International Journal of Human–Computer Interaction

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/hihc20

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To cite this article: Sarah-Maria Castritius, Patric Schubert, Christoph Dietz, Heiko Hecht, Lynn Huestegge, Magnus Liebherr & Christian T. Haas (2021) Driver Situation Awareness and Perceived Sleepiness during Truck Platoon Driving – Insights from Eye-tracking Data, International Journal of Human–Computer Interaction, 37:15, 1467-1477, DOI: 10.1080/10447318.2021.1894800

To link to this article: https://doi.org/10.1080/10447318.2021.1894800

Published online: 17 Mar 2021.

INTERNATIONAL JOURNAL OF HUMAN–COMPUTER INTERACTION
2021, VOL. 37, NO. 15, 1467–1477
https://doi.org/10.1080/10447318.2021.1894800

Driver Situation Awareness and Perceived Sleepiness during Truck Platoon Driving – Insights from Eye-tracking Data

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ABSTRACT

Truck platoon driving technology uses vehicle-to-vehicle communication to allow one truck to follow another in an automated fashion. The first vehicle is operated manually, the second vehicle is driven semi-automatically once platoon-mode is activated. In this mode, the driver merely has to monitor traffic. Semi-automated driving in passenger cars has been shown to increase driver sleepiness and reduce situation awareness. The aim of the present study was to gain first insights whether this also applies to semi-automated platoon driving and whether platoon-specific situations pose special visual demands. In a first on-road experiment, ten professional truck drivers experienced a two-vehicle platooning system on a German highway as platoon follower or leader. In addition, all drivers conducted reference drives with a single truck. Driver situation awareness was measured with eye-tracking recordings, perceived sleepiness with subjective ratings. The results showed that the lead vehicle drivers kept their eyes less time on the road ahead as compared to normal truck driving. In particular in situations that required decoupling, drivers (in the lead vehicle as well as in the following vehicle) spent about 40% of fixations on the HMI. That is, situation awareness was reduced, amounting to potentially risky behavior, as the platoon goes blindfolded when both drivers attend to the display. Drivers did not report higher perceived sleepiness in semi-automated platoon drives than in the manual reference drives. Adequate solutions to reduce the time spent looking away from the road are required. Head-up displays should be investigated for this purpose, as they can simplify driver communication and present platoon-specific information while the eyes remain on the road.

1. Introduction

Truck platooning is an attempt to increase the level of automation and at the same time drastically reduce the following distances between trucks to achieve fuel savings through slipstream driving (Dávila, 2013; Lammert et al., 2014; McAuliffe et al., 2017, 2018). The following vehicles of a platoon are coupled electronically to a lead vehicle, in a semi-automated fashion (Bergenhem et al., 2012; Nowakowski et al., 2015). At level-2 automation (SAE International, 2018), the driver of the following vehicle has to monitor the system and the traffic, but is relieved of all manual driving tasks. However, "system monitoring with either rare or even no overt perceptual-motor requirements" (Desmond & Hancock, 2001, p. 455) constitutes a low-demand situation and leads to passive driver fatigue. (Desmond & Hancock, 2001; May & Baldwin, 2009). Driver fatigue, sleepiness and drowsiness are often used interchangeably – in the following, we use the term "perceived sleepiness" to describe the instantaneous feeling of sleepiness/tiredness caused by circadian factors, sleep deprivation, active tasks engagement or passive monotonous tasks. It relates to the concept of driver fatigue described by May and Baldwin (2009).

Different simulator studies showed that driver engagement decreased after prolonged automated driving (level-2 automation), causing increased reaction times (Neubauer et al., 2012; Saxby et al., 2013) and higher crash risk (Saxby et al., 2013). As sleep-related factors are already one of the main causes of accidents involving heavy vehicles (International Road Transport Union (IRU), 2007; Evers & Auerbach, 2005; Starnes, 2006), it is important to take driver sleepiness into account when developing automated systems for commercial drivers. There is evidence that truck platooning, which automates steering and acceleration of the following vehicle, leads to higher subjective sleepiness ratings than manual truck driving (Hjälmdahl et al., 2017).

Besides boredom or fatigue, secondary tasks can lead to decreased situation awareness, which is defined as the perception, comprehension, and anticipation of driving-related information (Endsley, 1995). Vision is the most important sensory channel for information processing in car driving (Cole, 1972; Sivak, 1996). Drivers tend to look away from the road during automation and often fail to monitor the driving situation, they are out-of-the-loop (Merat et al.,

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2019, p. 92). To retain a sufficient level of situation awareness, the driver needs to scan relevant areas of the driving scene to stay in-the-loop. Eye-tracking has frequently been used to assess situation awareness during driving, by determining gaze patterns or gaze reaction times (Louw et al., 2017; Louw & Merat, 2017; Zeeb et al., 2016). The percentage of time that participants look at the road center has been found to be reduced in automated driving (Jamson et al., 2013; Louw et al., 2017). During automation or when vision is obscured, drivers also look around more, as measured by the horizontal and vertical dispersion of gaze (Louw & Merat, 2017). In contrast, gaze dispersion has been shown to decrease for high workload situations while driving (Nunes & Recarte, 2002; Recarte & Nunes, 2003).

