Validating a novel set of driving scenarios and measures for assessing driving skill and style:

A high-fidelity driving simulator study

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Koen Martijn Verschoor
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Work outline

This work presents the development and evaluation of the high-fidelity driving simulator study I conducted at the Porsche Research and Development Facility in Weissach, Germany. The entire study consisted of two separate experiments investigating manual and automated driving behavior. This work will focus on the first topic. In total, three manual driving scenarios were developed to assess different aspects of manual driving. The participant selection was the same for the manual and automated driving experiments, allowing future work to investigate how strong manual driving behavior correlates with automated driving behavior. More details regarding the automated driving experiments are covered in the appendices.

Abstract

Although the capabilities of automated driving systems (ADS) are growing, the human operator remains in charge of driving the vehicle outside the operational design domain and after requests to intervene. The vehicle sensors required for ADS and new regulation for driver availability monitoring systems stimulate the development of systems that can monitor human driving ability. Such systems could allow for ADS to track possible driving skill degradation, monitor driver impairment, or adapt to the driver's needs. However, knowledge is required about how to assess human driving ability effectively.

This work proposes a novel method to capture driving skill and style based on curve driving, straight-road driving, and driving through road narrowings. In addition to conventional measures, the study introduces new measures, including the relationship between steering angle and eye movements. Employing a high-fidelity simulator, we compared the vehicle-control-related measures (i.e., driving skill measures), trajectory-planning and speed-related measures (i.e., driving style measures), and eye movements of sixteen inexperienced and thirteen experienced drivers. It was examined which of these measures are valid, i.e., allow a statistical discrimination between experienced and inexperienced drivers. The study was complemented with two expert drivers serving as a benchmark.

The results showed that the experienced drivers adopted a more abrupt braking style when approaching curves and a higher speed through the different track sections than the inexperienced drivers. No statistically significant differences were observed between the skill measures of the experienced and inexperienced drivers. An analysis of lead times obtained through a cross-correlation between horizontal gaze angle and steering angle showed that eye movements generally preceded steering movements. However, differences in lead times between experienced and inexperienced drivers were not statistically significant, which may have been caused by eye-tracking measurement inaccuracies, the layout of the driving task and strong intra-individual variability in looking behavior. The eye-tracking results of the road-narrowings showed that the experienced and inexperienced drivers reduced their vertical gaze dispersion, while only the experienced drivers statistically significantly reduced their horizontal gaze dispersion compared to the straights. In other words, the experienced drivers showed increased horizontal gaze tunneling from the straights to the narrowings, while the inexperienced drivers only showed vertical gaze tunneling. The results of the expert drivers showed consistent higher speed, lower control activity, and more of a racing line through the curves than the experienced and inexperienced drivers. Furthermore, the results showed that the expert drivers adopted a more variable horizontal gaze strategy between different curves.

Overall, these results indicate that driving style and eye-movement measures, but not driving skill measures, allow differentiating between experienced and inexperienced drivers using a driving simulator. These findings may be explained by the fact that driving is a self-paced task, i.e., more competent drivers increase their own task demands by driving faster. Future research could examine how strongly scores the present driving and eye-movement measures correlate with drivers' take-over quality in automated driving scenarios.

Nomenclature

Acronym	Description
ADAS	Advanced driver assistance systems
ADS	Automated driving systems
LP	Lateral position
SD	standard deviation
SDLP	Standard deviation lateral position
MISC	Misery Score
AS error	Anticipatory steering error
DOF	degrees of freedom

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1 Introduction

Throughout the last years, automated driving has become a major topic in the automotive industry. However, current automated driving systems (ADS) belonging to SAE L3 and L4 [7] offer a limited operation design domain (ODD), meaning the driver is still frequently required to operate the vehicle manually. For these ADS, drivers rely on manual operation outside the ODD, during voluntary manual control inside the ODD or, for conditional automated vehicles (SAE L3 [7]), during forced interventions which can occur due to malfunctioning or when approaching the ODD boundary.

The growing applicability of ADS raises the concern of skill degradation [8, 9]. At the same time, paradoxically, drivers are expected to be confronted with challenging circumstances when the automation fails [10]. In order to guarantee safe vehicle operation during manual driving or forced interventions, drivers need to retain their driving skill [10] and cognitive abilities (e.g. [8, 11]). An in-vehicle driving ability assessment system could enable ADS to track possible driving skill degradation, account for it, or even restrict voluntary manual operation for certain circumstances. Moreover, such an assessment may prove valuable in developing ADS that can adjust to the driver's preferences or attend a driver to their impairments. The vehicle sensors required for automated driving and new (EU) regulation for driver availability monitoring systems [12] support developing such tools. Yet, an accurate driving skill assessment is required.

When assessing manual driving, usually, the distinction is made between driving style and driving skill [13]. Driving style is frequently referred to as the way drivers choose to drive, e.g., driving speed. Driving skill reflects a person's driving capabilities, e.g., vehicle manoeuvring control. This dichotomy between driving skill-style resembles the division between driving performance and driving behavior, lower-order and higher-order driving skills, and errors and violations [13–18]. There is a bidirectional interplay between the higher- and lower-order driving skill components, i.e. driving style and skill [16, 19]. It is considered that the performance at higher-order skill components, i.e., motives, attitude, personal traits and lifestyle, affects the demand of the lower-order skills. However, studies have shown that improvements at the lower-order skill components can also result in skill overestimation, causing drivers to adapt their operational strategy [19, 20]. Thus, safe vehicle operation depends on both driving skill and style.

As for many human-performed tasks, including driving, experience yields skill. As drivers become more skilled, more conscious activities become unconscious [21], which translates to driving tasks shifting from rule- or knowledge-based behavior to skill-based behavior according to Rasmussen's information-processing taxonomy [22–24]. As a result, cognitive resources become available [25]. Likewise, the over-representation of novice drivers in road traffic crashes declines as they gain experience [26, 27]. An opposite effect occurs with ageing, which is typically accompanied by impairments and decline in perception [28], cognitive functions [29, 30] and motor abilities [31], all relevant for safe vehicle operation [32]. Investigating crash and driver fatality rates, corrected for the travelled distance, show an increased representation of elderly drivers [32–34].

An important element of the driving task is curve driving, which requires a driver's driving skill for vehicle control and trajectory planning skills, i.e. the selected driving style, for the choice of path and speed.

A large amount of literature has been devoted to the relation between eye movements and steering control for (curve) driving. Land et al. [35] stated that drivers predominantly direct their gaze towards the tangent point while driving curves. The tangent point is a (non-stationary) point on a curve where the driver's line of sight is tangential to the inner edge of the road [36]. The second main steering model postulates that the gaze is directed towards the future path that the driver is intended to take [37, 38]. Research has shown that the driver's gaze leads the steering inputs by approximately one to two seconds [35, 39]. Moreover, this gaze behavior is sometimes interrupted by anticipatory look-ahead fixations at a curve many seconds before entering it [40].

Work of Lehtonen et al. [41] found that experienced drivers spend a larger fraction of their gaze on anticipatory look-ahead fixations over curves and less on the road-ahead compared to inexperienced drivers. Furthermore, experienced drivers were found to be more capable of effectively adjusting their visual search strategy to the environmental conditions [42, 43] and rely less on their foveal vision for vehicle control than inexperienced drivers [44]. Research has also shown that experienced drivers concentrate their gaze further ahead of the vehicle than inexperienced drivers [45]. Lastly, research has shown that expert drivers, on an on-track environment, have a horizontal offset from their tangent point, which changes for different curves [36], and that this variable gaze behavior is not found for non-expert drivers [46].

1.1. Research gap

Currently, many different methods are used to assess manual driving. These methods include on-road assessments in real traffic or on a closed-circuit, driving assessments in a simulator environment, cognitive evaluations or self-evaluations [47, 48]. Most on-road and simulator driving assessments are restricted to extracting driving skill (e.g. [20, 49–51]) or driving style (e.g. [52–54]), lacking to obtain their interaction and relation with eye movements. In order to obtain a complete image of the driver's driving abilities, it is argued that all these components should be included when assessing manual driving. Furthermore, to serve future ADS developments, a validation step is required to determine which measures allow to effectively differentiate between different skilled drivers.

1.2. study aim and approach

In summary, an accurate driving ability assessment is required to enable the integration of the drivers' driving characteristics into future ADS. Accordingly, knowledge is needed about how to assess human driving ability effectively.

This study proposes a novel method specially designed to capture driving skill, driving style and eye movements. A high-fidelity driving simulator experiment was conducted to investigate the effectiveness of the proposed driving scenario and measures to differentiate between different skilled drivers. This was done by comparing the performance and behavior of experienced and inexperienced drivers. The study was complemented with two expert drivers serving as a benchmark. The proposed method uses curve driving [1], straight-road driving and driving through road-narrowings [55] to capture a wide variety of measures. In addition to more conventional measures, the study introduced new measures, such as track-out distance, track-out lateral position, steering integral curve recovery and the relationship between steering angle and eye movements. The wide selection of measures also allowed to gain insights into the interaction between skill-style and supportive eye movements. All redundant measures were removed from the analysis.

The driving skill measures of this study were selected to capture the lower-order driving skill components, also referred to as the operational-level/vehicle-control-level of the driving task according to Michon's behavioral taxonomy [56]. The driving skill measures consisted of measures capturing control activity and control precision. The driving style measures were designed to capture trajectory planning skills (choice of path and speed [41]) and speed-related measures. Although eye movements are closely related to driving skill and driving style, they were considered separately in this study.

This study also explores if the correlation between the horizontal gaze and steering input, i.e. lead times, could potentially be used to differentiate between different skilled drivers. Based on Lehtonen et al. [41] and Mourant et al. [45], it is expected that the more capable drivers would adopt a higher lead time because they are more invested in trajectory planning and therefore looking further ahead than less skilled drivers. Thus, it was anticipated to find a higher lead time for experienced drivers than inexperienced drivers.

The road-narrowings, based on the work of Melman et al. [55], were intended to induce mental workload to the driver [57, 58]. Research has shown that cognitive load can cause gaze tunneling (e.g. [59, 60]). Based on Crundall et al. [61], it is expected that the induced stress/mental workload from the narrowing would cause more visual gaze tunneling for the inexperienced than the experienced drivers, thereby allowing to differentiate between the experienced and inexperienced drivers.

2
Method

2.1. Participants

Thirty-eight Porsche AG employees were recruited to participate in this study. All participants were in possession of a valid driving licence and had normal or corrected-to-normal vision. A total of 7 participants had to be excluded from the data recordings due to incompleteness of the recording, motion sickness or malfunctioning equipment, leaving 31 participants for the analysis. To accompany for ageing effects, an age limit of 40 years was introduced. The sample included three groups, consisting of: (1) inexperienced, (2) experienced, and (3) expert drivers. For this study, the inexperienced group were required to held their first driving licence less than three years (similarly to the work of Underwood [43]). The experienced group were required to held their first driving licence for more than seven years and needed to have driven at least 10.000 km last year. When extrapolation the yearly mileage over these seven years, it is expected that the criteria of 70.000 km accumulated life-time mileage as stated by Lajunen et al. [62] for experienced drivers is matched. Table 2.1 shows an overview of the participant data. The expert drivers group consists of one professional test driver and one ex-professional racing driver. The research was approved by the ethics committee of Porsche AG (see Appendix J), and all participants provided written informed consent.

Table 2.1: Demographic and driving experience data.

	Experimental group			
	Inexperienced	Experienced	Expert	Total
Age (<21 / 21-30 / 31-40)	16 / 0 / 0	0 / 6 / 7	0 / 0 /2	16 / 6 / 9
Gender (male / females)	9 / 7	8 / 5	2 / 0	19 / 12
Driver's license possession in years (<5 / 5-10 / 11-20 / 21-40)	16 / 0 / 0 / 0	0 / 2 / 10 / 1	0 / 0 / 2 / 0	16 / 2 / 12 /1
Prior experience with driving simulator studies (# part.)	0	3	1	4
Driving frequency (daily / 4-6* / 1-3* / 1-4* /<1 a month)	6 / 5 / 3 / 2	10 / 3 / 0 / 0	2 / 0 / 0 / 0	18 / 8 / 3 / 2
Last year's driven mileage in kilometres (1-1000 / 1001-5000 / …	1 / 5 /	0 / 0 /	0 / 0 /	1 / 5 /
5001-10,000 / 10,001-20,000 / 20,001-50,000)	4 / 4 / 2 / 0	0 / 6 / 7 / 0	0 / 0 / 1 / 1	4 / 10 / 10 / 1

(*): per week.

2.2. Apparatus

The study was conducted in the high-fidelity hexapod driving simulator at the Porsche Research and Development Facility in Weissach, Germany [63–66]. The 6-DOF moving base platform (eMove eM6-640-1800) was fitted with a fully functional mock-up of a Porsche Boxter interior (for more details, review Appendix L). The platform has an actuator stroke of 640 mm and the motion cueing was according to a classical washout algorithm. The vehicle dynamics software was based on the all-electric Porsche Taycan Turbo (for more details, review Appendix M). The simulator data was logged at 10 Hz.

A 180 deg testing environment was achieved by projectors displaying 3840 × 2160 pixels on all three sides. The visualization was refreshed at a frequency of 60 Hz. Only the left mirror was functional and integrated in the projected image. Surrounding speakers generated realistic wind, tire and artificial electric vehicle noises [67]. Figure 2.1 shows the simulator layout as used during this study.

During the experiment, participants wore Dikablis eye-tracking glasses [68] and Empatica's E4 wristband [69], logging at 60 Hz and 4-64 Hz (depending on the signal), respectively. The measurements from the wristband were not included in this study. A handheld tablet was placed on the front passenger seat and provided post-experiment questions to the participant.

Figure 2.1: The Porsche high-fidelity hexapod driving simulator as used during the experiment. For more details, see Appendix L.

2.3. Experimental conditions

During the experiment, participants drove 30.7 kilometres (equal to seven laps) on a single-lane oval track with a road width of 3.6 m. The drivers encountered four 90 deg curves with inner radii of 40 m, 80 m, 120 m and 160 m separated by straight-road sections. In the remainder of this work, these curves will be referred to as R1, R2, R3 and R4, respectively. The curves were presented in the order of 80 m, 40 m, 120 m and 160 to make it less predictable. The curve layout used for this study had no clothoides sections.

The participants encountered two road narrowings each lap, starting from the second lap and continuing onward. The narrowings were presented in a counterbalanced order (using a Latin-square method) to eliminate order and sequence effects (for more details, see Appendix J). During the road narrowing, the road width reduced from 3.6 m to 2.2 m, similarly reducing the possible lateral movement on either side of the vehicle to 0.82 m and 0.12 m.

The lengths of the straight-road sections were determined using the expected average minimum curve driving speed [1], and the average acceleration for a normal driving style of 1.2 m/s^2 [70], to provide the participants with enough distance to recover speed after the curves. A similar approach was used for the straight-road sections after the narrowings (using [71]). Figure 2.2 gives a schematic visualisation of the experimental layout. There were road signs after each curve indicating the maximum speed of 100 km/h and road signs highlighting the curves and narrowings (see figure 2.3).

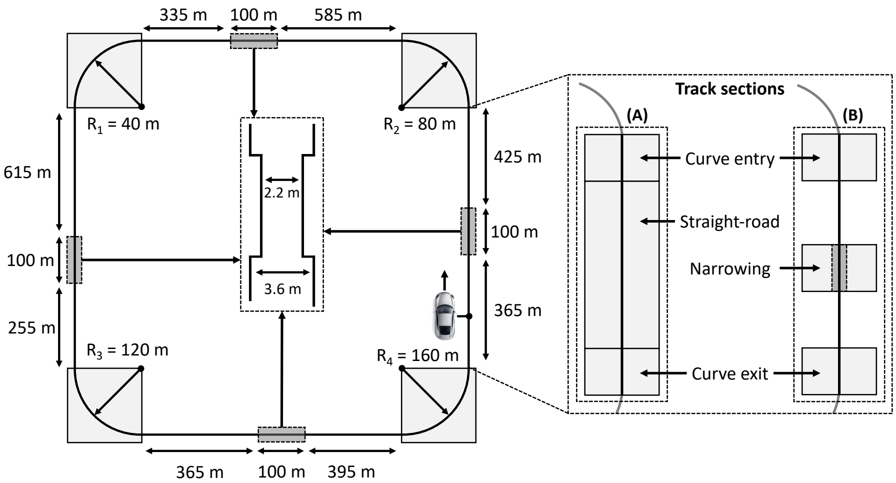

Figure 2.2: Schematic visualisation of the manual driving scenario, including corresponding distances. The right part of the figure visualises how the straights were divided into different track sections for the analysis. Track sections (A) and (B) show how the layout differs depending on whether a road-narrowing was present. The dark grey boxes represent the narrowings that could be activated. The light grew boxes on the left part of the figure represent the curves. The driving direction was counterclockwise.

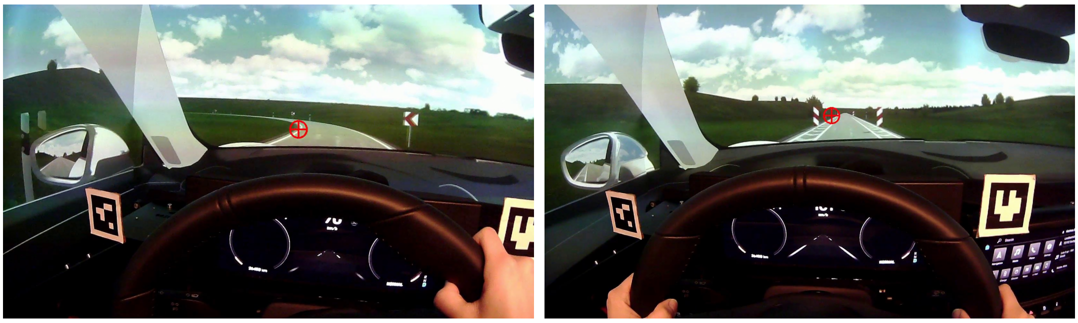

Figure 2.3: Left: curve R3 (with an inner radius of 120 m) taken from the front eye-tracking camera frame of references. Right: The 100 m road-narrowing, also taken from the front eye-tracking camera. The red dot indicates the current gaze location. The projected simulator environment shows the road signs used for the curve and road-narrowing track sections. The QR-markers in the cabin were used for localizing the gaze direction.

