The influence of alcohol and automation on drivers’ visual behavior during test track driving

Citation for the original published paper (version of record):
Tivesten, E., Broo, V., Ljung Aust, M. (2023). The influence of alcohol and automation on drivers’ visual behavior during test track driving. Transportation Research Part F: Traffic Psychology and Behaviour, 95: 215-227. http://dx.doi.org/10.1016/j.trf.2023.04.008

Transportation Research Part F: Psychology and Behaviour 95 (2023) 215–227

Contents lists available at ScienceDirect

Transportation Research Part F: Psychology and Behaviour

journal homepage: www.elsevier.com/locate/trf

The influence of alcohol and automation on drivers' visual behavior during test track driving

Emma Tivesten [a,b,*], Viktor Broo [a], Mikael Ljung Aust [a]

[a] *Volvo Cars Safety Centre, PV22, Göteborg, Sweden*
[b] *Chalmers University of Technology, Göteborg, Sweden*

ARTICLE INFO

Keywords:
Intoxication
Attention
Visual time-sharing
Assistance
Autonomous
Manual

ABSTRACT

Background: Driving under the influence of alcohol severely increases crash risk. Impairment detection during driving is therefore key to improve traffic safety. However, future detection systems need to capture impairment for more reasons than alcohol intoxication and must also function in all driving modes (manual, assisted, autonomous). Driver Monitoring Systems (DMS) are promising candidates for such broader impairment detection.
Method: A test track study investigated the effects of alcohol intoxication on drivers' visual behavior both when just driving and when engaged in a non-driving related task. Twenty-six participants performed two drives: 1) sober baseline, 2) with a target blood alcohol concentration of 0.1%. The participants drove in either manual, assisted, or autonomous drive (AD) mode.
Results: Intoxication influenced glance behavior in all driving modes. It was most evident during visually demanding non-driving related tasks where it resulted in longer single and total off-path glance durations. Additionally, when just driving in manual mode, almost one third of the drivers displayed gaze concentration to the forward roadway when intoxicated. For sober driving, the difference in visual behavior between manual and assisted mode were moderate. In contrast, there was a huge shift towards longer off-path glances, lower percent road center, and lower off-path glance frequency in AD mode.
Conclusions: Intoxication clearly affects drivers' on/off road glance behavior. However, it is necessary to account for both driving mode and engagement in non-driving related tasks to reliably distinguish sober from drunk driving. Glance metrics has the potential to serve as a subset of indicators for a broader DMS-based detection of impaired driving, which can inform the decisions on when to activate in-vehicle countermeasures.

1. Introduction

The detrimental effects of alcohol on road safety are well-known and empirically established. For example, according to the Swedish national road administration, 28% of Swedish fatal crashes in 2020 involved an intoxicated driver (SNRA, 2020). Of those, 19% involved alcohol only, while the remaining 9% involved drugs or a combination of alcohol and drugs. These numbers correlate well with global statistics, which estimate that up to 35% of the motor vehicle fatalities are related to alcohol impairment (NHTSA, 2017; Valen et al., 2019; World Health Organization, 2018). Additionally, there is a well-established dose-dependent increase of

---

[*] Corresponding author at: Volvo Cars Safety Centre, PV22, Göteborg, Sweden.
E-mail address: emma.tivesten@volvocars.com (E. Tivesten).

https://doi.org/10.1016/j.trf.2023.04.008
Received 18 July 2022; Received in revised form 23 March 2023; Accepted 13 April 2023

relative crash risk as a function of blood alcohol concentration (BAC). Relative crash risk is clearly elevated at BAC 0.04–0.05%, and increases exponentially for BAC greater than 0.1% (Blomberg et al., 2009).

Many types of countermeasures to combat drunk driving have been tried, ranging from public education campaigns to alcolocks in vehicles (Ferguson, 2012). However, given the current crash statistics for Sweden and other countries, it is safe to say that more needs to be done.

From a car manufacturer's perspective, the most straightforward way to minimize risk when drivers are impaired is to apply countermeasures directly in the vehicle. For instance, recent advances have been made using passive breath analyzers for in-vehicle detection of alcohol specifically (Lukas et al., 2017; Zaouk et al., 2019). However, since impairment can stem from more sources than alcohol (e.g., other drugs, sudden sickness, sleepiness), it is important to develop detection methods that go beyond detecting alcohol specifically. A broader detection method that captures impaired driving in general, regardless of the underlying cause, will cover more impaired states and have a higher positive impact on traffic safety.

To address impaired driving, one must solve two problems. The first is detection, i.e., being able to empirically determine when drivers are deviating so far from their normal behavior that they can be classified as impaired. The second is what to do once impairment is detected, i.e., how to leverage a vehicle's Advanced Driving Assistance Systems (ADAS) in such a way that the risk elevation that stems from impaired driving is mitigated without causing too much driver irritation in case of false detections. In this study, while acknowledging the difficulties of the second problem, we only focus on the first, i.e., finding ways to reliably detect impairment while driving.

Numerous laboratory studies have demonstrated that BAC has a negative effect on the cognitive functions and skills essential for safe driving, such as the capacity for divided attention, executive functions, perception, psychomotor skills, reaction time and vigilance. Furthermore, these effects occur at BAC levels equal to, or much below, the legal limit in many countries (e.g., see reviews by Garrisson et al., 2021; Jongen et al., 2016; Moskowitz & Fiorentino, 2000; Moskowitz & Robinson, 1988).

In driving simulator studies, BAC has been shown to influence a wide range of performance measures including standard deviation of lane position (SDLP), the number of lane excursions, response times to unexpected safety–critical events, car-following performance, and standard deviation of speed (Irwin et al., 2017; van Dijken et al., 2020; Yadav & Velaga, 2019, 2021). A review by Irwin et al. (2017) concluded that SDLP is both the most studied and the most sensitive of these metrics.

Additionally, a review by Martin et al. (2013) concluded that BAC and task complexity are the most relevant variables when trying to observe impaired driving performance. While a visually demanding non-driving related task (NDRT) can reduce driving performance in terms of SDLP in its own right (Irwin et al., 2015), the combined effects of alcohol and NDRTs interact to further reduce driving performance (Harrison & Fillmore, 2011; Rakauskas et al., 2008; Van Dyke & Fillmore, 2015). Also, a recent driving simulator study by Ahlström et al. (2023) found that with increased levels of alcohol, drivers adopted smaller safety margins (e.g., speed, time headway) and a higher engagement in a self-paced NDRT.

Given the findings cited above, one might conclude that metrics related to operational control are highly promising when trying to detect alcohol impairment (Lee et al., 2010). However, when looking into the future of driving, one can see that assisted driving (where the vehicle performs most of the control tasks while the driver supervises driving) and autonomous driving corresponding to SAE level 3 (SAE, 2021), are taking over a larger share of the total driving. Since the vehicle performs the majority of the operational control in assisted and autonomous driving, metrics based on operational control are not a viable option. Still, detection of driver impairment remains important in both modes. Consequently, a broader approach that can capture impairment for reasons beyond alcohol intoxication in all three driving modes (manual, assisted, and autonomous) is needed.

A promising technology candidate for achieving broad impairment detection in all driving modes is what is often referred to as Driver Monitoring Systems (DMS), see Hayley et al. (2021). DMS refers to any set of in-vehicle sensors aimed to determine the driver's state and typically includes eye tracking sensors that can track visual behavior patterns. DMS are expected to be widely introduced on the market and to make a significant contribution to road safety in the coming years (Hayley et al., 2021; Lenné et al., 2020).

The reason DMS are expected to have an impact on traffic safety is because the driving task is to a considerable extent guided by visual input. Consequently, visual attention is essential for safe driving. For example, it has been shown that long off-path glance durations increase crash risk in naturalistic driving (Liang et al., 2014). Hence, a number of metrics that capture drivers' visual patterns have been developed to study safety in driving, including percent road center (PRC, the percentage of time drivers spend with their eyes on the forward path), the number of off-path glances and the distribution of off-path glance durations (Horrey & Wickens, 2007; ISO, 2020; Klauer et al., 2006; Liang et al., 2014; Morando et al., 2019; Victor et al., 2015). Maximum off-path glance duration during a NDRT is another metric that captures long off-path glance durations (ISO, 2020). In a similar fashion, the NHTSA design guidelines for manual-visual in-vehicle tasks include metrics such as the percentage of off-path glance durations longer than 2.0 s and total eyes off road time to assess which NDRTs are safe to perform while driving (NHTSA, 2013).