Situation awareness can either be assessed during regular driving, or in situations that impose special demands, such as taking over vehicle control after a period of automated driving. Although manual take-over situations are very challenging, other human-machine interactions such as handing control to the automated system can be demanding as well (Flemisch et al., 2012; Lu & De Winter, 2015; Lu et al., 2016). In platoon driving, four different situations with intensive human-machine interaction can be distinguished. First, the driver of the following vehicle starts the platoon coupling process and is handing control to the automated platoon driving system (coupling platoon follower). In current realizations of platooning, the driver of the leading vehicle has to decide if he accepts the coupling request (coupling platoon leader). Only if the coupling request is accepted, the automated system takes over control and decreases the distance between the vehicles. As soon as the platoon mode is ended and the vehicles decouple, the driver of the following vehicle is requested to take over manual control of the vehicle (decoupling platoon follower). The driver of the leading vehicle, in turn, is notified that the following vehicle is being decoupled (decoupling platoon leader). Take-over situations of semi-automated vehicles have been studied intensively (Merat et al., 2014; Strand et al., 2014; Zeeb et al., 2016). However, it is yet unclear how much visual demand the platoon-specific transitions of control require. When the visual demands are high and both drivers of the platoon are looking at the human-machine-interface, the entire platoon is practically blindfolded during transitions of control. Therefore, assessing the visual demand in platoon-specific situations can be crucial for a safe operation of the technology.

The current study presents data from the first large-scale on-road experiment of level-2 automated platoon driving with commercial truck drivers in Germany (*Elektronische Deichsel – Digitale Innovation EDDI)*. We assessed driver state, subjective sleepiness ratings and eye-tracking data during the test drives. Other data pertaining to this project, such as user acceptance, have been published elsewhere (Castritius, Dietz et al., 2020; Castritius, Hecht et al., 2020). Given that the driving task was reduced to monitoring and potential response to take-over requests for the driver in the following truck of the platoon, we expected lower levels of situation awareness during semi-automated truck platooning in comparison to manual driving (Hypothesis 1), as measured by the percentage of gazes toward the road center. Furthermore, we expected that resuming control after automated truck platoon driving in the following vehicle would be the most challenging transition, resulting in higher shares of fixations on the HMI display (Hypothesis 2). For the driver of the following truck, we also expected higher subjective sleepiness ratings, in comparison to regular truck driving (Hypothesis 3).

2. Methods

2.1. Participants

Ten truck drivers voluntarily participated in the test drives. They were recruited from a freight transport company. The drivers were between 29 and 54 years old ($M = 39.3$, $SD = 7.9$) and had many years of job experience ($M = 14.2$, $SD = 5.6$). None of the drivers had extreme sleep habits, as measured by a self-assessment questionnaire of circadian rhythm (Horne & Ostberg, 1976) (Moderate evening type = 1; Neither type = 4, Moderate morning type = 5).

2.2. Apparatus

The platoon that was used for the on-road test drives consisted of two trucks of the manufacturer *MAN*. They were specially equipped for the platooning operation, including additional buttons, light strips on the steering wheel and a display with a human-machine-interface (HMI) for truck platoon driving. The light strips indicated the current platoon mode (blue: active/red: platooning ended and manual take-over requested/white: deactivated). Furthermore, the display showed special information about the platoon status in active platoon mode: position of the vehicle in the platoon ($1^{st}/2^{nd}$), distance between the driver's truck and the other truck in the platoon (constantly updated value in meters). It also displayed error messages in case the platoon was decoupled unexpectedly, as would happen when a passenger car entered the gap between the two trucks.

Eye movements were measured with a wearable eye tracker (*Tobii Glasses 2)*. With a weight of about 45 g and an appearance of rimmed glasses, the eye tracker was similar to conventional glasses. Yet it contained a scene camera to record the view ahead, and four infrared cameras, fixed on the driver's pupils, to detect the gaze. Eye-tracking data were recorded with a frequency of 50 Hz. In addition, the following subjective measures were taken: (1) In the beginning and the end of the project, participants indicated the probability to fall asleep during platoon driving on a modified version of the *Epworth sleepiness Scale* (ESS) (Johns, 1991), (0 = I would never fall asleep, 1 = low probability to fall asleep, 2 = medium probability to fall asleep, 3 = high probability to fall asleep). (2) Before and after each test drive (pre/post), participants indicated their level of alertness/sleepiness on the *Karolinska sleepiness scale* (KSS) (Åkerstedt & Gillberg, 1990). (1 = extremely alert to 9 = extremely sleepy, fighting sleep.) After the test drives, they also had the opportunity to indicate if they experienced a low point in sleepiness during the drive. (3) Before each test drive, participants indicated how many hours they had slept and how long they had been awake since sleeping, to assure that the prerequisites were comparable between driving modes.

2.3. Procedure

Participants were informed about the platoon driving project *Elektronische Deichsel – Digitale Innovation EDDI* and the details of the study in a kickoff session and gave their informed consent. This research complied with the *American Psychological Association Code of Ethics* and was approved by the *Institutional Review Board* at *Hochschule Fresenius*, University of Applied Sciences. Data acquisition consisted of two parts: Reference drives and platooning test drives.

The reference drives were conducted on German Highway A9 between May and June 2018. The drives were embedded in the regular day-to-day operation of the trucking company. The reference drives started at approx. 6 p.m. at a logistics hub in Munich. From there, participants drove to Nuremberg, exchanged their trailers at a logistic hub and drove back to Munich. They were accompanied by a researcher and wore the mobile eye-tracking and EEG devices. Results of the EEG measurement will be presented elsewhere. Drivers were instructed to drive as they would normally and not to talk with the researchers on the passenger seat. One course from Munich to Nuremberg or vice versa was considered as one reference drive, and lasted about two hours. Before and after every reference drive, the drivers filled out a short questionnaire. This procedure resulted in a total of 20 reference drives. After all drivers had completed the reference drives, they participated in an intensive training on the platoon driving system. The training included theoretical lessons and practical training in a driving simulator, on a test track, and in real traffic.

