Effect of different alcohol levels on take-over performance in conditionally automated driving

Katharina Wiedemann⁎, Frederik Naujoks, Johanna Wörle, Ramona Kenntner-Mabiala, Yvonne Kaussner, Alexandra Neukum

Würzburg Institute for Traffic Sciences, WIVW, Veitshöchheim, Germany

ARTICLE INFO

Keywords:
Blood alcohol
Controllability
Driver fitness
Driving simulation

ABSTRACT

Automated driving systems are getting pushed into the consumer market, with varying degrees of automation. Most often the driver’s task will consist of being available as a fall-back level when the automation reaches its limits. These so-called take-over situations have attracted a great body of research, focusing on various human factors aspects (e.g., sleepiness) that could undermine the safety of control transitions between automated and manual driving. However, a major source of accidents in manual driving, alcohol consumption, has been a non-issue so far, although a false understanding of the driver’s responsibility (i.e., being available as a fallback level) might promote driving under its influence. In this experiment, N = 36 drivers were exposed to different levels of blood alcohol concentrations (BACs: placebo vs. 0.05% vs. 0.08%) in a high fidelity driving simulator, and the effect on take-over time and quality was assessed. The results point out that a 0.08% BAC increases the time needed to re-engage in the driving task and impairs several aspects of longitudinal and lateral vehicle control, whereas 0.05% BAC did only go along with descriptive impairments in fewer parameters.

1. Introduction

Several vehicle manufacturers have announced automated driving features in their current or upcoming production vehicles (e.g., the “traffic jam pilot” in the Audi A8; Audi, 2017). These driving functions will still require the driver as a fallback level (so-called “conditionally automated driving”, SAE L3, SAE, 2014) to intervene in case of system limits or malfunctions (Gold et al., 2017). Thus, the driver’s role will change from manually operating the vehicle to intervening occasionally (Naujoks et al., 2017b). Concerns have been expressed that the switch from automated to manual driving might not be handled safely as a disengagement from driving related tasks can go along with decreased situation awareness (Feldhütter et al., 2018; Strand et al., 2014), drowsiness (Jarosch et al., 2017; Neubauer et al., 2014) and increased engagement in non-driving related tasks (NDRTs, see Merat et al., 2012; Naujoks et al., 2016b). Those psychological conditions might impair the driver’s ability to re-engage in the driving task when a system limit is reached (Marberger et al., 2017; Naujoks et al., 2019).

During conditionally automated driving, the automated driving system will indicate the need for manual control by a so-called “take-over request” (TOR). Thereby, the driver will have to notice and interpret the TOR, possibly interrupt an ongoing NDRT (Large et al., 2017; Pfleging et al., 2016), interact with the vehicle controls and perform the required driving maneuver (Naujoks et al., 2018). This re-engagement process will afford cognitive and motoric re-configurations of the driver’s state to meet the demands of the driving situation (Marberger et al., 2017). Typically, such task switches have been shown to go along with increased reaction times, mental effort and error rates in cognitive psychology (so-called “switch costs”, Altmann and Trafton, 2004; Salvucci and Bogunovich, 2010; Trafton et al., 2003), which can be reflected in worsened vehicle control directly after a transfer of control event (Merat et al., 2014; Naujoks et al., 2017a).

There is a growing body of research that investigates the circumstances that lead to prolonged take-over times, such as unobtrusive take-over requests (e.g., Naujoks et al., 2014; Petermeijer et al., 2017) or engagement in NDRTs (Dogan et al., 2017; Ko and Ji, 2018; Payre et al., 2017). However, one major cause of accidents in manual driving, alcohol consumption (Krüger and Vollrath, 2004; Taylor et al., 2010), has been a non-issue in the context of automated driving so far. A false understanding of the driver’s responsibilities when using conditionally automated vehicles (i.e., not knowing that the drivers is still the fall-back level) might promote driving under the influence of alcohol. While it is not yet known whether drivers will be more willing to drive under the influence of alcohol when using automated vehicles, its well-known impact on skills related to driving, such as reaction time, tracking and psychomotor performance (Hindmarch et al., 1991; Moskowitz and
Kenntner-Mabiala (1988; Schnabel, 2011) is undisputed and will likely worsen problems associated with transfer of control from automated vehicles.

