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Sleep in highly automated driving: Takeover performance after waking up

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ABSTRACT

Takeover performance in automated driving is subject to investigation in the context of a variety of driver states such as distraction or drowsiness. New driver states will emerge with increasing automation level with drivers potentially being allowed to sleep while driving a highly automated vehicle. Still at some point during a drive, drivers will be required to or voluntarily take back control of the vehicle. A simulator study was conducted to investigate drivers' ability to take over the vehicle control after sleeping. In a within-subjects study design N = 25 test drivers completed a drive using a highly automated driving system a) during day time after a full night of sleep and b) early in the morning after a night of partial sleep deprivation. During the second drive, sleep was measured in drivers according to the American Academy of Sleep Medicine (AASM) standard using electroencephalography (EEG). In total, the participants had to handle four takeover requests (TORs) from the system, two while being awake (day drive) and two when being awakened from sleep stage N2 (morning drive). The objective criticality of the situations was assessed performing the Takeover Controllability rating (TOC-rating). The results indicate that the applied takeover time of 60 s was sufficient for drivers to reengage in driving after sleeping. Reaction times were extended by about 3 s after sleep compared to the wake condition. Takeover performance assessed with the TOC-rating however was clearly worse after sleep than after wakefulness which was also reflected in the drivers' subjective perception of the criticality of the situation. Further research is needed on how to deal with performance impairments after waking up from sleep during automated driving.

1. Introduction

The technology leap from SAE level 3 (L3) to level 4 (L4) automated driving (SAE, 2018) is expected to solve many human factors issues concerning driving automation. Main human factor issues are associated with L2 and L3 automated driving systems. Topics of concern are drivers not being able to constantly monitor the traffic when driving with an L2 system or not being able to appropriately respond to a takeover request (TOR) in L3 automated driving (Kyriakidis et al., 2017). When using L4 automated systems drivers are not required as a fallback option nor are they needed to monitor the surrounding traffic. However, this does not mean that all human driver-related issues are solved. One major benefit that marks the transition from L3 to L4 automated vehicles is the opportunity for the driver to sleep while driving in automated mode. Some vehicle manufacturers already advertise the possibility for drivers to sleep while being driven by their L4 automated vehicles (BMW, 2018). It could be argued that enabling the driver to sleep while being driven enhances traffic safety. Sleep and even short naps enhance cognitive and motor performance in terms of vigilance, alertness and executive functions (Milner and Cote, 2009; Hartzler, 2014). Strategic naps are, for instance, used in aviation to increase or maintain pilots' performance on long haul flights. The most common recommendation is the 'NASA nap', a 40-minute planned rest period (Rosekind et al., 1994, p. 64). This time period best balances the benefits in terms of performance improvement while minimising impairments due to sleep inertia (Rosekind et al., 1995). Sleep inertia, the "grogginess, disorientation, and sleepiness that can accompany awakening from a nap" (Rosekind et al., 1995, p. 64) is a major negative effect of sleep and potential safety threat in operational settings. In aviation, the issue of sleep inertia is widely known and dealt with in regulations by aviation administrations (see e.g. FAA, 2010; EASA, 2019). In L4 automated driving, the driver will be allowed to sleep but

Abbreviations: AASM, American Academy for Sleep Medicine; EEG, Electroencephalograhy; HMI, Human-machine interface; NDRA, Non-driving related activity; SAE, Society of Automobile Engineers; TOC-rating, Take-Over Controllabiliy rating; TOR, Take-over request

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still has the option to reengage in the driving task whenever wanted. This means that clarification is needed as to whether after sleeping one is able to take back the driving task. The aim of the presented study is to assess drivers' takeover performance after sleeping.

1.1. Sleep and automation

When automation reaches a level where the driver is enabled to sleep while driving but still has the opportunity to drive her- or himself, the question arises: Is a driver able to take back the vehicle control after sleeping?

Automated driving systems are classified into different automation levels. The arguably most broadly used taxonomy for automated driving research is the taxonomy provided by the Society of Automotive Engineers (SAE, 2018). It defines six levels of automation, starting with level 0 (L0, no automation) and ending with level 5 (L5, full automation) where the driver is never required to intervene. Common understanding is that drivers are allowed to sleep when driving with automation level 4 and higher. By definition, for L4 systems the driver is not the fall-back option. The system is capable of handling all driving situations safely without intervention of the driver, e.g., by stopping in a safe place. Nevertheless, it has to be expected that L4 systems will not be able to handle full drives in automated mode but only parts of a drive, e.g., certain sections on motorways. When reaching the end of an automated section (e.g., an exit or roadworks), the driver is notified in advance to prepare adequately for taking back control. If she or he does not respond, the L4 system is able to handle the situation safely. This procedure of notification basically resembles a TOR of an L3 system but with much longer takeover times. To keep wording simple, this procedure is called a TOR throughout the paper. Until full automation is realized, which means a complete removal of the human driver from the vehicle control, it has to be understood what capabilities of the driver are needed for her or him to reengage in the driving task after being driven automatically. For a detailed discussion of requirements to the driver state for each automation level see Herzberger, Voß, and Schwalm (2017).

In L2 systems, the driver is required to execute parts of the driving task (e.g., monitoring the traffic) and is required to supervise the system functioning. Therefore, engaging in other activities or even closing the eyes is not permitted (SAE, 2018). Research suggests that monitoring the system for longer periods causes vigilance decrements (Greenlee et al., 2018) and fatigue (Körber et al., 2015). These findings are supported by repeated reports about drivers being filmed while sleeping behind the wheel of their L2-automated cars (DPA, 2019; Guarino, 2016; Solon, 2018).