Platooning test drives were conducted with a two-truck platoon and followed the same procedure as the reference drives. At approx. 6 p.m., a team of two participants drove from Munich to the logistic hub in Nuremberg and back. However, the platoon drives were conducted with a dummy load so that the drivers did not have to exchange trailers in Nuremberg but instead took a half-hour pause. After this pause, the drivers switched their positions in the platoon (leader/follower). Again, one course counted as one test drive and participants filled out a short questionnaire after each test drive. A team of drivers completed two test drives (to Nuremberg and back) per day, for four days in one week. This procedure resulted in 33 platoon test drives, as 7 drives were canceled due to driver sickness, weather, or traffic conditions and could not be re-acquired. Like in the reference drives, a researcher accompanied one of the drivers in the platoon to collect eye-tracking and EEG data.

One direction consisted of 145 km in total, thereof 82 km were supposed to be driven in active platoon mode. However, platoon driving was occasionally interrupted by traffic events and technical issues. In this case, the driver of the following vehicle was requested to resume manual control, and the lead vehicle driver received notice of the decoupling procedure. After each interruption, platoon mode was reestablished as soon as possible. To do so, the driver of the following vehicle sent a request to the lead vehicle. Only if this request was accepted by the driver, coupling was initiated.

After all on-road drives had been completed, participants expressed their subjective impressions of truck platoon driving in one-on-one interviews.

2.4. Data preprocessing

More than 100 hours of eye-tracking video data were collected during the drives. These data were processed with the specialized software *Tobii Pro Lab*. The software displays eye movements within the scene camera video recording. To analyze the data, the recordings were mapped to pictures ("snapshots") that showed the forward view from inside the vehicle, including the steering wheel and the display. During this mapping, the gaze position included in the eye-tracking video was assigned to the respective position on the snapshot. This procedure was partly automated and manually confirmed. The following areas of interest were defined on the snapshot for further processing of the data: Side mirror, road ahead, HMI. Different time sections of interest were defined for the analysis of situation awareness during platoon driving: (1) regular (platoon) driving, (2) platoon-specific transition.

(1) For the analysis of situation awareness during regular driving, 5-minute intervals of eye-tracking data were analyzed. One interval halfway through each reference drive and each test drive in the leading and the following vehicle of the platoon was chosen. It was assured that platoon driving mode was active for at least 5 minutes prior to the interval onset and that the interval did not contain platoon transitions or other sudden events. Data sets of four participants were incomplete due to technical issues or cancellation of drives and could not be included. This resulted in 6 complete data sets aggregated per participant and driving mode. As dependent variables, the mean percentages of total fixation duration on the different areas of interest were analyzed (fixation share). The eye-tracking variables were aggregated per participant and driving condition (reference/platoon leader/platoon follower).
(2) For the analysis of platoon-specific transitions, eye-tracking data of 30-second intervals after each transition onset were chosen. This resulted in a total of 495 coupling and decoupling intervals. Intervals were excluded from the analysis if data quality was low (211 intervals excluded) or if the transition was shorter than 30 s (118 intervals excluded). Short transitions occurred if a driver re-initiated the platooning system right after a decoupling phase. As a result, 166 situations entered the analysis (coupling platoon leader: 55 and follower: 54; decoupling platoon leader: 27 and follower: 30). As dependent variables, the mean percentage of total fixation duration on the different areas of interest (fixation share), was analyzed. The variables were aggregated per participant and platoon transition (coupling leader and follower, decoupling leader and follower). As a second analysis of platoon specific transitions, the time course of HMI-fixations was examined. We performed this analysis for all platoon-specific transitions

respectively (coupling platoon leader/follower; decoupling platoon leader/follower). For every frame (16 ms) of the video data, we calculated in how many of all cases the HMI was fixated.

KSS ratings of the reference drives (*N* = 20), test drives in the lead vehicle (*N* = 33), and the following vehicle of the platoon (*N* = 33) were aggregated per participant. The same applies for the answer to the sleep-related questions prior to the respective drives.

2.5. Statistical analysis

Eye-tracking data of 5-minute intervals were analyzed using a Friedman ANOVA with the factor driving mode (reference/leader/follower), due to non-normal distribution. Eye-tracking data of 30-second intervals during transition situations in the leading and in the following vehicle were analyzed separately due to uneven cell fill. The data were compared using paired sample t-tests. The time course of HMI-fixations was analyzed descriptively only. For the analysis of KSS ratings, a within-subjects ANOVA with the factors time (pre/post) and driving mode (platoon leader/platoon follower/reference drive) was performed. ESS ratings were analyzed using a cumulative link model for ordinal data, as the scale only included four rating levels. Level of significance was set to $p = .05$ for all analyses.

3. Results

3.1. Eye-tracking results – gaze distribution

Eye-tracking data during 5-minute intervals of regular driving situations showed significant differences of fixation shares on the road ahead between driving modes ($X^2(2) = 7$, $p = .03$). That is, the percentage of time participants spent looking on the road was lower for the leading vehicle of a platoon than for the reference drives ($X^2(2) = 1.5$, $p = .028$). The percentage of time spent looking at the display did not differ significantly ($X^2(2) = 4$, $p = .135$). However, a tendency of higher shares of fixations on the HMI for the platoon leader is apparent (reference: $M = 5.7$, 95%-CI = 2.5–8.8; platoon leader: $M = 15.0$, 95%-CI = −0.7–30.7; platoon follower: $M = 4.62$, 95%-CI = 0.53–8.72).