In this first-of-its-kind study, a sample of drivers completed three drives in a high fidelity driving simulator with different blood alcohol concentrations (BACs: placebo vs. 0.05% vs. 0.08%). Kenntner-Mabiala et al. (2015) used the same alcohol levels to investigate alcohol related impairments of manual driving in the same driving simulator. The test course involved typical take-over situations that have already been used to study take-over performance in the context of automated driving (see Gold et al., 2017, for a review). The aim of the study was to investigate, whether these dosages – as in manual driving conditions – would go along with impairments of the participants’ reactions to the take-over request and their driving performance in the subsequent period of manual driving. The investigated BACs were chosen as benchmarks as a limit of 0.05% is the legal limit in most European countries and up to 0.08% is the limit in several states in the US. We also expected to find alcohol-related impairments of take-over performance as epidemiological research on accident risks suggests a linear increase from BACs between 0.04–0.10% and an exponential increase above 0.1% (Borkenstein et al., 1974; Krüger and Vollrath, 2004).

2. Method

2.1. Driving simulator

The study was conducted using the moving-based driving simulator at the Würzburg Institute for Traffic Sciences (WIVW GmbH, see Fig. 1) and the driving simulation software SILAB. 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 and can briefly display a linear acceleration up to 5 m/s² or 100°/s² on a rotary scale. It consists of 6 electro-pneumatic actuators (stroke ± 60 cm; inclination ± 10°). Three LCD projectors are installed in the dome of the simulator and provide a projection of a 240° screen image. LCD displays serve as exterior and interior mirrors.

2.2. Study design and sample

The study was carried out in a within-subject design with the experimental variables BAC-level (BACs: placebo vs. 0.05% vs. 0.08%) and driving situation (five levels, see Section 2.4). Each driver completed the five test situations with all BAC-levels in three different test sessions. The order of the BAC-levels was balanced within the sample.

The study was approved by the ethics committee of the Bavarian State Medical Association (Bayerische Landesärztekammer, Munich). Prior to the study, all participants had a counselling meeting with a psychologist in which they were informed about the procedure and gave informed consent. For their complete participation, subjects received 120 Euro.

Participants did not know that there was a 0.00% condition. They were only informed that they will be driving under the influence of different blood alcohol concentrations and that their maximum blood alcohol concentration would be 0.08%. To make the placebo condition more compelling, odours of alcohol were diffused in the room where the drinks were applied. Participants were randomly assigned to one of six possible treatment sequences, which were recorded in a randomization scheme. They remained blinded to the treatment sequence until database lock.

The participants were recruited from the WIVW test driver panel. In accordance with the ethical requirements, invitations containing all relevant information about the study were sent to all panellists between the age of 23 and 50 years who had passed a standardized simulator familiarization training. This training is aimed at improving handling of the simulated vehicle (e.g., accelerating, braking, keeping the vehicle in the lane and overtaking) and avoiding symptoms of simulator sickness (Hoffmann and Buld, 2006). It consists of two training sessions (duration: about two hours per session) in the same simulator used in this study. 41 drivers were screened to check if they meet the following inclusion criteria:

- Holding of a valid driving license
- Having no acute or chronic disease
- No medication intake during the study (except for oral contraceptives)
- Moderate alcohol use as defined by the criteria by Dawson et al. (1995): consumption of a minimum of one alcoholic beverage per month and a maximum of 14 alcoholic beverages per week
- No more than six points on a screening questionnaire for the risk of alcohol abuse (Feuerlein et al., 1976)
- For females: reliable birth control during the study, negative pregnancy test at each driving session

In total, N = 36 (n = 17 female) participants took part in the study. All but five participants had taken part in previous simulator studies. They had a mean age of 33 years (SD = 9.22).

2.3. System description and non-driving related task

The automated driving system used in the study took over the longitudinal and lateral control and kept a set speed of 130 km/h. Thus, the drivers could take their hands off the steering wheel and their feet off the pedals. The system had a visual-auditory HMI that was developed and used in prior studies (Naujoks et al., 2016a). The visual interface was presented in a simulated Head-Up Display (HUD) and contained status indicators to support the drivers’ awareness of the system mode (i.e., system available, system active, take-over request). Take-over requests were accompanied by a generic warning tone and a speech output (“take-over driving”, see Forster et al., 2017). The visual part of the take-over requests showed a picture of hands grasping a steering wheel and a message box (“Take over!”). System activation required pushing two buttons on the steering wheel simultaneously;

Fig. 1. The WIVW moving-based driving simulator. Hexapod movement system (left) and simulator interior with vehicle mock-up and image projection (right).
deactivation required either pushing the buttons once again, braking or steering. Furthermore, it was possible to override the system’s speed control by accelerating.