Given the importance of vision for safe driving and the ability of DMS-based systems to analyze drivers' gaze patterns, a DMS-based approach could provide the basis needed for the type of broad impairment detection discussed above. The aim of this study is therefore to investigate the effect of alcohol on drivers' visual behavior in manual, assisted and autonomous driving mode.

Research on how alcohol influences visual behavior in driving is limited, but some insights exist. Moskowitz and Ziedman (1979) showed in a simulator study that drivers take longer time to read route signs while using fewer and longer fixations when influenced by alcohol. Ahlström et al. (2023) found that drivers increased their engagement in a self-paced NDRT with increasing alcohol intake, and they directed more and longer glances towards the NDRT.

It is also known that the influence of alcohol on cognitive and motor processes (e.g., perceptive/motor abilities, memory, executive functions) causes decreased oculomotor accuracy/speed (e.g., smooth pursuit, saccade latency and velocity), and alters the number of fixations and dwell time needed during tasks such as visual exploration or decision-making (Maurage et al., 2020). Exactly how these effects manifest themselves in driving is, however, less clear. On one hand, alcohol intoxication can lead to increased gaze concentration to the road center and fewer fixations to the peripheral areas (Belt, 1969; Moskowitz & Robinson, 1988). On the other hand, it may also lead to more dispersed and erratic visual scanning patterns as indicated by gaze entropy measures (Shiferaw et al., 2019).

The present study specifically targets severe impairment, i.e., impairment that corresponds to a BAC above the legal limit in most countries and a severely elevated crash risk. We investigate the effect of alcohol intoxication in different driving modes by comparing two repeated drives: 1) sober baseline and 2) intoxicated (target BAC 0.1%), with participants assigned to either manual, assisted or Autonomous Drive (AD) mode.

The following research questions were posed:

1) What is the effect of alcohol intoxication on drivers' glance behavior when just driving in manual mode (i.e., when not performing a specific NDRT)?
2) What is the effect of alcohol intoxication on drivers' glance behavior in different modes (manual, assisted, AD) when performing a visual-manual NDRT?
3) What is the effect of mode (manual, assisted, AD) when performing a NDRT when driving sober and when driving intoxicated?

2. Material and methods

The study has a mixed study design. All participants performed two drives, first a sober baseline drive and then a second drive while influenced by alcohol. Participants were also divided into three driving mode groups (see section 2.1).

The study was reviewed and approved by the Swedish Ethical Review Authority (Dnr: 2019–05395).

2.1. Participants

All participants ($N = 32$) were Volvo Cars employees who did not work as test drivers, had a Body Mass Index (BMI) of 19–30, followed a regular sleeping-pattern (i.e., only working regular daytime hours) and had driven at least 5,000 km during the last year. Furthermore, all participants consumed alcohol at least twice a week and had a moderate intake of standard drinks as defined by NIAAA (2020), corresponding to 2 to 9 units/week for women and 3 to 14 units/week for men. Six participants were excluded from the analysis, two because gaze coding was not possible due to the driver wearing sunglasses and four due to missing data. The final sample contained twenty-six participants, including seventeen male and nine female between the ages of 25 and 66 years ($M = 42.9$, $SD = 12.5$). The participants were divided into three driving mode groups including manual ($n = 10$), assisted driving ($n = 8$), and AD ($n = 8$), as described in section 2.2.

2.2. Test environment and equipment

The study was conducted at the AstaZero rural road test track, located outside of Gothenburg, Sweden. The test track has two travel lanes and is designed to resemble a typical Swedish rural road with posted speeds of 70 km/h and 90 km/h. See AstaZero (2023) for more details. The test vehicle was a Volvo XC90 MY 2017. The vehicle had its maximum speed limited to 50 km/h and was equipped with an additional set of pedals on the passenger side, allowing a safety driver to intervene if needed. For data acquisition, the test vehicle was equipped with a data logger that recorded vehicle signals and video data including views of the drivers face and the forward roadway. A breathalyzer was used to measure breath alcohol concentration (BrAC) to estimate the participants' blood alcohol concentration (BAC).

Participants were divided into three groups using different levels of automation (SAE, 2021): manual driving (SAE Level 0), assisted driving (SAE Level 2) and autonomous drive (SAE Level 3–4). In manual mode, the participants drove manually without any assisted driving systems engaged. In assisted mode, test participants drove with Volvo's Pilot Assist system engaged. Pilot Assist performs both longitudinal and lateral control but requires drivers to always supervise as well as to keep their hands on the steering wheel. If the function cannot detect any hands on the wheel, a warning sound is issued together with the visual message "Apply steering". For AD mode, the Pilot Assist system was used with the "hands-on-wheel"-reminder disabled to simulate an autonomous drive experience. Participants were also informed that the vehicle took full responsibility for the driving task, but that the driver needed to be prepared to resume manual driving if requested to do so by the vehicle. Consequently, the driver was free to completely disengage from the driving task in AD mode.

A test leader was present in the rear right seat during all drives. In addition, a safety driver was present in the front passenger seat for all drives except the baseline drives in manual and assisted mode.

2.3. Procedure

At recruitment, the participants were given a brief description of the test setup and an estimation of the amount of alcohol to be consumed during the test. The day prior to their participation, each participant performed a drug test and had their weight recorded at a health care center. The drug test was performed to ensure that the participants would not be affected by any unreported substances that could affect the outcome of the study. The weight was needed to estimate the alcohol required for the test.

Upon arrival, all participants received general information about the experiment and were asked to sign an informed consent form. All participants also performed a breathalyzer test to verify that they were sober before starting the procedure.

Table 1
Overview of selected segments included in the analysis from the baseline (BL) and the intoxicated (IN) drive, including selected driving mode in manual (M), assisted (A), or AD.

Drive	Mode	Segment	NDRTs	Duration	Lap
BL	M	S1	–	30 s	1
	M, A, or AD	S2	Radio	12–50 s	2
	M, A, or AD	S3	Dialing	13–30 s	2
	M, A, or AD	S4	Temperature	5–23 s	3
IN	M	S1	–	30 s	1
	M, A, or AD	S2	Radio	13–54 s	2
	M, A, or AD	S3	Dialing	11–114 s	2
	M, A, or AD	S4	Temperature	6–32 s	3

2.3.1. *Non-driving related tasks (NDRTs)*

The participants were instructed to perform three visual-manual tasks during each drive using the center stack display. The tasks were performed in the following order: 1) Manually tune the radio to a specified frequency, 2) Call your own phone by entering the phone number manually, 3) Set the car heater to a specific temperature.

The participants received instructions on how to perform the tasks and got the opportunity to practice them while seated in the test vehicle at stand still. They were informed that if they did not successfully complete a task they needed to start over. Participants assigned to assisted or AD mode were instructed on how to activate these modes.

2.3.2. *Baseline drive*

Each participant drove sober for four laps around the test track at 50 km/h taking approximately 30 min. The baseline session started with 5 min manual driving followed by 25 min of the assigned driving mode (manual, assisted, or AD).

Once the participants finished their first lap, they were asked to perform the NDRTs. All tasks were initiated during straight road segments. The radio and dialing tasks were performed during the second lap and the temperature task was performed at the beginning of the third lap. The participant reported their sleepiness using the Karolinska sleepiness scale, KSS (Åkerstedt & Gillberg, 1990) at the start of the drive and at the end of each lap.

2.3.3. *Drinking session*

After the baseline drive, a drinking session took place in an office space. The participant was offered their share of alcohol, aiming for a target BAC of 0.1%. Each participant received a total amount of 4 ml of 37.5 vol% vodka per kilogram body weight.

The participants were provided with soft drinks, juice, and ice to mix with the alcohol. They were instructed to consume the alcohol within 45 min, to keep the consumption at a high pace while maintaining the risk of discomfort of nausea low. After the participants had finished their drinks, they were instructed to wait for 15 min before rinsing their mouth with water to reduce any remaining alcohol residue. Then, participants were transported back to the test track and got seated in the driver seat of the test vehicle. Just before driving, the participants assessed their KSS value and performed another breathalyzer test to establish their BrAC level. The drinking session, including the waiting time, was designed so that the second drive would start close to an estimated peak blood alcohol, and that the measured BrAC would be a good estimation of actual BAC based on a previous study presented by Lukas et al. (2017).

2.3.4. *Intoxicated drive*

A second drive while intoxicated was then performed, repeating the baseline drive procedure during the first four laps. The intoxicated drive was extended compared to the baseline drive and lasted for up to nine laps on the test track, and the drivers continued driving in their assigned mode. The session ended after completing nine laps, or earlier if the participant either fell asleep, felt unwell, or if the safety driver assessed the driving as too unstable. All twenty-six participants completed the first four laps (corresponding to the baseline drive), twenty-five participants completed seven laps, and twelve participants completed the full distance of nine laps. Another breath analyzer test was performed immediately after the drive, with the exception of one participant that felt unwell.