In the context of L3 systems, drivers are no longer required to constantly monitor the driving environment. They are allowed to engage in non-driving related activities (NDRAs). This automation level was found to reduce drivers' workload on one hand, but on the other hand, when being engaged in NDRAs drivers are at risk of losing their situation awareness for the driving task (De Winter et al., 2014). This can be especially problematic since the driver is still the fall-back option and in case of system boundaries the driver has to respond to a TOR and take back the vehicle control. When not being engaged in NDRAs, the driver's situation awareness can even be improved with L3-systems (De Winter et al., 2014), but evidence also suggests that due to mental underload drivers are more prone to experience fatigue (Naujoks et al., 2018a). Vogelpohl et al. (2018) compared the progression of drowsiness of drivers in a simulator study during a drive with an L3-system and a manual drive. In the L3-condition drivers exhibited facial indicators of fatigue after 15–35 min of driving while in the manual driving condition the same levels were only observed after 40 min. Additionally, drivers in the L3-condition reached higher levels of fatigue. Similar results were found by Schömig et al. (2015) although only on a descriptive level. It has to be considered that the proneness to fatigue varies individually and not all drivers are at higher risk of falling asleep in automated driving (Feldhütter et al., 2018).

Drowsiness and fatigue are critical driver states in L3 automated driving - due to an insufficient arousal level drivers are impaired in their reactions to a TOR. Naujoks et al. (2018a) observed prolonged reaction times to a TOR when drivers were fatigued. It has to be defined which driver state (i.e. which level of attention) is the minimal required state for drivers to be able to take over vehicle guidance when necessary.

The issue of sleep becomes of high interest in L4-automated vehicles. The driver is no longer the fall-back option in case of system limits. The driver not only has the option to engage more deeply in NDRAs - some vehicle manufacturers even promote the possibility to sleep during a drive with an L4 automated system (BMW, 2018). However, as long as the human driver still has the option to operate the vehicle manually it has to be understood whether after sleeping he or she is able to take over the vehicle control and is able to drive. The issue of performance decrements due to sleep inertia may play a crucial role here (Ferrara and De Gennaro, 2000; Tassi and Muzet, 2000).

One area that we can learn from when trying to deal with sleep in an operational setting is aviation. On long-haul flights pilots often have the possibility and are even advised to sleep in order to restore their alertness (Hartzler, 2014). Recommendations on the duration of naps for pilots while they are on duty are very detailed accounting for the threat of sleep inertia. Most national and international aviation associations refer to the 'NASA nap'. The NASA nap is a recommended rest period of 40 min which is designed to be long enough for a restoring nap but short enough to minimize the occurrence of deep sleep which produces the highest sleep inertia. In a study assessing the NASA nap, pilots effectively slept 25.8 min of the 40-minute period (Rosekind et al., 1994). The NASA nap is implemented with slight differences by different aviation associations such as the European Union Aviation Safety Agency (EASA, 2019), the Australian Civil Aviation Safety Authority (CASA, 2013) or the International Civil Aviation Association (ICAO, 2015). These regulations in the field of aviation emphasize the relevance of sleep inertia in operational settings. It is however questionable if findings from studies on pilots can be directly transferred to drivers. As opposed to drivers, pilots are highly trained. The duration of the sleep period may also vary a lot for drivers.

In the area of driving automation, very few studies have addressed sleep as a relevant driver state so far. To our knowledge only one study has investigated drivers' takeover performance after sleep in automated mode. In the driving simulator study by Hirsch et al. (2020), n = 44 participants completed a highly automated motorway drive in a driving simulator. Participants were encouraged to sleep during the drive. The point of sleep onset was determined based on video monitoring in combination with the visual inspection of muscle tonus, respiratory rate and pulse rate. The ability of taking back the vehicle control was investigated varying the takeover time between subjects. Participants were warned 1 min, 7 min or 15 min before the actual takeover additionally to a no-sleep control group that had to take over within 15 s. In order to avoid deep sleep, participants were awakened after 15–20 minutes of sleep. No differences between the groups were found in any of the performance indicators such as longitudinal and lateral guidance, reaction times, subjective mental workload, and subjective difficulty of takeover.

It seems surprising that no performance impairments were found given the findings from research on sleep inertia (Hilditch et al., 2017; Tassi and Muzet, 2000). The experimental design raises doubts that the participants were sleeping before the takeover requests. No sleep manipulation such as sleep deprivation was used and to our experience without the use of EEG it is hardly possible to reveal the sleep status of an individual with eyes closed. A paradigm of inducing sleep via sleep deprivation in combination with an early test time and detecting sleep with the EEG proved to be highly valid in one previous driving simulator study (Wörle et al., 2019).

1.2. Sleep

In order to understand human performance after sleep one has to gain an understanding of the structure and mechanisms of sleep. Sleep is defined as a "behavioral state of perceptual disengagement from and unresponsiveness to the environment" (Carskadon and Dement, 2017, p. 15). Sleep has to be understood not as a continuous process but rather as a sequence of different states characterized by different arousal thresholds, the sleep stages (AASM, 2017; Carskadon and Dement, 2017):

- W (wakefulness): This state covers the whole range from tension to relaxation.
- N1 (light sleep): Also referred to as "dozing". In this transitional state, sleep can easily be discontinued. The stage only accounts for about 2–5% of total sleep time.
- N2 (stable sleep): In healthy human adults this stage accounts for 45–55% of total sleep time of an average night's sleep. More intense stimuli are required to produce arousals than in N1.
- N3 (deep sleep): Sleep stage with the highest arousal thresholds. Deep sleep or Slow Wave Sleep (SWS) accounts for 10–20% of an average night sleep.
- R (rapid-eye-movement sleep, REM sleep): This stage is also referred to as "dream sleep". Arousal thresholds are variable in this stage.

