume manual control safely and comfortably. In addition, the risks of drivers with automation systems being distracted by secondary tasks should be weighed against the risk of falling asleep. In contrast to drivers of conventional vehicles, it may make sense for drivers with an automation system to be distracted by a secondary task that is controlled by the vehicle to prevent tiredness setting in.

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Notes

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