The BrACs measured just before the drive were in most cases close to the target of 0.1% ($n = 26$, $M = 0.100$, $SD = 0.018$, $Min = 0.067$; $Max = 0.139$ %) while a larger mean and standard deviation was observed for female drivers ($n = 9$, $M = 0.107$, $SD = 0.020$, $Min = 0.083$; $Max = 0.139$ %) compared to male drivers ($n = 17$, $M = 0.096$, $SD = 0.016$, $Min = 0.067$; $Max = 0.126$ %). The BrACs after the intoxicated drive were on average slightly lower ($n = 25$, $M = 0.095$, $SD = 0.015$, $Min = 0.065$; $Max = 0.123$ %), although the individual change during the drive ranged between −0.041 to + 0.013 %.

2.4. *Data processing and coding*

Four video segments were extracted for manual annotations from each drive (Table 1). The first 30-second segment (S1 in Table 1) was selected on a specific stretch of road during the first lap on the test track. Segment S1 was selected to get reference data for all participants in manual mode when not performing a specific NDRT. The following segments (S2-S4 in Table 1) included the NDRTs that the participants were instructed to perform while in the driving mode according to their assigned group. The start of the task segments S2-S4 was defined by the onset of the first off-path glance towards the center stack display, and the end was defined by the

Table 2
Overview of the results on the effect of intoxication, and the effect of driving mode during the baseline (BL) and intoxicated (IN) drive, respectively. The star symbols indicate the comparisons that were statistically significant at 0.05 (*), 0.01(**), and 0.001 (***) level after adjusting for multiple tests. The Δ-symbols indicate the effect sizes that were either moderate (Δ) or high (Δ Δ), while small effect sizes are not shown. The grey symbols indicate the effect sizes that were not statistically significant. See Appendix A for test statistics.

		Effect of intoxication			**Effect of mode (BL)**				**Effect of mode (IN)**			
Metric	**Segment (task)**	*Manual*	*Assisted*	*AD*	Mode	*M-AD*	*M-A*	*A-AD*	Mode	*M-AD*	*M-A*	*A-AD*
PRC	S1(No)	** Δ										
[%]	S2(Radio)	Δ	ΔΔ	** ΔΔ	** ΔΔ	**		*	***ΔΔ	**		**
	S3(Dial.)	Δ	Δ	** ΔΔ	***ΔΔ	**		**	***ΔΔ	**		**
	S4(Temp.)				**Δ	**		*	***ΔΔ	**		
GF-off	S1(No)	*** ΔΔ										
[N]	S2(Radio)		Δ	* Δ	*Δ	*			***ΔΔ	**		**
	S3(Dial.)		Δ	* Δ	***ΔΔ	**		**	**ΔΔ	**		**
	S4(Temp.)				**ΔΔ	**		**	**Δ	**		*
TGT	S2(Radio)	**ΔΔ	*ΔΔ	ΔΔ								
[s]	S3(Dial.)	*ΔΔ	Δ	**ΔΔ								
	S4(Temp)	Δ	Δ	Δ								
MaxGD	S2(Radio)	**ΔΔ	**ΔΔ	**ΔΔ	***ΔΔ	**		**	**ΔΔ	**		**
[s]	S3(Dial.)	**ΔΔ	*ΔΔ	**ΔΔ	***ΔΔ	**		**	***ΔΔ	**		**
	S4(Temp)	Δ	**ΔΔ	Δ	**ΔΔ	**		*	**Δ	*		*
GD>2s	S2(Radio)	**ΔΔ	*ΔΔ	**ΔΔ	** ΔΔ	**		*	**ΔΔ	**		**
[%]	S3(Dial.)	**ΔΔ	ΔΔ	Δ	** ΔΔ	**			**ΔΔ	**		**
	S4(Temp.)		* Δ		** ΔΔ	**		*	**Δ	*		

end of the last glance towards the display. Only the completed tasks were included in segment S2-S4. One participant failed at the first attempt to perform the dialing task while intoxicated but completed this task from start to end during the second attempt. The participants successfully completed all other tasks on the first attempt.

Video views of the drivers face and the forward roadway were used to assess the drivers' gaze direction. The gaze direction was coded for each video frame during the selected segments, creating a time series at 20 Hz corresponding to the sampling frequency of the recoded video. A specific area of interest (AOI) was coded for each frame inspired by the UDRIVE Annotation Codebook (Bärgman et al., 2017). The AOI categories were then merged into three categories: eyes on path, off path, or unknown if the drivers' gaze direction could not be determined. Gaze directed to the forward roadway was considered as on path, and other directions as off path. The category unknown was treated as missing data.

2.5. *Analysis*

The effects of intoxication and driving mode on participants' visual behavior were analyzed using descriptive statistics and non-parametric statistical tests. The metrics PRC (percent road center) and GF-off (off-path glance frequency) were investigated for all segments. PRC was defined as the percentage of time with eyes on path, and GF-off defined as the number of ongoing off-path glances during each segment. Additionally, three metrics were investigated for the NDRT segments S2-S4. These were: TGT (total glance time) defined as the sum of all off-path glance durations [s], GD $>$ 2 s defined as the percentage of off-path glances longer than 2 s [%], and MaxGD defined as maximum off-path glance duration [s] during each segment.

Differences in glance metrics between driving modes (manual, assisted, AD), and drives (baseline, intoxicated) were visualized for each segment using boxplots. In addition, cumulative off-path glance distributions were plotted for all glances during the NDRT segments (S2-S4) with individual curves for each driving mode (manual, assisted, AD) and drive (baseline, intoxicated).

The effect of intoxication was evaluated by performing a within-subject comparison for each metric during the intoxicated drive compared to the baseline drive using Wilcoxon signed rank test. A separate comparison was applied for each segment and driving mode. The effect of automation was evaluated by comparing the three driving modes (manual, assisted, AD) for each segment during the baseline and intoxicated drive separately using a Kruskal-Wallis test. The Benjamini-Hochberg false discovery rate (Benjamini & Hochberg, 1995) was applied to all tests to adjust for multiple testing to determine which tests that were statistically significant when using an accepted false discovery rate (FDR) of 5%. The tests that were accepted by the FDR procedure and had a raw p-value less than 0.05 were labelled as statistically significant at the level according to the raw p-value. The Mann-Whitney U post-hoc tests were performed to make pairwise comparisons between the three driving modes when the Kruskal-Wallis test was statistically significant, and Bonferroni corrections were applied to the post-hoc tests to adjust for multiple testing for each pairwise comparison. The effect size

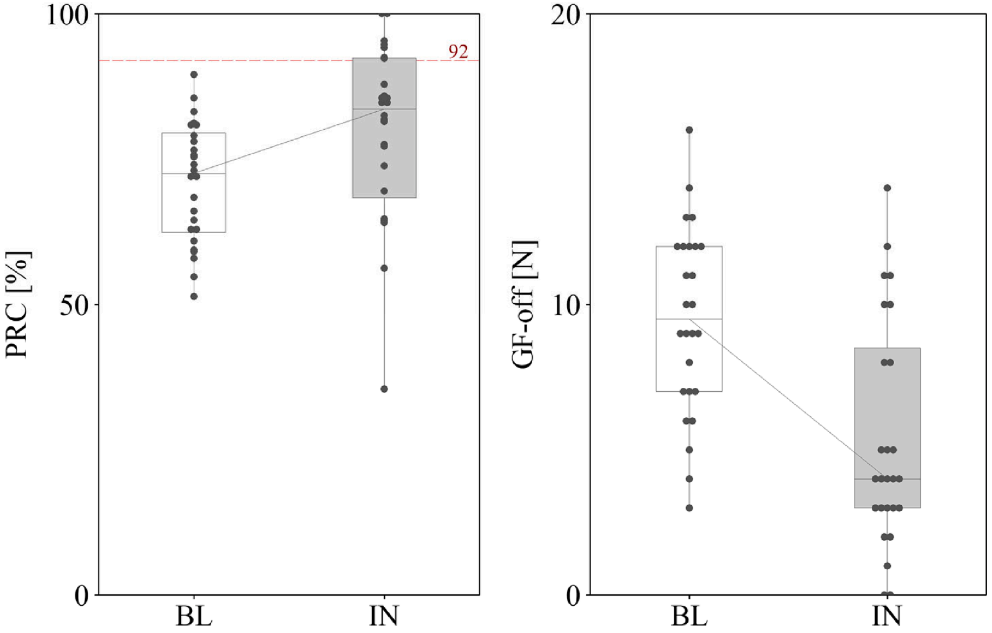

Fig. 1. Boxplots of PRC (left) and GF-off (right) including individual markers for segment S1 (30 s, no tasks, manual mode). Each panel includes the repeated drives (BL = sober baseline, IN = intoxicated drive) with interconnecting median lines.