Humans usually enter sleep through lighter sleep stages (e.g. N1) and then proceed to deeper sleep stages. Sleep is not a linear process; it is rather characterized by a constant change between different states. Even the onset of sleep is not a clearly defined point in time. A change in EEG pattern, for instance, is not necessarily accompanied by the subjective perception of sleep. However, the deeper the sleep the stronger the cues that are needed to wake a person and the longer it takes until the person is fully alert (Carskadon and Dement, 2017).

1.3. Sleep inertia

When being awakened from sleep, humans experience a period of confusion, disorientation and impairments in cognitive and behavioural performance, often referred to as "sleep inertia". It is also described as a "period of transitory hypovigilance, confusion, disorientation of behaviour and impaired cognitive and sensory-motor performance that immediately follows awakening" (Ferrara and De Gennaro, 2000, p. 3). In this state, humans show decreased performance in a variety of tasks such as reaction time tasks, visual-perceptual tasks, memory tasks and cognitive tasks (Tassi and Muzet, 2000). After sleep, every phase of wakefulness begins with sleep inertia, which suppresses neurobehavioural functioning for a brief period of time (Gabehart and van Dongen, 2017). The time course and duration of sleep inertia is subject to discussion. Depending on the operationalization of sleep inertia, its effects vary from 1 min to 4 h (Tassi and Muzet, 2000). However, most severe performance impairments are observed within the first 20 min after awakening (Ferrara and De Gennaro, 2000). The duration and extent of sleep inertia depends on many factors: The sleep stage prior to awakening is one of the most critical ones: Slow Wave Sleep (SWS, sleep stage N3) prior to waking up clearly produces the highest performance impairments (Tassi and Muzet, 2000; Ferrara and De Gennaro, 2000). Other factors influencing sleep inertia are the time of the day (Borbély et al., 2016) and type of task (Tassi and Muzet, 2000; Trotti, 2017) as well as the duration of prior sleep with e.g., 30-minute naps producing higher performance impairments than 10-minute naps (Hilditch et al., 2016; Tassi and Muzet, 2000). Factors modulating sleep inertia are very complex. Nevertheless, performance decrements due to sleep inertia can cause a high risk in operational settings and have to be understood in the context of automated driving.

2. Objective

The aim of our study is to gain an understanding about drivers' capabilities of regaining the vehicle control after waking up from sleep in highly automated driving. In order to approach a standardization of the driver state, it is aimed to wake all drivers from stable sleep (sleep stage N2).

3. Method

The study is conducted in the high-fidelity moving base driving simulator of the WIVW GmbH (see Fig. 1). The mock-up consists of a production type BMW 520i. The motion system uses six degrees of freedom and can display a linear acceleration up to 5 m/s². All vehicle dynamics and noises are displayed realistically. The simulation software is Silab® Version 6.0 (WIVW GmbH, Veitshöchheim).

Every participant completes two drives. The drives take place on a three-lane motorway with slight curvature and a speed limit of 120 km/h. The drives are completed using a highly automated motorway system.

Fig. 1. High-fidelity driving simulator at WIVW.

3.1. System implementation

The automated system is implemented as an SAE L4 automated motorway system. When activated, the system executes longitudinal as well as lateral vehicle guidance. When the system is available for activation, a message appears on the speedometer display. The system can be activated by pressing an activation/deactivation button at the steering wheel. When system limits are met, a gradual takeover request is issued. The sequence of the takeover request is depicted in Table 1.

The system can be deactivated either by braking, steering or pressing the activation/deactivation button at the steering wheel. If the driver does not deactivate the system within 60 s after the first warning, a minimal risk manoeuvre is initiated. The vehicle executes a safe stop in its current lane.

Table 1
Gradual takeover request.

Time until emergency stop	Acoustic warning	LED colour change
60 seconds	"Manual driving in 60 seconds"	Green
15 seconds	"Manual driving in 15 seconds"	Green
11 seconds	Warning tone	Orange
7 seconds	Warning tone	Red
Emergency stop		Red

3.2. Test scenarios

During each drive, the drivers have to handle two different takeover scenarios. The first takeover scenario is a workzone (“Roadworks”). Construction vehicles block the middle lane and one of the adjacent lanes. Drivers have to move to the third, unblocked lane to avoid crashing into the workzone. Signs indicating the direction of required lane changes in order to avoid the workzone are placed on the side of the road 60 s., 45 s., 30 s. and 15 s. before passing the workzone. After passing the workzone, the automation is not available for 4 min and the drivers have to drive manually until they are able to reactivate the system. The position of the free lane (outer left or outer right) varies between the two drives, meaning that the correct driver reaction to avoid the roadworks in the second drive cannot be directly based on the first drive. This was done to minimize learning effects.

The other takeover scenario is the exit before the end of the drive. One minute before reaching the exit an arrow is presented on an in-vehicle display showing to the right. The drivers have to change lanes to the right and then have to enter the exit. Both takeover scenarios are graphically depicted in Fig. 2.

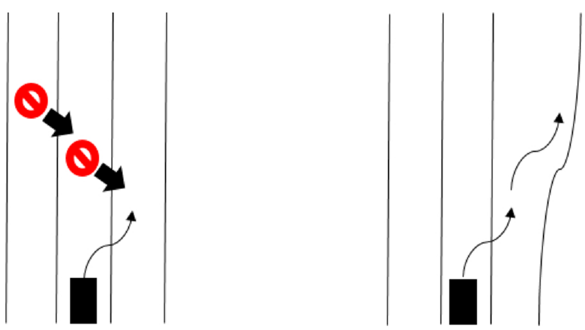

Fig. 2. Takeover scenarios Roadworks (left) and Exit (right).