The fixation share in regular driving situations as well as coupling and decoupling situations is shown in Figure 1. Although not perfectly comparable, as 150 s intervals were analyzed for regular driving situations and 30 s intervals for platoon transitions, it is clear that participants spent more time looking at the HMI during platoon transitions. Due to uneven cell fill, the results of gaze behavior in platoon transitions were analyzed for the platoon leader and the platoon follower separately. T-tests for paired samples showed that the time platoon leaders spent looking at the road ahead and at the HMI did not differ significantly between coupling and decoupling situations (HMI shares leader: $t(6) = 2.194$, $p = .08$; Road ahead shares leader: $t(6) = 2.988$, $p = .062$). In contrast, for the platoon follower, fixation shares on the road ahead and the HMI differed between coupling and decoupling situations, (HMI shares follower: $t(5) = 4.397$, $p = .014$; Road ahead shares follower: $t(5) = 4.075$, $p = .020$). In decoupling (vs. coupling) situations, drivers of the following vehicle spent less time looking at the road ahead (coupling: $M = 70.29$, decoupling: $M = 55.40$) and more time looking at the HMI (coupling: $M = 26.86$; decoupling: $M = 42.20$).

It becomes apparent that the drivers attended to the HMI for about 30 percent of the time during platoon coupling and decoupling situations. Fixation shares of the follower in platoon decoupling situations were the highest. The drivers attended to the HMI on average for 40 percent of the time in these situations.

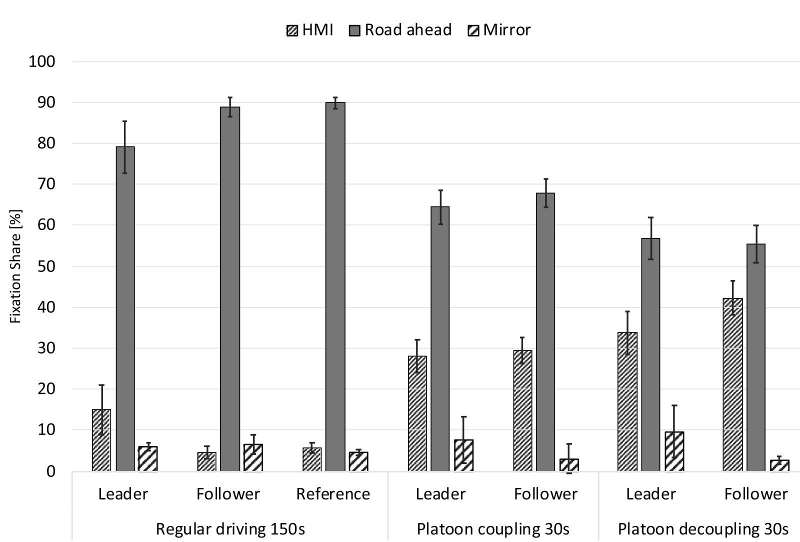

Figure 1. Fixation shares in different driving situations (regular driving, platoon coupling and decoupling). The data were derived from reference drives with a single truck "Reference" ($n = 20$) and platoon drives as first vehicle in the platoon "Leader" ($n = 33$) and the rear truck "Follower" ($n = 33$). For regular driving situations 150-s intervals were analyzed, for platoon transitions 30 s intervals. The fixation shares signify the percentage of time participants looked at one of the defined areas of interest: the human-machine-interface (HMI), the side mirror (Mirror) or the road ahead (Road ahead). Data were aggregated per participant and driving mode; mean ± 1 SE.