Not being engaged in any task during an automated drive can cause fatigue (Neubauer et al., 2012, 2014). In order not to confound the effect of alcohol with fatigue (Jarosch et al., 2017) and to implement real life conditions, it was assumed that during the automated drive, participants would engage in a NDRT. Therefore, a RSVP (rapid serial visual presentation; Broadbent and Broadbent, 1987) task was presented to ensure that participants didn’t look at the road when the take-over request was issued. Participants were presented with a series of letters on a Head-Down Display at the lower half of the middle console (see Fig. 2). In-between the letters, numbers appeared randomly (i.e., with a probability of 20%) to which the participants had to react by pressing a button positioned at the arm rest. Visual feedback was provided on the same display (correct response: a green “o” is presented; incorrect response: a red “x” is presented). The participants were always engaged in a RSVP task at the moment when the TORs were issued, but there was also time to rest between the blocks of the RSVP tasks. Table 1 shows specifics of the RSVP tasks.

### 2.4. Take-over situations

The test course consisted of a three-lane motorway with low traffic density. During the one-hour drive, seven take-over situations were encountered to simulate system failures and limits. The situations are typical system limits that have already been used in human factors studies on automated driving (see Gold et al., 2017). These test situations varied in the required driver response, either only requiring vehicle stabilization (operational level of driving task according to Michon, 1985) or requiring an additional lane change to avoid an obstacle (tactical level of the driving task according to Michon, 1985, see Table 2). The stabilization scenarios consisted of a work zone, a road segment with missing lane markings and road segments with high curvature. The avoiding scenarios consisted of two situations in which a broken-down vehicle blocked the driver’s lane, either with (lane change not possible) or without traffic (lane change possible) on the left lane. To lower the possibility of anticipating the required lane change, two distractor events were used but not included in data analysis. In these events, the broken-down vehicle was standing on the shoulder so that no lane change was required. The driver’s task thus consisted of deciding whether a lane change was required or not, and to check whether it could be immediately executed or not.

The lead time of the TORs (i.e., time budget until the respective situation was reached) was set to 10 s in every scenario to give the participants sufficient time to re-engage in the driving task (Eriksson and Stanton, 2017; Merat et al., 2014). During this period, the automated lateral control was kept up until the system was deactivated by the driver or until the lead time was over. Longitudinal control was deactivated with the TOR resulting in the system no longer accelerating (see Forster et al., 2017 for a more detailed description). After reaching the system limit, the automation was unavailable for a route section that corresponded with approximately 40 s of driving.

The test course consisted of the test situations and additional driving scenarios without the occurrence of special situations in which the automation worked reliably. These “filling” scenarios varied in length (“short”: 5 km, approx. 2.5 min; “medium”: 10 km, approx. 5 min; “long”: 15 km, approx. 7.5 min) to avoid anticipation effects (i.e., participants being able to predict when the next take-over situation would occur). Test situations and filling scenarios were combined to three random orders with the constraint that there was always a filling scenario between test situations.

### 2.5. Dependent measures

Take-over time was measured as the time elapsed between issuing of the TOR and the deactivation of the automated driving system by the participants (Marberger et al., 2017). Take-over quality was assessed by several indicators of the lateral (such as the standard deviation of lateral position and the standard deviation of the steering wheel angle) and longitudinal control (such as the standard deviation of velocity) during the manual driving period after the control transition (Merat et al., 2014). In those situations that required avoiding an obstacle on the road, minimum time-to-collision and minimum headway to the broken down vehicle were additionally assessed (Naujoks et al., 2015).

Table 3 gives an overview about the behavioral dependent measures.

To understand how drivers evaluated the take-over situation, they were asked to indicate the criticality of the situation on the “rating scale for the assessment of driving and traffic situations” (Naujoks et al., 2015; Neukum and Krüger, 2003).