3.3. Data logging

Table 2 gives an overview of all data that were logged in the study which are relevant for the presented analyses.

Table 2
Data logged throughout the drives.

Data source	Parameter
Driving data (SILAB®)	Throttle
	Takeover
	HandsOn
Video of the drive (bird’s eye perspective)	TOC-rating
Eyetracking data (SmartEye®)	First road glance
	First display glance
	First mirror glance
Questionnaires	Criticality scale, Neukum and Krüger (2003)
	Pre- and post-drive questionnaires
EEG (Brainvision®) *(only logged in morning drive)*	Sleep stages W, N1, N2 (according to AASM, 2017)

3.4. Procedure

Before the first drive, all participants are informed about the study, give their informed consent and complete the first part of a questionnaire on their sleep the night before the drive. After filling in all pre-drive questionnaires, participants complete a 10-minute introduction drive where they have the possibility to familiarize themselves with the system functionality and handling. They experience a minimal risk manoeuvre and a takeover situation where they have to deactivate the automation and retake the vehicle control.

After the familiarization drive, every participant completes the first test drive which takes approx. 35 min. They enter the motorway from a rest area and activate the system. After 10 min of highly automated driving, they experience the first takeover situation Roadworks. After another 10 min, drivers experience the final takeover scenario Exit and leave the motorway at the upcoming exit. On stopping the car, the first drive is finished.

Participants are instructed to sleep no longer than four hours the night before the second drive. They arrive at the test facilities by taxi at 6 a.m. After completing a short questionnaire, electrodes are placed according to the International 10–20 system (Keenan and Hirshkowitz, 2017). Then participants enter the simulator and start the drive. They are explicitly instructed to try to sleep after activating the automated system. The EEG recording is constantly monitored by an expert evaluator. The experimenter issues the first takeover situation Roadworks when drivers are experiencing sleep stage N2 but not earlier than 30 min after the start of the drive. When drivers have completed the takeover situation and the subsequent manual drive, they activate the automation and try to sleep again. The experimenter issues takeover situation Exit when participants experience N2 sleep again or when the maximum test time of 2 h is over.

During both drives, participants rate the takeover situations directly after experiencing them. They judge the criticality of the situation on a 10-point criticality scale with the categories ranging from 0 = “nothing noticed” to 10 = “uncontrollable” (Neukum and Krüger, 2003, see Fig. 3).

After the drive, participants complete a post-drive questionnaire that asks about their perception of sleep during the drive. They are compensated for their participation and are taken home by taxi.

Uncontrollable	10
	9
Dangerous	8
	7
	6
Unpleasant	5
	4
	3
Harmless	2
	1
Nothing noticed	0

Fig. 3. Schematic presentation of the Criticality scale (adapted from Neukum and Krüger, 2003).

3.5. Sample

N = 25 drivers (11 female, 14 male, mean age = 37.8 years, sd = 11.8) complete two drives with the automated system in the driving simulator. Mainly frequent drivers are included in the study (mean annual mileage = 23380 km). All participants have completed an extensive training at the driving simulator before participating in the study in order to avoid learning effects and simulator sickness.

4. Data analysis

The sleep manipulation paradigm proves highly valid. All drivers

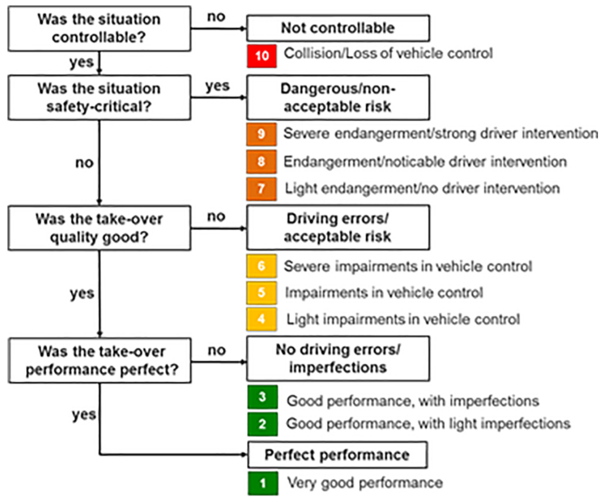

Fig. 4. Rating process TOC-rating (www.toc-rating.de/en).

except for one fall asleep and reach sleep stage N2. The aim of triggering the takeover situation in sleep stage N2 succeeds for 20 drivers in the situation Roadworks. For both takeover requests one driver is awake before the takeover request, one experiences light sleep (N1) and two drivers are awakened during deep sleep (N3).

The objective criticality of the takeover situations is rated with the Take-Over Controllability rating (TOC-rating) that is performed by trained raters based on video recordings of the takeover situations. A schematic process of the TOC-rating is depicted in Fig. 4, for a detailed description see Naujoks et al. (2018b). The rating scale ranges from 1 = "Perfect" to 10 = "Not controllable". One advantage of assessing the criticality of a driving situation with the TOC-rating over analysing driving parameters such as deviation of lane position or speed is the holistic view of the takeover situation, which makes its outcome comparable across different takeover scenarios.

Furthermore, for both scenarios reaction times are calculated for various components of the required takeover reaction. The reaction times quantify the time needed after onset of the TOR until drivers glance on the road (first road glance), glance in the mirror (first mirror glance), glance at the human-machine interface (HMI) of the system (first display glance), put their hands on the steering wheel (HandsOn), take back control, i.e. deactivate the system (Takeover), press the gas pedal (Throttle) and change lanes to avoid the roadworks (Lane change).