2.4. Procedure

Before the drive, participants filled out a demographic questionnaire and received instructions containing information about the following drive and the purpose of the tablet for the post-driving questionnaire. The participants were requested to operate the vehicle as they normally do, not depart the road or hit any road markers and adapt their speed to the driving circumstances. When seated in the car, the eye-tracking glasses were handed over to the participant and calibrated using D-Lab behavioural research software (version 3.5). The participants were informed that they would be operating a Porsche Taycan Turbo and that the experience may differ from reality. Additionally, they were informed that radio communication was available for relevant questions or other necessities during the entire experiment.

The simulation started with two other manual driving scenarios, which are outside the scope of this paper (see Appendix H). These scenarios combined took around 15 min to complete. In between each scenario, the drivers were asked to rate their sickness [72], the perceived mental workload of the last driving task (according to the NASA TLX questionnaire [73]) and given a short break. After completing all three simulations, the drivers filled out a feedback form. Finally, the experimental room and simulator were thoroughly cleaned and disinfected before the next experiment started. All involved were mandatory to wear a face mask at all times.

2.5. Track labels for the analysis

For the analysis, the manual driving scenario was divided into three parts: (1) curve driving, (2) straight-road driving and (3) road-narrowing operation. A fixed distance of 100 m before and after the curve were labelled as curve entry and curve exit sections (see Figure 2.2). The track section between the curve entry and curve exit, in other words, the actual curve, will be referred to as curve. Only for the curve entry braking behavior measures, the curve entry distance was set to 150 m (to approx. match the 6 s of [36, 41]) to ensure all desired braking behavior was captured.

The straight-road measures were only calculated for the straights where no narrowings were encountered and did not include the curve entry and exit section (Figure 2.2). So, the track sections in-between the curve exit and the road-narrowing and curve entry and road-narrowing were not part of the straight-road sections.

A road departure was counted as an event in which half of the vehicle width went outside of the road boundaries for the non-narrowing parts of the track. If a road departure occurred, the data of that curve was excluded from the analysis. Furthermore, if the road departure was followed by a straight-road without narrowing, that straight-road section would also be excluded. The performance of the first lap was considered a test drive and thus excluded from the analysis.

2.6. Eye-tracking data processing

First, blink and outlier gaze points were removed from the horizontal and vertical gaze coordinates. Outliers were individually defined for each participant as any gaze coordinate outside the range of mean $\pm 3\times$standard deviation in either horizontal or vertical direction [74]. In total, an average of 1.7% and 1.9% of the horizontal and vertical was removed, respectively. The removed gaze data was restored using linear interpolation. Furthermore, a median filter with a 100 ms interval was applied [75].

Based on manual inspection of the eye-tracking data, it was observed that the data contained many systematic errors as a result of wrong calibration, relative movement of the glasses with respect to the participants head (e.g. due to the participant touching it) in the period after calibration and before starting the manual driving session, or both. Given that drivers primarily look straight ahead during straight-road driving [76], the decision was made to use the individual median gaze location on the straight-road sections as a correction for the gaze results. In more detail, the median horizontal and vertical gaze location was calculated over all straight-road sections that were part of the analysis (as defined in Section 2.5 and visualised by Figure 2.2) for each individual separately and used as a correction on all gaze coordinates captured during the experiment. For the remainder of this work, this individual gaze coordinate correction will be referred to as the *reference*, similar to [41].

2.7. Dependent measures

Prior to the analysis, all data was synchronized and up-sampled to 100Hz in MATLAB (version 2020b).

The dependent measures consist of three main groups: (1) driving skill measures, (2) driving style measures and (3) perceptual skill measures. For the analysis, the measures were divided into curve driving, straight-road driving and driving through road-narrowing (as explained in Section 2.5). Table 2.2 gives an overview of the dependent measures that were calculated for the manual driving session. The measures were divided into subgroups reflecting the performance or behavior the combined measures were intended to capture. The following sections 2.7.1 to 2.7.3 elaborate on the individual measures used for this study.

As stated in the introduction, the driving skill measures were selected to capture lower-order skill components, also referred to as vehicle-control [16, 56]. The skill measures (mainly) captured control activity and driving precision during the different track sections. The driving style measures were designed to capture trajectory planning (choice of path and speed), including speed-related measures for the different track sections. The perceptual skill measures explored the eye-steering coordination (i.e., lead times), potential gaze adaptation for the narrowings and how the gaze is distributed when curve driving.

Table 2.2: Overview of all dependent measures that were captured during the manual driving session, including the corresponding categorisation.

Track segment	Measures categorization					
	Driving style		Driving skill		Perceptual skills	
	Label	Measures	Label	Measures	Label	Measures
Curves	Speed control through the curves	• Mean speed curves • Mean throttle position curves • Throttle and brake activation curves • Speed difference over curves	Curve control activity	• Throttle variance curves • Steer steady curves • Steering integral curves	Eye movements curve	• Mean and SD horizontal gaze from the reference curves (3x) • Mean and SD vertical gaze from the reference curves (3x)
	Braking behavior entering the curves	• First braking moment curve entries • Max. brake pedal position curve entries • Braking smoothness curve entries	Curve control precision/accuracy	• SDLP curves • AS error	lead time curves	• (Constrained) lead time curves • (Constrained) correlation coefficient lead time curves
			Curve recovery control activity	• Steering integral curve recovery • Steer steady curve recovery		
	Driving line through the curves	• Turn-in distance and LP • Track-out distance and LP • Mean LP curves				
Straights	Straight-road speed and track position	• Mean speed straights • Mean LP straights	Straight-road control activity	• Steer steady straights	Straight-road gaze activity	• SD hortizontal gaze from the reference straights • SD vertical gaze from the reference straights
			Straight-road control precision	• SDLP straights		
Narrowings	Narrowing speed and track position	• (Delta) mean speed narrowings • (Delta) mean LP narrowings • Speed difference over narrowings	Road-narrowing control activity	• (Delta) steer steady narrowings	Gaze adaptation narrowings	• Delta mean horizontal gaze from the reference narrowings • Delta mean vertical gaze from the reference narrowings • (Delta) SD hortizontal gaze from the reference narrowings • (Delta) SD vertical gaze from the reference narrowings • Delta mean abs. hortizontal gaze from the reference narrowings • Delta mean abs. vertical gaze from the reference narrowings
			Road-narrowing control precision	• (Delta) SDLP narrowings		

LP: Lateral position, SDLP: Standard deviation lateral position, AS error: Anticipatory steering error. Delta refers to the difference between the straights and the narrowings, abs: absolute.

2.7.1. Curve driving measures

Curve driving: driving style

- *Mean speed curves* (km/h).
- *Mean throttle position curves* (0-1): was defined as the mean throttle position, taken over the time period when the throttle position was above 2% (of its range) in the curves. No throttle activation is resembled by zero and fully depressed by one. The measure signals the amount of throttle input when activated, independent of the throttle time, allowing to differentiate between the effect of throttle input and time on the speed control.
- *Throttle activation curves* (0-1): was defined as the fraction of time the throttle input was above 2% in the curves.
- *Brake activation curves* (0-1): was defined as the fraction of time the brake input was above 2% in the curves.
- *Speed differences curves* (Δkm/h): The speed differences between the curve beginning and the ending of the curve. A positive speed differences curves means the drivers increased their speed over the curves.
- *First braking moment curve entries* (s): was defined as the time from the first moment the brake input was above 2% to the start of the curve, reflecting an aspect of anticipation [20, 77]. When no brakes were applied over 150 m before the start of the curve, the value was not included in the calculation.
- *Maximum brake pedal position curve entries* (0-1): were calculated for the curve entries [78]. A high maximum brake position curve entries indicates a more aggressive and abrupt braking behaviour when approaching the curves.
- *Braking smoothness curve entries* (-): the absolute time derivative of the braking position signal as a measure of how aggressive and abrupt the driver builds-up and releases the braking position [79] during the curve entry section (excluding the curve). A high braking smoothness means an aggressive and abrupt brake pedal control by the driver.
- *Turn-in distance* (m): was defined as the distance from the curve beginning to the first moment the steering wheel is 4 deg directed towards the inner-lane during the curve entry section (excluding the curve). A high value means the driver turns-in early when entering the curve. Figure 2.4 gives an illustration of the measure.
- *Turn-in LP* (m): the lateral position on the first moment the steering wheel is 4 deg directed towards the inner-lane when entering the curve. A high value means the vehicle is more towards the outer lane of the track when entering the curve. An illustration can be found in figure 2.4.
- *Track-out distance* (m): was defined as the distance from the curve ending to the first moment the steering wheel is 4 deg directed towards the inner-lane when exiting the curve. A high value means the driver utilized much distance to rotate the vehicle for the upcoming straight. Figures 2.4 gives an illustration of the measure.
- *Track-out LP* (m): the lateral position on the first moment the steering wheel is 4 deg directed towards the inner-lane when exiting the curve. A high value means the vehicle is more towards the outer lane of the track when exiting the curve. An illustration can be found in figure 2.4.
- *Mean LP curves* (m): the distance of the center of the vehicle to the center of the lane during the curves [18]. A positive LP means that the participant drove to the right of the lane center, further away from the curve center.

Curve driving: driving skill

- *Throttle variance curves* (0-1): was calculated as a measure of throttle activity [46, 80, 81].
- *Steer steady curves* (0-1): defined as the fraction of time the absolute steering wheel velocity was below 1 deg/s [80] through the curves. A low steer steady curves indicates a high steering control activity.
- *Steering integral curves* (deg): indicator for steering control activity [1, 79]. The steering integral is very sensitive for the driving line taken by the driver. Therefore, the integral was taken from the

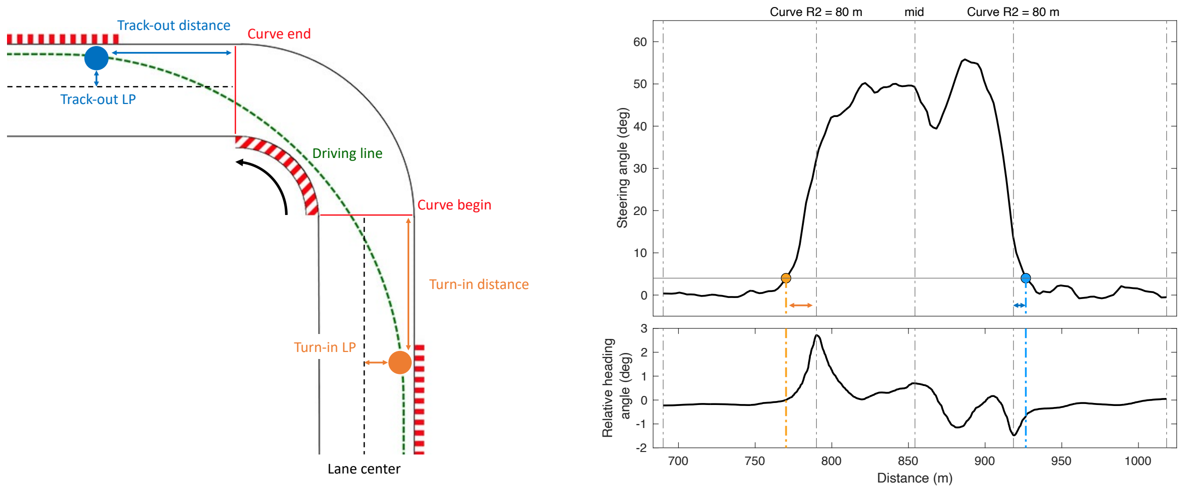

Figure 2.4: Left: an illustration of the turn-in (distance and LP) and track-out (distance and LP) measures designed to evaluate the adopted driving line through the curve by the driver. The drawn red curbs in the figure were not present during the experiment but were added to make the figure easier to interpret. The black arrow indicates the driving direction. Top right: an example illustrating the turn-in distance (in orange) and track-out distance (in blue) for cure R2. The black horizontal line indicates the 4 deg criteria used to establish the turn-in and track-out locations. Bottom right: shows the relative heading angle of the vehicle compared to the track. A positive heading angle indicates the vehicle is pointing towards the inner lane. The heading angle is an roughly estimated value. The mean take-away is that the vehicle is almost aligned with the straight-road section on the turn-in and track-out location.

turn-in to track-out location (see 2.4). A high-value signals the vehicle is under-steering or that the driver is making many steering corrections throughout the curve, or both [79].

- *Standard deviation of lateral position (SDLP) curves* (m): was used as a measure of driving precision through the curve [80, 82, 83].
- *Anticipatory steering (AS) error* (deg): was defined as the absolute difference between required steering input, calculated according to [2], and the first local maximum steering wheel input [1]. The AS error measure is based on the assumption that drivers starts with an anticipatory steering action before entering the cure [84]. A positive and negative AS error indicates a too large and too small initial steering input, respectively. The larger the absolute AS error value, the less accurate the initial steering control action. Figure 2.5 give a visualisation of the measure. For the required mathematical expression and vehicle model specification, review Appendices M and N.
- *Steering integral curve recovery* (deg): was calculated from the track-out location (see Figure 2.4) to the end of the curve exit section, serving as an indicator for the amount of steering activity after the first moment the vehicle is straightened for the upcoming straight. A high-value signals a high steering activity needed to restabilize the vehicle after the curve.
- *Steer steady curve recovery* (0-1): defined as the fraction of time the absolute steering wheel velocity was below 1 deg/s [80], calculated from the track-out location (see Figure 2.4) to the end of the curve exit section. Compared to steering integral curve recovery, steer steady curve recovery signals the time (instead of total steering effort) the driver is actively steering to restabilize the vehicle after the curve. A low steer steady curve recovery indicates a high time duration of high steering control activity.

Curve driving: perceptual skill

- *Mean horizontal gaze from the reference curves* (pixel): were calculated for the curve entry, curve and curve exit sections, separately.
- *Mean vertical gaze from the reference curves* (pixel): were calculated for the curve entry, curve and curve exit sections, separately.
- *Standard deviation (SD) horizontal gaze from the reference curves* (pixel): indicator for the horizontal gaze dispersion during the different curve sections [85, 86].
- *Standard deviation (SD) vertical gaze from the reference curves* (pixel): indicator for the horizontal gaze dispersion during the different curve sections [85, 86].

- *Lead time curves* (s): the corresponding time shift when the correlation between horizontal eye movements and steering input is the strongest [74, 87, 88]. The lead time reveals how much the horizontal eye movements are leading the steering input. Figure 2.6 gives an illustration of how the lead times are determined. For more details about the definition and calculation, see Appendix N.
- *Constrained lead time curves* (s): was calculated similarly as the lead time curves but given an additional constrain that the corresponding correlation coefficient had to be at least 0.7, which is considered a high correlation size [89], keeping only the strong attributes (see Figure 2.6).
- *Correlation coefficient lead time curves* (R): the correlation coefficient linked to the lead time curves (see Figure 2.6 or Appendix N).
- *Constrained correlation coefficient lead time curves* (R): the correlation coefficient linked to constrained lead time curves (see Figure 2.6 or Appendix N).

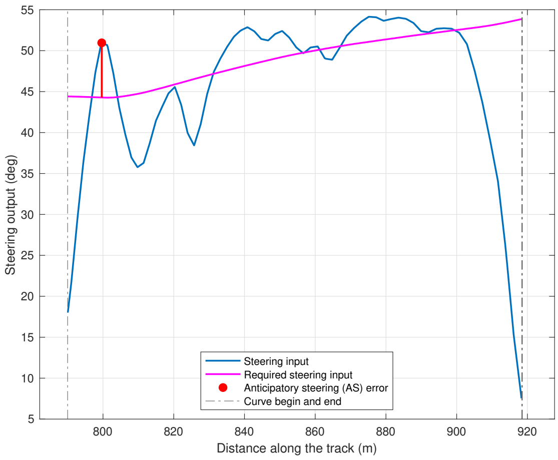

Figure 2.5: An example illustrating the anticipatory steering error [1]. The required steering angle (in purple) is calculated calculated according to [2].

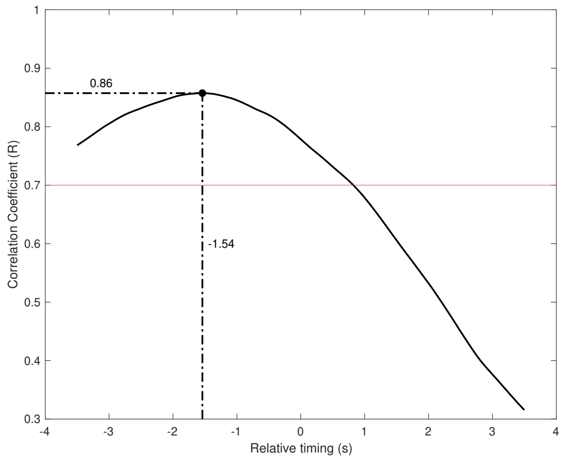

Figure 2.6: An example cross-correlogram between the horizontal gaze location relative to the reference and steering wheel rotation taken from a random participant, curve and lap. The y-axis value indicates the degree of covariation between the two signals, and the x-axis value indicates the time interval by which the eye movements and steering signal are offset. A negative relative timing indicates that the eye movements led the steering signal. Thus, for this example, the lead time was 1.54 seconds, with a corresponding correlation coefficient of 0.86. The red line illustrates the constrain for the minimum correlation coefficient used for the 'constrained' lead time and 'constrained' correlation coefficient.