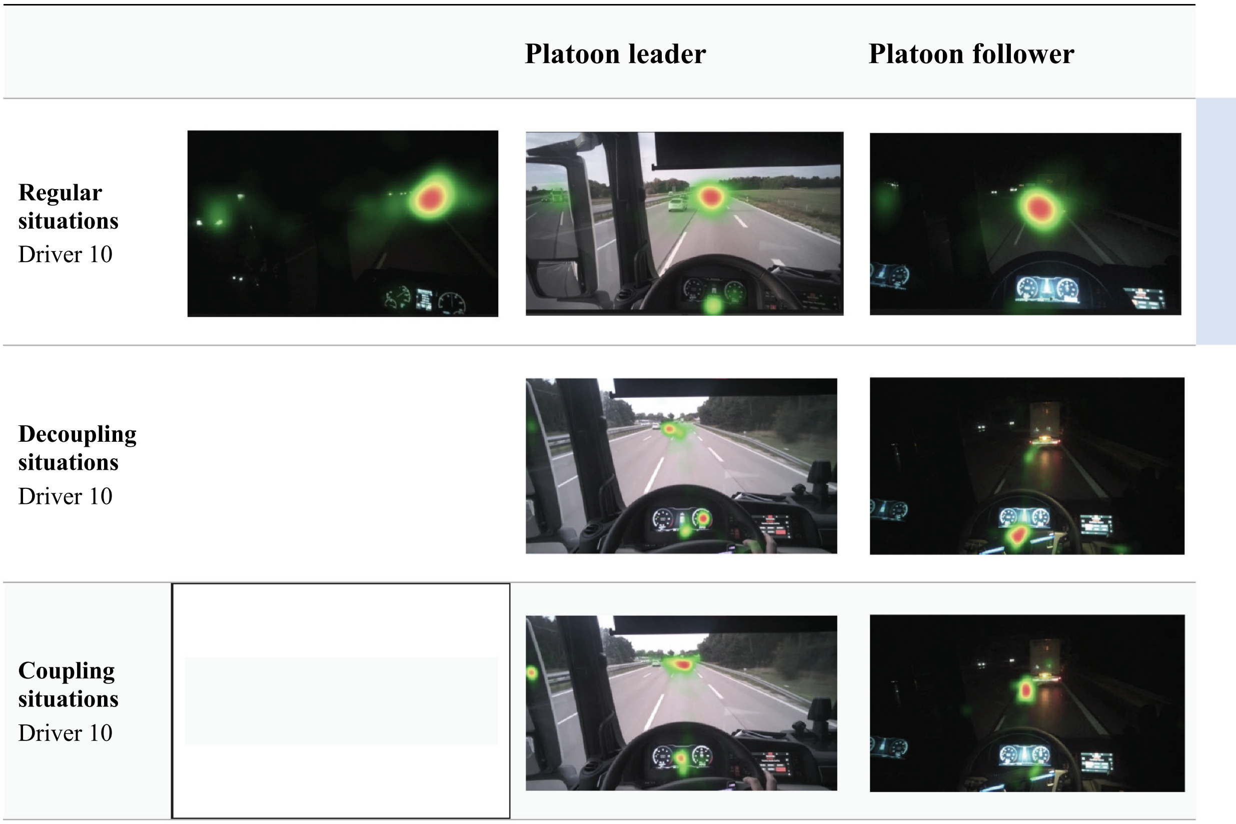

Figure 2. Exemplary gaze plots of platoon-specific situations in the leading and the following vehicle of the platoon. The plots show how the gaze data are distributed – the time the participant spent looking at a location is coded with different colors ranging from red: long duration to green: short duration. 30-second intervals after transition onset were analyzed.

Exemplary gaze plots of one participant during regular driving situations and during platoon transitions are shown in Figure 2. Note that the drives to Nuremberg were conducted in daylight, drives back to Munich in the dark. However, direction of travel was counterbalanced across conditions. It becomes apparent that the focus of the gaze is on the road for all driving modes during regular situations. However, for the platoon lead driver, a second focus on the HMI becomes apparent. The driver seems to have checked the display for platoon-specific information like platoon mode and the distance between the two trucks. Gaze plots of the same driver during platoon transitions demonstrate that the decoupling situations can be especially challenging for both the leader and the follower of a platoon. The driver's main focus was on the HMI during a decoupling situation in the following vehicle and both on the HMI and the road ahead for the other platoon transitions. Taking over manual control after automated driving thus seems most challenging in terms of visual attention.

3.2. Eye-tracking results – gaze time-course during transitions

Besides analyzing the general gaze distribution, the time-course of HMI fixation during platoon-specific situations is of special interest. To illustrate it, we analyzed the video data of 166 valid transition situations frame by frame (16 ms per frame). For every frame, we registered whether or not the HMI was fixated. Then, we calculated the percentage of cases with HMI fixation per frame. We did not account for the timing of the transition situations during the drive, as we did not find indications for prominent differences between gaze distribution in early and late phases of the drive. Figure 3 shows the development of HMI fixations for coupling and decoupling situations. It becomes apparent that the development of HMI fixations differs between platoon transitions, but is similar for the lead and the following vehicle in the respective situation. In decoupling situations, the HMI was inspected within the first two seconds in about 60–80% of cases. In the subsequent seconds, both drivers frequently inspected the HMI. It was fixated in about 40% of cases during the first 20 seconds. This is surprising, as the lead vehicle driver did not have to react to the decoupling maneuver in any way. However, the lead vehicle driver's gaze behavior was similar to that of the driver in the following vehicle, both were frequently observing the display. In coupling situations, the HMI was inspected immediately after coupling was initiated in about 40–60% of cases. However, this share dropped to about 20% of cases within the first five to ten seconds and stayed at that level. In coupling situations, the HMI seems to attract the gaze to a lesser extent for both drivers.

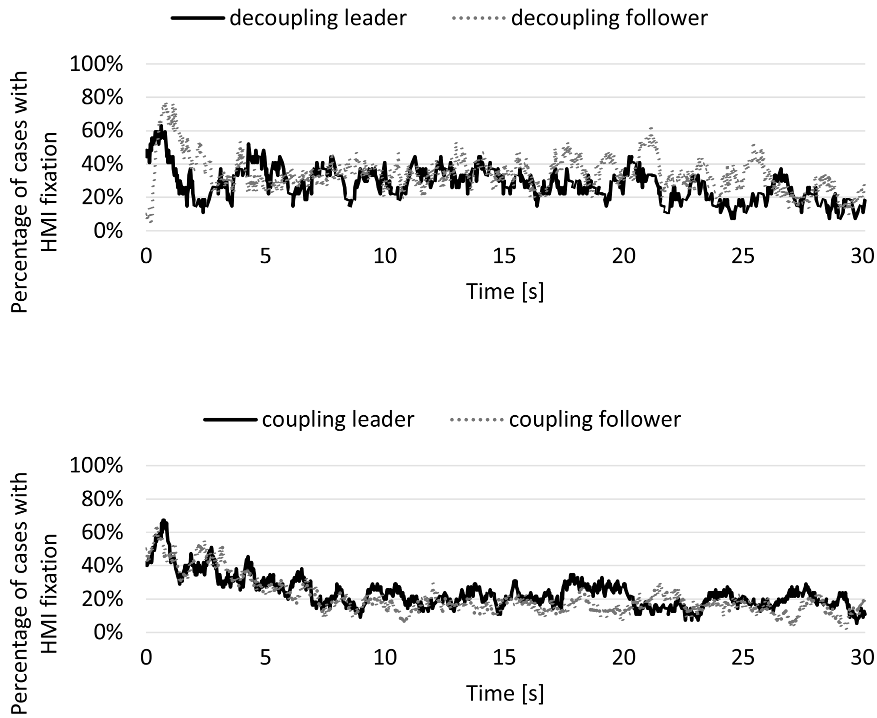

Figure 3. Time-course of gaze. Percentages indicate the amount of cases in which the HMI was fixated. Cases refers to all coupling and decoupling situations that were recorded (N = 166).

