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# Sleep inertia in automated driving: Post-sleep take-over and driving performance

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ABSTRACT

Sleep is emerging as a new driver state in automated driving. Post-sleep performance impairments due to sleep inertia, the transitional phase from sleep to wakefulness that can take up to 30 min, are a potential safety issue. Take-over performance immediately after sleep is impaired and drivers perceive the take-over as critical. The aim of the presented study was to assess take-over behavior immediately after sleep and driving behavior during the 10 min after sleep. A study with N = 31 drivers was conducted in a high-fidelity driving simulator. Take-over performance and driving performance were assessed a) under alert baseline conditions and b) after awakening from electroencephalography-confirmed stable sleep. Take-over performance 15 s after awakening was impaired resulting in more driving errors compared to the alert baseline. Lane keeping was dramatically impaired in the first 3 min after sleep and recovered rapidly. Drivers drove slower after sleep and speed keeping was less stable for at least 10 min. The results suggest that human-machine interaction design should account for the drivers' impaired post-sleep driving performance.

## 1. Introduction

Impairments in driving performance are evident for a number of driver states such as alcohol intoxication (Kenntner-Mabiala et al., 2015) or fatigue (Thiffault and Bergeron, 2003). With progresses in driving automation and thus the option for the driver to engage in non-driving related activities (NDRAs), drivers are potentially more distracted (Louw et al., 2019; Naujoks et al., 2016) and more at risk to lose their situation awareness (De Winter et al., 2014). When using a highly automated driving system, drivers become fatigued faster and reach higher levels of fatigue (Vogelpohl et al., 2019).

A great part of human factors issues focuses on driving automation at lower automation levels like partially automated driving systems (automation level 2 according to SAE, 2018) and conditionally automated driving systems (SAE level 3). By SAE level 4, high automation, a new driver state is likely to arise: Drivers will sleep while being driven by their cars. Level 4 automated vehicles are not available for purchase at this point, but even drivers using partially automated systems were found to misuse their automation system to sleep during the drive. Impressive examples are videos filmed by passengers of other vehicles that show users of SAE level 2 systems asleep behind the wheel (Guardian, 2019; Guarino, 2016; Lloyd and Chang, 2019; Solon, 2018). Even at this level of automation, which requires the driver to be attentive at all time (SAE, 2018), drivers misuse the system and sleep behind the wheel. When potential users of automated vehicles are asked about their perceived benefits of automated driving, one of the most desired ways to spend an automated drive is to rest or sleep (Becker et al., 2018; Kyriakidis et al., 2015). It is therefore reasonable to predict that sleep will emerge as a new driver state in automated driving. While sleep could be highly beneficial to restore a fatigued driver's alertness (Hartzler, 2014), post-sleep performance is impaired due to "sleep inertia". Sleep inertia is defined as the "period of transitory hypo-vigilance, confusion, disorientation of behavior and impaired cognitive and sensory-motor performance that immediately follows awakening" (Ferrara and De Gennaro, 2000). In a previous driving-simulator study, drivers' take-over performance from automated to manual driving was clearly impaired immediately after sleep (Wörle et al., 2020). Drivers were awakened from electroencephalography (EEG) - confirmed stable sleep with a visual-acoustic request to intervene (RtI) by the automated driving system (ADS). 60 s after the first warning, a roadwork site appeared on the motorway that had to be avoided by the drivers. After sleep, drivers' reactions were delayed and the sequence of actions to

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take back the vehicle control was changed. Drivers' performance was rated worse after sleep with the standardized Take-Over Controllability Rating (TOC-rating, www.toc-rating.de/en) and drivers perceived the situation as more critical. However, a take-over time of 60 s was sufficient for all drivers to wake up and take back vehicle control.

In the previous study, drivers' performance immediately after awakening was assessed. However, research on sleep inertia suggests that it takes up to 30 min for sleep inertia to wear off (Ferrara and De Gennaro, 2000; Tassi and Muzet, 2000). It is therefore crucial to not only consider drivers' performance immediately after awakening but also subsequent driving performance for a longer time period. The first aim of the presented study is thus to assess manual driving behavior in the period after sleep.

In the previous study (Wörle et al., 2020), drivers were awakened 60 s before the actual test scenario. 60 s proved to be a sufficient warning time for drivers to take back vehicle control after sleep. However, vehicle manufacturers state shorter take-over times for ADS that are soon to be introduced to the market (e.g. 15 s; Griffon et al., 2019). It is hypothesized that with a shorter take-over time after awakening, drivers perform worse in the take-over scenario. The second aim of the presented study was thus to assess whether after sleep, drivers are able to safely take back vehicle control when provided with a shorter take-over time.

Two scenarios are implemented in a driving simulator study to assess manual driving behavior and take-over performance after sleep separately.

### 1.1. Driving performance in automated driving

The human factors of automated driving focus to a large extent on transitions from automated to manual driving (Kyriakidis et al., 2017). The take-over process is described as a driver state transition from an "AD (automated driving) compatible driver state", e.g., a driver being engaged in an NDRA, to a manual driver state. The driver state transition is described on a sensory, motoric and cognitive level. Required actions during the process might be to interrupt an NDRA, start a visual orientation, gaze on the road and put the hands on the steering wheel and feet on the pedals. When the take-over is completed, the driver has to handle the system limit and stabilize vehicle control (Marberger et al., 2017). The take-over process is impacted by the driver state. The take-over time is longer for drivers when they are engaged in an NDRA (Zhang et al., 2019), at a blood alcohol level of 0.08% (Wiedemann et al., 2018) and when they are sleep-deprived (Vogelpohl et al., 2019). Our previous study on take-over performance after sleep shows not only that the take-over time is prolonged but also that the take-over performance is worsened. After sleep, drivers performed fewer safety glances when changing lanes and their lane-keeping was impaired (Wörle et al., 2020).