2.7.2. Straight-road driving measures

Straight-road driving: driving style

- *Mean speed straights* (km/h): were calculated for the straights where no narrowings were encountered.
- *Mean LP straights* (m): were calculated for the straights where no narrowings were encountered and used as a measure for lane keeping bias [80].

Straight-road driving: driving skill

- *Steer steady straights* (0-1): defined as the fraction of time the absolute steering wheel velocity was below 1 deg/s [80]. A low steer steady straight signals a low steering control activity on the straights.
- *SDLP straights* (m): was used as a measure of lane keeping precision [80, 82, 83].

Straight-road driving: perceptual skill

- *Standard deviation (SD) horizontal gaze from the reference straights* (pixel): indicator for the horizontal gaze dispersion on the straights [85].
- *Standard deviation (SD) vertical gaze from the reference straights* (pixel): indicator for the vertical gaze dispersion on the straights [85].

2.7.3. Road-narrowing measures

Road-narrowing: driving style

- *Mean speed narrowings* (km/h).
- *Delta mean speed narrowings* (Δkm/h): the mean speed difference between the straight-road sections and the narrowing sections [71].
- *Speed difference narrowings* (km/h): the difference in speed between the beginning of the narrowing and the end of the narrowing. An indicator for speed control over the narrowing.
- *Mean LP narrowings* (m): used as a measure for lane keeping bias during the narrowings.

Road-narrowing: driving skill

- *Steer steady narrowings* (0-1): defined as the fraction of time the absolute steering wheel velocity was below 1 deg/s [80]. A low steer steady straight signals a low steering control activity during the narrowings.
- *SDLP narrowings* (m): was used as a measure of lane keeping precision during the narrowings [80, 82, 83].

Road-narrowing: perceptual skill

- *Delta mean horizontal gaze from the reference narrowings* (Δpixels): the differences in mean horizontal gaze from the reference between the narrowings and straights. A negative value signals a reduction in mean horizontal gaze location during the narrowings.
- *Delta mean vertical gaze from the reference narrowings* (Δpixels): the differences in mean vertical gaze from the reference between the narrowings and straights. A negative value signals a reduction in mean vertical gaze location during the narrowings.
- *Standard deviation (SD) horizontal gaze from the reference narrowings* (pixel): indicator for the horizontal gaze dispersion during the narrowings [85].
- *Standard deviation (SD) vertical gaze from the reference narrowings* (pixel): indicator for the vertical gaze dispersion during the narrowings [85].
- *Delta standard deviation (SD) horizontal gaze from the reference narrowings* (Δpixels): the differences in SD horizontal gaze from the reference between the narrowings and straights. A negative value signals a reduction in the horizontal spread of visual search during the narrowings.
- *Delta standard deviation (SD) vertical gaze from the reference narrowings* (Δpixels): the differences in SD horizontal gaze from the reference between the narrowings and straights. A negative value signals a reduction in the vertical spread of visual search during the narrowings.
- *Delta mean absolute horizontal gaze from the reference narrowings* (Δpixels): the differences in mean absolute gaze from the reference between the narrowings and straights. A negative value signals a reduction in the horizontal spread of visual search during the narrowings.
- *Delta mean absolute vertical gaze from the reference narrowings* (Δpixels): the differences in mean absolute gaze from the reference between the narrowings and straights. A negative value signals a reduction in the vertical spread of visual search during the narrowings.

2.8. Statistical analysis

All dependent measures were computed for each track section, curve radius and lap separately. The average performance for each participant was calculated using the outputs per lap. Finally, the mean and standard deviations group averages were calculated using the average performances of the participant of each experimental group per track segment. The horizontal and vertical distributions were calculated using non-parametric kernel density estimation, separately for each driver, curve and lap.

The average distributions were determined using the average performance of the participants of the experimental group.

Differences between the experienced and inexperienced group were statistically analyzed with a Welch's t-test ($\alpha = 0.05$). Cohen's d (ds) was used to assess the effect size [90]. For the mathematical expression, including the formula for estimating the confidence interval for the effect size, see Appendix N. A post-hoc paired t-test was performed with Bonferroni corrections applied to the two pairwise comparisons between the straight-road and road-narrowing performance ($\alpha = 0.05$). The same method was applied to investigate the differences among the different curve radius.

3
Results

During the manual driving session, the 31 participants drove seven laps (including one test lap) on the oval track, encountering 28 90-degree curves, 12 narrowings, and 28 straight-road sections. One participant completed only 6.5 laps, missing two curves, one straight and one narrowing, but was still included in the analysis. In total, eight curves and five straights were excluded from the analysis due to road departure. The maximum number of road departures counted per participant was one. Table 3.1 gives an overview of how the road departures were distributed among the experimental groups and track sections. The MISC results of one participant were missing because the participant did not complete the form.

Table 3.1: Overview of the total number of deleted track sections from the analysis for each experimental group due to a road departure. Road departures from the test lap are not included in the overview because they are not part of the analysis. Recap: the analysis of each participant included six curves, twelve narrowings and twenty-four straights.

Experimental group	Total number of road departures per track section						
	Curve R1 (= 40 m)	Curve R2 (= 80 m)	Curve R3 (= 120 m)	Curve R4 (= 160 m)	Straights	Narrowings	Total
Inexperienced	4	0	0	0	0	0	4
Experienced	3	1	0	0	0	0	4
Expert	0	0	0	0	0	0	0

3.1. Curving driving

3.1.1. Curve driving: driving style

- **Speed control through the curves**: Figure 3.1 shows the vehicle speed as a function of travelled distance for all four curves and experimental groups. On average, the experienced drivers adopted a higher mean speed through the curves than the inexperienced drivers, but this effect did not reach statistical significance (Tables A.1 to A.4). Yet, it can be observed that the experienced drivers had a significantly higher speed increase over the tighter two curves (R1 and R2) than the inexperienced drivers. This can be explained by the difference in throttle activation curves (for curves R1 and R2), which were significantly higher for the experienced drivers. Tables A.1 to A.4 also show that the mean throttle position curves were not significantly different between the experienced and inexperienced drivers, strengthening this observation. Furthermore, it was found that both groups had little braking activation in the four curves, ranging from 0.3% (for R4) to 5.1% (for R1), particularly in respect to the amount of the throttle activation, which ranged from 62.7 (for R1) to 84.8% (for R4). So, the observations show that the experienced had a higher throttle activation through the tighter curves resulting in a larger speed increase than the inexperienced drivers.

  The expert drivers ran the highest mean speed for all four curves. Similarly, their speed differences over the curves (end-begin) were the largest for the two tighter curves (R1 and R2), which can be linked to their relative high mean throttle position curves compared to the other two groups (see Tables A.1 to A.4). Figures 3.1 and C.1 shows how the high mean throttle position of the expert drivers resulted in a large speed increase when exiting the curve.

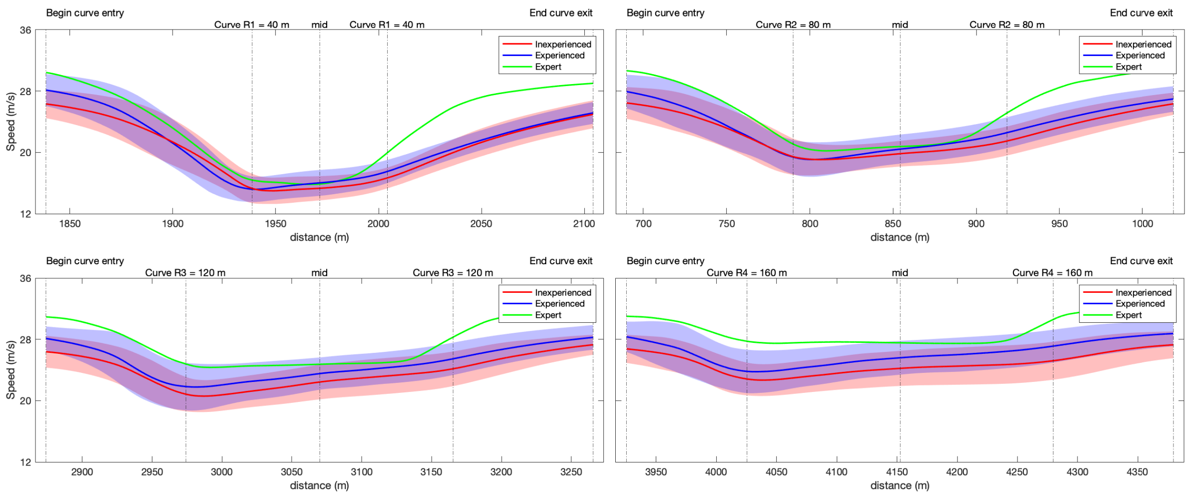

Figure 3.1: Overview of vehicle speed as a function of travelled distance for the inexperienced, experienced and expert drivers for the four different curves. The group averages are presented by the solid lines and the standard deviation by the transparent areas. The grey dotted lines indicate the different track sections.

- **Braking behavior entering the curves**: Tables A.1 to A.4 and Figures C.3 to C.5 show the first braking moment, maximum brake pedal position and braking smoothness for all four curve entries. On average, the experienced drivers used a statically significant higher maximum brake pedal position when approaching the tighter two curve entries (R1 and R2) than the inexperienced drivers. For the wider curves (R3 and R4), no significant differences were observed between both groups. A similar pattern was found in the comparison of braking smoothness between both groups, meaning a significantly higher braking smoothness for the experienced drivers for curve entries R1 and R2. No significant differences were found between the first braking moment of the experienced and inexperienced drivers' for all four curves. Figure C.2 shows that the experienced and inexperienced drivers managed to do the vast majority of their speed regulation before entering the curve. Overall, the experienced drivers adhered a more abrupt braking style compared to the inexperienced drivers.

  The expert drivers used an almost identical maximum brake pedal position when approaching the curves as the inexperienced group. It was found that the expert drivers had the lowest braking smoothness compared to both the experienced and inexperienced drivers, with the only exception of the tightest curve R1. The first braking moment of the expert drivers were almost identical to those of the experienced and inexperienced drivers. So, although the expert drivers had the highest mean speed on the straights, their braking style was the most smooth of all experimental groups.
- **Driving line through the curves**: Figures D.1 to D.4 show the driving vehicle paths for the inexperienced, experienced and expert drivers for all four curves. It can be seen that there were no clear significant differences between the adopted driving line of the experienced and inexperienced drivers (also see Tables A.1 to A.4 and Figure 3.2).

  The expert drivers, however, seemed to adopt another driving line strategy through the curves. Figures 3.2 and D.1 to D.4 (and Tables A.1 to A.4) show that the expert drivers adhered to a larger turn-in distance (except for curve R1) and a higher turn-in LP when entering the curves than the experienced and inexperienced drivers. This translates to steering into the curve earlier and positioning the vehicles further away from the curve center, respectively. Over the curves, the expert drivers stayed closer to the center of the curves, and when exiting the curve, they consistently used more distance (i.e., a larger track-out distance) and a wider part of the track (i.e., a higher track-out LP) to straighten the vehicle (see Figure 3.3). Figure C.6 shows the steering wheel angle as a function of travelled distance for the three experimental groups and the four different curves. Together, Figures 3.2 and C.6 show that the difference in steering and driving line strategy of the expert drivers was most apparent when exiting the curves. Furthermore, Figures 3.2 and D.1 to D.4 demonstrate how the expert drivers seemed to position the vehicle towards the inner lane before exiting the curves R2, R3 and R4. Overall, the expert drivers adopted to a larger extent a racing line through the curves, which deviated the most from the driving line of the experienced and inexperienced drivers when exiting the curves.

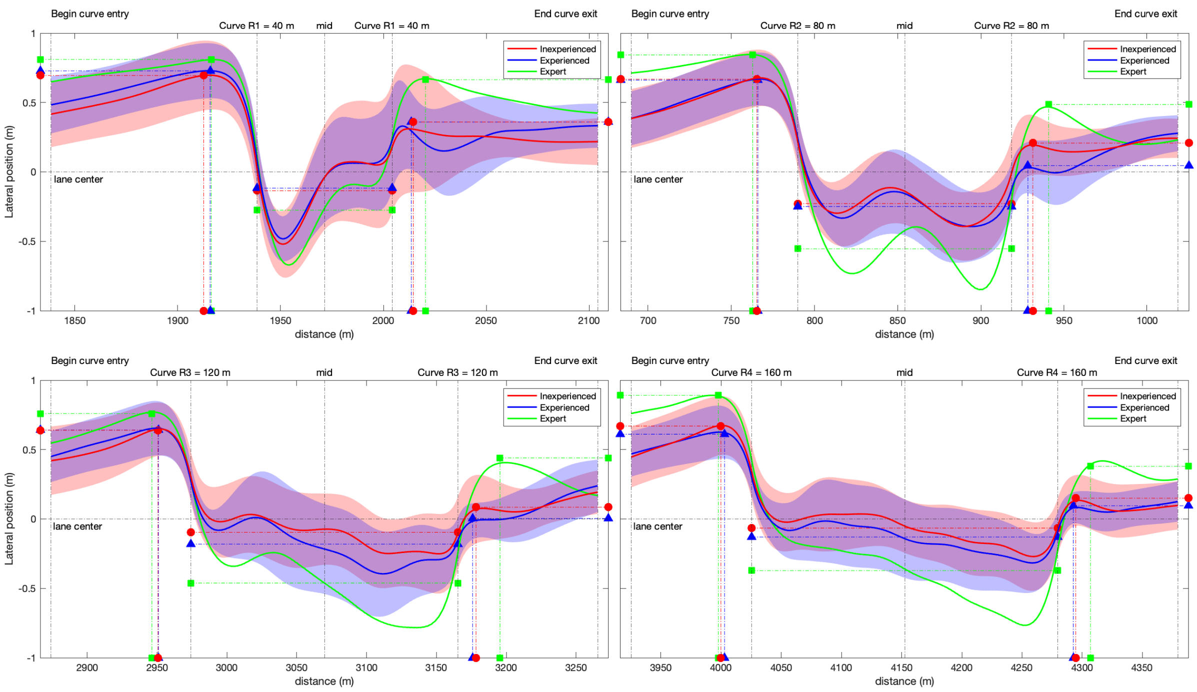

Figure 3.2: Overview of the lateral position (LP) as a function of travelled distance for the inexperienced, experienced and expert drivers for the four different curves. The lateral position is defined as the distance between the center of the vehicle and the center of the driving lane. A negative lateral position denotes a position left of the lane center, in other words, a displacement towards the curve center. Hence, a positive lateral position signals a displacement away from the curve center. The group averages are presented by the solid lines and the standard deviation by the transparent areas. The turn-in LPs and distances (*–*), mean LP curves (*–*) and track-out distances and LPs (*–*) are highlighted for each curve. The symbols: ○, △ and □ are used to differentiate between the inexperienced, experienced and expert driver group, respectively. The grey dotted lines indicate the different track sections.

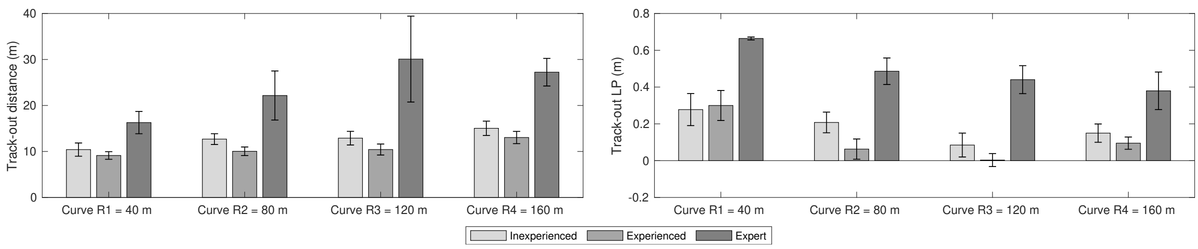

Figure 3.3: Mean of the track-out distance (left) and track-out LP (right) for the four curves and three experimental groups. Error bars indicate standard errors.

3.1.2. Curve driving: driving skill

- **Curve control activity**: Tables A.1 to A.4 show that no significant differences were found between the throttle variance curves, steer steady curves and steering integral curves of the experienced and inexperienced drivers for all four curves. Pairwise comparison using the average performance of all participants showed a significant ($p < 0.01$) increase of steer steady curves and reduction of steering integral curves with increasing curve radius. This indicates that the steering control activity reduced with increasing curve radius.

The curve control activity of the expert drivers showed contrasting results compared to the other two groups. The main differences were observed in throttle variance curves and steering integral curves, which were much higher and lower, respectively, for all curves compared to the other two groups. This indicates that the expert drivers had a higher throttle control activity but lower steering control activity in the curves.

- **Curve control precision/accuracy**: no significant differences were obtained between the SDLP curves and AS error of the experienced and inexperienced drivers' for all four curves (see tables A.1 to A.4).

  The precision measures of the expert drivers, as presented in Tables A.1 to A.4, show no clear differences compared to the experienced and inexperienced drivers. The expert drivers did show slightly lower AS error results than the experienced and inexperienced drivers, but this was not consistent for all curves.

- **Curve recovery control activity**: Tables A.1 to A.4 show that no significant differences were found between the steering integral curve recovery and steer steady curve recovery of the experienced and inexperienced drivers for all four curves. Pairwise comparison using the average performance of all participants showed a significant ($p < 0.01$ - $p = 0.03$) reduction of steering integral curve recovery with increasing curve radius, with the exception of the difference between the widest two curves R3 and R4 ($p = 0.11$). The steer steady curve recovery was found to remained fairly constant amongst the different curve exits (see Table A.5). This shows that on average, the participants made more steering actions to stabilize the vehicle exiting the tighter curves, while the time fraction of active steering remained fairly constant amongst the different curve exits.

  The expert drivers showed a noticeable lower steering integral curve recovery than the experienced and inexperienced drivers for all curves (see tables A.1 to A.4). In addition, their steer steady curve recovery was relatively high for the tighter two curves, R1 and R2, compared to the other two experimental groups but showed similar performance for the wider curves R3 and R4. Thus, the expert drivers needed less steering control activity to stabilize the vehicles after the curve for the upcoming straight-road section.