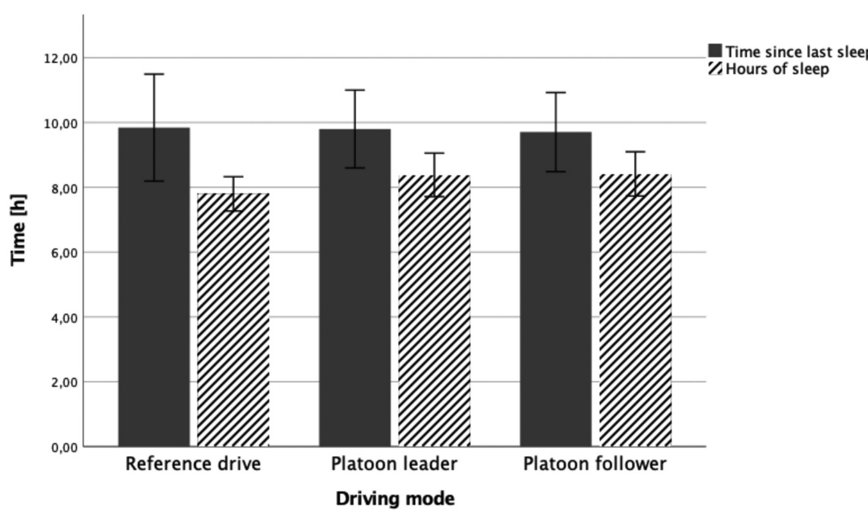

Figure 4. Results of sleep-related questions prior to each drive. The participants indicated how many hours they had slept before each drive (Hours of sleep) and how much time had passed since their last sleep (Time since last sleep). Mean values per participant and driving mode. Error bars: ± 95% CI.

3.3. Subjective results – driver sleepiness

The drivers answered sleep-related questions before each test drive. Descriptive results are shown in Figure 4. Participants had slept for a minimum of 6 hours (max. 10.5) prior to the drives. The number of hours did not differ significantly among driving modes ($F(1.04, 18) = 1.096$, $p = .325$, $\eta^2 = .109$). The number of hours the drivers were awake since they last slept ranged between 3.6 and 14.5 but did not differ significantly between driving modes ($F(2,18) = .006$, $p = .994$, $\eta^2 = .001$).

Before and after each reference and each test drive, participants also rated their subjective sleepiness. A within-subjects ANOVA showed a significant effect of time ($F(1,9) = 20.239$, $p = .001$, $\eta^2 = .692$). As shown in Figure 5 subjective ratings increased during the test drives. However, absolute values of the ratings were rather low. The highest value was 5.5 and occurred after a reference

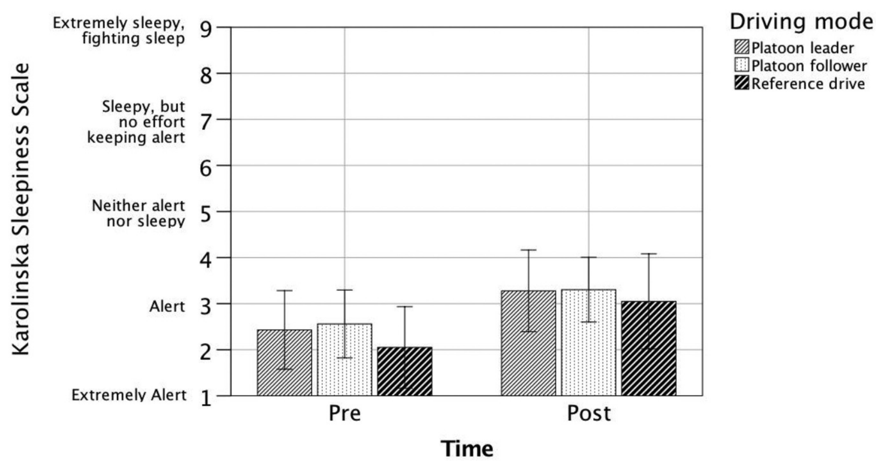

Figure 5. Subjective sleepiness before and after reference and platoon drives. Mean values derive from aggregated ratings per participant. Error bars: 95% CI.

drive. It indicates that the respective driver was "neither alert, nor sleepy". Furthermore, driving mode did not significantly influence the sleepiness ratings. Neither the effect of driving mode ($F(2,18) = 1.352$, $p = .284$, $\eta^2 = .131$), nor the interaction between driving mode and time was significant ($F(2,18) = 0.203$, $p = .818$, $\eta^2 = .022$). Adding the time since last sleep as a covariate to a mixed effects model showed a similar pattern and further confirmed the results. Wald-tests showed significant results for time ($X^2(1) = 47.280$, $p < .001$), but not for mode ($X^2(1) = 1.257$, $p = .262$), or time x mode ($X^2(1) = 0.094$, $p = .759$), but a significant effect of time since last sleep ($X^2(1) = 34.185$, $p < .001$).

Participants also indicated whether they experienced a low point in their alertness during the drive. Results are presented descriptively, as low points were indicated only occasionally. During platoon drives in the lead vehicle, seven of the drivers experienced a low point in at least one of the test drives. Ratings ranged between 2 and 7 ($M = 3.9$, 95%-$CI = 3.3$–4.5). During platoon drives in the following vehicle, eight of the drivers experienced a low point and rated it between 2 and 7 ($M = 4.1$, 95%-$CI = 3.5$–4.7). During the reference drives, seven drivers indicated at least one low point. Mean ratings on low points were slightly higher during the reference drive than during the platoon drives and ranged between 2 and 8 ($M = 5.8$, 95%-$CI = 4.5$–7.0). Two of the drivers did not report a low point during any of the drives.