As discussed above, not only the drivers' immediate reaction after sleep is impaired by sleep inertia, but also subsequent driving performance is likely to be affected. Effects of sleep inertia are observable between 1 min and (under extreme conditions) 4 h after awakening. Usually, sleep inertia wears off after 30 min (Tassi and Muzet, 2000).

Parameters of driving behavior that have proven to be sensitive to the driver state are measures of longitudinal guidance such as speed choice and speed variability. Results on speed choice however, are ambiguous: No impact of alcohol intoxication is evident on speed choice (Kenntner-Mabiala et al., 2015) while fatigued drivers are found to choose higher speeds in some studies (Boyle et al., 2008) and lower speeds in other studies (Du et al., 2015). In a comparison of driving behavior for different levels of sleepiness, at lower levels drivers increased the driving speed while at high levels, they decreased it (Hargutt, 2003). The impact of adverse driver states on variability of speed and lane position are less ambiguous: Fatigued and intoxicated drivers show higher variability of speed (Anund et al., 2008; Du et al., 2015) and variability of lane position, i.e., impairments in steering behavior (Anund et al., 2008; Du et al., 2015; Hargutt, 2003; Kenntner-Mabiala et al., 2015). In automated driving, driver state effects are investigated mainly for parameters of take-over behavior: Fatigued drivers are found to react slower to requests to intervene and to perform safety glances with a timely delay (Vogelpohl et al., 2019). Similar effects were found for alcohol intoxication (Wiedemann et al., 2018).

### 1.2. Sleep inertia and performance

In contrast to driver states such as distraction, alcohol intoxication or fatigue, sleep inertia is rarely investigated as a driver state neither in manual driving nor in automated driving. Hirsch, Diederichs, Widlroither, Graf, and Bischoff (2020) found no impairments on take-over performance after a 20-min nap. Similarly, no impairments are evident on lane-keeping and speed-keeping performance after a 10-min nap in a simulated driving task (Hilditch et al., 2017). A previous study on take-over performance however, yielded clear impairments in take-over performance after sleep (Wörle et al., 2020). Sleep stages were assessed via EEG evaluation according to the American Academy of Sleep Medicine standard (AASM, 2017) and the take-over scenario was triggered only when sleep stage N2 ("stable sleep") was classified. In contrast to the study by Hilditch et al. (2017) where participants were asleep for only 10 min and the study by Hirsch et al. (2020) where sleep was not confirmed via EEG evaluation, the driver state was controlled more reliably. Effects of sleep inertia after awakening are stronger the deeper a person is asleep before awakening (Ferrara and De Gennaro, 2000; Tassi and Muzet, 2000). Sleep is usually entered via light sleep (N1 according to AASM, 2017) and it takes several minutes until deeper sleep stages are entered (Carskadon and Dement, 2017). Performance impairments due to sleep inertia are, for instance, apparent after a 30-min nap, but not after a 10-min nap (Hilditch et al., 2016). The duration of sleep and the sleep stage before awakening both have a large impact on the duration and magnitude of sleep inertia. The strongest effects of sleep inertia are evident for humans awakened form deep sleep (N3 according to AASM). After stable sleep (N2), sleep inertia is not as long-lasting and after light sleep (N1), there are barely any effects provable. Results for the rapid eye movement (REM)-sleep stage are ambiguous (Ferrara and De Gennaro, 2000; Tassi and Muzet, 2000).

In aviation where pilots are allowed and even advised to take naps during a flight, the 'NASA Nap' protocol is in place to avoid safety issues due to sleep inertia: Aviation operators are allowed a 40-min rest period where they have the opportunity to sleep. Following the rest period, they have to refrain from returning to duty for 20 min to let sleep inertia dissipate. The aim of restricting the duration of the rest period is to avoid deep sleep which produces the strongest effects of sleep inertia. Since sleep inertia is also apparent after lighter sleep stages, pilots can only return to duty after waiting for 20 min to let sleep inertia dissipate (Rosekind et al., 1995). The NASA Nap is implemented with slight variations in aviation operator guidelines (EASA, 2019; ICAO, 2015)

No such protocol is in place for drivers. The NASA Nap paradigm cannot be transferred to drivers since a pilot's task demands cannot be directly compared to the characteristics of the driving task. Different tasks are differentially sensitive to sleep inertia. An often implemented measure to assess the behavioral component of sleep inertia is the Psychomotor Vigilance Task (PVT, Hilditch et al., 2016; Santhi et al., 2013; Signal et al., 2008). The PVT is a single-reaction task where subjects have to respond to a visual stimulus via a button press as fast as possible.

Sleep inertia is also evident on complex cognitive tasks, memory tasks, logical reasoning, and some more (Tassi and Muzet, 2000). The more complex a task, the more sensitive they are to sleep inertia (Wickens et al., 2014). Task speed is more sensitive to sleep inertia than task accuracy (Tassi and Muzet, 2000; Wickens et al., 2014).

## 2. Objectives

The primary objective of the presented study was to assess the impact of sleep inertia on manual driving behavior. Driving parameters that have proven to be sensitive to other driver states (like fatigue or alcohol intoxication) are compared after sleep and in an alert baseline condition.

As a long take-over time after sleep of 60 s proved to be feasible in a previous study, the second aim was to investigate take-over performance after sleep with a more realistic take-over time of 15 s. Following the widely applied NASA Nap paradigm, it was aimed at avoiding deep sleep and therefore awaken drivers in stable sleep (sleep stage N2 according to the AASM classification).