### 2.6. Procedure

The three test sessions that each participant completed took place on three separate days. A maximum of four test sessions was conducted per day. Data collection was completed after 11 weeks. For each of their test sessions, participants were instructed not to eat anything later than four hours before arriving at the test site. After arriving they were given a standardized snack. Female participants performed a pregnancy test. After that, the participants drank four beverage doses containing each a 200 ml mixed drink of vodka with either orange juice or bitter lemon. The appropriate alcohol dosages to reach the respective target BACs (0.00%, 0.05% and 0.08%) were calculated for each participant using Neubauer et al., 2012, Neubauer et al., 2014, Neubauer et al., 2015, Neubauer et al., 2016). The alcohol dosages were calculated using a breathalyzer (ACE AF-33) at five times (before starting the drinking session, twice during the drinking session, after the
## Table 2
Description of the test scenarios.

<table>
<thead>
<tr>
<th>Test situation</th>
<th>Required response</th>
<th>Test situation</th>
<th>Required response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoiding, lane change possible</td>
<td>Lane change to the left</td>
<td>High curvature</td>
<td>Stabilizing</td>
</tr>
<tr>
<td>The driver has to avoid a broken-down vehicle; there is no traffic on the left lane so that a lane change is possible without endangering other road users</td>
<td></td>
<td>The driver has to drive through a double curve bending to the right and the left.</td>
<td></td>
</tr>
<tr>
<td>Avoiding, lane change not possible</td>
<td>Braking</td>
<td>Missing lane markings</td>
<td>Stabilizing</td>
</tr>
<tr>
<td>The driver has to avoid a broken-down vehicle; the left lane is blocked by other vehicles, a lane change is not possible without endangering other road users</td>
<td></td>
<td>On a segment with missing lane markings, the driver has to keep the vehicle on the driving path (speed limit: 100 km/h)</td>
<td></td>
</tr>
<tr>
<td>Work zone</td>
<td>Stabilizing</td>
<td>Distractor</td>
<td></td>
</tr>
<tr>
<td>The driver has to drive through a work zone with secondary lane markings; following the secondary lane markings requires a lane change to the shoulder (speed limit: 80 km/h)</td>
<td></td>
<td>Vehicle on shoulder, straight road section; Control is transferred due to a vehicle standing on the shoulder; the road segment is slightly bend; this situation resembles the avoiding scenarios, but no lane change is necessary</td>
<td></td>
</tr>
<tr>
<td>Distractor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle on shoulder, bend road section; Control is transferred due to a vehicle standing on the shoulder; the road segment goes straight; this situation resembles the avoiding scenarios, but no lane change is necessary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Table 3
Dependent measures.

<table>
<thead>
<tr>
<th>Dependent measure</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timing aspects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hands-on time</td>
<td>[s]</td>
<td>Time elapsed between TOR and hands-on signal detected by pressure sensors in the steering wheel</td>
</tr>
<tr>
<td>Take-over time</td>
<td>[s]</td>
<td>Time elapsed between TOR and deactivation of the automation (by button press, brake pedal or steering)</td>
</tr>
<tr>
<td>Take-over quality: Lateral guidance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD of lateral position</td>
<td>[m]</td>
<td>Standard deviation of lateral position in the manual driving period after the TOR</td>
</tr>
<tr>
<td>SD of steering wheel angle</td>
<td>[rad]</td>
<td>Standard deviation of steering wheel angle in the manual driving period after the TOR</td>
</tr>
<tr>
<td>Maximum steering wheel velocity</td>
<td>[rad/s]</td>
<td>Maximum velocity of the steering wheel rotation in the manual driving period after the TOR</td>
</tr>
<tr>
<td>Maximum lateral acceleration</td>
<td>[m/s²]</td>
<td>Maximum lateral acceleration in the manual driving period after the TOR</td>
</tr>
<tr>
<td>Take-over quality: Longitudinal guidance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation of velocity</td>
<td>[km/h]</td>
<td>Standard deviation of velocity in the manual driving period after the TOR</td>
</tr>
<tr>
<td>Maximum velocity</td>
<td>[km/h]</td>
<td>Maximum velocity in the manual driving period after the TOR</td>
</tr>
<tr>
<td>Minimum velocity</td>
<td>[km/h]</td>
<td>Minimum velocity in the manual driving period after the TOR</td>
</tr>
<tr>
<td>Maximum deceleration</td>
<td>[m/s²]</td>
<td>Maximum deceleration in the manual driving period after the TOR</td>
</tr>
<tr>
<td>Minimum time-to-collision</td>
<td>[s]</td>
<td>Minimum time-to-collisions to the broken-down vehicle in the avoiding scenarios</td>
</tr>
<tr>
<td>Minimum distance</td>
<td>[m]</td>
<td>Minimum headway to the broken-down vehicle in the avoiding scenarios</td>
</tr>
</tbody>
</table>
drinking session and after the drive). At each of these time points, drivers also assessed their sleepiness using the 9-point “Karolinska Sleepiness Scale” (Åkerstedt and Gillberg, 1990). To check whether the participants would be aware of the alcohol conditions, they were also asked to assess their level of drunkenness on a 15-point scale.