3.1.3. Curve driving: perceptual skills

- **Horizontal gaze movements curves**: Tables A.6 to A.9 and Figure 3.5 show the mean and standard deviation of the horizontal (and vertical) gaze from the reference for the three different curve sections: entry, curve and exit. In general, no consistent significant differences were obtained between the mean horizontal gaze from the reference for the curve entry, curve and curve exit sections among the different curves of the experienced and inexperienced drivers. The same holds for the standard deviation. Yet, Figure 3.5 and Tables A.6 to A.9 show that the inexperienced had a larger inwards mean gaze movement than the experienced drivers for all individual curve entries and curves. This resulted in a significant difference for the collapsed mean horizontal gaze location using all curve entries ($p = 0.046$) but no significant difference for the collapsed mean horizontal gaze location curves ($p = 0.055$) using all curve sections. The horizontal gaze distribution for the curves (see Figure E.3) shows that although the inexperienced drivers looked more eccentric to the direction of the curve than the experienced drivers, they also spent a larger fraction of their gaze inspecting the outer side of the curve (highlighted by the grey boxes) than the experienced drivers. Figure E.4 demonstrates that this difference is caused by a specific individual who spend a relatively large fraction of their gaze towards this part of the track. Furthermore, Figure E.1 demonstrates no large variation between curves in the horizontal gaze distribution for the curve entry and exit sections for all experimental groups. So, the drivers adopted a fairly consistent horizontal scanning strategy, independent of the approaching or exiting curve.

  Figures 3.5 and E.3 shows how the expert drivers had the largest variance between their horizontal gaze distributions for the different encountered curves. This signals that the expert drivers made the largest horizontal scanning adaption depending on the curve. Also, Figure E.1 shows that the expert drivers had a consistent relatively large positive mean horizontal gaze location for the curve exit sections. This indicates that the experts' shifted their gaze outwards, away from the curve center, during the curve exit sections.

- **Vertical gaze movements curves**: similar to the horizontal modes, no consistent significant differences were obtained between the mean and standard deviation vertical gaze from the reference for the curve entry, curve and curve exit sections among the different curves of the experienced and inexperienced drivers (see Tables A.6 to A.9 and Figure 3.5). Figure 3.5 illustrate how the experienced drivers increased their mean vertical gaze location for all individual curve entries and curve sections relative to their reference (i.e., straight-road driving), which was not the case for the inexperienced drivers. Figure E.7 presents the vertical gaze distribution for each curve and experimental group separately. It shows how the inexperienced drivers used a larger fraction of their gaze time to inspect low pixels in respect to their references. This difference is highlighted by the grey boxes. Figure E.8 demonstrates the percentage of gaze time the different driver groups designated to the grey boxed areas for each participant and experiment group, separately. It was found that the inexperienced drivers spend a significantly larger fraction of their time inspecting this part of the track ($p = 0.03$, $ds = 0.84$).

  Tables A.6 to A.9 and Figure 3.5 show that the expert drivers adopted a relatively high mean vertical gaze location from their reference through the curves and curve exit sections compared to the experienced and inexperienced drivers. In addition, the expert drivers had a relatively low vertical gaze dispersion for these track sections. Figure E.7 shows that this can be explained by the relatively little gaze time the experts' designated to inspect the pixels below their reference.

- **Lead time curves**: Tables A.6 to A.9 show that with or without a constrain for the correlation size, no significant differences were obtained between the lead time of the experienced and inexperienced drivers for any of the curves. Figure 3.6 illustrates the large inter-individual and intra-individual differences for the calculated (unconstrained) lead times for each curve. The same holds for the corresponding correlation coefficients (see Table A.10 and Figure C.7). Figure C.7 demonstrates how certain participants showed a consistent positive correlation between the eye–steering coordination, which translates to a gaze movement away from the curve center when curve driving. The introduced constrain for the lead time correlation coefficient resulted in a data reduction of 44.1%, and eliminated all the data samples of one experienced and three inexperienced drivers. Table A.10 shows that the constrain did not result in large differences compared to the unconstrained lead time (using all participants). The average (unconstrained) lead time using all participants ranged from 0.58 s (for R1) up to 1.36 s (for R3) (see Table A.10). Pairwise comparison using the average performance of all participants showed significant ($p = <0.01$-0.05) differences for the constrained lead times between the different curve radius except for the comparison between the two widest curves R3 and R4 ($p = 0.94$). This indicates that on average, the drivers increased their lead time with increasing curve radius, with a stagnation at curve R3. Overall, the determined lead times were inadequate for obtaining differences between the experienced and inexperienced drivers.

3.1.4. Curve driving: Overview

Figure 3.4 gives an overview of the effect sizes for the comparisons between the inexperienced and experienced drivers for the curve driving measures. The figure shows that the obtained effect sizes for the driving skill measures ranged from 0.00 to 0.43, indicating that the driving skill measures only showed small differences between experienced and inexperienced drivers. The measures capturing the taken driving line through the curves showed small to medium effects sizes between the experienced and inexperienced drivers; however, as mentioned earlier, the results showed that no statically significant differences were found for these measures between both experimental groups. The speed-related driving style measures, i.e., speed control through the curve and braking behavior entering the curves, showed medium (0.50) to large (1.16) effects sizes, indicating to be most suitable to differentiate between experienced and inexperienced drivers. The (constrained) lead time curves only showed a small effect size between the experienced and inexperienced drivers, confirming that our lead time results were inadequate for effectively obtaining differences between experienced and inexperienced drivers. Overall, the speed-related driving style measures showed to be the most effective measures to discriminate between experienced and inexperienced drivers for curve driving.

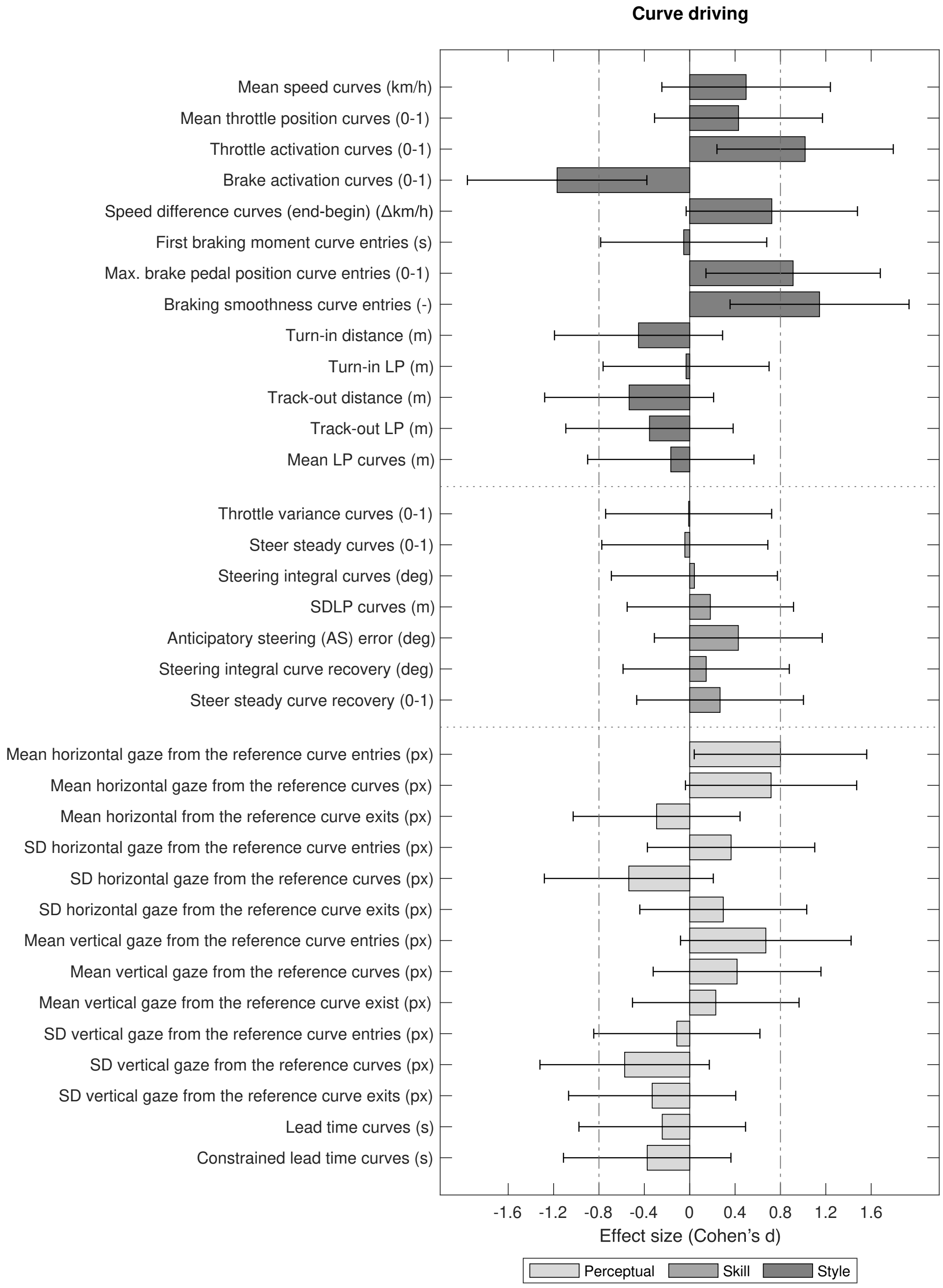

Figure 3.4: Overview of the effect sizes (Cohen's d (ds)) for comparisons between the inexperienced and experienced drivers for the average curve driving skill, style and perceptual measures using all four curves. Error bars indicate the estimated corresponding 95% confidence interval. According to Cohen [3], an absolute ds of 0.20, 0.50, and 0.80 can be interpreted as small, medium, and large effects, respectively. The two vertical lines highlight the 0.8 and -0.8 ds values. A positive effect size, for example, for the mean speed curves, indicates that the group average of the experienced drivers is higher than the group average of the inexperienced drivers for this measure. For the used mathematical expressions, see Appendix N.

3.2. Straight-road driving

3.2.1. Straight-road driving: driving style

- **Straight-road speed and track position**: The straight road driving results in Table B.1 show that the experienced drivers' mean speed was significantly higher than those of the inexperienced drivers. No significant differences were obtained between the mean LP straights. Both the experienced and inexperienced drivers adopted a mean LP position at the right side of the center lane, similar to the Turn-in LP obtained for the curves.

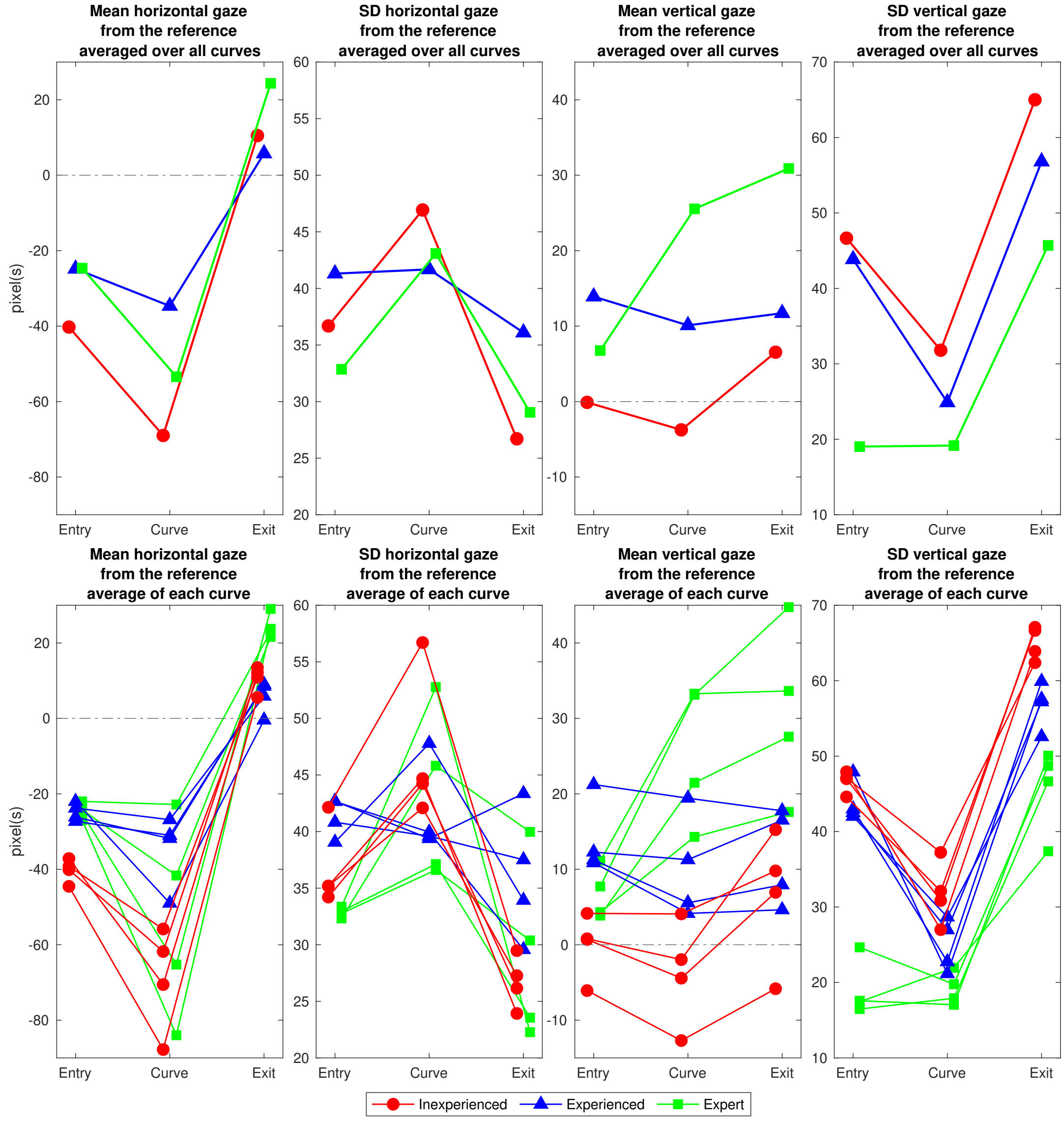

Figure 3.5: Overview of the mean and standard deviation of the horizontal and vertical gaze from the reference for the different curve sections (i.e., entry, curve and exit) and experimental groups (i.e., inexperienced, experienced and expert drivers). The four top figures present the group averages using all four curves, and the bottom four figures present the mean results for each curve and experimental group separately. So, for the bottom four figures, there are four data points for each track section and experimental group, one for each curve (R1-R4). The lines connect the data points that belong to each other. The four most left figures present the horizontal modes, and the four most right figures the vertical modes. For the definition of the references, see chapter 2.6.

The expert drivers ran the highest mean speed on the straights compared to the experienced and inexperienced drivers. Furthermore, it was found that their mean LP was the most towards the right in comparison to the other two driver groups.

3.2.2. Straight-road driving: driving skill

- **Straight-road control activity**: No significant difference was obtained between the steer steady straights of the experienced and inexperienced drivers (see Table B.1), marking no significant difference in control activity on the straights.

  The expert drivers had the highest steer steady straights compared to the experienced and inexperienced drivers, reflecting the lowest control activity on the straights of the three experimental

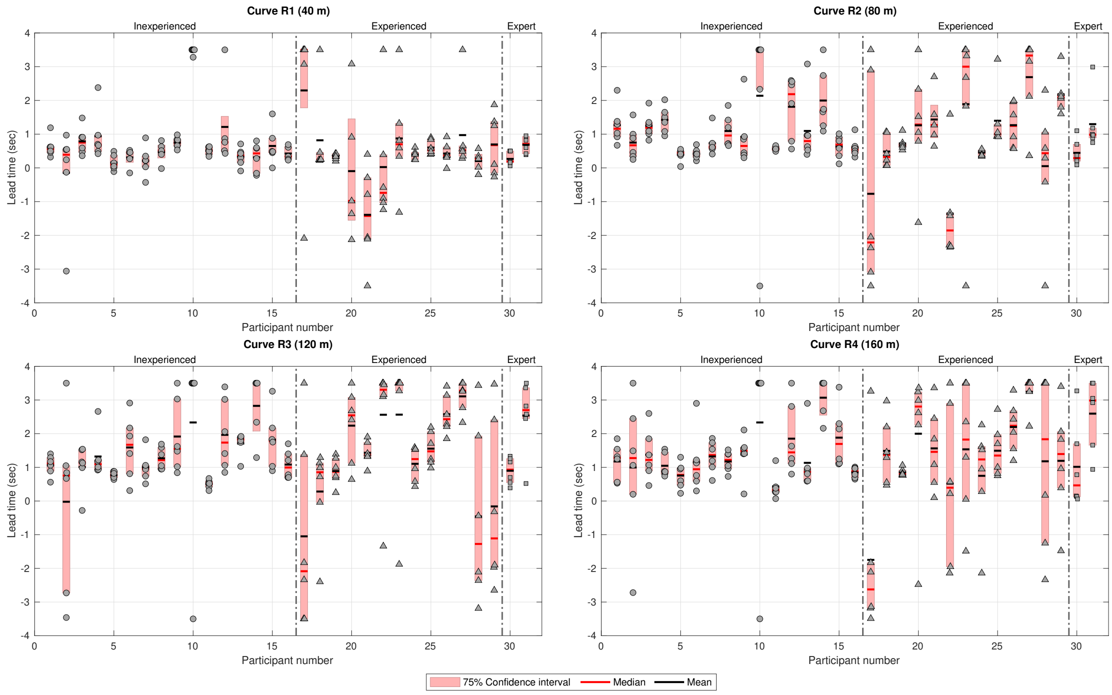

Figure 3.6: Overview of the (unconstrained) lead time curve for each curve, participant and individual lap, separately. The corresponding correlation coefficient are presented in Figure C.7.

groups.