## 3. Materials and methods

### 3.1. Basic approach

Each participant experienced six driving sessions in a high-fidelity driving simulator on six different days. In all six driving sessions, drivers had an automated motorway chauffeur of SAE level 3 (L3MC) available for their use. Drivers were instructed that while they were using the L3MC, they were free to engage in side-activities. Still, they had to respond to requests to intervene (RtI) by the system and they were responsible for the drive. Participants were instructed to use the L3MC as they would use it if they had it available in their daily life. The system instruction suggested that they were not allowed to sleep during the drives (see section 3.4). In contrast to strictly experimental studies, naturalistic driving studies (like, e.g., the widely known 100-car naturalistic driving study; Neale et al., 2002) generally aim at capturing driver behavior as realistic as possible and they provide a high ecologic validity. We consider our study approach as "semi-naturalistic" since instructions provided much freedom for drivers to behave as naturalistic as possible. On the other hand, naturalistic behavior was restricted due to the simulator environment and the fixed routes and durations of drives.

The duration of the drives varied between 30 min and 90 min. The drives in sessions 1, 2, 4 and 6 had a duration of 30 min and the drives in sessions 3 and 5 had a duration of 90 min. One of the long drives was scheduled at 6 a.m. ("Morning Drive"). Drivers were instructed to sleep not more than 4 h the night before the session and to consume no caffeinated beverages 24 h prior to the session. In the pre-questionnaire of the Morning Drive, drivers were asked at what time they went to bed and at what time they had woken up and when they had last consumed a caffeinated beverage. This setup has proven to be highly valid to induce sleep in drivers in previous driving simulator studies (Wörle et al., 2020, 2019). The other 90-min drive was scheduled during daytime without prior sleep restriction ("Baseline Drive"). During the Morning Drive and the Baseline Drive, EEG was recorded to detect sleep. The order of the Baseline Drive and the Morning Drive was varied to avoid sequence effects (see Table 1). For a full description of the study design, please refer to Metz, Wörle, Hanig, Schmitt & Lutz (2020).

**Table 1**
Order of the driving session for group A and group B.

| Session | Group A | Group B |
|---|---|---|
| 1 | Short drive | Short drive |
| 2 | Short drive | Short drive |
| 3 | **Morning Drive** | **Baseline Drive** |
| 4 | Short drive | Short drive |
| 5 | **Baseline Drive** | **Morning Drive** |
| 6 | Short drive | Short drive |

Only the Morning Drive and the Baseline Drive are included in the analyses for this paper. During the drives, the drivers experienced two different take-over scenarios ("Roadworks" and "Rain Drive"). In the Baseline Drive the take-over scenarios occurred at fixed points during the drive. In the Morning Drive, the take-over scenarios were issued when a sleep expert detected N2 sleep in the driver's EEG.

### 3.2. Driving simulator and automated motorway chauffeur (L3MC)

The study was conducted using a moving-base driving simulator that runs with the driving simulation software SILAB® 6.0 (WIVW GmbH, Fig. 1, left). The integrated vehicle's console is identical with a production type BMW 520i with automatic transmission. To simulate a realistic steering torque, a servo motor based on a steering model is used. The motion system uses six degrees of freedom. It consists of 6 electro-pneumatic actuators. Three LCD projectors provide a projection of a 240° screen.

When the L3MC was activated via a button at the steering wheel, it performed longitudinal and lateral guidance automatically. It operates within a speed range of 0–130 km/h and always adheres to the posted speed limit. When a slower lead vehicle is detected, the L3MC performs an automated lane change to overtake the vehicle. System boundaries were roadwork sites, motorway intersections, missing lane markings and motorway entrances and exits. 15 s before a system boundary was reached, an RtI was issued. The RtI consisted of an auditory beeping signal and a visual warning on the speedometer display (see Fig. 1, right). If the driver did not react to an RtI, the L3MC performed a minimal risk maneuver, i.e., the vehicle came to a stop in its current lane.

### 3.3. Test drives

The two test drives (Morning Drive and Baseline Drive) were both conducted on a three-lane motorway. The environmental conditions were designed monotonously, e.g., fog restricted the visibility and the traffic volume was low. The speed limit was 120 km/h at all times and the L3MC rarely overtook slower lead vehicles. The Baseline Drive took place during daytime after a full night of sleep. The Morning Drive was scheduled at 6 a.m. and drivers were allowed to sleep not more than 4 h the night before the drive. It was aimed to induce sleepiness in drivers and so they would be more prone to fall asleep during the drive.

The Baseline Drive started on a rest area and drivers entered the motorway in manual mode. On the motorway, the L3MC was available, drivers activated it and drove in automated mode. After 2 min, the first RtI was issued. Drivers were presented with the first take-over scenario "Roadworks" followed by the scenario "Rain Drive". After the Rain Drive, the L3MC was available for 40 min. Then, an RtI was issued and drivers were presented with the scenarios "Roadworks" and "Rain Drive" again. After the second Rain Drive scenario, the L3MC was available again for a short period and then the drive was finished. The take-over scenarios were placed such that in the baseline scenarios at the beginning of the drive, drivers were expected to be alert. After 40 min of automated driving in the second take-over scenarios, they were expected to be fatigued.

The Morning Drive started on a rest area and drivers entered the motorway in manual mode. On the motorway, the L3MC was available, drivers activated it and drove in automated mode. A sleep expert monitored the driver's EEG constantly during the drive. The first take-over scenario "Rain Drive" was issued by the experimenter when the driver fell asleep and reached stable sleep (sleep stage N2) for a constant period. If the driver did not sleep at all, the first take-over scenario was issued 50 min after the start of the drive. After the scenario, the L3MC was available again. If sleep stage N2 was detected a second time, the take-over scenario "Roadworks" was issued. In the Morning drive, we