After drinking, the participant performed a 15-minute familiarization drive. Thereby, system activation, deactivation and the reaction to a TOR was practiced. The RSVP-task was also explained and practiced. The subsequent test drive took about one hour. In total, one experimental session took about two hours and 15 min. After each test session, participants were taken home by a WIVW employee to make sure that they arrived safely at home. Altogether, three WIVW employees with different responsibilities were present during the test session (1. supervision of drinking, 2. supervision of simulator practice and test drive, 3. shuttling home).

3. Results

3.1. Missing cases

3.1.1. Self-reports and breathalyzer measurements

The following missing cases were due to a failure to collect or note down measurements or self-reports by the experimenters:

- In 5 cases, the breath alcohol level was not recorded
- In 1 case, the self-reported drunkenness was not recorded
- In 5 cases, the self-reported sleepiness (on the KSS scale) was not recorded
- There were no missing cases of the self-reported criticality

3.1.2. Driving data

In one experimental session, simulator data were lost because of a technical failure (BAC-level 0.08%). Simulator data of the remaining test sessions were included in the analysis. In three situations, drivers deactivated the automation without a reason, so that the test situations could not be produced. This happened twice in the work zone situation (BAC-levels: 0.08% and 0.00%), and once in the broken-down vehicle scenario (lane change not possible, BAC-level: 0.08%).

3.2. Alcohol level and sleepiness

As shown in Table 4, the respective target alcohol level was reached at the end of the drinking session, with mean alcohol levels of 0.050% and 0.078%. After the drive, the alcohol levels were 0.045% and 0.080% respectively. The participants’ self-assessed level of drunkenness is shown in Fig. 3. As evident from the figure, the values were in line with the BAC conditions.

Table 5 depicts the sleepiness ratings measured at the same time points as the breath alcohol. The KSS-ratings were analyzed using a full-factorial multivariate Analysis of Variance (MANOVA) with the within-subject factors “BAC-level” and “Time of measurement”. There was a significant main effect of the time of measurement on the self-reported sleepiness (F(4,30) = 6.23, p = .001, η² = 0.45). Planned comparisons to the first measurement (prior to drinking) show that the KSS-ratings already increased during the drinking session, but that the largest increase is found between the end of the drinking session and the end of the simulator drive. However, even at the end of the drive, the average sleepiness levels were still relatively low (M = 4.43, SD = 1.61, category: “rather alert”).

3.3. Take-over time and quality

The dependent variables were analyzed using a full-factorial multivariate Analysis of Variance (MANOVA) with the within-subject factors “BAC-level” and “Driving situation”. The results pertaining to the different BAC-levels are shown in Table 6.

Regarding the take-over time, there was an increase in both the time it took drivers to take their hands back on the steering wheel and the time until they deactivated the automation. However, this increase was only significant in the 0.08% BAC condition, but not in the 0.05% condition. Considering the lead time of the TOR of 10 s, it appears that the drivers were still rather fast in taking back control from the automated vehicle. In both situations, there was a main effect of the driving scenario (hands-on time: F(4,28) = 3.82, p = .013, η² = 0.35; take-over time: F(4,28) = 7.54, p < .001, η² = 0.52), but no significant interaction effect (hands-on time: F(8,24) = 2.08, p = .079, η² = 0.41; take-over time: F(8,24) = 1.55, p = .192, η² = 0.34). A distribution of the driver’s take-over times across all test situations is provided in Fig. 4.