Subjective and objective measures for reactions to TORs are compared for takeover situations after wakefulness and after sleep stage N2.

5. Results

5.1. Takeover times

Reaction times after the issue of the first takeover request (acoustic output "Manual driving in 60 s") are compared for the driver states (wake vs. sleep). For all indicators except the first glance to the display, reaction times are significantly longer after sleep compared to awake (HandsOn: $F(1, 46) = 5.6109$, $p < 0.05$; Takeover: $F(1, 46) = 8.9651$, $p < 0.05$; Throttle: $F(1, 44) = 18.898$, $p < 0.001$; Road glance: $F(1, 43) = 9.3963$, $p < 0.01$; Lane change: $F(1, 38) = 9.5507$, p= < 0.01; Mirror glance: $F(1, 42) = 4.9739$, $p < 0.05$). The only indicator with a significant difference between the two takeover situations is the time until lanes are changed ($F(1, 38) = 8.7884$, $p = .00521$).

Furthermore, there are differences in the timely order of the components of the takeover reaction. In both conditions, drivers first glance at the road. Next, drivers visually check the rear-view mirror. Then, behaviour differs between the conditions: When being awake, drivers put their hands on the steering wheel and take over the driving.

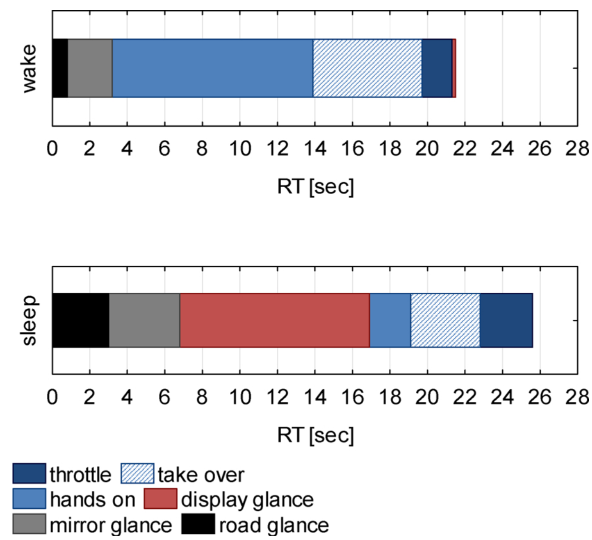

Fig. 5. Time sequence of takeover reaction in situation Roadworks.

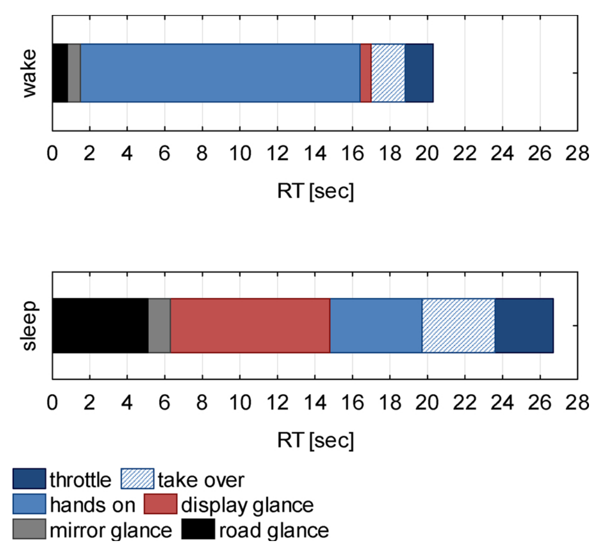

Fig. 6. Time sequence of takeover reaction in situation Exit.

Afterwards, they check the display with the information about the system state. After sleep, drivers first check the display and then put the hands on the wheel and take over the vehicle control. The sequence of the takeover reactions in situations Roadworks and Exit is shown in Figs. 5 and 6. For detailed reaction times please refer to Table A1 in the appendix.

In the post-drive questionnaire, drivers are asked about the appropriateness of the timing of the takeover request on a 9-point scale ranging from 1 = "too early" to 9 = "too late". Most drivers indicate that the warning time of 60 s between the first warning and the actual situation after sleeping is "at the right time". Only four drivers state that the takeover request is a little too late (see Fig. 7).

5.2. Objective criticality of takeover situations

The overall performance of the drivers in the takeover situations is evaluated with the TOC-rating. The rating is worse for drivers after sleep (Fig. 8). When taking over after stable sleep the situation is rated as being more critical than when taking over after wakefulness for situation Roadworks (Wilcoxon test $z = 3.25$, $p = .0012$, $N = 22$). For situation Exit there is a tendency (Wilcoxon test $z = 1.93$, $p = .0537$, $N = 21$).

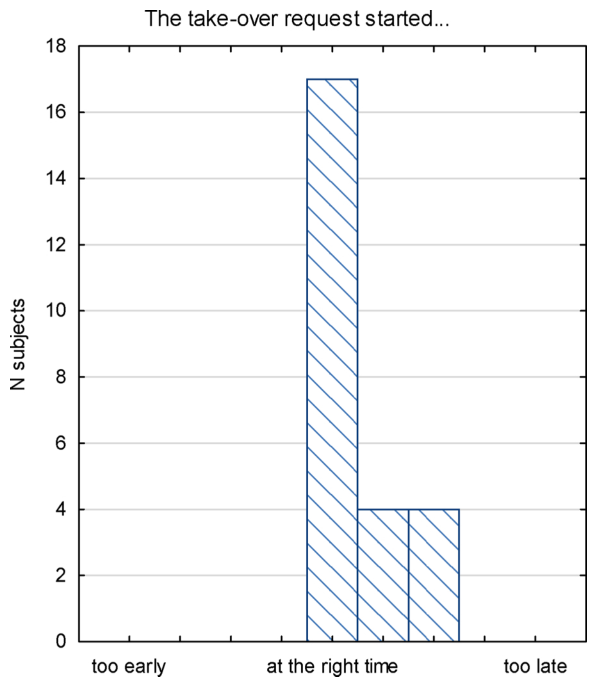

Fig. 7. Subjective evaluation of the takeover time.