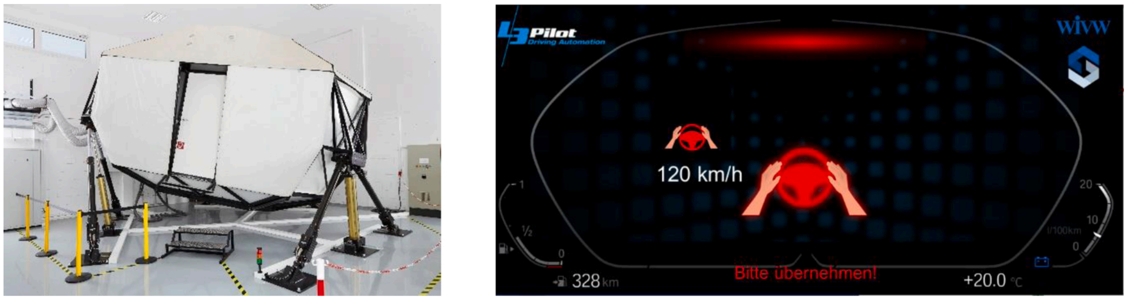


**Fig. 1.** High-fidelity driving simulator (left) and display with visual request to intervene (right).

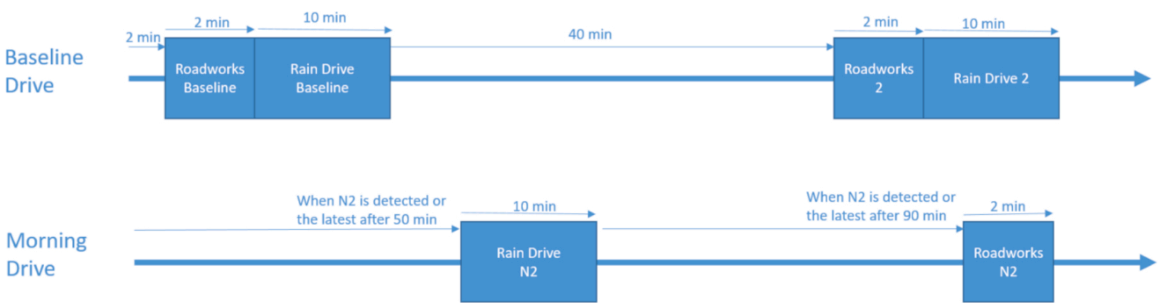


**Fig. 2.** Sequence of the Baseline Drive and the Morning Drive.

assessed the two take-over scenarios separately because we assumed that the situation Roadworks would be highly activating after awakening and thus impact the behavior in the situation Rain Drive if it was directly following. The sequences of both drives are depicted in Fig. 2.

### 3.3.1. *Scenario "Roadworks"*

In the scenario "Roadworks", two lanes of a three-lane motorway were blocked by a construction vehicle that carried a sign pointing in the direction of the free lane. The scenario required a lane change to the free lane. Due to traffic on the free lane, drivers had to check before changing lanes. The roadworks were pre-announced by three signs next to the motorway pointing in the direction of the free lane. The scenario required an appropriate perception and interpretation of the signs and a strategic lane change afterwards. The scenario "Roadwork Site" was implemented with two permutations: Drivers either had to change lanes to the left lane or to the right lane.

### 3.3.2. *Scenario "Rain Drive"*

In the second take-over scenario, an RtI occurred because of heavy rain. Drivers had to take back control, stay in their lane and continue driving on a three-lane motorway with low traffic volume under rather monotonous conditions. After 10 km, a truck changed lanes from the right lane to the center lane in front of the ego vehicle. The driver had to react quickly by braking and changing lanes. The speed limit was set to 120 km/h. The scenario required actions such as keeping the vehicle in the lane and keeping the posted speed limit. The "Rain Drive" took about 10 min of manual driving.

## 3.4. *Experimental procedure*

In the first session, all participants gave their informed consent and filled in an extensive pre-questionnaire [an adapted version of the L3 Pilot pre-questionnaire (Metz et al., 2020a); Annex]. Then, they completed an introductory drive where they learned the handling of the L3MC (e.g. activating and deactivating) and experienced a take-over scenario, as well as a minimal risk maneuver. Then, drivers were instructed for the test drives. They were instructed about the capabilities and boundaries of the L3MC. The drivers' responsibility was clarified using the actual wording of the German Road Transport Law on the use of ADS (BMJV, 2017). The instruction emphasized that drivers had to be attentive in a way that they were ready to react to a TOR at any time during the drive. Drivers were free to use their driving time as they would like to use it in real life, e.g., they were free to bring with them whatever they want to engage in during the drives. Then, drivers completed their first 30-min test drive. After the drive, they filled in the L3 Pilot post-drive questionnaire (Metz et al., 2020a; Annex). The procedure was similar for all driving sessions, only that the pre-and post--questionnaires were shorter in the following sessions.

EEG was only measured in session 3 and 5 (Baseline Drive and Morning Drive). For the EEG recording, the Brainvision amplifier V-Amp and the Brainvision Recorder software were used (both Brainproducts, Garching, Germany). Sixteen electrodes were placed according to the International 10–20 system (Jasper, 1958) with the mastoids as reference electrodes. After each take-over situation, drivers were asked to rate their perceived criticality of the situation on the 10-point Criticality scale (Neukum and Krüger, 2003; see Fig. 3 left) and their subjective sleepiness on the Karolinska Sleepiness Scale (KSS; (Åkerstedt and Gillberg, 1990; see Fig. 3 right).

Throughout the drives, videos of the driving scene and of the driver were recorded. Those videos were later used for conducting the TOC-rating.