Regarding lateral vehicle control, a significant main effect of the BAC-level was only present regarding the standard deviation of lane position, showing a worsening of lateral vehicle control in the 0.08% BAC-level compared with the placebo condition and the 0.05% BAC-level. However, looking at the maximum steering wheel velocity and the maximum lateral acceleration, a non-significant trend in the same direction was present, which also indicates a worsening of lateral vehicle control. The driving situation had a significant impact on all measures of lateral vehicle control (standard deviation of lateral position: F(4,28) = 202.96, p < .001, η² = 0.97; standard deviation of steering wheel angle: F(4,28) = 1061.17, p < .001, η² = 0.99; maximum steering wheel velocity: F(4,28) = 39.92, p < .001, η² = 0.85; maximum lateral acceleration: F(4,28) = 299.10, p < .001, η² = 0.97), but again there was no statistically significant interaction effect on any of the dependent measures (standard deviation of lateral position: F

<table>
<thead>
<tr>
<th>Time of measurement</th>
<th>BAC condition (%)</th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to drinking</td>
<td>0.00</td>
<td>35</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>36</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>35</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>20 minutes after beginning</td>
<td>0.00</td>
<td>36</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>36</td>
<td>0.003</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>35</td>
<td>0.050</td>
<td>0.013</td>
</tr>
<tr>
<td>50 minutes after beginning</td>
<td>0.00</td>
<td>36</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>35</td>
<td>0.049</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>35</td>
<td>0.077</td>
<td>0.014</td>
</tr>
<tr>
<td>End of drinking session</td>
<td>0.00</td>
<td>36</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>36</td>
<td>0.050</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>36</td>
<td>0.078</td>
<td>0.013</td>
</tr>
<tr>
<td>After simulator drive</td>
<td>0.00</td>
<td>36</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>36</td>
<td>0.045</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>35</td>
<td>0.080</td>
<td>0.012</td>
</tr>
</tbody>
</table>
Regarding the participants’ longitudinal control, there was no statistically significant main effect on their velocity (standard deviation, minimum and maximum), but planned contrasts to the placebo group revealed that the standard deviation of velocity increased and the minimum velocity decreased with the 0.08% BAC-level. Again, the driving situation had a significant impact on the participants’ velocity control (standard deviation of velocity: $F(4, 28) = 159.36$, $p < .001$, $\eta^2 = 0.96$; maximum velocity: $F(4, 28) = 13.02$, $p < .001$, $\eta^2 = 0.65$; minimum velocity: $F(4, 28) = 202.17$, $p < .001$, $\eta^2 = 0.97$). An inspection of the interaction effects revealed that the impact of BAC-level partly depended on the driving scenario (standard deviation of velocity: $F(8, 24) = 2.89$, $p = .021$, $\eta^2 = 0.49$; maximum velocity: $F(8, 24) = 2.18$, $p = .067$, $\eta^2 = 0.42$; minimum velocity: $F(8, 24) = 2.44$, $p = .044$, $\eta^2 = 0.45$). As can be seen in Fig. 5, the interaction effect can be attributed to the fact that both the standard deviation of velocity increased and the minimum velocity decreased with the BAC-level in the avoiding situation in which a lane change was possible. Apparently, drivers in the placebo group performed better in those situations in which a reduction of velocity was not necessary.

This effect can be further explained when the participants’ maximum deceleration is considered. As evident from Table 6, the drivers were braking stronger both with the 0.05% and 0.08% BAC condition
compared to the placebo condition. However, there was also a significant main effect of the driving situation ($F(4,28) = 57.87, p < .001, \eta^2 = 0.89$) and an interaction effect ($F(8,24) = 3.36, p = .010, \eta^2 = 0.53$) on this measure, showing that the increase was mainly due to the avoiding scenario (lane change possible, see Fig. 6).

There was no main effect of the BAC-level on the driver’s minimum headway and time-to-collision in the avoiding scenarios (see Table 6), which were again largely affected by the driving situation (minimum time-to-collision: $F(1,33) = 83.48, p < .001, \eta^2 = 0.72$; minimum headway: $F(1,33) = 118.38, p = < .001, \eta^2 = 0.78$). While there was no interaction effect between the independent variables on the minimum time-to-collision ($F(2,32) = 1.25, p = .300, \eta^2 = 0.07$), the interaction effect reached significance with regard to the minimum headway ($F(2,32) = 4.20, p = .024, \eta^2 = 0.21$). As evident in Fig. 7, drivers had a lower minimum headway to the broken-down vehicle in the 0.05% and 0.08% BAC condition compared to the placebo condition if lane change was possible whereas there was no difference if it was not.