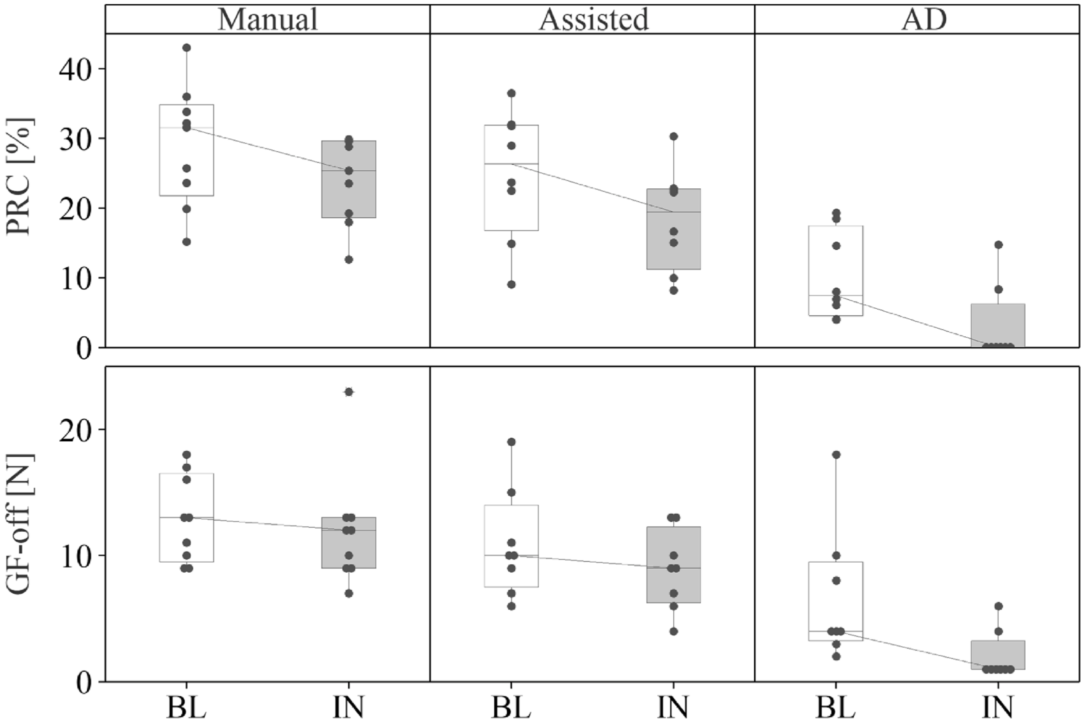

Fig. 2. Boxplots for segment S2 (radio task) where the upper subplots show PRC, and the lower subplots show GF-off. Each subplot column shows values for the groups assigned to manual, assisted, or AD mode. Each subplot is categorized according to the two repeated baseline (BL), intoxicated (IN) drives with interconnection median lines.

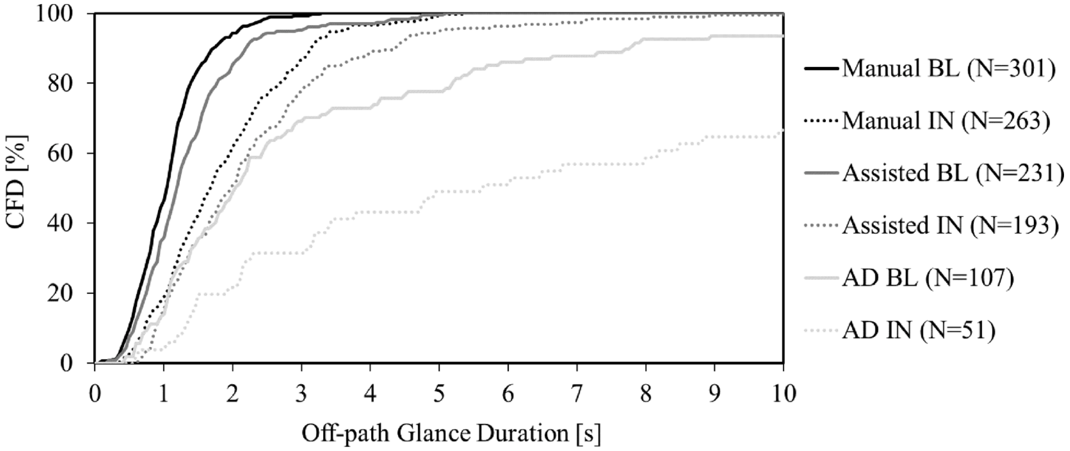

Fig. 3. Cumulative frequency distributions for all off-path glance durations during the three task segments combined. Solid lines represent the baseline (BL) drive, and dashed lines represent the intoxicated (IN) drive. The grey scale represents manual, assisted, and AD mode, respectively. The total number of off-path glances for each curve is presented in the legend.

was estimated by calculating the r-value for Wilcoxon signed rank test and the epsilon-square value (E_R^2) value for the Kruskal-Wallis test according to Tomczak and Tomczak (2014).

3. Results

This chapter presents examples from the descriptive statistics, and an overview of the results from the statistical tests in Table 2. Appendix A presents details on all test statistics.

3.1. The effect of alcohol when just driving in manual mode

In manual mode, when just driving and not performing any specific NDRT, intoxicated drivers spent more time looking on the road and had fewer off-path glances. The boxplots in Fig. 1 illustrate the difference in PRC and GF-off between the sober baseline drive (white boxes) and the intoxicated drive (grey boxes) during the 30-second non-task segment (S1). Almost one third (n = 7/26) of the drivers showed gaze concentration towards the road (PRC > 92%; Victor and Larsson, 2004) during the intoxicated drive, while this was not present during baseline (n = 0/26). The results from the Wilcoxon signed rank tests showed statistically significant differences in segment S1 between the baseline and intoxicated drive, with moderate effect size for PRC ($Mdn_{BL} = 73$, $Mdn_{IN} = 84$, $Z = -2.93$, $p = 0.002$, $r = -0.41$) and high effect size for GF-off ($Mdn_{BL} = 9.5$, $Mdn_{IN} = 4.0$, $Z = -3.95$, $p < 0.0001$, $r = -0.55$).

3.2. The effect of alcohol when performing NDRTs in the different driving modes

In all driving modes, when performing NDRTs the median PRC and median GF-off were lower during the intoxicated drive. The boxplots in Fig. 2 show the difference between the baseline (white boxes) and intoxication (grey boxes) on PRC and GF-off during the radio task (S2) for each driving mode. The same trends were present for the dialing (S3) and the temperature task (S4). However, these differences were not statistically significant except for the radio and dialing task in AD mode, where both metrics were significant, and the effect size was high (r = -0.63, see Appendix A for complete test statistics).

Furthermore, the median TGT was longer during the intoxicated drive compared to baseline for all tasks and driving modes, except for the temperature task in manual mode that had similar TGT during both drives (Appendix A). On average, the dialing and radio tasks both had approximately twice as long TGT and twice as many off-path glances as the temperature task across drives and modes. The effect of intoxication on TGT was only statistically significant in four out of six comparisons for the radio and dialing task, and in no comparisons for the temperature task (Table 2, Appendix A). Two extreme outliers during the intoxicated drive for the dialing task in assisted mode (TGT = 68.1 s) and in AD mode (TGT = 74.8 s) are worth noting. The TGT outlier in assisted mode had longer and approximately twice as many off-path glances during the intoxicated drive compared to the baseline, while the outlier in AD mode consisted of one short and one exceptionally long off-path glance (73.4 s).

The glance duration metrics were more sensitive in detecting differences between baseline and intoxicated drives during the two more demanding tasks (radio and dialing), as indicated by the statistically significant differences and effect sizes shown in Table 2 and Appendix A. The MaxGD metric showed statistically significant differences and high effect size between the intoxicated and baseline drive for all driving modes during the radio and dialing tasks. The difference between the drives were smaller during the temperature task and only statistically significant in the assisted mode as illustrated in Table 2. The GD > 2 s followed a similar pattern, but with lower effect sizes and slightly fewer statistically significant results compared to MaxGD as shown in Table 2 (see Appendix A for complete test statistics).