- **Straight-road control precision**: As shown in Table B.1, the SDLP straights were not significantly different between the experienced and inexperienced drivers, implying no significant difference in control precision on the straights.

  On average, the expert drivers had the lowest control precision on the straight, i.e., the highest SDLP straights, compared to the experienced and inexperienced drivers. However, the differences were marginal.

3.2.3. Straight-road driving: perceptual skill

- **Straight-road gaze dispersion**: Table B.2 shows the standard deviation horizontal and vertical gaze from the reference as captured on the straights. It can be seen that no significant difference were found between the horizontal and vertical gaze dispersion of the experienced and inexperienced drivers. On average, both groups had a larger vertical than horizontal gaze dispersion, contrary to curve driving. Figure E.11 shows that this can be explained by the relatively high gaze time towards the high gaze locations (order of 100 pixels above the reference) during straight-road driving, which is almost identical for the experienced and inexperienced drivers.

  The expert drivers showed a similar horizontal and slightly lower vertical gaze dispersion than the experienced and inexperienced drivers.

3.2.4. Straight-road driving: overview

Figure 3.7 gives an overview of the effect sizes for the comparisons between the inexperienced and experienced drivers for the straight-road (and road-narrowing) driving measures. The figure shows how the mean speed on the straights was an effective measure to discriminate between experienced and inexperienced drivers. The obtained effect sizes for the driving skill measures ranged from 0.34 to 0.41, indicating that the driving skill measures only showed small differences between experienced and inexperienced drivers. Likewise, the perceptual skill measures on the straights also showed only small differences between experienced and inexperienced drivers. Thus, the speed on the straight allows to effectively differentiate between the experienced and inexperienced drivers, while the driving skill and eye-movement measures for the straight-road sections did not.

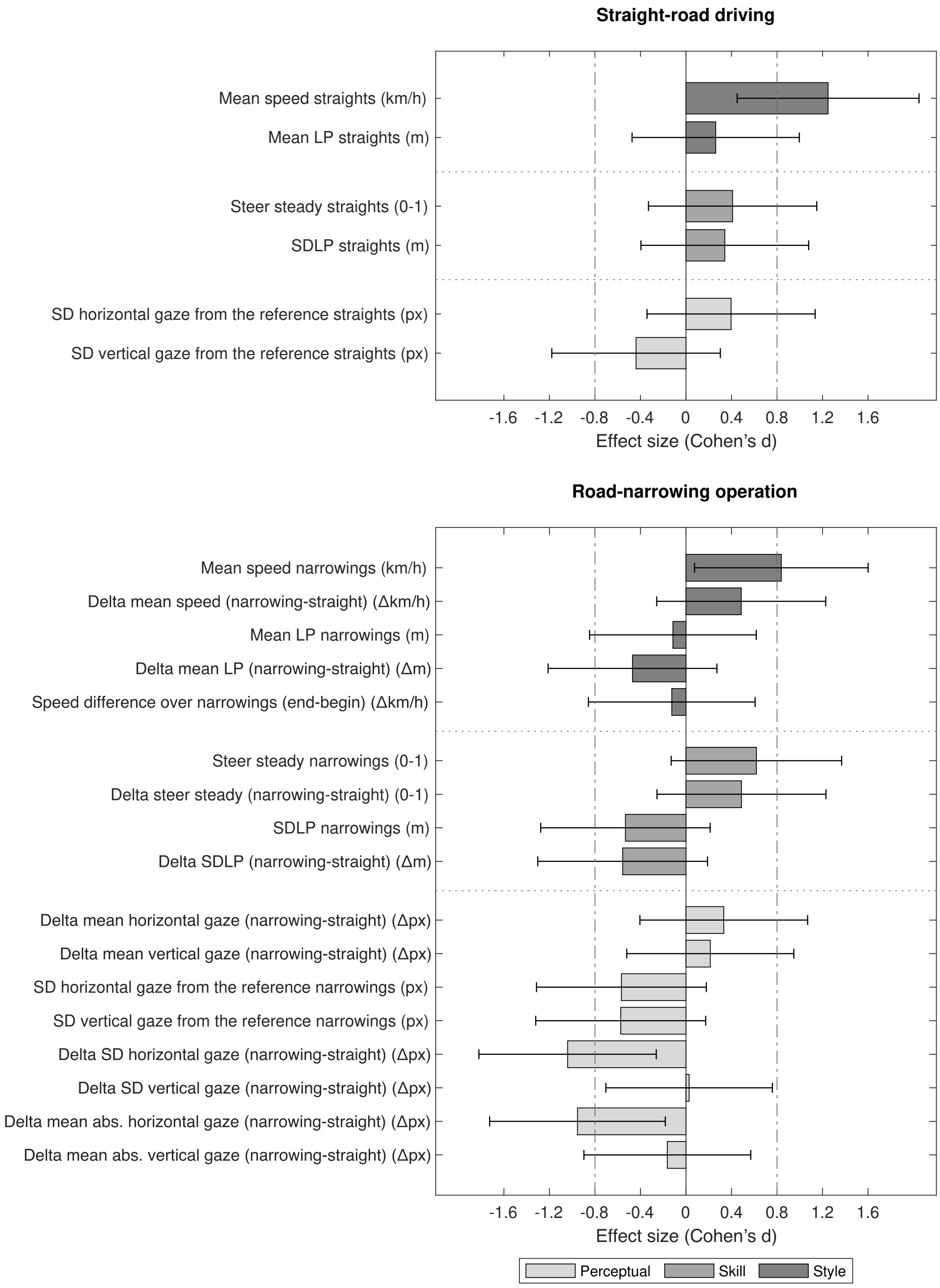

Figure 3.7: Overview of the effect sizes (Cohen's d (ds)) for comparisons between the inexperienced and experienced drivers for the average straight-road and road-narrowing driving skill, style and perceptual measures. Error bars indicate the estimated corresponding 95% confidence interval. According to Cohen [3], an absolute ds of 0.20, 0.50, and 0.80 can be interpreted as small, medium, and large effects, respectively. The two vertical lines highlight the 0.8 and -0.8 ds values. A positive effect size, for example, for the mean speed straights, indicates that the group average of the experienced drivers is higher than the group average of the inexperienced drivers for this measure. For the used mathematical expressions, see Appendix N.

3.3. Road-narrowings

3.3.1. Road-narrowings: driving style

- **Narrowing speed and track position**: Table B.1 lists the mean speed, speed difference over the narrowings and LP position for the narrowings for all three groups, including a comparison between the straight-road and narrowing driving performance, referred to as delta. It can be seen that the experienced drivers ran a significantly higher speed through the narrowings than the inexperienced drivers. Pairwise comparison showed that only the inexperienced drivers significantly adapted their speed (compared to the straights) ($p = 0.03$), while the experienced drivers only significantly adapted their mean LP ($p = 0.05$) for the narrowings. In addition, no significant differences were found between the speed differences over the narrowings of the experienced and inexperienced drivers.

The expert drivers ran the highest speed through the narrowings and made the most prominent correction to their LP position. This can be explained by their LP straights, which was the largest of all three experimental groups. However, their mean shift in LP was still very marginal.

3.3.2. Road-narrowings: driving skill

- **Road-narrowing control activity**: Table B.1 reveals that there were no significant differences in control activity, i.e., steer steady narrowings, between the experienced and inexperienced drivers. Pairwise comparison showed that both groups had a significantly lower steer steady during the narrowings than the straights (experienced: $p = 0.02$; inexperienced $p < 0.01$), signalling an increased control activity.

  The expert drivers showed a minor non-significant increase in steer steady during the narrowings (compared to the straights). Overall, the expert drivers had the lowest control activity, which did not significantly deviate from their straight-road control activity.
- **Road-narrowing control precision**: Table B.1 shows the (delta) SDLP narrowings for all three experimental groups. No significant differences were obtained between the SDLP narrowings of the experienced and inexperienced drivers. Pairwise comparison showed that the experienced and inexperienced significantly reduced their SDLP during the narrowing compared to the straights (all: $p < 0.01$), indicating the drivers increased their driving precision during the road-narrowing sections.

  Although the differences were marginal, the expert drivers showed the highest precision, i.e., lowest SDLP, during the narrowings of all three experimental groups.

3.3.3. Road-narrowings: perceptual skill

- **Gaze adaptation narrowings**: Figures E.9 and E.11 and Table B.2 show no large variance between the straight-road and road-narrowing horizontal and vertical gaze distribution for both the experienced and inexperienced drivers. Likewise, pairwise comparison showed that the mean horizontal and vertical gaze location did not significantly change between the straight-road and narrowing sections for experienced and inexperienced drivers. The experienced drivers, however, significantly reduced their horizontal and vertical gaze dispersion ($p < 0.01$), while the inexperienced divers only significantly reduced their vertical gaze dispersion ($p < 0.01$). Moreover, a significant difference was obtained between the delta SD horizontal gaze and delta mean abs. horizontal gaze of the experienced and inexperienced drivers (see Table B.2). Thus, the experienced drivers reduced their horizontal gaze dispersion during the narrowings, while the inexperienced drivers did not.

  Figure E.9 show how the expert drivers significantly shifted their mean horizontal gaze location towards the right during the road-narrowings in comparison to straight-road sections ($p = 0.04$). In addition, the expert drivers had the largest reduction in the horizontal and vertical gaze dispersion, but this effect did not reach statistical significance.

3.3.4. Road-narrowings: overview

Figure 3.7 gives an overview of the effect sizes for the comparisons between the inexperienced and experienced drivers for the road-narrowing (and straight-road) driving measures. The figure shows how the mean speed through the narrowings was an effective measure to discriminate between experienced and inexperienced drivers. The effect sizes of the driving skill measures captured during the narrowings were slightly higher than the straights and curves but showed no statically significant differences between both groups. Lastly, the perceptual skills show a large effect size for the horizontal gaze dispersion reduction (i.e., delta SD horizontal gaze (narrowings-straight) and delta mean abs. horizontal gaze (narrowings-straight)). In general, the results show how the driving style and eye movement measures, but not the driving skill measures, allow to effectively differentiate between the experienced and inexperienced drivers during the road-narrowings.

3.4. Self-reported scores measures

Table G.1 lists the MISC and perceived TLX mental workload scores for all three experimental groups. The table shows no significant differences in the self-reported perceived TLX mental workload and MISC scores of the experienced and inexperienced drivers. The expert drivers rated a similar MISC score and noted the lowest score for perceived TLX mental workload compared to the inexperienced and experienced drivers.

3.5. Correlational Analysis

Appendix F contains the correlation matrix of the dependent measures. The correlation analysis was conducted using the average performance of all participants (i.e., the inexperienced, experienced and expert drivers combined), and curves collapsed.

- **Speed selection**: Table F.1 shows significant correlations between the mean speed curves, mean speed straight and mean speed narrowings. This indicates that drivers who drove faster did this for all track sections.
- **Initial steer action and curve driving precision**: Table F.1 shows significant correlations between AS error, SDLP curves and mean speed curves. This indicates that a higher AS error value reduced the curve driving precision of the driver. Moreover, drivers who took a higher speed into and through the curves were more sensitive for making a higher AS error and larger SDLP curves.
- **Turn-in driving line**: Table F.1 shows a significant correlation between turn-in LP and mean straights LP. This indicates that the driver's lane-keeping bias also affected their turn-in LP. Furthermore, Table F.1 shows a significant correlation between turn-in distance and mean speed curves. This means that drivers who adopted a higher speed into and through the curves also turned into the curve earlier.
- **Track-out driving line**: Table F.1 shows significant correlations between track-out distance, track-out LP and TLX mental workload. This indicates that the adopted driving line exiting the curve played a role on the perceived mental workload of the driving task. In other words, drivers who used a larger distance and width of the track to straighten the vehicle when exiting the curve also noted lower perceived mental workload.
  Furthermore, Table F.1 shows significant correlations between track-out distance, steering integral curves and steering integral curve recovery, meaning that drivers who used a larger track-out distance had lower control activity in the curve and during the curve exit section.
  Thirdly, Table F.1 shows a significant correlation between track-out distance and throttle variance curves, indicating that drivers who used more distance to straighten the vehicle during the curve exit had a more throttle activity in the curves.
  Lastly, Table F.1 shows a significant correlation between the track-out LP and the mean horizontal gaze from the reference curve exits. Indicating that the drivers who adopted a wider line exiting the curve also spend a larger fraction of their gazes inspecting higher gaze locations; in other words, more gaze time towards the outer side of the track.
  To conclude, these observations show how the adopted driving when coming out of the curve affected vehicle stability both in and after the curve, was supported by the horizontal gaze, allowed for higher acceleration for the upcoming straight and showed that drivers who adopted this driving line rated a lower overall mental workload.
- **Lead time and curve exiting**: Table F.1 shows significant correlations between constrained lead time curves and steering integral curve recovery. This suggests that drivers who had a higher lead time had a higher vehicle stability when exiting the curve.
- **Driving control activity**: Table F.1 shows consistent significant correlation between the control activity measures amongst the different track sections: curves, straights and narrowings, indicat-

ing that drivers who used a more active control activity did so for all track sections.

- **Driving precision**: Table F.1 shows consistent significant correlations between the precision measures of the curve and straight-road driving sections. This indicates that drivers who were more precise did so for the curves and straight-road sections.
- **Driving precision and gaze dispersion during narrowings**: Table F.1 shows significant correlations between SDLP narrowings, SD horizontal gaze from the reference narrowings and mean speed narrowings. This indicates that less precise drivers had a higher horizontal gaze dispersion and adopted a lower speed during the narrowings.

4
Discussion

In this work, we investigated which vehicle-control-related measures (i.e., driving skill measures), trajectory-planning and speed-related measures (i.e., driving style measures), and eye-movement measures allow to statistical discrimination between experienced and inexperienced drivers. Such knowledge is required to assess human driving ability effectively and could, amongst other applications, allow future ADS to integrate the drivers' driving characteristics into the design. A novel method was developed utilizing curve driving, straight-road driving and driving through road narrowings to capture a wide variety of conventional and newly introduced measures. A systematic comparison was made between inexperienced and experienced drivers to determine the validity of the measures. The study was complemented with two expert drivers serving as a benchmark.

The obtained driving skill measures, primarily designed to capture (1) driving precision and (2) control activity, showed no significant differences between the experienced and inexperienced drivers during during any of the track sections. Similarly, the effect sizes demonstrated that the driving skill measures were not suitable for differentiating between experienced and inexperienced. In the case of the expert drivers, the steering control activity was substantially lower than those of the experienced and inexperienced drivers during all track sections while maintaining a similar level of control precision. The work of Irmscher et al. [91] mentioned a similar difference in steering control activity but between inexperienced and expert drivers.

In contrast to the driving skill measures, the driving style measures revealed significant differences between the experienced and inexperienced drivers. Our results showed that the experienced drivers adopted a significantly higher mean speed on the straights and narrowings. Although no statistically significant differences were found for the mean speed through the curves, the experienced drivers showed a significantly larger speed increase over the two tightest curves than the inexperienced drivers, caused by their significantly higher throttle activation. Overall, the driving speed measures showed to be the most effective measures for differentiating between the experienced and inexperienced drivers. This relation between driving experience and higher speed selection in a driving simulator environment has also been stated by other work (e.g. [92]).

For the braking behavior, it was found that the experienced drivers adopted a significantly more abrupt braking style when entering the tighter two curves (R1 and R2) than the inexperienced drivers. Our results showed no differences in the first braking moment of the experienced and inexperienced drivers, which was not consistent with the results of Muttart et al. [77]. The reason for this may be that experienced drivers preferred a higher driving pace over a smooth ride, or perhaps because the inexperienced drivers were aware of their lack of driving skill, thereby adopting a braking strategy that matched the experienced drivers who approached the curves faster. Even though the expert drivers adopted the highest speeds on the straights, they showed a similar, less abrupt braking style as the inexperienced drivers when entering the curves. This may be explained by their (1) more anticipatory speed regulation due to better trajectory planning skills [77], (2) their better understanding of the adverse effects of abrupt braking on vehicle stability [79, 93], or (3) both. Interestingly, the expert drivers did not start braking earlier when approaching the curves, a measure that may reflect more anticipatory speed regulation [20]. It could have been that the expert drivers adopted more coasting when approaching the curves or were capable of more optimising their braking input over the curve entry, diminishing the need for abrupt brake inputs.

The eye-tracking results of the road narrowings showed that the experienced and inexperienced drivers significantly reduced their vertically gaze dispersion compared to the straights. However, for the horizontal mode, only a significant reduction in gaze dispersion was observed for the experienced drivers. Since the recording lengths of the narrowings and straights were not the same (due to differences in track section length), it is not appropriate to directly compare the standard deviation of the straight with the narrowings. The mean absolute horizontal and vertical gaze results, which are expected to be less sensitive for the recording length, showed an identical difference in the gaze adaption between the experienced and inexperienced drivers (as mentioned above). In line with these observations, for both measures, a significant difference was found between the horizontal gaze dispersion adaptation (i.e., delta SD horizontal gaze and delta mean abs. horizontal gaze) of the experienced and inexperienced drivers. This result was contrary to our expectation that inexperienced drivers would be more sensitive for the induced stress/mental workload from the narrowing resulting in a larger visual gaze tunneling. An explanation may be that the experienced drivers are more effective in adjusting their gaze strategy to the driving circumstances, while the inexperienced drivers adopted a more fixed visual search strategy [42, 43]. In more detail, the experienced drivers may felt no need to scan the environment during the narrowings since they perceived no direct threat/risk from the road markers. The lower steering precision during the narrowings (i.e., higher SDLP narrowings) of the inexperienced drivers may have contributed, yet, the differences between the experienced and inexperienced drivers did not reach statistical significance. In addition, on average, both groups managed to reduce their SDLP compared to the straights, which, according to this reasoning, should also have allowed for a reduction in horizontal gaze dispersion of the inexperienced drivers. Overall, the adaptation in visuals gaze strategy during the narrowing showed to be an effective measure to differentiate between the experienced and inexperienced driver, but future work could examine the underlying reason for this behavior difference between the experienced and inexperienced drivers.