At the beginning and the end of the project, participants indicated their subjective probability to fall asleep, while driving in a platoon and in a regular truck. Results show that participants rated the probability to fall asleep in a regular truck as low, before and after the on-road experience (Pre: $Mdn = 1$; Post: $Mdn = 1$). The same applied for driving in the leading truck of a platoon (Pre: $Mdn = 1$, Post: $Mdn = 0$). For the following truck of a platoon, the probability to fall asleep was rated as "medium" before the test drives. In contrast, after the on-road experience the probability was rated as rather low (Pre: $Mdn = 2$; Post: $Mdn = 0.5$). Results of the cumulative link model showed a significant difference between pre and post ratings ($\chi^2 = 4.5$, $p = .034$). Yet, neither the differences between driving modes ($\chi^2 = 4.37$, $p = .11$), nor between the interaction of time and driving mode ($\chi^2 = 2.69$, $p = .26$) were significant.

In one-on-one interviews after the test phase, drivers reported their experience of sleepiness during the drives. They indicated that they did not become tired during these short drives but suggested that longer drives could be a problem:

- *"We only drove for two hours, changed positions and drove two hours back, and then it was already done. But I guess, with eight hours driving time or nine hours, it will definitely be different."* (Driver 8).
- *"Did you notice a difference in alertness and attention?" – "No."* (Driver 5).
- *"I didn't get more tired. Not at all. Because, as I said: You need to always concentrate anyway, no matter if you're driving regularly or in a platoon. And in the leading or following truck, it doesn't really matter. You need to always concentrate* (Driver 1).
- *„[. . .] because the system is not mature yet I, for my part, stayed concentrated [in the following vehicle], deliberately stayed concentrated or didn't let myself get distracted"* (Driver 6).

They also reported that driving in the leading truck was slightly more demanding than driving in the following vehicle or alone:

- *"Basically, the difference in comparison to regular driving is only small. Only this thought, there is someone else with me that I have to look after. I need to watch. I need to drive with foresight."* (Driver 8)
- *"The alertness was a bit less in the following than in the leading truck. Because you always thought, yes, nothing happens, nothing can happen. You trust your colleague but you're still alert."* (Driver 6)

4. Discussion

This study presents first on-road data on gaze behavior as well as subjective sleepiness during level-2 truck platooning by commercial drivers.

In contrast to our assumptions, the **drivers of the following truck** did not exhibit differences in gaze behavior between manual driving and semi-automated platoon driving, during regular driving situations. Specifically, there was no significant difference in the time that participants attended to the road center in the following vehicle of a platoon compared to manual driving. In both cases, the mean share of gazes on the road ahead was about 90% for both modes, indicating that situation awareness was not decreased due to semi-automated driving. Drivers still attended to the most relevant region for gaining driving-related visual information, the road ahead. They can be considered to have been in the loop. Therefore, hypothesis 1 is rejected. However, in **drivers of the leading vehicle of the platoon**, the fixation share on the road ahead was reduced to about 75%. Thus, counterintuitively, the driver of the lead truck devoted less attention to the road ahead than did the driver of the following truck. However, this does not necessarily mean that situation awareness was reduced in the leading vehicle of the platoon. To the contrary, the drivers of the lead truck tended to seek out information on the HMI-display, monitoring the coupled platooning. Not only the road ahead, but also the road section directly behind the vehicle was important for the drivers' safe operation of the vehicle. The drivers in the leading truck tried to gather information about the status of the following vehicle through glancing at the HMI and the mirror, instead of focusing on the road ahead only. However, the amount of time participants spent looking at the road center can still be considered as overall comparable to regular driving. For example, the results of a simulator study by Louw and Merat (2017) showed that car drivers looked at the road center in 75% of the time during manual driving.

We have analyzed four different platoon-specific situations – coupling and decoupling situations in the leading and the following vehicle of the platoon. These situations are most relevant for platoon systems that require communication between the leading and the following vehicle, such as the one developed by *MAN*, tested within the EDDI project. In this application of platoon driving, the driver of the lead vehicle had to accept the coupling request of the following vehicle and was informed when platoon mode was terminated. It was expected that resuming control after automated truck platoon driving in the following vehicle would be the most challenging transition, as the driver has to resume manual control after semi-automated driving. Indeed, decoupling situations in the following vehicle required the highest amount of visual attention. In decoupling situations, the drivers of the following vehicle spent more time looking at the HMI and less time looking at the road center compared with coupling situations. During decoupling their share of fixations on the road was reduced to about 60% in comparison to about 75% in coupling situations. Thus, for the driver of the following truck, decoupling demands more attentional resources than does coupling; hypothesis 2 is confirmed.

Although the amount of time participants spent looking at the road did not differ between coupling and decoupling situations in the leading vehicle of the platoon, the visual demand seems to be slightly higher than in manual driving. That is, although the drivers of the leading truck do not experience the change of driving mode themselves, the share of fixations on the road was reduced to about 75% in comparison to about 90% in manual driving. Likewise, the share of fixations on the HMI was increased from 7% in the reference drives to over 20% in the platoon-specific situations. Although not perfectly comparable (because the analysis of regular driving situations included 5-minute intervals, and the analysis of platoon-specific situations included 30-second intervals), the difference is quite obvious. The drivers of the lead vehicle apparently tried to monitor the coupling/decoupling of the following vehicle. Such monitoring was not required, the driver of the leading truck merely had to accept (or reject) an incoming request for coupling. Once granted, the coupling functioned automatically without need to interfere or monitor. As only a small proportion of the following truck was visible in the driver-side rearview mirror, due to the short following distance, the information about the status of the following vehicle had to be extracted from the HMI display. It provided continuous information about the exact distance between the vehicles, which could have led to a close observation of its development. This trend of frequently inspecting the display was also visible in the development of HMI fixations during platoon transitions. The drivers of the leading vehicle attended to the HMI in a similar manner as the drivers of the following vehicle, although their driving task did not change much between coupled and uncoupled driving.