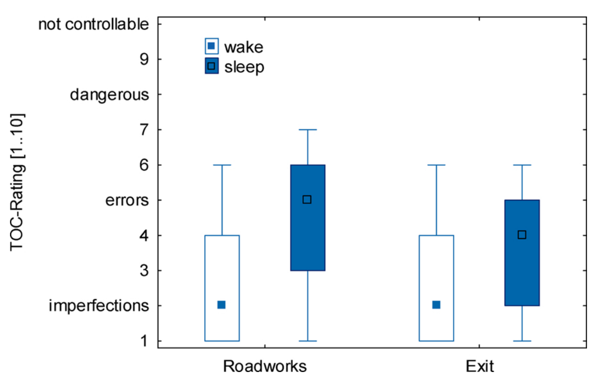

Fig. 8. Distribution of TOC-ratings for both scenarios after wakefulness and after sleep. Median, quartiles and range without outliers are shown.

While no driving errors are found in 70% of both takeover situations for the drivers after wakefulness, only 39% have no errors when taking over after N2 sleep. In 57% of the situations, a TOC-rating of 4 or higher is given which means that observable driving errors after the takeover request occur and 4% of the takeover situations after sleep are rated as "dangerous" (TOC-rating > 6).

The most common driving errors that occurred after N2 sleep compared to after wakefulness are impairments in lane keeping (i.e. strong oscillations in the lane), delayed lane changes and delayed or missing use of the indicator when changing lanes. An overview of the error categories from the TOC-rating can be seen in Fig. 9 for situation Roadworks and in Fig. 10 for situation Exit. Only those error types from the TOC-rating scheme that occurred at least once are shown.

5.3. *Subjective criticality of the takeover situations*

The drivers' subjective perception of the takeover situation reflects the results from the objective TOC-ratings. Paired sample t-tests comparing the subjective ratings after wakefulness and after sleep of the situations' criticality are calculated separately for the situations Roadworks and Exit (Fig. 11). The takeover in situation Roadworks is perceived as unpleasant (M = 4.16, SD = 2.12) after sleep and this rating is significantly higher than after wakefulness (M = 1.72; SD = 1.34, Wilcoxon test z = 3.92, p < 0.001, N = 20). The same is true for situation Exit: Mean criticality ratings after wakefulness (M = 1.09, SD = 0.60) are significantly lower than after sleep (M = 3.22, SD = 1.65, Wilcoxon test z = 3.72, p < 0.001, N = 18).

5.4. *Willingness to sleep in automated driving*

In the post-drive questionnaire after the second drive, drivers are asked whether they would sleep during a drive with a similar system in real traffic. N = 10 subjects indicate their willingness to sleep during an automated drive and N = 15 subjects indicate that they would not sleep. When asked for the reason behind their choice not to sleep during an automated drive, most participants state their impaired driving performance after waking up ("dazed feeling after waking up", "fuzzy driving after sleep"), lack of trust in the automation and the subjective stress when being awakened by the system.

6. Discussion

While a sleeping driver is considered as "non retrievable to the driving task" by some (Herzberger et al., 2017, p. 800) and no performance impairments after waking up were found by others (Hirsch et al., 2020) the truth might lie somewhere in between. The aim of our simulator study was to investigate the ability of a driver to reengage in the driving task after sleeping while the vehicle is operating in automated mode.

All drivers woke up due to the acoustic alarm and took back the vehicle control within one minute. Takeover reactions were delayed by a few seconds which we do not consider as critical for a total takeover time budget of 60 s. However, takeover performance after sleep was clearly impaired compared to wakefulness. Drivers rated the takeover after sleep as "unpleasant".

Drivers' takeover strategy was different when reacting to the TOR after sleep than after being awake. After glancing at the road and to the mirrors, drivers glanced at the display which displays the system state whereas when taking over after wakefulness drivers first took over the vehicle control and checked the display afterwards. In the process of gaining an understanding of the current situation after awakening, drivers apparently wanted to confirm the system state by checking the display directly after checking for the surrounding traffic (road glance and mirror glance). One reason might be that the acoustic TOR was capable of arousing drivers from sleep but that drivers were not able to fully understand the meaning of the TOR.

Besides the first glance at the display, all other reactions such as the hands-on time or the time until first throttle press are significantly longer for drivers after sleep. Apparently, drivers' reactions are delayed after sleep which in time-sensitive takeover scenarios might lead to safety-critical situations. On the other hand, in our study the system was implemented as a highly automated system (SAE L4) and thus provided a large takeover time of one minute. This time was sufficient even for drivers awakened from sleep to take control back and to handle the situation without accidents. After waking up drivers first built an understanding of the situation, i.e. they looked at the road and in the mirrors, before they took back the vehicle control. No participant engaged in the driving task rashly after waking up. After sleep, the takeover reactions were delayed by about 3 s.