4.1. Style-skill interaction

Overall, our results showed that the experienced (and expert) drivers adopted a higher speed than the inexperienced drivers. Moreover, the results of the road narrowings showed that only the inexperienced drivers significantly reduced their speed compared to the straights. It is expected that the experienced drivers, with more developed driving skill, adopted their speed (i.e., driving style) to maintain a certain safety margin. In other words, they adjusted their driving style to guarantee a certain level of vehicle control. This risk compensation behavior has also been stated by other work (e.g. [1, 94, 95]). A similar but opposite effect has been found for elderly drivers, who adapt their driving speed (i.e., driving style) to compensate for their lack of driving ability [78]. However, in the case of elderly drivers, the driving style adaptation is driven by impaired and declined perception, cognitive functions and motor abilities [28–31], and for experienced drivers, it seems to be driven by their developed driving skill.

4.2. Curve driving line & eye-movements of the expert drivers

The results capturing the driving line through the curve (belonging to the driving style measures) showed no significant differences between the experienced and inexperienced drivers. However, the expert drivers adopted more of a racing line through the curves, which primarily seemed to benefit the vehicle curve recovery activity during the curve exit sections. The track-out distance and track-out LP showed how the expert drivers used a larger part of the track (both width and length) after the curve to straighten the vehicle and used less steering activity, i.e., a lower steering integral curve recovery, to stabilize the vehicle for the upcoming straight. In line with this statement, our results showed a positive and significant correlation between track-out distance, steering integral curves and steering integral curve recovery. In addition, the results demonstrated that the expert drivers had a larger throttle variance in the curve compared to experienced and inexperienced drivers. Similarly, a positive and significant correlation was obtained between track-out distance and throttle variance curves. Thus, it is expected that the expert drivers' wider curve exiting driving line positively affected their curve and curve exit control activity and allowed faster acceleration out of the curves [96]. This demonstrates how driving expertise affected both driving style and driving skill.

The horizontal and vertical gaze movements for the curve exit sections revealed that the expert drivers spent a larger fraction of their horizontal gaze towards the outer side of their reference and shifted their vertical gaze location more upwards than the experienced and inexperienced drivers. Moreover, a positive and significant correlation was obtained between mean horizontal gaze from the reference for the curve exit and track-out LP. This gaze behavior during the curve exit is expected to support the wider driving line, but further research is needed to validate this statement.

The driving line of the expert drivers also showed how they positioned the vehicle towards the inner lane before exiting the curves R2-R4. Future work needs to point out if this is indeed the case and whether this behavior can potentially be explained by the expert drivers adopting a double apex driving line through the curves or other trajectory (e.g. [97]). Moreover, if this vehicle positing at the inner lane before exiting the curve were part of their operation strategy, it would demonstrate the expert drivers' rich memory representation of the lap since they account for the road geometry beyond the current range in view [36]. It would be interesting to investigate how it is linked to their visual strategy in the curve and if it was indeed learned throughout the course of the experiment.

The eye-tracking results for the curves showed that the expert drivers had the largest variability in horizontal scanning strategy between the different curves. These results are consistent with the results of Land et al. [36], who found that an expert driver while racing on a closed-track had a horizontal offset from the tangent point that changed for different curves, meaning that different curves were treated slightly different. However, the eye-tracking data required a correction using the median gaze location on the straights, so inter-individual gaze strategy differences on the straights also affected the gaze distributions for the curves. Furthermore, the eye-tracker data seemed to contain quite some inaccuracies; thus, a validation step may be required.

4.3. Eye–steering cross-correlation: lead times

The introduced cross-correlation between horizontal gaze and steering angle showed that, on average, gaze led the steering input during curve driving. However, due to large inter-and intra-individual variability, the cross-correlation was inadequate for describing differences between the experienced and inexperienced drivers. Similarly, the variability in the corresponding correlation coefficient shows that eye–steering correlation was not highly consistent. Chattington et al. [88] reported that in natural driving on the open road, eye–steering coordination is highly consistent, but that at least 60 s recordings, translating to five curve cycles in their study, are required to describe this eye–steering coordination consistently. For this study, the lead times were calculated per curve, and the average recording lengths ranged from 13.1 s (for R1) to 17.8 s (for R4), which means that this criteria was not met. Furthermore, it is expected that the inaccuracies of the eye-tracker also negatively affected the reliability of the cross-correlation and thus also lead time. To elaborate on this, specific participants showed consistent positive correlations between the horizontal gaze and steering angle, which translates to an eye-steering behavior in which the driver shifts his/her gaze away from the curve center, opposite to its steering input during curve driving. Such behavior is very uncommon and is expected to be caused by wrong calibration or inaccuracies of the eye-tracker. Thus, future work could replicate this analysis using a more accurate eye-tracker and adapted driving scenario to determine if the lead times differ between experienced and inexperienced drivers and may be an effective measure to distinguish both groups.

The average obtained lead times using all participants ranged from 0.58 to 1.36 s for the different curve radii. This is in line with the reported lead time of ca. 1-2 s in literature [35, 39, 88, 98, 99]. Our results showed a significant increase in lead time with increasing curve radius, which stagnated at curve R3. This observation was unexpected. Lethonen et al. [40] stated that cognitive load led to shorter anticipatory look-ahead lead time that occurred many seconds before the curve. This effect may also explain the reduction in lead time for tighter curves. However, as stated above, future work is required to validate these results using a more accurate eye-tracker.

4.4. The implications of the results for automated driving systems applications

Since the conducted study consisted of two separate experiments, manual and automated driving, an obvious follow-up step would be to investigate how the results of this study correlate with drivers' take-over quality in automated driving scenarios. Such knowledge could be valuable for ADS to predict the operator's take-over quality or model their driving behavior during a take-over scenario (see Appendix P for considerations for predicting take-over performance). In addition, this knowledge may allow designers to adapt the settings of a take-over request to account for the drivers' driving ability characteristics. Deviation from a fixed design envelope to a more adaptive take-over design may enhance safety, comfort, and the availability of the automation since the system is better aware of the variations in drivers' characteristics (for more details about adaptive take-over systems, see Appendix P).

While for manual driving, potential skill benefits may be suppressed by the operator's driving style (i.e., speed selection), for automated driving, the system is in charge of the 'driving style', thereby determining the take-over condition. Hence, without any driver centred ADS adaptions, it is expected that more skilled drivers would allow higher take-over quality, especially during more safety-critical take-over requests. Yet, higher-skilled drivers may be less motivated to attain a higher level of driver readiness, allowing their motives, attitude, personal traits and lifestyles, or 'automated driving operation style' to diminish their potential skill benefits. Future work could further explore these topics.

5

Limitations

The findings of this study have to be seen in the light of some limitations. These limitations are stated below and are ordered by topic: participants, apparatus and others.

- With a sample size of 31 participants and the smallest experimental group for the comparison of only 13 participants, the study might not have had enough power to reliably detect an effect associated with driving experience. It is recommended for future studies to replicate the study with a higher sample size.
- The study sample size merely consisted of Porsche AG employees, leading to a bias, as this group is professionally related to (sport)cars and is expected to have an above-average affinity with driving. In addition, a few inexperienced and experienced participants mentioned to participate in online sim-racing in their free time, which may also have affected their driving performance/behavior during this study. Overall, the participant group of this work may be less representative of the average (German) driver. It is recommended for future work to incorporate questions about home sim-driving/racing into the demographic questionnaire.
- The overall results of this study showed limited differences between the experienced and inexperienced drivers. In addition to the aforementioned reasoning, it can be argued that the selection criteria for inexperienced drivers could have also contributed: according to Lajunen et al. [62], novice drivers can be classified by less than 25,000 km lifetime driving experience and moderately experienced drivers by 25,000-70,000 km. Based on the assumption that the years of driving experience were equally distributed among the inexperienced drivers, it is expected that at least a few drivers could be classified as moderately experienced drivers. So, the inexperienced drivers may not all have been entirely inexperienced/novice.
- The difference between the experienced and inexperienced drivers was not solely limited to the driving experience but also included apparent age differences. Age is a demographic variable frequently found to be related to risky driving. For example, younger drivers violate the law more often than older drivers [100, 101].
- The expert driver group of this study consisted of one professional test driver and one ex-professional racing driver. It is argued that both drivers can be classified as highly experienced drivers due to their high amount of practice and driving training. However, the goal of their driving trainings may have differed, potentially affecting their driving style, driving skill and eye movements differently.
- The study was performed in a driving simulator rather than in an actual vehicle. However, there is evidence that driving-simulator measures are predictive for on-the-road performance (e.g. [102]).
- In this work, the simulator data was logged at 10 Hz. This output frequency was considered insufficient to accurately determine jerk (and acceleration) measures. Bellem et al. [103] mentioned that these measures were prerequisites to differentiate between different driving styles. Future work could integrate these measures to further deepen the analysis into driving style.
- The results indicated that the 150 m (to approximately match the 6 s of [36, 41]) before the curve was not sufficient to capture all braking behavior. However, since the vast majority of the braking behavior was captured by the 150 m, it is expected to have a negligible effect on the results.
- The vehicle dynamics software in this study was based on the all-electric Porsche Taycan Turbo.

With a maximum power of 626 hp and maximum torque of 850 Nm (see Appendix M), the modelled vehicle well outperforms the average vehicle. Operating such a high performance vehicle may required the drivers to slightly adapt their brake and throttle control. In addition, after the experiment a few participants mentioned to never have driven an electric vehicle before. These two observations regarding the vehicle (dynamics) characteristics may have influenced the results.

- During the experiment, drivers solely relied on their vision to detect if the vehicle was on or off-track. The surface coefficient in the simulator environment was the same for on and off-track, meaning the drivers could not detect if the vehicle was driving outside of the driving road via motion cues. In addition, there were no vibrations on the steering wheel or sound effects informing the driver that the vehicle was driving on the driving lines or off-track. This can be observed in the results, showing that many drivers consistently drove slightly off-track, e.g. when approaching the left-hand curve and slightly driving offtrack with the right outer tires.
- Due to the lack of precision of eye-tracking data, a correction was required to include the data in the analysis. Therefore, it was not possible to determine the exact gaze locations of the drivers. The median gaze location on the straights was used as a reference to correct the eye-tracking data. Thus, individual differences in gaze strategy on the straights also affected the observed visual behavioral changes during curve driving. Furthermore, it is expected that wrong pupil detection and malfunctioning of the eye-tracker hardware compromised the accuracy of the eye-tracking data.
- The introduced manual driving scenario allows capturing a wide variety of measures. Still, it does not include interaction with surrounding traffic, e.g., following distance (e.g. [14]) or hazard perception (e.g. [13, 78, 104]). Hazard perception, i.e. the ability to anticipate potentially dangerous road and traffic situations, is consistently linked to crash risk [105], and therefore an important aspect of driving. Since this is not captured in this driving scenario, it can be considered a limitation of the proposed driving scenario. Jet, both methods may be very complementary to each other.

6 Conclusion

- This high-fidelity driving simulator study has shown that the assessment of lower-order driving skill components, commonly referred to as driving skill, were insufficient to differentiate between experienced and inexperienced drivers.
- The adopted driving speed and braking style, classified as driving style measures, showed to be effective measures to differentiate between experienced and inexperienced drivers.
- The results highlight the possibility that the experienced drivers adapted their speed (i.e. driving style) to increase the task demand, potentiality suppressing their vehicle-control performance (i.e. driving skill measures).
- The road narrowing was an effective method to induce a gaze adaptation compared to straight road driving, against expectation, only resulting in a horizontal gaze dispersion reduction (i.e. gaze tunneling) for the experienced and not the inexperienced drivers. So, this newly introduced measure showed to be suitable for differentiating between the experienced and inexperienced drivers.
- The obtained eye-steering coordination, i.e. lead time, showed to be inadequate for describing differences between the experienced and inexperienced drivers, which may have been caused by eye-tracking measurement inaccuracies, the layout of the driving task and strong intra-individual variability in looking behavior.
- The driving skill results of the expert drivers showed similar driving precision to the inexperienced and experienced drivers but consistently used less steering control activity.
- The results showed how the experts' more of a racing line through the curve (i.e. driving style) increased vehicle stability and reduced control activity, especially when exiting curves, demonstrating how their expertise affected their driving style and driving skill. The newly introduced 'track-out distance', 'track-out lateral position' and 'steering integral curve recovery' measures demonstrated to be suitable for capturing this behavior.
- During the curve exits, the horizontal gaze modes showed that the expert drivers spent a larger fraction of their gaze towards the outer side of their references and vertically above their references, which is argued to support their wider curve exiting driving line.
- The eye-tracking results showed that expert drivers adopted a more variable horizontal gaze strategy between different curves, however, validation is required because of the inaccuracies in the eye-tracking measurements.

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A

Appendix A: Curve driving results

This appendix presents the driving style, driving skill and perceptual skill measures captured during curve driving for all three experimental groups. Section A.1 presents the driving style and driving skill measures for each curve radius separately, including a group comparison between inexperienced and experienced drivers. Section A.2 gives an overview of the combined driving style and driving skill results using all participants for all radii. Section A.3 lists the perceptual skill measures for each curve radius separately, including a group comparison between inexperienced and experienced drivers, again, followed by an overview of all the average results using all participants for all radii (see Section A.4).

A.1. Curve driving style and skill measures for curve R1-R4

Table A.1: Mean and standard deviation of the driving style and driving skill measures captured during curve driving (in R1) for the three experimental groups. The table also includes a group comparison between inexperienced and experienced drivers. The (∘) markers indicate the driving style measures, and the (•) markers indicate the driving skill measures.

Curve R1 (with an inner radius = 40 m)								
Measure	Experimental group						Group comparison	
	Inexperienced		Experienced		Expert		Inexp. vs. Exp.	
	mean	std	mean	std	mean	std	p-value	Cohen's d
∘ Mean speed curves (km/h)	55.49	5.48	57.76	5.80	59.56	2.14	0.29	-0.40
∘ Mean throttle position curves (0-1)	0.11	0.04	0.12	0.02	0.31	0.22	0.54	-0.22
∘ Throttle activation curves (0-1)	0.63	0.21	0.79	0.10	0.69	0.31	**0.01**	-0.94
∘ Brake activation curves (0-1)	0.05	0.06	0.01	0.01	0.08	0.12	**0.01**	1.04
∘ Speed difference curves (end-begin) (Δkm/h)	4.88	5.56	8.29	2.34	12.64	1.55	**0.04**	-0.77
∘ First braking moment curve entries (s)	4.86	1.31	4.91	1.19	5.13	0.97	0.92	-0.04
∘ Max. brake pedal position curve entries (0-1)	0.27	0.06	0.32	0.05	0.27	0.06	**0.01**	-1.03
∘ Braking smoothness curve entries (-)	0.02	0.01	0.02	0.01	0.02	0.02	**0.01**	-1.37
∘ Turn-in distance (m)	25.81	6.27	22.79	4.06	22.11	0.02	0.13	0.56
∘ Turn-in LP (m)	0.69	0.25	0.73	0.19	0.81	0.27	0.61	-0.19
∘ Track-out distance (m)	10.40	5.77	9.12	2.98	16.28	3.43	0.45	0.27
∘ Track-out LP (m)	0.28	0.35	0.30	0.29	0.66	0.01	0.85	-0.07
∘ Mean LP curves (m)	-0.19	0.25	-0.15	0.17	-0.28	0.02	0.58	-0.20
• Throttle variance curves (0-1)	0.00	0.00	0.00	0.00	0.05	0.06	0.36	0.33
• Steer steady curves (0-1)	0.04	0.04	0.04	0.03	0.07	0.00	0.94	0.03
• Steering integral curves (deg)	223.77	31.24	226.48	33.41	190.26	12.31	0.83	-0.08
• Anticipatory steering (AS) error (deg)	4.34	11.36	7.08	8.03	3.66	10.02	0.45	-0.27
• SDLP curves (m)	0.27	0.12	0.30	0.16	0.29	0.12	0.52	-0.25
• Steering integral curve recovery (deg)	43.79	21.10	46.39	21.61	15.45	3.67	0.75	-0.12
• Steer steady curve recovery (0-1)	0.17	0.08	0.22	0.09	0.30	0.05	0.17	-0.54

Table A.2: Mean and standard deviation of the driving style and driving skill measures captured during curve driving (in R2) for the three experimental groups. The table also includes a group comparison between inexperienced and experienced drivers. The (∘) markers indicate the driving style measures, and the (•) markers indicate the driving skill measures.