The BAC had no statistically significant impact on the driver’s self-reported criticality of the take-over situations (see Table 6). There was a significant main effect of the driving situation ($F(4,32) = 22.17, p < .001, \eta^2 = 0.74$), but no interaction between the BAC-level and driving situation ($F(8,28) = 0.76, p = .637, \eta^2 = 0.18$).

### 4. Discussion

This paper dealt with the influence of different BAC-levels on drivers’ ability to take back manual control when a conditionally automated vehicle reaches its limits. Vehicle automation is a promising solution to many problems associated with modern day traffic. Nevertheless, safety concerns have been expressed whether drivers will be able to re-engage safely in the driving task because of their relief from continuous operation of the vehicle. Overreliance on the capability of automated driving systems, could, however, promote misuse and a more incautious attitude towards driving under the influence of alcohol, which could further complicate taking back control from automated vehicles.

Many studies have documented alcohol-induced impairments on manual driving performance (see Irwin et al., 2017 for a recent review). However, the changed role of the driver during conditionally automated driving requires a re-assessment of this relationship. On the one hand, it could be expected that there might be an even greater impact of BAC in driving performance because of the need to switch from the engagement of some sort of non-driving related activity (NDRT) back to manual driving. Switch costs are a well-documented phenomenon in cognitive psychology that usually manifests in increased response times and error rates (Altmann and Trafton, 2004; Monk et al., 2004; Salvucci et al., 2009), which could be intensified by the sedating effects of alcohol consumption. On the other hand, it could be that drivers are better able to compensate alcohol-related driving skill degradation for short time periods of manual driving (as in case of mostly automated driving with occasional manual control) compared to fully manual driving. Indeed, most studies that investigated the effect of alcohol on
manual driving have used longer periods of continuous driving, begin-
ing from 5 to over 60 min (Irwin et al., 2017).

Looking at the behavioral data of our experiment reveals that the BAC indeed influenced take-over time negatively. However, only a BAC-level of 0.08% increased take-over times significantly compared with the placebo condition. Consistent with prior studies on manual driving, alcohol also increased the standard deviation of lateral position (Arnedt et al., 2001; Kenntner-Mabiala et al., 2015; Louwerens et al., 1987; Schumacher, 2015), but again this increase was only evident in the condition with BAC of 0.08%. Other indicators of lateral vehicle control, such as the maximum lateral acceleration or the standard deviation of steering wheel angle, also pointed towards a worse vehicle control, however, the comparison did not fulfill generally accepted significance criteria.

Longitudinal vehicle control was only impaired in the avoiding scenario in which a lane change was possible. The impairment of longitudinal control was visible in an increase in the standard deviation of speed as well as a higher deceleration with increased BAC, but only in one of the test situations. Taken together, these results are in line with studies on alcohol-related impairments during manual driving conditions (Kenntner-Mabiala et al., 2015). In a recent meta-analysis of simulator studies, Irwin et al. (2017) report that SDLP is a more sensitive indicator of alcohol-induced driving impairment than other driving performance measures, and that the magnitude of impairments of longitudinal control measures such as the standard deviation of speed is usually low.

Alcohol is known to impair various aspects of cognitive functioning relevant to safely controlling a vehicle. One special interest of this research was the combined effect of alcohol level and automation use on the sleepiness of the participants. At low alcohol doses and while BAC is ascending, alcohol’s stimulating effects usually prevail, while at low alcohol doses and while BAC is descending, it has predominantly sedating effects (Petrocelli et al., 1994; Pohorecky, 1977). On the other hand, the use of automated driving systems itself has been shown to increase sleepiness (Jarosch et al., 2017; Neubauer et al., 2012), and it has been shown that negative effects of alcohol on driving performance are worsened by sleep deprivation (Roehrs et al., 1994). It could thus be expected that there would be an interaction between the BAC-level and automation usage on sleepiness. However, our results do not support this concern as there was no effect of BAC on the reported sleepiness and no interaction with the time of measurement. Instead, a consistent increase in the reported sleepiness was observed when the ratings before and after the automated simulator drive were compared. This suggests a uniform moderate increase of automation-induced sleepiness in all BAC conditions, which might be due to the rather simple NDRT (Jarosch et al., 2017).