## 3.5. *Study sample*

N = 31 participants were recruited from the WIVW test driver panel. Thirteen participants were female and the mean age of the sample was

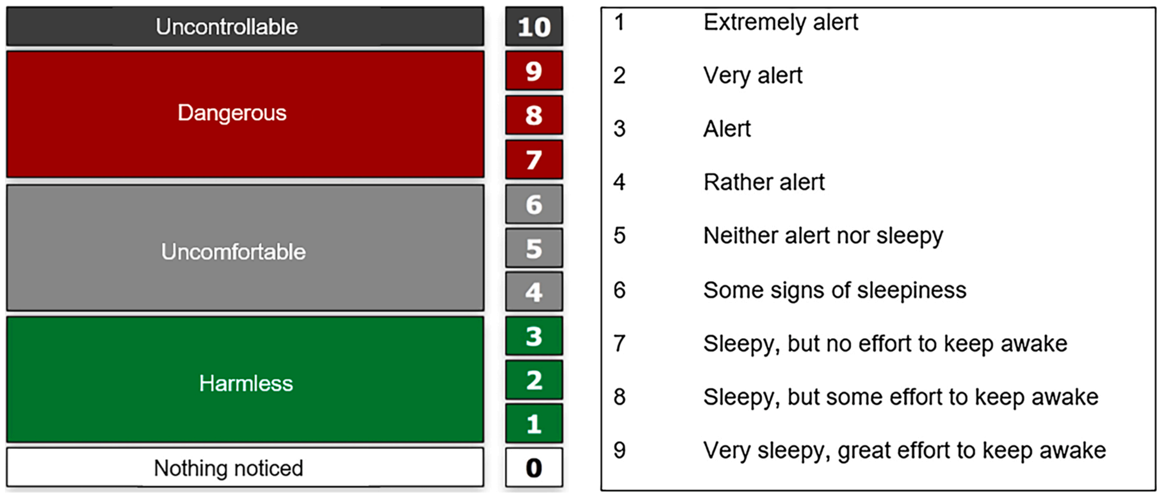


**Fig. 3.** Criticality scale (left, after Neukum and Krüger, 2003, left) and Karolinska Sleepiness Scale (right, Åkerstedt and Gillberg, 1990, right).

37 years (SD = 12 years). All participants held a valid driving license and had completed an extensive training in the driving simulator before participating in the study. The aim of the driving simulator training is to avoid learning effects during the study and to screen out participants who are susceptible to simulator sickness (Hoffmann and Buld, 2006).

### 3.6. Data analysis

To investigate the impact of sleep inertia on take-over performance and driving behavior, performance parameters were compared for the same scenario in a baseline condition where drivers were awake and alert before the RtI and the same scenario where drivers were asleep before the RtI. Sleep was scored following "The AASM Manual for the Scoring of Sleep and Associated Events" (AASM, 2017). The AASM scoring manual is the standard for scoring sleep in clinical settings, e.g. sleep laboratories. Based on EEG characteristics, the following sleep stages are differentiated:

- N1: Light sleep
- N2: Stable sleep
- N3: Deep sleep
- R: Rapid-Eye movement sleep

The aim was to issue the RtI when the driver shows sleep stage N2 (stable sleep) constantly. The AASM scoring approach was slightly adapted to the study conditions. In the original scoring system, sleep stages are assigned to successive EEG episodes of 30 s. We adapted the approach such that we were able to score sleep in real time: Sleep stage N2 was assigned as soon as the first characteristic of N2 was apparent in the EEG (i.e. a K-complex or a sleep spindle).

Other than expected, stable sleep occurred not only during the Morning Drive but also before the second take-over situation in the Baseline Drive. At the same time, only a subsample of drivers experienced stable sleep during the Morning drive. This is the reason why the analysis is not based on a comparison of the two drives but on the driver state coded prior to the analyzed situations. To avoid that a large proportion of the sample is excluded from the analysis, the driver state is

**Table 2**
Frequency of the scenarios “Roadworks” and “Rain Drive “for the baseline condition and after sleep.

| | Scenario “Roadworks” | Scenario “Rain Drive” |
|---|---|---|
| Baseline | 31 | 31 |
| After sleep | 8 | 11 |


**Fig. 4.** Hierarchical rating process of the Take-Over Controllability rating.

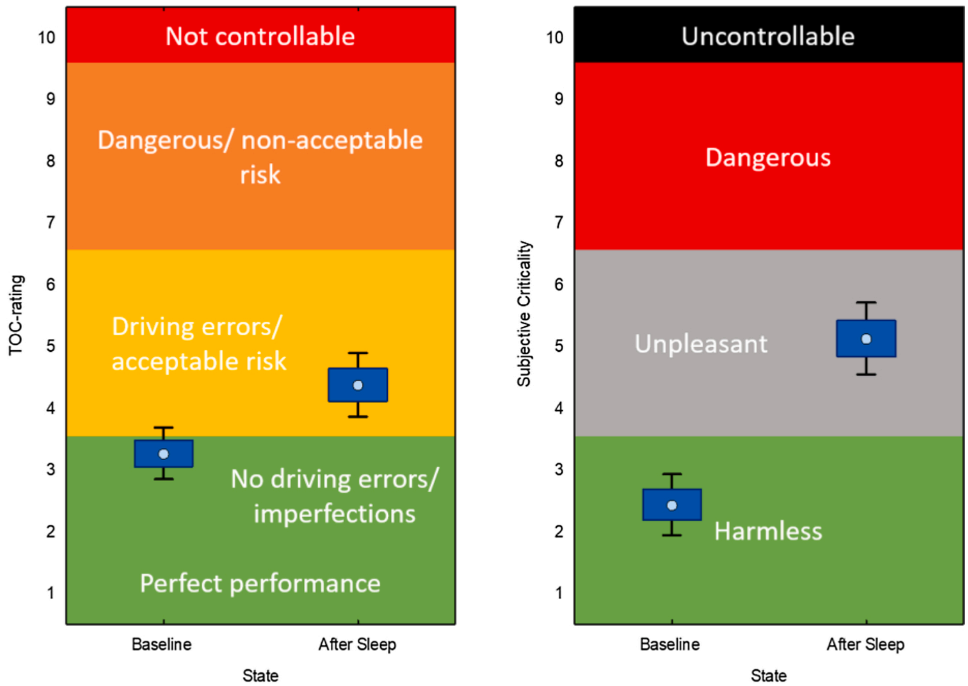


**Fig. 5.** Mean final score of the TOC-rating (left) and mean subjective criticality (right) in the baseline condition and after sleep.

treated as a between-subjects factor, including all baseline scenarios and all after sleep scenarios as independent samples in the analysis.