3.3. The effect of driving mode during NDRTs when sober and when intoxicated

The median PRC and median GF-off were highest in manual mode, slightly lower in assisted mode, and significantly lower in AD mode for all task segments (S2-S4) during both drives (Appendix A). The Kruskal-Wallis tests revealed a statistically significant effect of driving mode on both PRC and GF-off during all the task segments. For these twelve comparisons (two metrics, three tasks, two drives), the post-hoc tests showed statistically significant differences between manual and AD mode for all comparisons (n = 12/12), in most comparisons between assisted and AD mode (n = 10/12), while none of the comparisons between manual and assisted mode as shown in Table 2 (and Appendix A). The estimated effect size for PRC was moderate to high during the baseline task segments (0.49 – 0.65), and even more pronounced during the intoxicated task segments (0.57 – 0.73). The GF-off during the task segments mirrored the findings for PRC, although the estimated effect size was slightly lower during baseline (0.31 – 0.63), as well as the intoxicated drive (0.49 – 0.67). On the contrary, there appears to be no effect of driving mode on TGT during any of the drives.

The off-path glance distribution was shifted toward slightly longer durations in assisted mode, and much longer in AD mode, compared to manual mode during both drives as shown in Fig. 3. Consequently, driving mode affected the long off-path glance durations, which was most evident when comparing AD mode to manual and assisted mode as illustrated in Table 2. There was a statistically significant effect of driving mode on both MaxGD and GD > 2 s for all task segments. The more demanding tasks (radio, dialing) showed greater differences across driving modes than the temperature task. Furthermore, there was a similar effect of driving mode on MaxGD and GD > 2 s, while a slightly stronger effect was observed for MaxGD (Table 2, and Appendix A).

4. Discussion

The aim of this study was to investigate the effect of alcohol on drivers' visual behavior in manual, assisted and autonomous driving modes as a first step towards understanding whether Driver Monitoring Systems that measure visual behaviors can provide a viable path toward general detection of severe driver impairment.

Overall, the results show that BAC, driving mode and NDRT engagement all influence drivers' glance behavior. Section 4.1-4.3 discusses the results, section 4.4 discusses the overall implications for a DMS-based impairment detection approach, and finally Section 4.5 discusses future work and limitations.

4.1. The effect of alcohol when just driving in manual mode

About one third of the drivers showed gaze concentration effects when intoxicated and driving manually, which is in line with the previous finding that BAC is associated with gaze concentration to the road center (Belt, 1969). Alcohol intoxication increased PRC and decreased off-path glance frequency during the 30-second non-task segments in manual mode. Metrics that capture gaze concentration thus seem a promising candidate for impairment detection.

This corresponds well with other studies of risk associated driver states. For example, the multi-distraction detection algorithm (Lee et al., 2013; Victor & Larsson, 2004) uses PRC values exceeding 92% (over a 60-seconds moving window) to detect gaze concentration associated with cognitive distraction. The same metric and threshold was also found as one of the indicators of overreliance in assisted automation (Tivesten et al., 2019).

This suggests that using an in-vehicle DMS to compute PRC or similar metrics in-real time may reliably capture gaze concentration that could be due to alcohol intoxication as well as other forms of impairment or disengagement from the driving task. Since PRC naturally fluctuates when computed over a moving time window and variability decreases with increasing window size, we suggest using a longer time window than applied in this study (e.g., a 60-second rather than a 30-second window) to increase robustness. Also, including the number of off-path glances per minute may further improve the ability to detect different forms of driver impairment.

4.2. The effect of alcohol when performing NDRTs in the different driving modes

When drivers were performing NDRTs, the effect of intoxication on PRC pointed in the opposite direction compared to the non-task segment. The participants had both lower PRC and fewer off-path glances during the intoxicated drive compared to baseline, for all NDRTs across all three driving modes. Intoxication also resulted in longer total glance time and longer off-path glances.

It follows that understanding context will be important if one wants to detect impairment using visual behavior metrics. Since the effects go in opposite directions depending on whether the driver is engaged in a visual NDRT or not, keeping track of task engagement becomes a prerequisite to being able to interpret changes in visual behavior.

These results mirror the findings from the simulator study by Moskowitz and Ziedman (1979) who found that drivers needed more time to read road signs, using fewer glances and longer dwell times, when influenced by alcohol. This suggests a considerable reduction in the performance of cognitive functions and skills at BAC 0.1% (Garrisson et al., 2021; Jongen et al., 2016; Moskowitz & Fiorentino, 2000; Moskowitz & Robinson, 1988), that becomes more evident when the driver needs to divide attention between the NDRT and driving.

Ahlström et al. (2023) also found that increasing BAC led to longer off-path glances during a self-paced NDRT, but also that the drivers directed more glances to the task, in contrast to the present study. However, the off-path glance frequencies in Ahlström et al. (2023) were associated with an increased engagement in a NDRT during a complete drive as opposed to off-path glance frequency for specific tasks as investigated in the present study.

The effect of intoxication was stronger for the more visually demanding tasks (i.e., radio, dialing). This is not surprising since previous studies have found that BAC and task complexity (in general) are the most important factors for detecting alcohol impairment (Martin et al., 2013; Moskowitz & Robinson, 1988).

Overall, the metric most sensitive to BAC in the present study was maximum off-path glance duration. TGT and GD > 2 s showed more varied results. The metric GD > 2 s also has limitations in the current analysis since most drivers had fewer off-path glances during the NDRTs when driving intoxicated. For instance, when a task is completed using two off-path glances, the percentage of glances longer than 2 s can only assume three values (i.e., 0%, 50%, or 100%). This was most evident in AD mode where participants could disengage completely from the driving task, enabling them to complete a NDRT using a single off-path glance. This makes GD > 2 s a less robust metric when applied to short visual time-sharing segments.

To overcome this problem, another approach may be to look for extreme off-road glance durations. For instance, in manual and assisted mode, only one of seventeen participants had off-path glances longer than 4 s during the baseline tasks segments, while twelve of seventeen had off-path glances longer than 4 s during the intoxicated task segments.

However, in AD mode, since there was no need to quickly return the gaze to the road, several outliers were recorded. For instance, one driver performing the dialing task in AD mode had a maximum off-path glance duration of 9 s in baseline and 73 s while intoxicated. Measuring extreme off path glance durations will thus be of limited use in AD mode, especially for drivers that decide to look away from the road during the complete AD duration as observed in Pipkorn et al. (2022). Relying on extreme off-path glance durations to detect alcohol impairment should therefore be reserved for manual and assisted driving.

4.3. The effect of driving mode during NDRTs when sober and when intoxicated

The effect of assisted mode on glance behavior during NDRTs was moderate while the effect of AD was exceptionally large when compared to manual mode.

While Morando et al. (2020) found no difference in PRC between manual and assisted mode during visual time-sharing segments in naturalistic driving, here the median PRC was slightly lower in assisted compared to manual mode for all NDRTs. It is possible that the relatively low driving demand, combined with more demanding NDRTs and the assisted mode itself being experienced as quite reliable invited participants in the present study to spend less time with their eyes on road in assisted mode, compared to Morando et al. (2020).

In AD mode, the PRC and number of off-path glances dropped significantly during NDRTs compared to manual and assisted mode. For instance, the median PRC during NDRTs in AD mode was only at 4–7% in baseline. Similarly, Klingegård et al. (2020) found that PRC was on average at 20% during visually demanding NDRTs during AD mode in real traffic. Many participants also reported that they could disconnect from the driving task with ease.

In the present study, the effect of AD mode on glance behavior was even more pronounced during the intoxicated drive. Half of the more demanding tasks (i.e., radio, dialing) were performed using a single off-path glance (i.e., PRC = 0 %; GF-off = 1), in contrast to at least two glances being used for completing these tasks during the baseline drive.

The TGT needed to complete the NDRTs did not reveal any statistically significant differences across driving modes. Participants used fewer and longer glances in AD mode which could potentially make the tasks easier and faster to complete. On the other hand, AD mode does not create the same sense of urgency to look back at the road as in manual or assisted mode. Overall, TGT does not seem to be sensitive to driving mode when investigating specific tasks, but it could be a more revealing metric when analyzing all visual time-sharing segments in naturalistic driving.

The shift in off-path glance distribution is moderate when comparing assisted to manual mode (as illustrated in Fig. 3). A similar moderate shift in glance distribution for assisted mode has also been found in naturalistic driving studies (Morando et al., 2020; Noble et al., 2019) and on the test track (Llaneras et al., 2013). This highlights that the effect of assisted mode on visual behavior is quite small in comparison to the effect of intoxication at the level of BAC 0.1%. The very large shift in glance distributions toward long glances in AD mode in the present study has also been observed in AD mode on public roads (Klingegård et al., 2020; Pipkorn et al., 2022) who also reported a high percentage of off-path glances longer than 2 s.