Results of driver sleepiness show that, surprisingly, drivers in the following truck, whose attentional demands had been reduced, did not report increased perceived sleepiness during semi-automated driving. The subjective sleepiness ratings slowly increased during the course of a drive, but absolute values indicate that this shift was between the verbal anchors "extremely alert" and "alert" of the KSS scale. Furthermore, no significant differences between regular truck driving and truck platoon driving (neither for the leading nor for the following driver) were found. The expected high sleepiness ratings during platoon mode did not materialize, thus hypothesis 3 could not be confirmed. The results are in line with a recent simulator study on truck platoon driving. Hjälmdahl et al. (2017) reported differences in sleepiness between fully automated platoon driving and manual driving, but not between semi-automated platoon driving and manual driving. Mean KSS ratings ranged between 3 to 7 in their simulator study, which is similar to the low-point ratings reported here. Yet, only values of 7 and up can be seen as critical for road safety, because behavioral changes and physiological changes are unlikely to occur until KSS exceeds the value of 6 (Ingre et al., 2006). It is important to mention that the drives only lasted for 45 minutes in the simulator study by Hjälmdahl et al. (2017) and about two hours in the test drives presented here. It is yet unclear to what extent longer periods of platoon (vs. manual) driving might increase sleepiness.

All in all, coupling and decoupling situations seem to not only affect the driver of the following vehicle, but also lead to higher visual demands for the lead vehicle driver. This could be partially owed to the procedure of the test drives. The drivers started in teams and were instructed to stay close together and to re-couple the platoon when possible. They might therefore have been very considerate of each other and most interested in information about the other platoon vehicle. Other operational concepts of truck platoon driving, such as cooperative active cruise control (CACC), involve less communication between the drivers. CACC is used as a regular adaptive cruise control system and does not require the lead vehicle driver to react to a platooning request from the following vehicle (Nowakowski et al., 2015; Yang et al., 2018). Thus, in applications of CACC driving, the lead vehicle driver could be less interested in information about the following vehicles of the platoon. However, this assumption has to be verified in further studies.

4.1. Limitations

A major limitation of the study at hand is associated with the small sample size. Compared to a laboratory study, the sample was small, however, for a field study with high safety standards and multiple practical constraints, the sample appears acceptable. As mentioned above, for this on-road experiment a special permit from the German Government was required and participants had to undergo specific training schedules due to high safety standards. Other than case studies, the sample did allow for statistical testing, and the results presented here give an exclusive insight in the usage and the effects of an innovative technological system in a realistic environment aiming at high external validity.

As a result of the eye-tracking measurement with a head-mounted device, drivers had to be accompanied by researchers. This could have induced in the driver a higher motivation to stay alert, resulting in higher situation awareness and less sleepiness. It is yet unclear how situation awareness and driver sleepiness develop without an observer on the passenger seat, with lower motivation to perform well, and over the course of longer driving periods. Also, platoon driving was occasionally interrupted in the test drives, which led to several shorter platoon driving periods instead of one long continuous platooning period. Frequent coupling and decoupling situations could have enhanced the alertness of the drivers. This could have prevented the development of low demand situations that are known to foster sleepiness and reduced situation awareness. To achieve high external validity, we decided to have drives during daylight and at nighttime. They were balanced across participants and driving condition to control for this potential confound.

Due to varying sunlight conditions in the on-road setting and vibrations caused by the truck, the eye-tracking measurement was less reliable than in laboratory settings. Therefore, no high-resolution analyses of saccades, exact fixation positions, and individual fixation durations were performed. Differentiating between fixations and fast eye movements (saccades) is based on the calculated gaze position and the speed and angle of its change. However, fast changes of gaze positions in this on-road setting could also have been caused by external sources such as the vibration of the truck, and could therefore not reliably be assigned to the drivers' gaze behavior. However, the inaccuracies of the measurement were successfully bypassed by inspecting broad areas of interest only, instead of performing a more fine-grained analysis of horizontal and vertical gaze dispersion. Furthermore, to increase data reliability, the automatic mapping of the eye-tracking video data was manually verified and adjusted. This procedure was very time-consuming, therefore only short periods within each drive were extracted for the present analyses.

4.2. Conclusion

It can be concluded that accompanied 2-hour drives did not lead to significantly higher ratings of subjective sleepiness, nor to substantially reduced situation awareness of the following vehicle driver of a two-truck platoon operating at level-2 automation. Surprisingly, in regular driving situations, drivers of the leading vehicle of the platoon spent a smaller proportion of time looking at the road ahead than they did in manual driving mode. The drivers seem to monitor the other platoon vehicle by looking at the HMI display and the side rearview mirrors. Making information about the following vehicle more accessible in the leading vehicle, for example, through an extended mirror or a head-up display, could assist the lead vehicle driver in this monitoring task.

With regard to the platoon-specific transitions (coupling/decoupling situations), taking over manual control in the following vehicle poses the highest visual demand. However, activating the platoon system in the following vehicle and monitoring the coupling/decoupling in the leading vehicle of the platoon can likewise affect gaze behavior. Human-machine interaction in these transition situations should be designed carefully for a safe operation of the system. Presenting relevant information closer to the road center with a head-up display could be a possible solution. Furthermore, presenting the distance between the vehicles using an analog scale, instead of implementing a constantly changing numerical display, could further facilitate the drivers' task.

Acknowledgments

We thank the research consortium consisting of MAN Truck & Bus AG, DB Schenker and Hochschule Fresenius for making the test drives on highway A9 possible. The experiments were part of the dissertation work by Sarah-Maria Castritius at the Department of Psychology, Mainz University, Germany.

Funding

This research was conducted within the research project "Elektronische Deichsel – Digitale Innovation" (electronic drawbar – digital innovation) funded by the German Federal Ministry of Transport and Digital Infrastructure [funding code: 16AVF1031B].

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