All drivers (N = 31) experienced the scenarios "Roadworks" and "Rain Drive" at the beginning of the Baseline Drive (condition Baseline meaning awake and alert). N = 15 drivers experienced EEG-confirmed N2 sleep at least once during one of the drives. For N = 11 drivers, we were able to trigger the scenario "Rain Drive" when sleep stage N2 was confirmed. For N = 8 drivers, we were able to trigger the scenario "Roadworks" after sleep stage N2 was confirmed again. Table 2 gives an overview of the situations that were included in the analyses.

The average sleep duration was 29.5 min (SD =15.0 min). The sleep episodes consisted of 29 % N1 sleep, 60 % N2 sleep and 11 % wake episodes.

### 3.6.1. TOC-rating

The take-over performance was evaluated with the Take-Over Controllability rating (TOC-rating) based on video recordings. The TOC-rating is an evaluation method to assess the controllability of a take-over situation. Trained raters assess the controllability of a take-over situation based on standardized criteria. Taking into account all rating criteria, an overall rating (ranging from 1 to 10) is given. Trained raters watch video recordings of the take-over situations. Following a hierarchical process, they assess whether the situation was controllable, whether it was safety-critical or whether the take-over was good or even perfect (see Fig. 4).

Following a rating sheet, driving errors are coded for the main categories "braking response", "longitudinal vehicle control", "lateral vehicle control", "lane change/lane choice", "securing/communication", "vehicle operation" and "driver facial expression".

More detailed information and training material for raters are available at www.toc-rating.de/en

The TOC-rating was performed using the TOC-rating tablet application. It was aimed at blinding the raters to the driver state. However, in most cases it was apparent from the video material when a driver had just awakened from sleep. The TOC-rating was performed for the take-over scenario "Roadworks". Two raters were intensively trained with help of the TOC-rating training videos at the website www.toc-rating.de/en. In order to avoid a rater effect, both raters evaluated take-over situations of both drives.

Independent t-tests were calculated to compare the final score of the TOC-rating, the subjective criticality assessed with the Criticality Scale and the subjective sleepiness assessed with the KSS for the scenario Roadworks in the baseline condition and after sleep.

### 3.6.2. Assessment of driving behavior

The scenario "Rain Drive" was a 22 000 m section on a three-lane motorway. With a speed limit of 120 km/h, the scenario took about 10 min to complete. The drivers' main task was to keep the vehicle in the central lane and to adhere to the posted speed limit. Performance parameters were calculated for sections of 2000 m each which corresponds to a driving duration of about one minute. Section 1 and section 5, where a merging truck had to be avoided, were excluded from the analyses. The situation with the merging truck was relevant for analyses that are not reported in this paper. The scenario started about 10 s after the system boundary was reached. Therefore, the take-over is excluded from the analyses of driving behavior. The analyzed performance parameters are:

- m(v) [km/h]: mean speed calculated for each 2000m-section
- sd(v) [km/h]: standard deviation of speed calculated for each 2000m-section
- sdlp [m]: standard devitation of lane postion calculated for each 2000m-section

The following parameters were included in the analyses:

- Subjective sleepiness measured on the 9-point Karolinska Sleepiness Scale (KSS, from 1 = "extremely alert" to 9 = "extremely sleepy, can't stay awake") only for the Morning Drive
- Objective sleepiness measured continuously with the PERCLOS algorithm based on the eyelid opening level recorded with Smart Eye Pro (SmartEye, Gothenburg, Sweden).
- Subjective criticality of the take-over situations on the Criticality Scale (Neukum and Krüger, 2003)
- Performance in the scenario "Roadwork site" assessed with the TOC-rating (www.toc-rating.de/en)

- Performance in the scenario "Rain drive" based on parameters of continuous vehicle control recorded with SILAB® 6.0 (WIVW GmbH, Veitshöchheim, Germany): m(v), sd(v), sdlp

Subjective ratings as well as take-over performance assessed with the TOC-rating are compared between subjects for the conditions Baseline and After Sleep.

The impact on measures of driving behavior over time are assessed calculating factorial ANOVAs to compare the main effects of driver state (Baseline and After Sleep) and section (1–11, section 1 and 5 are excluded) and the interaction effect between driver state and section for the driving parameters m(v), sd(v) and sdlp as well as for the objective measure of sleepiness via PERCLOS. As stated before, driver state is treated as a between-subject factor and driving section as a within-subject factor.

## 4. Results

### 4.1. *Take-over performance and subjctive criticality of the scenario Roadworks*

The final score of the TOC-rating was higher for drivers after sleep ($M = 4.37$, $SD = 0.74$) than in the baseline condition [$M = 3.32$, $SD = 1.19$, $t(37) = -2.36$, $p < .05$]. Therefore, after sleep, the rating yielded in average "driving errors", while in the baseline condition, it was only "imperfections" (see Fig. 5, left).

The higher objective criticality of the take-over situation was confirmed by the subjective perception of the drivers: After sleep, drivers rated the take-over situation as more critical ($M = 5.12$, $SD = 0.83$) than in the baseline condition [$M = 2.39$, $SD = 1.38$, $t(37) = -5.32$, $p < .001$]. After sleep, the take-over situation was perceived on average as "uncomfortable", while in the baseline condition, it was "harmless" (see Fig. 5, right).

The drivers' subjective sleepiness assessed with the KSS was higher after sleep ($M = 8.38$, $SD = 0.52$) than in the for drivers who had experienced a take-over situation without sleeping in the Morning Drive [$M = 3.52$, $SD = 1.43$, $t(37) = -9.34$, $p < .001$].