4.4. Overall implications of results for a broader impairment detecting strategy

The introduction of DMS in production vehicles offers the opportunity to identify when eye and head movements deviate from normal attentive driving, and thus creates a potential for detecting visual behavior effects that stem from diverse types of impairment (e.g., alcohol and drugs, sudden sickness, severe sleepiness, mind off driving).

The present findings suggest that extreme off-path glance durations and gaze concentration metrics may be useful to distinguish severe alcohol intoxication from sober driving in assisted and manual driving. They are less helpful in AD mode, though, since drivers may look away from the road for extended periods of time.

These metrics also seem sensitive to other types of impairment, such as visual and cognitive distraction or mind wandering. This supports the idea of a more general, DMS-based, impairment detection system where the selected metrics aim to identify driving epochs where the visual behavior deviates from normal safe driving. Different thresholds for these metrics could potentially indicate the severity of the impairment and consequently which type of intervention would be reasonable given the current situation.

Given that BAC influences visual behavior metrics depending on the context (such as whether the driver is performing a NDRT or not), glance-based metrics need to be combined with additional sources of information. For instance, other vehicle signals that can illuminate the driving context (e.g., driver steering input, infotainment use, or passenger interactions) could improve impairment detection performance. Furthermore, using active probing by issuing requests or reminders and evaluating the drivers' visual and operational response to these, may provide additional information on whether the driver is able to drive safely.

The present study specifically analyzed changes in visual behavior due to BAC under very controlled circumstances, i.e., during uneventful driving on a test track. Additional experimental and naturalistic driving studies that include different driving contexts, specific types of driver impairments, along with analysis of what normal, safe driving looks like, will be needed to provide a more solid basis for a more general driver impairment detection algorithm. Also, certain metrics are especially important for specific types of impairment (e.g., long eye closures indicate severe sleepiness) and need particular attention to reliably detect specific driver states.

4.5. Future work and limitations

This study should be considered as an initial exploratory study to investigate if visual behavior metrics are promising candidates for detecting alcohol intoxication. In total, there were twenty-six participants with valid glance data, resulting in between eight and ten participants per group assigned to different driving modes, and consequently the small sample size should be considered when interpreting the results. Also, the present study was performed on a rural road test track without the presence of other vehicles, with speeds restricted to 50 km/h. This simplifies the driving task, and hence may be less than optimal to capture differences between sober and intoxicated driving.

Further, a test leader was present in all drives, and a safety driver was present in all drives except the manual and assisted baseline drives. Thus, the influence of alcohol in manual and assisted mode may be a combined effect of both alcohol intoxication and the presence of a safety driver. However, there was no observed difference in PRC as a function of a safety driver presence in segment S1 (all in manual mode, no tasks) during the baseline drive. This observation suggests that the influence of the safety driver is small.

Finally, all participants performed the two drives (baseline and intoxicated) on the same day, which might have introduced learning effects with respect to both driving and the NDRTs. Since the observed effect of alcohol on glance behavior (longer single and total off-path glance duration, and fewer glances) points in the opposite direction of any learning effects, it is possible that the observed effects of alcohol were underestimated. However, since the driving demand was low, and the participants got to practice the NDRTs before the baseline drive, we estimated that the learning effect would be small in comparison to the effect of BAC 0.1%.

A driver that is attentive, sober, and alert has surprisingly stable behavior with eyes on path that naturally fluctuates around a PRC of 80 % within certain boundaries during naturalistic driving (Morando et al., 2019; Victor et al., 2005). As the current results suggest (along with numerous other studies), deviations from this normal visual behavior potentially indicate a variety of impaired driver states including alcohol intoxication, overreliance in assisted driving as well as cognitive or visual distraction, and can be captured using simple gaze behavior metrics. Future work should thus include continuously recorded DMS data to understand sensor capabilities and precision when it comes to capturing deviations from normal visual behavior using these simpler metrics.

However, since technology sometimes takes larger leaps in performance, it is also important to study more advanced visual behavior metrics that could be accessible in future vehicles. These types of metrics include characteristics of fixations, saccades, pupil dilations, smooth pursuit eye movements and gaze dispersion, all of which may be altered by the influence of alcohol (Maurage et al., 2020; Moskowitz & Robinson, 1988; Shiferaw et al., 2019). For instance, the standardized field sobriety tests include screening for impaired smooth pursuit eye movements (i.e., nystagmus) as an indication of drivers being influenced by alcohol or drugs (Stuster, 2006).

5. Conclusions

This study investigated the effect of BAC and driving mode (manual, assisted, AD) on drivers' glance behavior when just driving as well as when performing visually demanding NDRTs. The results show that drivers' glance behavior is sensitive to BAC, visually demanding NDRTs, and driving mode. It is thus highly recommended to further investigate glance behavior metrics as key indicators of intoxication and other types of severe impairment in a general DMS-based impairment detection approach.

However, the results also show that the change induced by intoxication in visual behavior metrics is strongly coupled to context. For example, the intoxication effects on PRC go in opposite directions depending on whether the driver is engaged in a NDRT or not. Keeping track of the context thus becomes a prerequisite to being able to interpret what changes in metrics mean. Ways to combine the visual behavior metrics with other vehicle data metrics such as driving performance measures and drivers' visual and operational response to system feedback (e.g., attention reminders, warnings, or take-over requests in AD mode) should therefore be explored. Also, while the gaze metrics studied here are simple, future DMS may include capabilities to evaluate more advanced eye metrics including the precision of smooth pursuit, saccades, and gaze dispersion. Studies of these more advanced metrics thus also needs to be pursued if one wants to be prepared for using the new enhanced technology once ready for deployment.

CRediT authorship contribution statement

Emma Tivesten: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Viktor Broo:** Methodology, Writing – original draft, Data curation. **Mikael Ljung Aust:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table A1
Test statistics for Wilcoxon signed rank test comparing the baseline (BL) and intoxicated (IN) drives for segment S1-S4. Kruskal-Wallis test comparing Manual, Assisted, and AD mode for each drive. Only statistically significant p-values reported, including post-hoc results at the 0.05(*), or 0.01(**) level after adjusting for multiple testing.