The TOC-ratings for the situations when drivers were sleeping show an increase in driving errors compared to takeover situations after wakefulness. The lateral vehicle control was especially impaired. When changing lanes, control glances were missing in a great amount of the takeover situations in the morning drive. This is a clear indicator of cognitive impairments after waking up. In addition, two takeover situations (or 4% of the situations) after sleeping were rated as dangerous which clearly is a safety issue.

The results of our study suggest that it might be feasible to get a

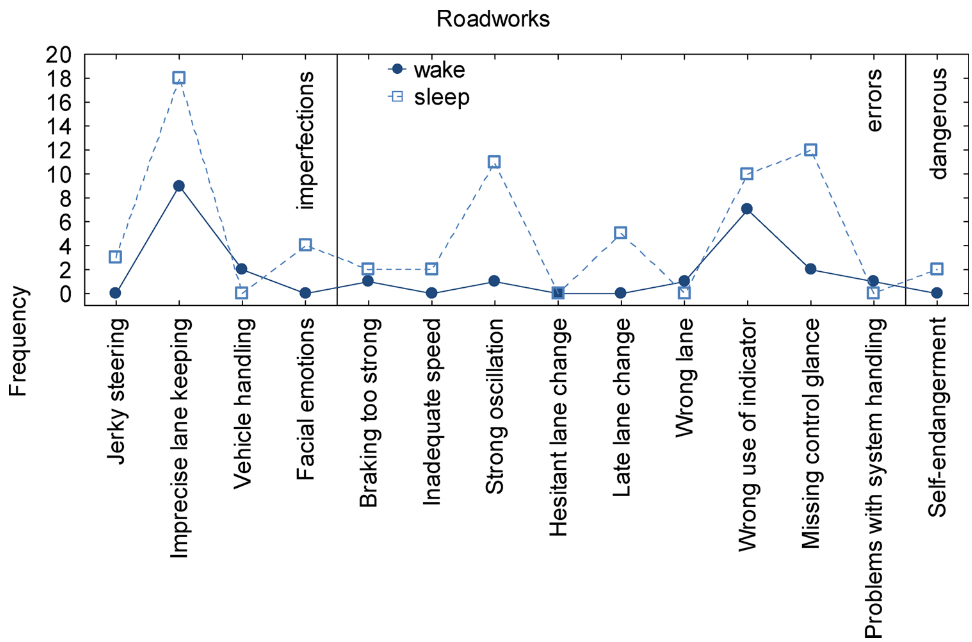

Fig. 9. Error categories from TOC-rating for situation Roadworks.

sleeping driver back into the vehicle guidance and have them take control back. Even though takeover times were prolonged for most parameters, all drivers in stable sleep (N2) woke up from the acoustic warning. It can be summarized that for a highly automated vehicle sleeping behind the wheel might be an option. This does not mean however that the current legislation is too strict in not allowing sleep in automated vehicles. At automation L2 and 3 different requirements are imposed on the driver. In L2 automated vehicles the driver has to monitor the driving permanently which is clearly not possible during sleep. In L3 automated driving the driver does not have to be attentive all the time but has to be able to reengage in the driving task within a short time frame of usually several seconds. For a sleeping driver this might hardly be manageable. Only for an L4 automated vehicle which can act as a fall-back option, drivers can be allowed to sleep.

Another factor is the subjective perception and acceptance of the takeover situations after sleep by the driver. While on average drivers rated the perceived criticality of the takeover situations after being awake as “harmless”, the takeovers after sleeping were rated as “unpleasant”. After the morning drive N = 15 out of 25 drivers stated that in reality they would not sleep during an automated drive. They indicated that they would not trust the system enough to sleep comfortably and they perceived the takeover situations as stressful and their own driving performance after waking up as clearly impaired. It has to be considered however that the system’s HMI was not specifically suited to a sleeping driver and by enhancing the “wake up modalities” and adapting takeover times to the driver’s state, the subjective perception and acceptance of sleeping while driving with an automated system could be promoted. Another limitation of the study is that in the wake condition, drivers did nothing while the automated system was driving. In reality it could be expected that drivers engage in non-driving related activities or are distracted otherwise and therefore might be impaired in their takeover performance, too.

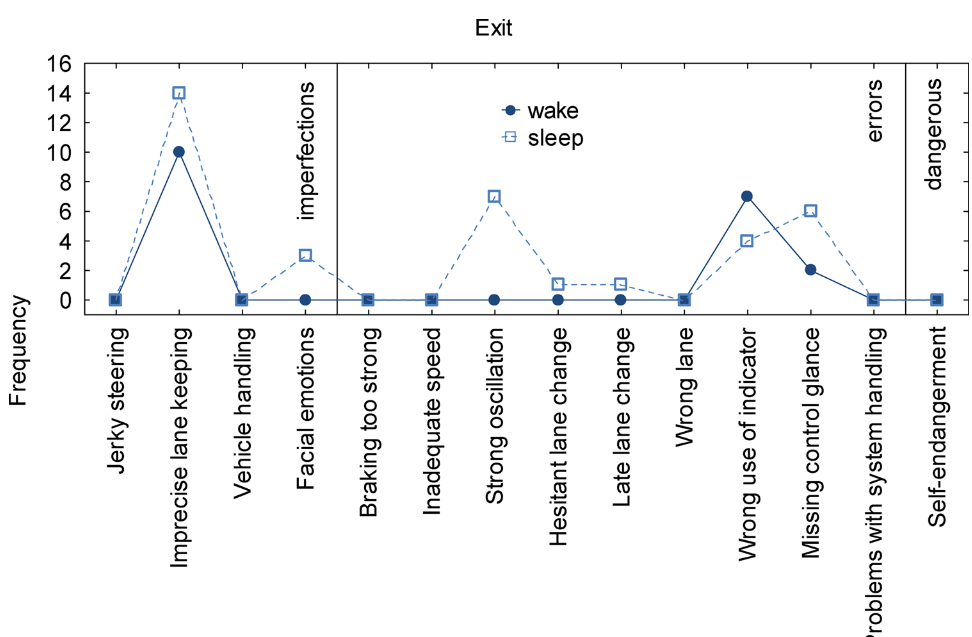

Fig. 10. Error categories from TOC-rating for situation Exit.