### 4.2. *Driving behavior in the scenario rain drive*

After sleep, drivers drove slower than in the baseline condition throughout the whole 10 min of the manual drive. There was a main effect of driver state on mean speed [$F(1, 40) = 7.07$, $p = .011$] and a main effect of section [$F(8, 320) = 2.44$, $p = .014$] but no interaction [$F(8, 320) = 0.68$, $p = .711$]. Averaged over all sections, after sleep, the mean speed was 112.4 km/h ($SD = 8.6$), while after wakefulness it was 117.7 km/h ($SD = 5.4$). The effect of section is based on lower speed during the middle of the manual drive (see Fig. 6).

Speed keeping is more unstable after sleep than in the baseline condition by trend [$F(1, 40) = 3.96$, $p = .053$]. There was no effect of section [$F(8, 320) = 1.04$, $p = .404$] and no interaction effect [$F(8, 320) = 0.69$, $p = .698$], see Fig. 7.

Drivers' lane-keeping performance was more unstable after sleep at the beginning of the manual drive. There was a main effect of driver state on the standard deviation of lane position [$F(1, 40) = 7.77$, $p = .008$], a main effect of section [$F(8, 320) = 4.50$, $p < .001$] and an interaction driver state*section [$F(8, 320) = 5.32$, $p < .001$]. Post-hoc Tukey tests reveal that the effect was mainly due to the high sdlp in section 2 after sleep. The mean difference in sdlp between Baseline and After Sleep in section 2 was 0.25 m, see Fig. 8.

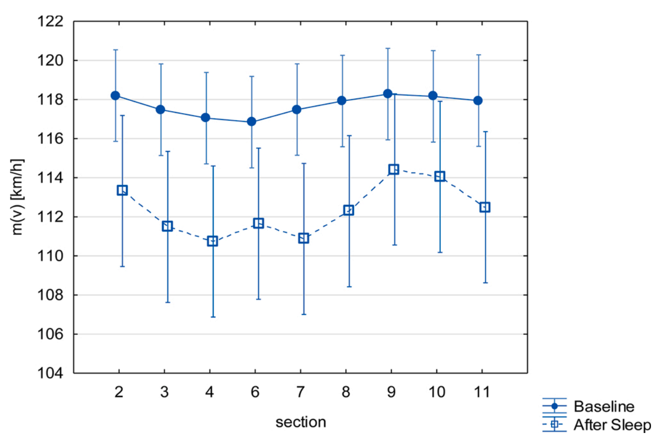


**Fig. 6.** Mean speed of drivers under alert baseline conditions and after sleep during the Rain Drive.

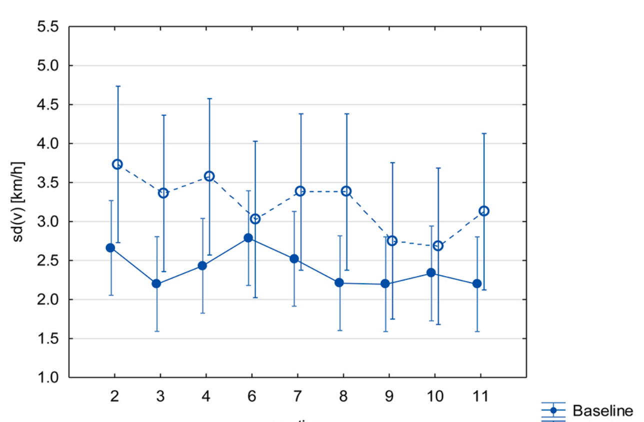


**Fig. 7.** Standard deviation of speed of drivers under alert baseline conditions and after sleep during the Rain Drive.

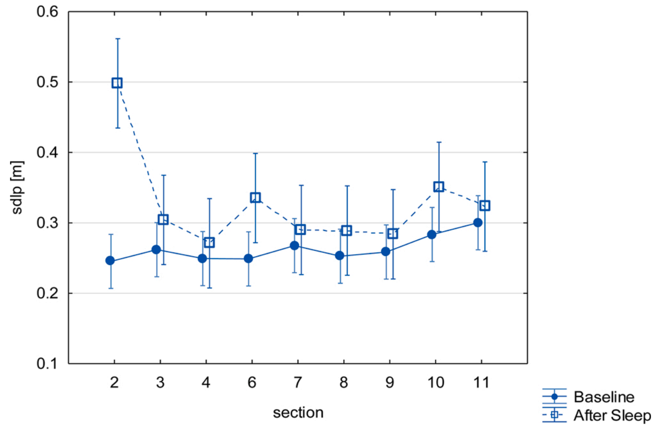


**Fig. 8.** Standard deviation of lane position of drivers under alert baseline conditions and after sleep during the Rain Drive.

## 5. Discussion

The primary aim of the presented study was to investigate the impact of sleep inertia on manual driving behavior and on take-over performance with a short take-over time. Therefore, drivers experienced two different take-over scenarios. Two driving scenarios were implemented to assess manual driving behavior (scenario Rain Drive) and take-over performance (scenario Roadworks) after sleep. In a previous study (Wörle et al., 2020), drivers were able to take back vehicle control from automated to manual driving when they were provided with a warning 60 s in advance. In reality, a take-over time of 60 s will not always be feasible. Therefore, we assessed drivers' take-over performance with a shorter take-over time of 15 s.

N = 31 drivers participated in a driving simulator experiment where they used a conditionally automated driving system for motorways (L3MC) repeatedly in different driving sessions. Even though drivers were instructed that they had to be receptive to RtIs, N = 15 drivers slept during at least one of the long drives that were included in the presented analyses. N = 11 drivers experienced the scenario "Rain Drive" after sleep and N = 8 drivers experienced the scenario "Roadworks" after sleep. Drivers' performance and subjective perception of the situations was always compared after sleep and in a wake baseline condition.

In the scenario "Rain Drive", drivers had to drive manually on a three-lane motorway. They had to keep the vehicle in the lane and adhere to a speed limit of 120 km/h for about 10 min. After sleep, lane keeping performance was impaired compared to the baseline condition. The effect was especially pronounced at the beginning of the drive where the deviation from the wake condition was as large as 0.25 m. In comparison, a study on driving performance under the influence of 0.08 % blood alcohol which was conducted in the same driving simulator (Kenntner-Mabiala et al., 2015), yielded a 0.05 m worsened lane keeping performance. However, lane keeping performance recovered fast and about 3 min after awakening, drivers were able to stabilize the lateral guidance to the baseline level.