Metric	Mode		Drive			Effect of intoxication			Effect of Mode (BL)						Effect of Mode (IN)					
			n	BL Mdn	IN Mdn	Z	p	r	H (2)	E_R^2	p	M AD	M A	A AD	H (2)	E_R^2	p	M AD	M A	A AD
PRC	S1	M	26	73	84	-2.93	.002	-.41												
[%]	S2	M	9	32	25	-2.07	-	-.49	13.1	.55	.001	**	-	*	15.4	.64	<.001	**	-	**
		A	8	26	19	-2.10	-	-.53												
		AD	8	7	0	-2.52	.008	-.63												
	S3	M	9	37	29	-1.36	-	-.32	15.7	.65	<.001	**	-	**	17.5	.73	<.001	**	-	**
		A	8	30	23	-1.40	-	-.35												
		AD	8	7	2	-2.52	.008	-.63												
	S4	M	9	30	25	-0.30	-	-.07	11.7	.49	.003	**	-	*	13.8	.57	.001	**	-	-
		A	8	17	17	-0.70	-	-.18												
		AD	8	4	0	-0.07	-	-.02												
GF-off	S1	M	26	9.5	4.0	-3.95	<.0001	-.55												
[N]	S2	M	9	13.0	12.0	-0.71	-	-.17	7.4	.31	.025	*	-	-	16.1	.67	<.001	**	-	**
		A	8	10.0	9.0	-1.26	-	-.32												
		AD	8	4.0	1.0	-1.96	.016	-.49												
	S3	M	9	15.0	11.0	-1.24	-	-.29	15.2	.63	<.001	**	-	**	15.0	.63	.001	**	-	**
		A	8	11.5	7.5	-1.40	-	-.35												
		AD	8	4.5	2.0	-1.96	.016	-.49												
	S4	M	9	6.0	5.0	-0.47	-	-.11	12.8	.53	.002	**	-	**	11.9	.49	.003	**	-	*
		A	8	6.0	5.0	-0.49	-	-.12												
		AD	8	1.5	1.0	-0.28	-	-.07												
TGT	S2	M	9	15.1	20.6	-2.67	.004	-.63	1.8	.08	-	-	-	-	.1	.00	-	-	-	-
[s]		A	8	13.9	22.7	-2.38	.016	-.60												
		AD	8	17.4	20.5	-2.10	-	-.53												
	S3	M	9	15.5	19.3	-2.31	.020	-.54	6.9	.29	-	-	-	-	4.3	.18	-	-	-	-
		A	8	17.2	18.9	-1.68	-	-.42												
		AD	8	18.2	25.7	-2.52	.008	-.63												
	S4	M	9	7.3	7.0	-1.48	-	-.35	.6	.03	-	-	-	-	4.2	.17	-	-	-	-
		A	8	7.4	10.4	-1.54	-	-.39												
		AD	8	7.6	9.4	-1.26	-	-.32												
MaxGD	S2	M	9	1.7	3.4	-2.67	.004	-.63	15.6	.65	<.001	**	-	**	13.8	.58	.001	**	-	**
[s]		A	8	2.1	4.2	-2.52	.008	-.63												
		AD	8	6.6	20.5	-2.52	.008	-.63												
	S3	M	9	2.0	3.3	-2.67	.004	-.63	15.8	.66	<.001	**	-	**	15.6	.65	<.001	**	-	**
		A	8	2.1	3.9	-2.38	.016	-.60												
		AD	8	9.7	19.3	-2.52	.008	-.63												
	S4	M	9	2.1	2.4	-1.95	-	-.46	12.2	.51	.002	**	-	*	11.6	.48	.003	*	-	*
		A	8	2.3	4.0	-2.52	.008	-.63												
		AD	8	6.5	8.7	-1.54	-	-.39												
GD>2s	S2	M	9	0	33	-2.67	.004	-.63	12.6	.53	.002	**	-	*	13.6	.57	.001	**	-	**
[%]		A	8	5	51	-2.38	.016	-.60												
		AD	8	50	100	-2.52	.008	-.63												
	S3	M	9	0	43	-2.67	.004	-.63	13.6	.57	.001	**	-	-	13.5	.56	.001	**	-	**
		A	8	7	40	-2.10	-	-.53												
		AD	8	50	100	-1.89	-	-.47												
	S4	M	9	8	25	-0.83	-	-.20	12.0	.50	.003	**	-	*	9.7	.40	.008	*	-	-
		A	8	23	53	-1.96	.016	-.49												
		AD	8	100	100	-0.07	-	-.02												

Data availability

The authors do not have permission to share data.

Acknowledgments

The authors would like to thank Regina Johansson, Elin Meltzer, Katerina Pistola, Joel Johansson, and Emma Kroon for preparing and performing data collection and video annotations. We would also like to thank Thomas Streubel for a first review on this manuscript, and Torrin Raoufi-Danner and Emma Nilsson for reviewing the revised version. We are also grateful for the work and valuable comments provided by the TRF reviewers that helped us improve this paper. This research was supported by the European Project L3Pilot, grant number 72305.

Appendix A

See Table A1.

References

Ahlström, C., Zemblys, R., Finér, S., & Kircher, K. (2023). Alcohol impairs driver attention and prevents compensatory strategies. *Accident Analysis and Prevention, 184*. https://doi.org/10.1016/j.aap.2023.107010

Åkerstedt, T., & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *The International Journal of Neuroscience, 52*(1–2), 29–37. https://doi.org/10.3109/00207459008994241

AstaZero. (2023). *AstaZero Rural Road*. https://www.astazero.com/en/tracks-facilities/rural-road/.

Bärgman, J., Nes, N. van, Christoph, M., Jansen, R., Veerle Heijne, Carsten, O., Dotzauer, M., Utech, F., Erik Svanberg, Cocron, M. P., Forcolin, F., & Jordanka Kovaceva. (2017). *the UDrive dataset and key analysis results*. 10.26323/UDRIVE.

Belt, B. (1969). *Driver eye movements as a function of low blood alcohol concentrations. Technical report*.

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological), 57*(1), 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Blomberg, R. D., Peck, R. C., Moskowitz, H., Burns, M., & Fiorentino, D. (2009). The Long Beach/Fort Lauderdale relative risk study. *Journal of Safety Research, 40*(4), 285–292. https://doi.org/10.1016/j.jsr.2009.07.002

Ferguson, S. A. (2012). Alcohol-Impaired Driving in the United States: Contributors to the Problem and Effective Countermeasures. *Traffic Injury Prevention, 13*(5), 427–441. https://doi.org/10.1080/15389588.2012.656858

Garrisson, H., Scholey, A., Ogden, E., & Benson, S. (2021). The effects of alcohol intoxication on cognitive functions critical for driving: A systematic review. *Accident Analysis and Prevention, 154*(December 2020), Article 106052. https://doi.org/10.1016/j.aap.2021.106052

Harrison, E. L. R., & Fillmore, M. T. (2011). Alcohol and distraction interact to impair driving performance. *Drug and Alcohol Dependence, 117*(1), 31–37. https://doi.org/10.1016/j.drugalcdep.2011.01.002

Hayley, A. C., Shiferaw, B., Aitken, B., Vinckenbosch, F., Brown, T. L., & Downey, L. A. (2021). Driver monitoring systems (DMS): The future of impaired driving management? *Traffic Injury Prevention, 22*(4), 313–317. https://doi.org/10.1080/15389588.2021.1899164

Horrey, W. J., & Wickens, C. D. (2007). In-vehicle glance duration: Distributions, tails and a model of crash risk. *Transportation Research Record: Journal of the Transportation Research Board, 2018*(1), 22–28. https://doi.org/10.3141/2018-04

Irwin, C., Iudakhina, E., Desbrow, B., & McCartney, D. (2017). Effects of acute alcohol consumption on measures of simulated driving: A systematic review and meta-analysis. *Accident Analysis and Prevention, 102*, 248–266. https://doi.org/10.1016/j.aap.2017.03.001

Irwin, C., Monement, S., & Desbrow, B. (2015). The Influence of Drinking, Texting, and Eating on Simulated Driving Performance. *Traffic Injury Prevention, 16*(2), 116–123. https://doi.org/10.1080/15389588.2014.920953

ISO. (2020). *ISO 15007:2020(en) Road vehicles — Measurement and analysis of driver visual behaviour with respect to transport information and control systems*. https://www.iso.org/obp/ui/#iso:std:iso:15007:ed-1:v1:en.

Jongen, S., Vuurman, E. F. P. M., Ramaekers, J. G., & Vermeeren, A. (2016). The sensitivity of laboratory tests assessing driving related skills to dose-related impairment of alcohol: A literature review. *Accident Analysis and Prevention, 89*, 31–48. https://doi.org/10.1016/j.aap.2016.01.001

Klauer, S. G., Klauer, S. G., Dingus, T. A., Dingus, T. A., Neale, V. L., Neale, V. L., Sudweeks, J. D., Sudweeks, J. D., Ramsey, D. J., & Ramsey, D. J. (2006). *The Impact of Driver Inattention On Near Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data, Report DOT HS 810594* (Issue April).

Klingegård, M., Andersson, J., Habibovic, A., Nilsson, E., & Rydstrom, A. (2020). Drivers' ability to engage in a non-driving related task while in automated driving mode in real traffic. *IEEE Access, 8*. https://doi.org/10.1109/ACCESS.2020.3043428

Lee, J. D., Fiorentino, D., Reyes, M. L., Brown, T. L., Ahmad, O., Fell, J., Ward, N., & Dufour, R. (2010). *Assessing the feasibility of vehicle-based sensors to detect alcohol impairment (Report No. DOT HS 811 358)* (Issue August).

Lee, J. D., Moeckli, J., Brown, T. L., Roberts, S. C., Schwarz, C., Yekhshatyan, L., Nadler, E., Liang, Y. L., Victor, T., Marshall, D. C., & Davis, C. (2013). *Distraction Detection and Mitigation Through Driver Feedback* (Issue May). *DOT HS, 811*, 547A.

Lenné, M. G., Roady, T., & Kuo, J. (2020). Chapter 11. Driver State Monitoring for Decreased Fitness to drive. In D. L. Fisher, J. Horrey, J. D. Lee, & M. A. Regan (Eds.), *Handbook of Human Factors for Automated, Connected, and Intelligent Vehicles*.

Liang, Y., Lee, J. D., & Horrey, W. J. (2014). A looming crisis: The distribution of off-road glance duration in moments leading up to crashes/near-crashes in naturalistic driving. *Proceedings of the Human Factors and Ergonomics Society*, 2102–2106. https://doi.org/10.1177/1541931214581442

Llaneras, R. E., Salinger, J., & Green, C. A. (2013). *Human Factors Issues Associated with Limited Ability Autonomous Driving Systems: Drivers' Allocation of Visual Attention to the Forward Roadway*. 92–98. 10.17077/drivingassessment.1472.