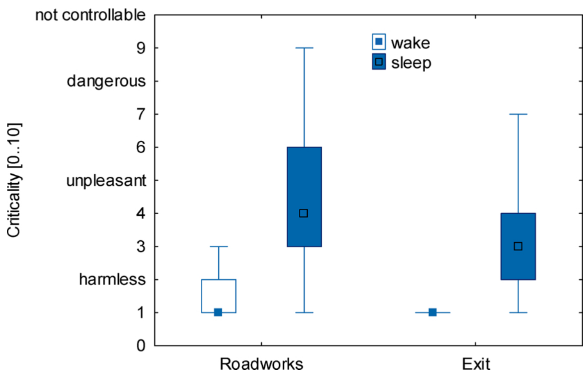

Fig. 11. Distribution of subjective criticality for both scenarios after wakefulness and after sleep. Median, quartiles and range without outliers are given.

7. Outlook

With automated vehicles increasingly entering the roads, the issue of sleeping drivers will gain in importance. Our study provides basic insight into drivers' behaviour and performance when taking over vehicle control from automated driving after sleeping. The results indicate the potential practicability of drivers sleeping in automated cars. For future L4 automated driving, it is planned that drivers will be allowed to sleep during a certain segment of the drive. Before this can become true, we have to investigate if and how sleeping drivers take vehicle control back as the vehicle approaches the end of the automated part of a drive. A takeover time of one minute as applied in our study seems to be manageable for drivers after stable sleep but still there was an increase in driving errors during the situation following immediately after the takeover request. Calibrating the optimal takeover time and investigating the takeover availability in different sleep stages are relevant issues for further research. Therefore a better understanding of the performance capabilities of drivers after different sleep stages is needed. We found that when being awakened from stable sleep (N2) drivers had delayed reactions but were able to reengage in driving. Further research is needed to investigate whether this applies to other states such as deep sleep (N3) or rapid eye movement sleep (R).

Furthermore, the takeover request applied in our study was not especially designed for sleeping drivers. An adaptation of the takeover request on the driver state might be one way to reduce performance impairments after being awakened. Therefor it can be referred to and learned from approaches used in aviation. In this area, the topic of fatigue and of continuing duty after a nap is part of on-flight routines and working procedures for crews on long haul flights. Research on sleep inertia highlights that the negative effects of sleep on driving performance might continue for a certain time after immediate takeover of the driving task. Therefore, it is not sufficient for future research to only study takeover performance directly after being awakened. Instead, manual driving performance after takeover needs to be investigated to capture the potential effects of sleep inertia on driving safety. In the end, it will be a question of HMI design if drivers are able to take vehicle control back safely after sleep. The takeover request needs to be designed in a way that the sleeping driver is supported in awakening, in gaining a full understanding of the driving situation, in actively taking vehicle control back and in reducing the effects of sleep inertia during the subsequent manual drive.

Author note

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CRediT authorship contribution statement

Johanna Wörle: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft. **Barbara Metz:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - review & editing. **Ina Othersen:** Conceptualization, Project administration. **Martin Baumann:** Writing - review & editing, Supervision.

Declaration of Competing Interest

None.

Appendix A

Table A1
Takeover times in awake and sleeping drivers in takeover situation Roadworks. All values are depicted in seconds [s]. N = number; m = mean; min = minimum; max = maximum; sd = standard deviation; A negative mean state difference means a shorter reaction time.

Performance measure	Mean state difference	Awake					After sleep				
		N	m	min	max	sd	N	m	min	max	sd
Situation Roadworks											
HandsOn	5.16*	25	13.9	2.3	49.4	15.5	24	19.1	4.2	56.9	15.7
Takeover	3.08*	25	19.7	2.6	50.8	18.0	24	22.8	5.0	48.0	15.3
Throttle	4.25*	25	21.3	2.6	53.5	18.3	23	25.6	6.5	51.3	15.6
Lane change	5.31	25	40.2	17.4	60.2	13.6	24	45.5	19.3	65.3	16.0
1st road glance	2.22*	24	0.8	0.0	6.5	1.5	23	3.0	0.1	13.9	3.0
1st display glance	−4.66*	15	21.5	0.2	52.3	17.6	11	16.9	1.0	40.5	13.9
1st mirror glance	3.67*	24	3.2	0.0	52.2	10.5	23	6.8	1.1	39.4	8.7
Situation Exit											
HandsOn	3.19*	25	16.5	1.8	58.1	17.9	24	19.7	3.3	51.7	16.7
Takeover	4.78*	25	18.8	3.3	50.4	16.9	24	23.6	4.9	48.8	16.2
Throttle	6.37*	25	20.3	3.3	53.3	17.2	23	26.7	6.7	60.0	16.4
Lane change	5.51	20	25.9	10.0	60.5	17.2	17	31.4	9.5	60.4	16.4
1st road glance	4.35*	24	0.8	0.0	11.7	2.4	24	5.1	0.0	47.8	9.6
1st display glance	−2.27*	13	17.0	0.3	35.9	10.5	13	14.8	1.4	43.8	14.8
1st mirror glance	4.79*	23	1.5	0.0	13.0	2.6	24	6.3	0.0	48.3	9.7

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