One limitation of the current study is that we used an alcohol placebo condition and no “no alcohol” control. It could be that the participants in the placebo condition altered their behavior as they expected to consume alcohol (Williams et al., 1981), which could have resulted in an underestimation of the true effect of alcohol in the collected driving performance measures (Irwin et al., 2017). However, given that the participants were rather precise in their estimates of drunkenness in the sense that the ratings matched the BAC conditions, it seems unlikely that such an effect has occurred. Another limitation of the study is the rather simple NDRT used to distract the participants from monitoring the driving environment before the take-over situations were encountered. It is quite likely that drivers would be willing or even desiring to engage in more complex and demanding tasks during an automated ride (Large et al., 2017; Pfeleging et al., 2016). One crucial factor in the disengagement from NDRTs could be the effort needed to interrupt the task and re-engage in driving related activities (Naujoks et al., 2017b). Alcohol consumption could impair the driver’s availability for manual control further than in our study in two ways: First, while drivers are generally not good at estimating the risk associated with engaging in distracting activities (Horrey et al., 2008, 2009), it could be that increased alcohol levels promote the engagement in more risky NDRTs during automated driving even more (Lane et al., 2004). Second, the cognitive and motoric processes involved in interrupting more complex NDRTs (Marberger et al., 2017) could be prolonged by the BAC.

As explained above, SDLP was not impaired until a BAC-level of 0.08%, whereas in other trials investigating deficits in manual driving it could already be shown that a BAC-level of 0.05% impairs lateral vehicle control. Since drug induced impairments of lateral control strongly depend on the characteristics (e.g., difficulty, duration) of the underlying test scenario in manual driving (Kaussner et al., 2010; Kenntner-Mabiala et al., 2015), a possible explanation might be that the take-over situations or the provided time budget of 10 s selected for this trial were too long or too easy to be sensitive to lower BAC-levels. Alcohol-related impairments might be more pronounced under higher time-pressure (when the available time budget is lower) or when the take-over situation is more complex (Gold et al., 2017). Furthermore, based on the present data, it cannot be concluded that a BAC-level of 0.05% does not impair take-over performance in automated driving. Specifically, there were several parameters indicating at least a descriptive worsening of take-over performance (e.g., take-over time). In fact, this conclusion can only be drawn based on tests for equivalence and sufficiently powered sample size. To answer these and more questions, there is a need for significantly more research in this area before definite conclusions about the impact of BAC on take-over performance can be drawn.

5. Conclusion

The current study assessed alcohol-induced impairments of take-over performance during conditionally automated driving, demonstrating a significant worsening of both take-over time and quality at a BAC-level of 0.08%. For 0.05% BAC, there was only a descriptive trend of worsening compared with the alcohol placebo condition. These results demonstrate that the risks associated with alcohol consumption will not disappear as a result of vehicle automation and that efforts have to be undertaken that this risk is not underestimated.

Key points

• Comparisons of placebo, 0.05% and 0.08% BAC in a high-fidelity driving simulator.
• Drivers were distracted from the driving environment by a simple NDRT.
• 0.08% BAC significantly worsened take-over time as well as several aspects of vehicle control.
• 0.05% BAC did only go along with descriptive impairments in fewer parameters.
• Future research should further address more complex NDRTs.

References

Åkerstedt, T., Gillberg, M., 1990. Subjective and objective sleepiness in the active in-
Arnedt, J.T., Wilde, G.J., Munt, P.W., MacLean, A.W., 2001. How do prolonged wake-
technology-portal.de/en/electrics-electronics/driver-assistant-systems/audi-a8-audi-
ai-traffic-jam-pilot.


Horrey, W.J., Lesch, M.F., Garabet, A., 2009. Dissociation between driving performance and drivers’ subjective estimates of performance and workload in dual-task condi-

Irwin, C., Judakhina, E., Desbrow, B., McCartney, D., 2017. Effects of acute alcohol consumption on measures of simulated driving: a systematic review and meta-an-


Ko, S.M., Ji, Y.G., 2018. How we can measure the non-driving-task engagement in au-


Ko, S.M., Ji, Y.G., 2018. How we can measure the non-driving-task engagement in au-


Ko, S.M., Ji, Y.G., 2018. How we can measure the non-driving-task engagement in au-

Ko, S.M., Ji, Y.G., 2018. How we can measure the non-driving-task engagement in au-

Ko, S.M., Ji, Y.G., 2018. How we can measure the non-driving-task engagement in au-