After sleep, drivers drove with a 5.5 km/h reduced speed compared to the baseline condition. Reduced driving speed is also observed for drivers under extreme levels of sleepiness (Boyle et al., 2008; Hargutt, 2003). Hargutt (2003) argues that while at lower levels of sleepiness, drivers regulate their arousal level by increasing the driving speed, at higher levels of sleepiness, they are not able to regulate their arousal and simply try to "get through" the drive and drive slower. This could also apply to the driving behavior for drivers who experience sleep inertia. Similar to extreme sleepiness, sleep inertia is characterized by a low arousal level and after awakening, drivers are not (yet) able to compensate for the low arousal. After sleep, drivers choose a lower speed and their speed keeping is more unstable. In contrast to the fast recovery of the unstable lane-keeping, the speed is unstable throughout the whole Rain Drive. The impairments in lane- and speed-keeping due to sleep inertia contrasts the findings of the driving simulator study of Hilditch et al. (2017). After a 10-min nap, no impairments were observable in lane- and speed-keeping in a 10-min simulated drive. This could be explained by the lower sleep depth that was probably reached in the rather short nap. In the presented study, it was ensured to wake all drivers in sleep stage N2. The deeper the sleep, the more performance is impaired after awakening (Hilditch and McHill, 2019; Tassi and Muzet, 2000).

The scenario "Roadworks" was designed such that it required more complex actions of the driver to solve the situation. The take-over performance was assessed with the Take-Over Controllability rating (TOC-rating). The results support the findings from a previous study on post-sleep take-over performance (Wörle et al., 2020): After sleep, the TOC-rating yielded in average "driving errors", while in the baseline condition drivers solved the situation with only "imprecisions". The objective criticality of the take-over situations was supported by the subjective perception of the drivers: While in the baseline condition, drivers perceived the situation as "harmless", after sleep they perceived it as "unpleasant". Drivers had to react to an RtI with a take-over time of only 15 s in contrast to 60 s in the previous study. Surprisingly, the shorter take-over time did not result in worse scores in the TOC-rating. The results suggest that a short take-over time of 15 s is feasible for drivers after stable sleep (sleep stage N2). It has to be considered however, that in the present study drivers were more familiar with the automated driving system and they had experienced different take-over situations in the preceding drives. Therefore, they were generally more experienced in handling take-over situations.

Drivers perceived themselves as sleepy after awakening. They were asked to rate their subjective sleepiness after they had passed the scenario "Roadworks", i.e., 40 s after the RtI. While in the baseline scenario, they rated themselves as "alert" to "rather alert", after sleep, drivers felt "sleepy, some effort to keep awake" to "very sleepy, great effort to keep awake, fighting sleep". This finding is in line with what is known about the subjective perception of sleep inertia which is associated with a lower arousal level and manifests as a desire to go back to sleep (Hilditch and McHill, 2019).

The presented results suggest that a sleeping driver can be awakened and take back the vehicle control after stable sleep. However, take-over performance 15 s after awakening is impaired and errors occur more frequently. Lateral vehicle guidance, i.e., lane-keeping, is dramatically impaired in the first 3min after awakening. These findings have strong implications for the design of human-machine interaction (HMI) concepts. To ensure driving safety, it should be avoided to hand over vehicle control within the first 3 min after awakening. It has to be ensured that the driver has reached a level of alertness that enables a safe take-over and safe vehicle guidance.

Due to the study design that allowed a high variation of driver behavior and thus driver states, it was not possible to analyze the driver state as a within-subject factor which would be favorable to capture a more accurate estimation of effects in a highly controlled experimental setting. One strong point of the study design, however, is the high ecologic validity and therefore transferability of results to real-world settings. In contrast to the more experimental approach in a previous study on take-over performance after sleep (Wörle et al., 2020), drivers were not explicitly instructed to sleep. It can be assumed that those drivers who slept during the study would be more prone to sleep in real driving.

For a general transferability of the presented findings, some crucial factors have to be considered: Sleep inertia, and thus post-sleep performance, is amplified by circadian rhythms (Hilditch and McHill, 2019; Tassi and Muzet, 2000). During the circadian low, i.e., during the biological night and early in the morning, sleep inertia is more severe than during daytime. The Morning Drive took place at 6 a.m., i.e., during the circadian low. Less severe impacts of sleep inertia on take-over and driving performance might be observed when drivers awaken during the circadian high. Drivers were awakened when sleep stage N2 was confirmed via EEG. The deeper the sleep before awakening, the more severe impacts of sleep inertia are observed (Ferrara and De Gennaro, 2000; Tassi and Muzet, 2000). This means that, if drivers are awakened after sleep stage N3 (“deep sleep”), impairments in take-over and driving performance are likely to be more severe and potentially longer lasting than after sleep stage N2. For the transferability of the results, this means that the effects we found can rather be expected after short naps than after longer periods of sleep. Impairments in driving performance can be expected to be higher after longer periods of sleep and after deeper sleep which is a crucial research gap when talking about higher automated driving. Automated driving systems of SAE automation level 4 will offer the driver the possibility to sleep during the drive but at the same time allow the driver to take over to drive manually. With progresses in vehicle automation and at some point, the opportunity for the driver to sleep while they still have the option to drive manually, sleep inertia is likely to arise as a new driver state. The presented study shows that sleep inertia has severe impacts on take-over and driving performance. Therefore, its relevance for driving safety has the potential to gain a similar relevance for drivers in automated driving as it has already for operators in the field of aviation.

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## CRediT authorship contribution statement

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

## Declaration of Competing Interest

The authors report no declarations of interest.

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