Curve R2 (with an inner radius = 80 m)								
Measure	Experimental group						Group comparison	
	Inexperienced		Experienced		Expert		Inexp. vs. Exp.	
	mean	std	mean	std	mean	std	p-value	Cohen's d
∘ Mean speed curves (km/h)	71.46	6.34	73.39	7.20	76.19	0.16	0.46	-0.29
∘ Mean throttle position curves (0-1)	0.11	0.04	0.13	0.03	0.24	0.14	0.09	-0.63
∘ Throttle activation curves (0-1)	0.68	0.18	0.82	0.10	0.74	0.18	**0.01**	-0.94
∘ Brake activation curves (0-1)	0.03	0.03	0.02	0.01	0.05	0.06	0.10	0.59
∘ Speed difference curves (end-begin) (Δkm/h)	7.38	6.70	11.48	3.70	14.60	2.77	**0.05**	-0.74
∘ First braking moment curve entries (s)	4.25	1.31	4.26	1.30	3.82	0.35	0.98	-0.01
∘ Max. brake pedal position curve entries (0-1)	0.21	0.04	0.26	0.05	0.21	0.04	**0.01**	-1.14
∘ Braking smoothness curve entries (-)	0.01	0.00	0.02	0.00	0.01	0.01	**<0.01**	-1.20
∘ Turn-in distance (m)	24.61	3.91	24.13	3.28	27.17	0.84	0.72	0.13
∘ Turn-in LP (m)	0.67	0.20	0.66	0.18	0.84	0.17	0.94	0.03
∘ Track-out distance (m)	12.69	4.68	10.04	3.38	22.16	7.55	0.09	0.64
∘ Track-out LP (m)	0.21	0.22	0.06	0.20	0.49	0.10	0.08	0.68
∘ Mean LP curves (m)	-0.23	0.21	-0.26	0.22	-0.55	0.13	0.66	0.17
• Throttle variance curves (0-1)	0.00	0.00	0.00	0.00	0.05	0.07	0.52	-0.25
• Steer steady curves (0-1)	0.07	0.03	0.08	0.02	0.12	0.06	0.39	-0.32
• Steering integral curves (deg)	145.87	22.71	146.66	23.58	115.69	6.26	0.93	-0.03
• Anticipatory steering (AS) error (deg)	-2.43	2.74	-0.40	2.75	-6.81	3.40	0.06	-0.74
• SDLP curves (m)	0.22	0.06	0.24	0.13	0.19	0.02	0.57	-0.23
• Steering integral curve recovery (deg)	27.66	9.39	30.27	11.02	14.21	1.93	0.50	-0.26
• Steer steady curve recovery (0-1)	0.19	0.07	0.20	0.10	0.25	0.08	0.66	-0.17

Table A.3: Mean and standard deviation of the driving style and driving skill measures captured during curve driving (in R3) for the three experimental groups. The table also includes a group comparison between inexperienced and experienced drivers. The (∘) markers indicate the driving style measures, and the (•) markers indicate the driving skill measures.

Curve R3 (with an inner radius = 120 m)								
Measure	Experimental group						Group comparison	
	Inexperienced		Experienced		Expert		Inexp. vs. Exp.	
	mean	std	mean	std	mean	std	p-value	Cohen's d
∘ Mean speed curves (km/h)	79.90	7.75	84.14	8.30	89.96	2.84	0.17	-0.53
∘ Mean throttle position curves (0-1)	0.11	0.03	0.12	0.03	0.17	0.12	0.61	-0.19
∘ Throttle activation curves (0-1)	0.79	0.11	0.85	0.14	0.81	0.12	0.26	-0.45
∘ Brake activation curves (0-1)	0.02	0.02	0.01	0.01	0.02	0.02	**0.04**	0.75
∘ Speed difference curves (end-begin) (Δkm/h)	11.93	5.59	13.03	6.68	12.60	11.39	0.64	-0.18
∘ First braking moment curve entries (s)	3.66	1.13	3.65	1.32	3.69	0.32	0.97	0.01
∘ Max. brake pedal position curve entries (0-1)	0.18	0.04	0.21	0.07	0.16	0.01	0.20	-0.52
∘ Braking smoothness curve entries (-)	0.01	0.00	0.02	0.01	0.01	0.00	0.23	-0.48
∘ Turn-in distance (m)	23.52	3.00	23.18	5.08	27.83	4.72	0.83	0.08
∘ Turn-in LP (m)	0.64	0.19	0.64	0.20	0.76	0.24	0.99	-0.01
∘ Track-out distance (m)	12.89	5.94	10.42	4.31	30.08	13.21	0.20	0.47
∘ Track-out LP (m)	0.08	0.26	0.00	0.13	0.44	0.11	0.28	0.39
∘ Mean LP curves (m)	-0.10	0.24	-0.18	0.24	-0.46	0.27	0.35	0.36
• Throttle variance curves (0-1)	0.00	0.00	0.00	0.00	0.05	0.06	0.80	-0.10
• Steer steady curves (0-1)	0.11	0.05	0.11	0.03	0.16	0.05	0.61	0.18
• Steering integral curves (deg)	121.87	23.26	121.99	16.59	95.13	4.16	0.99	-0.01
• Anticipatory steering (AS) error (deg)	-1.11	3.77	-0.24	4.17	-1.46	2.86	0.57	-0.22
• SDLP curves (m)	0.19	0.04	0.19	0.06	0.17	0.04	1.00	0.00
• Steering integral curve recovery (deg)	23.10	8.33	24.46	7.91	12.19	2.23	0.66	-0.17
• Steer steady curve recovery (0-1)	0.20	0.07	0.19	0.06	0.21	0.11	0.62	0.19

Table A.4: Mean and standard deviation of the driving style and driving skill measures captured during curve driving (in R4) for the three experimental groups. The table also includes a group comparison between inexperienced and experienced drivers. The (∘) markers indicate the driving style measures, and the (•) markers indicate the driving skill measures.

Curve R4 (with an inner radius = 160 m)								
Measure	Experimental group						Group comparison	
	Inexperienced		Experienced		Expert		Inexp. vs. Exp.	
	mean	std	mean	std	mean	std	p-value	Cohen's d
∘ Mean speed curves (km/h)	86.23	8.11	91.32	8.26	99.96	6.55	0.11	-0.62
∘ Mean throttle position curves (0-1)	0.10	0.03	0.11	0.02	0.19	0.18	0.25	-0.43
∘ Throttle activation curves (0-1)	0.70	0.16	0.84	0.13	0.67	0.15	**0.02**	-0.94
∘ Brake activation curves (0-1)	0.01	0.02	0.00	0.00	0.01	0.02	0.06	0.69
∘ Speed difference curves (end-begin) (Δkm/h)	8.58	4.74	11.87	5.68	10.18	13.71	0.11	-0.63
∘ First braking moment curve entries (s)	3.69	1.28	3.38	1.43	2.59	0.91	0.54	0.24
∘ Max. brake pedal position curve entries (0-1)	0.15	0.04	0.17	0.07	0.10	0.07	0.35	-0.37
∘ Braking smoothness curve entries (-)	0.01	0.00	0.01	0.01	0.01	0.00	0.20	-0.52
∘ Turn-in distance (m)	25.69	6.58	22.62	4.83	27.74	0.04	0.16	0.52
∘ Turn-in LP (m)	0.67	0.21	0.61	0.19	0.89	0.22	0.44	0.29
∘ Track-out distance (m)	15.04	6.20	13.03	4.83	27.24	4.25	0.34	0.36
∘ Track-out LP (m)	0.15	0.20	0.10	0.12	0.38	0.14	0.37	0.32
∘ Mean LP curves (m)	-0.07	0.20	-0.13	0.22	-0.37	0.27	0.42	0.31
• Throttle variance curves (0-1)	0.00	0.00	0.00	0.00	0.04	0.06	0.73	0.13
• Steer steady curves (0-1)	0.17	0.07	0.17	0.04	0.23	0.08	0.76	0.11
• Steering integral curves (deg)	99.03	23.78	99.25	14.68	80.73	16.07	0.98	-0.01
• Anticipatory steering (AS) error (deg)	-1.73	1.91	-1.75	1.97	-2.05	0.12	0.98	0.01
• SDLP curves (m)	0.18	0.06	0.17	0.04	0.19	0.02	0.61	0.19
• Steering integral curve recovery (deg)	20.10	6.44	19.89	7.07	11.18	0.62	0.94	0.03
• Steer steady curve recovery (0-1)	0.20	0.07	0.23	0.09	0.18	0.06	0.40	-0.33

A.2. Overview of the driving style and skill measures for all curves

Table A.5: Overview of the mean and standard deviation of the perceptual skill measures captured through the different curves R1-R4. The calculation included all participants. The (◦) markers indicate the driving style measures, and the (•) markers indicate the driving skill measures.

Measure	Curve							
	R1 (40 m)		R2 (80 m)		R3 (120 m)		R4 (160 m)	
	mean	std	mean	std	mean	std	mean	std
◦ Mean speed curves (km/h)	56.70	5.52	72.57	6.53	82.33	8.14	89.25	8.71
◦ Mean throttle position curves (0-1)	0.13	0.07	0.13	0.05	0.12	0.04	0.11	0.05
◦ Throttle activation curves (0-1)	0.70	0.19	0.74	0.16	0.82	0.12	0.76	0.16
◦ Brake activation curves (0-1)	0.03	0.05	0.03	0.03	0.01	0.01	0.01	0.02
◦ Speed difference curves (end-begin) (Δkm/h)	6.81	4.79	9.56	5.83	12.43	6.17	10.06	5.74
◦ First braking moment curve entries (s)	4.90	1.21	4.23	1.24	3.66	1.16	3.49	1.32
◦ Max. brake pedal position curve entries (0-1)	0.29	0.06	0.23	0.05	0.19	0.05	0.16	0.05
◦ Braking smoothness curve entries (-)	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.00
◦ Turn-in distance (m)	24.30	5.37	24.57	3.53	23.66	4.10	24.54	5.83
◦ Turn-in LP (m)	0.72	0.22	0.68	0.19	0.65	0.19	0.66	0.21
◦ Track-out distance (m)	10.25	4.86	12.19	5.12	12.96	7.30	14.98	6.39
◦ Track-out LP (m)	0.31	0.32	0.16	0.23	0.07	0.23	0.14	0.18
◦ Mean LP curves (m)	-0.18	0.21	-0.26	0.22	-0.16	0.25	-0.11	0.22
• Throttle variance curves (0-1)	0.01	0.02	0.01	0.02	0.01	0.02	0.00	0.01
• Steer steady curves (0-1)	0.04	0.03	0.08	0.03	0.11	0.04	0.18	0.06
• Steering integral curves (deg)	222.75	31.88	144.25	23.23	120.19	20.64	97.95	19.97
• Anticipatory steering (AS) error (deg)	5.44	9.78	-1.86	3.14	-0.77	3.81	-1.76	1.84
• SDLP curves (m)	0.28	0.14	0.23	0.09	0.19	0.05	0.18	0.05
• Steering integral curve recovery (deg)	43.05	21.58	27.89	10.38	22.97	8.28	19.44	6.75
• Steer steady curve recovery (0-1)	0.20	0.09	0.20	0.08	0.20	0.07	0.21	0.08

A.3. Perceptual skill measures for curve R1-R4

Table A.6: Mean and standard deviation of the perceptual skill measures captured during curve driving (in R1) for the three experimental groups. The table also includes a group comparison between inexperienced and experienced drivers.

Curve R1 (with an inner radius = 40 m)								
Measure	Experimental group						Group comparison	
	Inexperienced		Experienced		Expert		Inexp. vs. Exp.	
	mean	std	mean	std	mean	std	p-value	Cohen's d
Mean horizontal gaze from the reference curve entries (px)	-44.52	19.47	-22.01	19.42	-26.95	3.36	**<0.01**	-1.16
Mean horizontal gaze from the reference curves (px)	-87.78	61.94	-48.99	39.30	-83.98	22.03	0.05	-0.73
Mean horizontal from the reference curve exits (px)	5.56	19.67	-0.43	20.01	23.76	10.14	0.43	0.30
SD horizontal gaze from the reference curve entries (px)	42.15	12.80	39.06	14.26	33.36	16.41	0.55	0.23
SD horizontal gaze from the reference curves (px)	56.71	8.55	47.79	13.93	52.77	8.12	0.06	0.79
SD horizontal gaze from the reference curve exits (px)	29.48	26.03	33.93	32.36	22.27	2.92	0.69	-0.15
Mean vertical gaze from the reference curve entries (px)	4.15	31.17	21.23	16.18	7.73	16.30	0.07	-0.67
Mean vertical gaze from the reference curves (px)	4.09	47.05	19.43	31.25	33.14	40.13	0.30	-0.38
Mean vertical gaze from the reference curve exist (px)	9.79	29.74	17.76	21.61	44.75	19.59	0.41	-0.30
SD vertical gaze from the reference curve entries (px)	47.93	27.80	47.91	21.36	24.66	14.15	1.00	0.00
SD vertical gaze from the reference curves (px)	27.01	12.40	21.16	5.70	19.77	10.89	0.11	0.58
SD vertical gaze from the reference curve exits (px)	63.89	28.25	57.54	20.53	48.70	22.92	0.49	0.25
Lead time curves (s)	0.69	0.81	0.47	0.82	0.48	0.30	0.49	0.26
Correlation coefficient lead time curves (R)	-0.72	0.24	-0.57	0.22	-0.77	0.03	0.10	-0.62
Constrained lead time curves (s)	0.48	0.20	0.16	0.51	0.39	0.24	0.12	0.87
Constrained correlation coefficient lead time curves (R)	-0.83	0.07	-0.81	0.05	-0.84	0.02	0.42	-0.34

Table A.7: Mean and standard deviation of the perceptual skill measures captured during curve driving (in R2) for the three experimental groups. The table also includes a group comparison between inexperienced and experienced drivers.

Curve R2 (with an inner radius = 80 m)								
Measure	Experimental group						Group comparison	
	Inexperienced		Experienced		Expert		Inexp. vs. Exp.	
	mean	std	mean	std	mean	std	p-value	Cohen's d
Mean horizontal gaze from the reference curve entries (px)	-37.15	21.67	-26.15	20.17	-25.31	14.12	0.17	-0.52
Mean horizontal gaze from the reference curves (px)	-70.55	54.84	-31.82	37.02	-65.24	19.84	**0.03**	-0.81
Mean horizontal from the reference curve exits (px)	12.16	18.06	9.04	20.50	29.02	17.68	0.67	0.16
SD horizontal gaze from the reference curve entries (px)	35.19	11.29	40.82	14.43	32.32	12.53	0.26	-0.44
SD horizontal gaze from the reference curves (px)	44.68	8.07	39.60	10.44	45.82	18.04	0.16	0.55
SD horizontal gaze from the reference curve exits (px)	23.93	11.90	37.51	54.81	39.97	8.28	0.40	-0.36
Mean vertical gaze from the reference curve entries (px)	0.70	30.43	12.28	14.61	11.13	9.94	0.19	-0.47
Mean vertical gaze from the reference curves (px)	-4.43	44.50	11.27	28.31	33.28	24.39	0.26	-0.41
Mean vertical gaze from the reference curve exist (px)	6.94	28.76	16.51	25.65	33.64	3.71	0.35	-0.35
SD vertical gaze from the reference curve entries (px)	47.00	27.59	42.99	20.35	17.58	10.60	0.66	0.16
SD vertical gaze from the reference curves (px)	30.86	16.51	22.75	7.20	17.05	7.44	0.09	0.61
SD vertical gaze from the reference curve exits (px)	67.08	30.25	59.91	25.29	50.05	29.16	0.49	0.25
Lead time curves (s)	1.07	0.55	0.90	1.14	0.87	0.60	0.63	0.19
Correlation coefficient lead time curves (R)	-0.72	0.30	-0.48	0.29	-0.69	0.05	0.04	-0.80
Constrained lead time curves (R)	0.87	0.40	0.98	0.62	0.66	0.31	0.70	-0.22
Constrained correlation coefficient lead time curves (s)	-0.85	0.07	-0.81	0.05	-0.83	0.08	0.22	-0.58

Table A.8: Mean and standard deviation of the perceptual skill measures captured during curve driving (in R3) for the three experimental groups. The table also includes a group comparison between inexperienced and experienced drivers.

Curve R3 (with an inner radius = 120 m)								
Measure	Experimental group						Group comparison	
	Inexperienced		Experienced		Expert		Inexp. vs. Exp.	
	mean	std	mean	std	mean	std	p-value	Cohen's d
Mean horizontal gaze from the reference curve entries (px)	-39.22	18.52	-23.78	27.29	-24.25	23.24	0.10	-0.68
Mean horizontal gaze from the reference curves (px)	-55.83	55.96	-26.85	36.45	-41.65	12.48	0.11	-0.60
Mean horizontal from the reference curve exits (px)	10.90	18.93	5.89	15.95	21.61	0.68	0.45	0.28
SD horizontal gaze from the reference curve entries (px)	34.21	11.21	42.66	19.98	32.96	8.24	0.19	-0.54
SD horizontal gaze from the reference curves (px)	44.24	9.77	39.95	12.79	37.13	14.19	0.33	0.38
SD horizontal gaze from the reference curve exits (px)	26.16	20.19	29.57	25.17	23.56	1.33	0.70	-0.15
Mean vertical gaze from the reference curve entries (px)	0.79	19.69	11.25	13.50	3.86	2.07	0.10	-0.61
Mean vertical gaze from the reference curves (px)	-1.97	27.49	5.56	26.85	21.47	10.16	0.46	-0.28
Mean vertical gaze from the reference curve exist (px)	15.26	18.44	7.94	27.78	27.58	4.81	0.42	0.32
SD vertical gaze from the reference curve entries (px)	44.60	28.80	42.51	23.80	16.48	16.86	0.83	0.08
SD vertical gaze from the reference curves	32.11 (px)	15.03	26.98	11.41	17.91	15.18	0.31	0.38
SD vertical gaze from the reference curve exits (px)	66.65	27.62	57.21	20.80	46.65	14.00	0.30	0.38
Lead time curves (s)	1.39	0.71	1.28	1.32	1.72	1.16	0.80	0.10
Correlation coefficient lead time curves (R)	-0.67	0.35	-0.48	0.33	-0.66	0.03	0.15	-0.56
Constrained lead time curves (s)	1.21	0.38	1.34	0.76	1.51	1.10	0.68	-0.21
Constrained correlation coefficient lead time curves (R)	-0.87	0.07	-0.80	0.06	-0.80	0.04	**0.04**	-0.95

Table A.9: Mean and standard deviation of the perceptual skill measures captured during curve driving (in R4) for the three experimental groups. The table also includes a group comparison between inexperienced and experienced drivers.