Lukas, S. E., Zaouk, A., Ryan, E., McNeil, J., Shepherd, J., Willis, M., Dalal, N., & Schwartz, K. (2017). Driver alcohol detection system for safety (DAFSS) – Preliminary human testing results. *Proceedings of the 25th International Technical Conference on the Enhanced Safety of Vehicles*, *1*, 1–11.

Martin, T. L., Solbeck, P. A. M., Mayers, D. J., Langille, R. M., Buczek, Y., & Pelletier, M. R. (2013). A review of alcohol-impaired driving: The role of blood alcohol concentration and complexity of the driving task. *Journal of Forensic Sciences, 58*(5), 1238–1250. https://doi.org/10.1111/1556-4029.12227

Maurage, P., Masson, N., Bollen, Z., & D'Hondt, F. (2020). Eye tracking correlates of acute alcohol consumption: A systematic and critical review. In *Neuroscience and Biobehavioral Reviews* (Vol. 108, pp. 400–422). Elsevier Ltd.. https://doi.org/10.1016/j.neubiorev.2019.10.001

Morando, A., Victor, T., & Dozza, M. (2019). A Reference Model for Driver Attention in Automation: Glance Behavior Changes During Lateral and Longitudinal Assistance. *IEEE Transactions on Intelligent Transportation Systems, 20*(8), 2999–3009. https://doi.org/10.1109/TITS.2018.2870909

Morando, A., Victor, T., & Dozza, M. (2020). A Bayesian Reference Model for Visual Time-Sharing Behaviour in Manual and Automated Naturalistic Driving. *IEEE Transactions on Intelligent Transportation Systems, 21*(2), 803–814. https://doi.org/10.1109/TITS.2019.2900436

Moskowitz, H., & Fiorentino, D. (2000). *A Review of the Literature on the Effects of Low Doses of Alcohol (Report no. DOT HS 809 028)* (Issue January 2000). www.nhtsa.doi.gov.

Moskowitz, H., & Robinson, C. (1988). *Effects of low doses of alcohol on driving-related skills: a review of the evidence, National Highway Traffic Safety Administration, Report No.: DOT HS 807 280*. https://rosap.ntl.bts.gov/view/dot/1461.

Moskowitz, H., & Ziedman, K. (1979). Eye Movements and Skills Performance Measures under Alcohol in a Driving Simulator. *Proceedings of the Human Factors Society Annual Meeting, 23*(1), 389–393. https://doi.org/10.1177/107118137902300198

NHTSA. (2013). *Visual-Manual NHTSA Driver Distraction Guidelines for In-Vehicle Electronic Devices*. https://www.govinfo.gov/content/pkg/FR-2013-04-26/pdf/2013-09883.pdf.

NHTSA. (2017). *Alcohol Impaired Driving. Traffic safety facts report DOT HS 812450*. 10.32964/tj16.10.

NIAAA. (2020). *What Is A Standard Drink?* https://www.niaaa.nih.gov/alcohols-effects-health/overview-alcohol-consumption/what-standard-drink.

Noble, A. M., Klauer, S. G., Doerzaph, Z. R., & Manser, M. P. (2019). Driver Training for Automated Vehicle Technology – Knowledge, Behaviors, and Perceived Familiarity. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 63*(1), 2110–2114. https://doi.org/10.1177/1071181319631249

Pipkorn, L., Dozza, M., & Tivesten, E. (2022). Driver visual attention before and after take-over requests in automated driving on public roads. *Human Factors*.

Rakauskas, M. E., Ward, N. J., Boer, E. R., Bernat, E. M., Cadwallader, M., & Patrick, C. J. (2008). Combined effects of alcohol and distraction on driving performance. *Accident Analysis and Prevention, 40*(5), 1742–1749. https://doi.org/10.1016/j.aap.2008.06.009

SAE. (2021). *SAE J3016, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. https://www.sae.org/standards/content/j3016_202104/.

Shiferaw, B. A., Crewther, D. P., & Downey, L. A. (2019). Gaze entropy measures detect alcohol-induced driver impairment. *Drug and Alcohol Dependence, 204* (August), Article 107519. https://doi.org/10.1016/j.drugalcdep.2019.06.021

SNRA. (2020). *Fakta om alkohol och narkotika i trafiken*. https://www.trafikverket.se/resa-och-trafik/trafiksakerhet/Din-sakerhet-pa-vagen/Rattfylleri/fakta-om-alkohol-och-narkotika-i-trafiken/.

Stuster, J. (2006). Validation of the standardized field sobriety test battery at 0.08% blood alcohol concentration. *Human Factors, 48*(3), 608–614. https://doi.org/10.1518/001872006778606895

Tivesten, E., Victor, T. W., Gustavsson, P., Johansson, J., & Aust, M. L. (2019). Out-of-the-loop crash prediction: The automation expectation mismatch (AEM) algorithm. *IET Intelligent Transport Systems, 13*(8), 1231–1240. https://doi.org/10.1049/iet-its.2018.5555

Tomczak, M., & Tomczak, E. (2014). The need to report effect size estimates revisited. An overview of some recommended measures of effect size. *Trends in Sport Sciences*, *1*(21), 19–25. http://www.wbc.poznan.pl/Content/325867/5_Trends_Vol21_2014_no1_20.pdf.

Valen, A., Bogstrand, S. T., Vindenes, V., Frost, J., Larsson, M., Holtan, A., & Gjerde, H. (2019). Driver-related risk factors of fatal road traffic crashes associated with alcohol or drug impairment. *Accident Analysis and Prevention, 131*(0424), 191–199. https://doi.org/10.1016/j.aap.2019.06.014

van Dijken, J. H., Veldstra, J. L., van de Loo, A. J. A. E., Verster, J. C., van der Sluiszen, N. N. J. J. M., Vermeeren, A., Ramaekers, J. G., Brookhuis, K. A., & de Waard, D. (2020). The influence of alcohol (0.5‰) on the control and manoeuvring level of driving behaviour, finding measures to assess driving impairment: A simulator study. *Transportation Research Part F: Traffic Psychology and Behaviour, 73*, 119–127. https://doi.org/10.1016/j.trf.2020.06.017

Van Dyke, N. A., & Fillmore, M. T. (2015). Distraction produces over-additive increases in the degree to which alcohol impairs driving performance. *Psychopharmacology, 232*(23), 4277–4284. https://doi.org/10.1007/s00213-015-4055-2.Distraction

Victor, T., Dozza, M., Bärgman, J., Boda, C.-N., Engström, J., Flannagan, C., Lee, J. D., & Markkula, G. (2015). Analysis of Naturalistic Driving Study Data: Safer Glances, Driver Inattention, and Crash Risk. In *Analysis of Naturalistic Driving Study Data: Safer Glances, Driver Inattention, and Crash Risk*. 10.17226/22297.

Victor, T., Harbluk, J. L., & Engström, J. A. (2005). Sensitivity of eye-movement measures to in-vehicle task difficulty. *Transportation Research Part F: Traffic Psychology and Behaviour, 8*(2 SPEC. ISS.), 167–190. https://doi.org/10.1016/j.trf.2005.04.014

Victor, T., & Larsson, P. (2004). *Method and arrangement for interpreting a subjects head and eye activity* (Patent No. International publication number PCT WO 2004/034905 A1). https://patents.justia.com/patent/7460940.

World Health Organization. (2018). *GLOBAL STATUS REPORT ON ROAD SAFETY 2018*. https://www.who.int/publications/i/item/9789241565684.

Yadav, A. K., & Velaga, N. R. (2019). Modelling the relationship between different Blood Alcohol Concentrations and reaction time of young and mature drivers. *Transportation Research Part F: Traffic Psychology and Behaviour, 64*, 227–245. https://doi.org/10.1016/j.trf.2019.05.011

Yadav, A. K., & Velaga, N. R. (2021). A comprehensive systematic review of the laboratory-based research investigating the influence of alcohol on driving behaviour. *Transportation Research Part F: Traffic Psychology and Behaviour, 81*, 557–585.

Zaouk, A. K., Willis, M., Traube, E., & Strassburger, R. (2019). Driver Alcohol Detection System for Safety (DADSS)–a Non-Regulatory Approach in the Research and Development of Vehicle Safety Technology to Reduce Alcohol-Impaired Driving–A Status Update. *26th International Technical Conference on the Enhanced Safety of Vehicles (ESV): Technology: Enabling a Safer TomorrowNational Highway Traffic Safety Administration, 19–0260*.