Curve R4 (with an inner radius = 160 m)								
Measure	Experimental group						Group comparison	
	Inexperienced		Experienced		Expert		Inexp. vs. Exp.	
	mean	std	mean	std	mean	std	p-value	Cohen's d
Mean horizontal gaze from the reference curve entries (px)	-40.11	17.53	-27.30	26.48	-22.00	10.20	0.15	-0.58
Mean horizontal gaze from the reference curves (px)	-61.80	56.35	-31.00	33.12	-22.83	10.69	0.08	-0.65
Mean horizontal from the reference curve exits (px)	13.48	17.06	8.53	21.19	23.05	7.18	0.50	0.26
SD horizontal gaze from the reference curve entries (px)	35.19	14.17	42.68	14.00	32.77	24.22	0.17	-0.53
SD horizontal gaze from the reference curves (px)	42.09	8.58	39.38	14.54	36.61	8.64	0.56	0.23
SD horizontal gaze from the reference curve exits (px)	27.27	16.27	43.36	60.12	30.38	13.30	0.37	-0.38
Mean vertical gaze from the reference curve entries (px)	-6.08	25.74	10.87	17.87	4.32	7.54	**0.05**	-0.75
Mean vertical gaze from the reference curves (px)	-12.70	31.63	4.15	31.61	14.30	19.22	0.17	-0.53
Mean vertical gaze from the reference curve exist (px)	-5.83	21.52	4.64	30.38	17.60	12.70	0.31	-0.41
SD vertical gaze from the reference curve entries (px)	47.11	27.03	42.02	19.74	17.43	7.56	0.56	0.21
SD vertical gaze from the reference curves (px)	37.24	17.50	28.67	10.76	21.94	16.21	0.12	0.58
SD vertical gaze from the reference curve exits (px)	62.39	28.16	52.58	23.95	37.40	3.48	0.32	0.37
Lead time curves (s)	1.37	0.65	1.25	1.14	1.81	1.12	0.74	0.13
Correlation coefficient lead time curves (R)	-0.71	0.36	-0.47	0.30	-0.49	0.06	0.06	-0.72
Constrained lead time curves (s)	1.37	0.78	0.97	1.86	2.79	0.68	0.53	0.29
Constrained correlation coefficient lead time curves (R)	-0.86	0.06	-0.81	0.07	-0.79	0.04	0.12	-0.67

A.4. Overview of the perceptual skill measures for all curves

Table A.10: Overview of the mean and standard deviation of the perceptual skill measures captured through the different curves R1-R4. The calculation included all participants.

Measure	Curve							
	R1 (40 m)		R2 (80 m)		R3 (120 m)		R4 (160 m)	
	mean	std	mean	std	mean	std	mean	std
Mean horizontal gaze from the reference curve entries (px)	-33.95	21.57	-31.77	20.88	-31.78	23.42	-33.57	22.05
Mean horizontal gaze from the reference curves (px)	-71.27	54.07	-53.97	49.32	-42.76	47.99	-46.37	47.92
Mean horizontal from the reference curve exits (px)	4.22	19.82	11.94	19.10	9.49	17.25	12.02	18.48
SD horizontal gaze from the reference curve entries (px)	40.28	13.34	37.37	12.71	37.67	15.60	38.17	14.63
SD horizontal gaze from the reference curves (px)	52.71	11.64	42.62	9.69	41.99	11.22	40.60	11.26
SD horizontal gaze from the reference curve exits (px)	30.88	27.71	30.66	36.40	27.42	21.48	34.22	40.58
Mean vertical gaze from the reference curve entries (px)	11.55	25.89	6.23	24.20	5.38	17.12	1.70	23.02
Mean vertical gaze from the reference curves (px)	12.39	40.47	4.59	38.05	2.70	26.62	-3.89	31.68
Mean vertical gaze from the reference curve exist (px)	15.38	26.80	12.68	27.03	12.99	22.53	0.07	25.57
SD vertical gaze from the reference curve entries (px)	46.42	24.69	43.42	24.53	41.91	26.42	43.06	24.00
SD vertical gaze from the reference curves (px)	24.09	10.17	26.57	13.46	29.04	13.71	32.66	15.30
SD vertical gaze from the reference curve exits (px)	60.25	24.58	62.97	27.67	61.40	24.45	56.66	25.99
Lead time curves (s)	0.58	0.78	0.99	0.83	1.36	1.00	1.35	0.89
Correlation coefficient lead time curves (R)	-0.66	0.23	-0.61	0.31	-0.59	0.34	-0.60	0.34
Constrained lead time curves (s)	0.37	0.35	0.88	0.45	1.28	0.57	1.33	1.32
Constrained correlation coefficient lead time curves (R)	-0.82	0.06	-0.84	0.06	-0.84	0.07	-0.83	0.07

B

Appendix B: Straight-road and narrowing results

This appendix presents the driving style, driving skill and perceptual skill measures captured during straight-road driving and road-narrowing operation.

B.1. Straight-road and narrowing style and skill measures

Table B.1: Mean and standard deviation of the driving style and driving skill measures captured during straight-road and narrowing operation for the three experimental groups. The table also includes a group comparison between inexperienced and experienced drivers. The (∘) markers indicate the driving style measures and the (•) markers indicate the driving skill measures.

Measure	Experimental group						Group comparison	
	Inexperienced		Experienced		Expert		Inexp. vs. Exp.	
	mean	std	mean	std	mean	std	p-value	Cohen's d
∘ Mean speed straights (km/h)	100.56	2.71	105.68	5.36	113.58	2.35	**0.01**	-1.25
∘ Mean LP straights (m)	0.17	0.18	0.21	0.16	0.33	0.00	0.49	-0.26
• Steer steady straights (0-1)	0.55	0.11	0.61	0.16	0.69	0.04	0.30	-0.41
• SDLP straights (m)	0.14	0.04	0.15	0.03	0.18	0.00	0.35	-0.34
∘ Mean speed narrowings (km/h)	90.43	16.44	101.82	8.87	114.30	0.47	**0.03**	-0.84
∘ Delta mean speed (narrowing-straight) (Δkm/h)	-10.13	15.98	-3.87	7.51	0.72	1.87	0.18	-0.49
∘ Mean LP narrowings (m)	0.16	0.11	0.15	0.10	0.24	0.08	0.76	0.12
∘ Speed difference narrowings (end-begin) (Δkm/h)	0.40	0.84	0.31	0.57	-0.07	0.31	0.73	0.12
• Steer steady narrowings (0-1)	0.44	0.15	0.55	0.19	0.71	0.03	0.12	-0.62
• Delta steer steady (narrowing-straight) (0-1)	-0.11	0.10	-0.06	0.08	0.02	0.07	0.19	-0.49
• SDLP narrowings (m)	0.05	0.02	0.04	0.01	0.04	0.00	0.14	0.53
• Delta SDLP (narrowing-straight) (Δm)	-0.09	0.04	-0.11	0.03	-0.13	0.00	0.13	0.56

B.2. Straight-road and narrowing perceptual skill measures

Table B.2: Mean and standard deviation of the horizontal and vertical gaze measures captured during straight-road and narrowing operation for the three experimental groups. The table also includes a group comparison between inexperienced and experienced drivers.

Measure	Experimental group						Group comparison	
	Inexperienced		Experienced		Expert		Inexp. vs. Exp.	
	mean	std	mean	std	mean	std	p-value	Cohen's d
SD horizontal gaze from the reference straights (px)	43.35	23.28	54.46	33.05	52.73	27.98	0.32	-0.40
SD vertical gaze from the reference straights (px)	73.71	30.41	62.08	20.61	57.04	14.18	0.23	0.44
Delta mean horizontal gaze (narrowing-straight) (Δpx)	-4.40	11.74	-0.93	8.58	20.01	1.83	0.37	-0.33
Delta mean vertical gaze (narrowing-straight) (Δpx)	-1.59	28.03	3.24	13.08	1.17	11.20	0.55	-0.21
SD horizontal gaze from the reference narrowings (px)	35.36	31.66	21.59	8.46	15.95	4.21	0.11	0.57
SD vertical gaze from the reference narrowings (px)	44.21	22.75	32.98	14.66	19.44	6.18	0.12	0.57
Delta SD horizontal gaze (narrowing-straight) (Δpx)	-8.00	19.57	-32.87	28.42	-36.78	23.77	**0.01**	1.04
Delta SD vertical gaze (narrowing-straight) (Δpx)	-29.50	13.36	-29.10	16.12	-37.59	20.36	0.94	-0.03
Delta mean abs. horizontal gaze (narrowing-straight) (Δpx)	0.18	12.66	-10.56	9.23	-13.86	12.21	**0.01**	0.95
Delta mean abs. vertical gaze (narrowing-straight) (Δpx)	-11.41	12.50	-13.40	11.64	-16.71	9.73	0.66	0.16

C

Appendix C: Additional visitation of the results

C.1. Additional visualisations: speed control through the curves

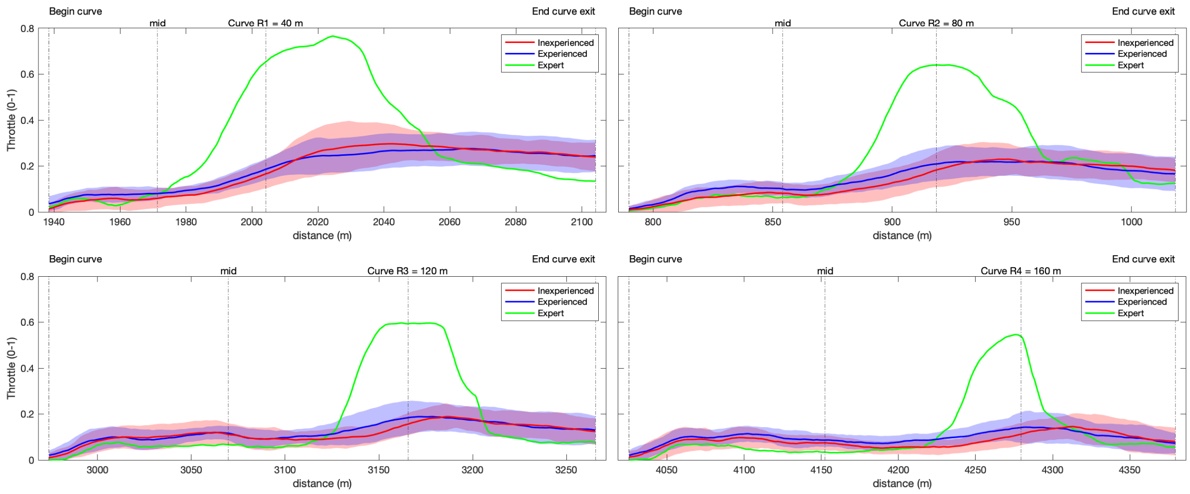

Figure C.1: Overview of throttle position as a function of travelled distance for the inexperienced, experienced and expert drivers for the four different curves. The group averages are presented by the solid lines and the standard deviation by the transparent areas. The grey dotted lines indicate the different track sections.

C.2. Additional visualisations: braking behavior entering the curve

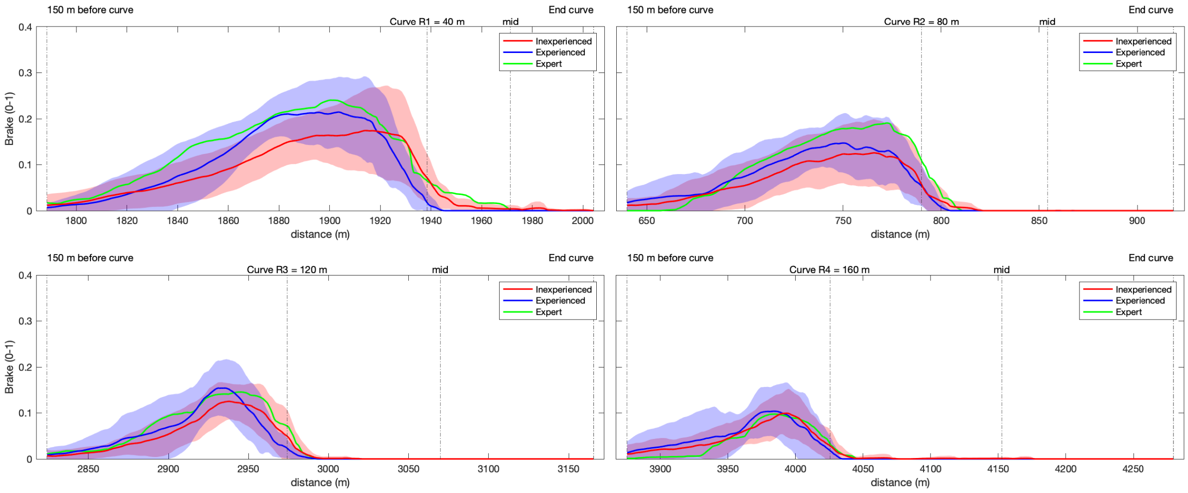

Figure C.2: Overview of brake position as a function of travelled distance for the inexperienced, experienced and expert drivers for the four different curves. The group averages are presented by the solid lines and the standard deviation by the transparent areas. The grey dotted lines indicate the different track sections.

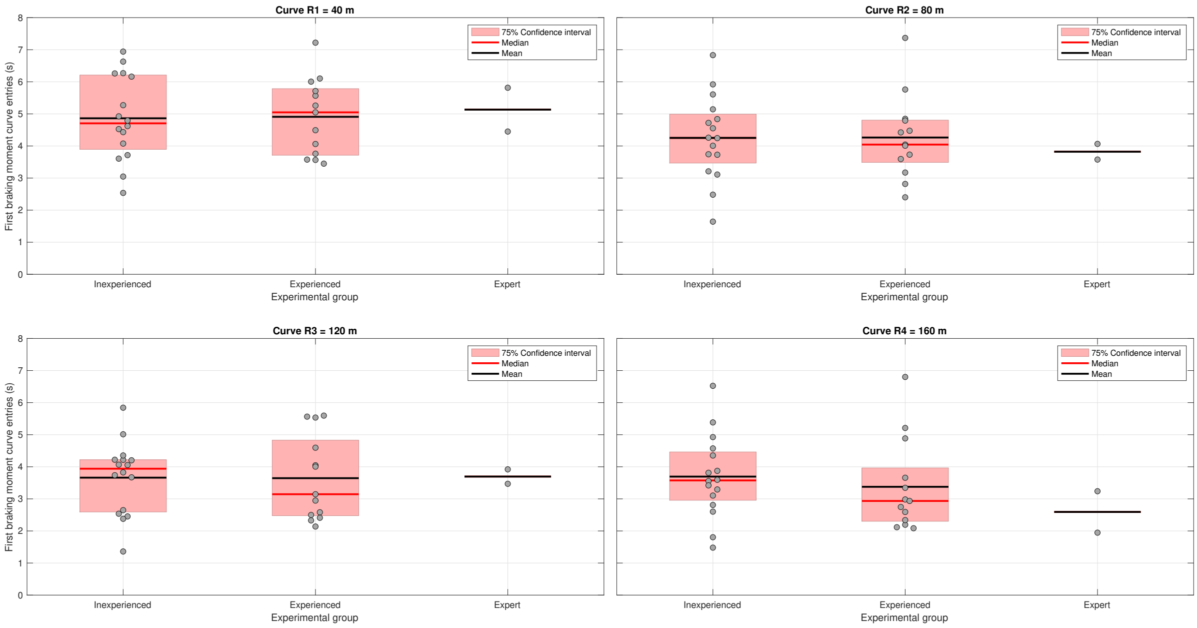

Figure C.3: Overview of the average mean first braking moment curve entries per participant and arranged per experimental group. Differences between the experienced and inexperienced drivers were declared statistically significant if p<0.05 and were highlighted by: (*).

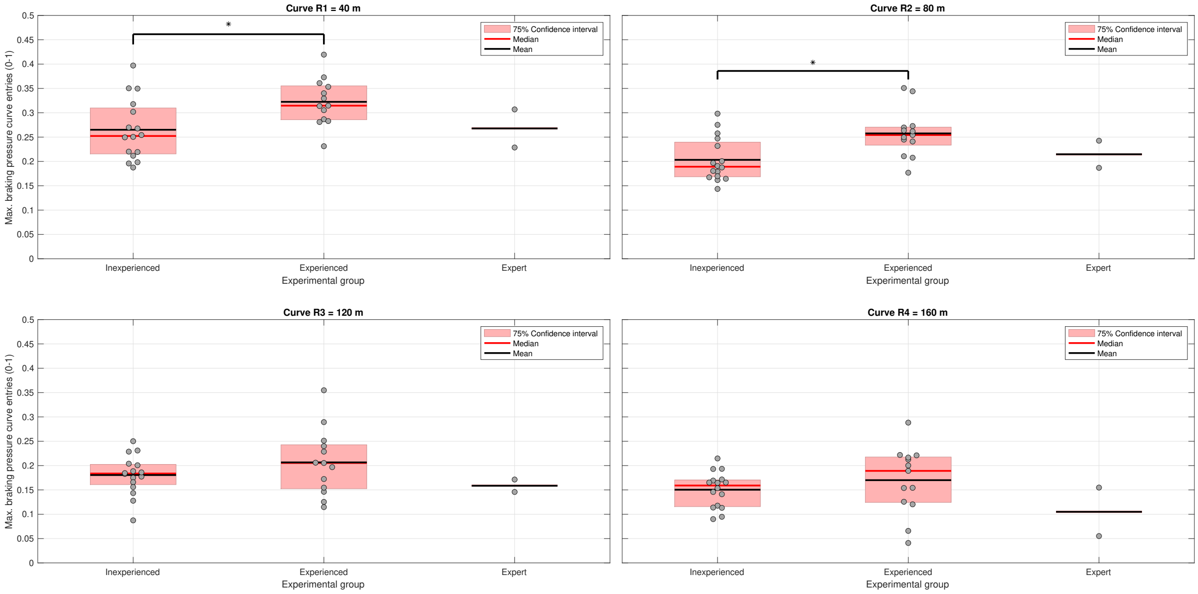

Figure C.4: Overview of the average mean braking pressure curve entries per participant and arranged per experimental group. Differences between the experienced and inexperienced drivers were declared statistically significant if p<0.05 and were highlighted by: (*).

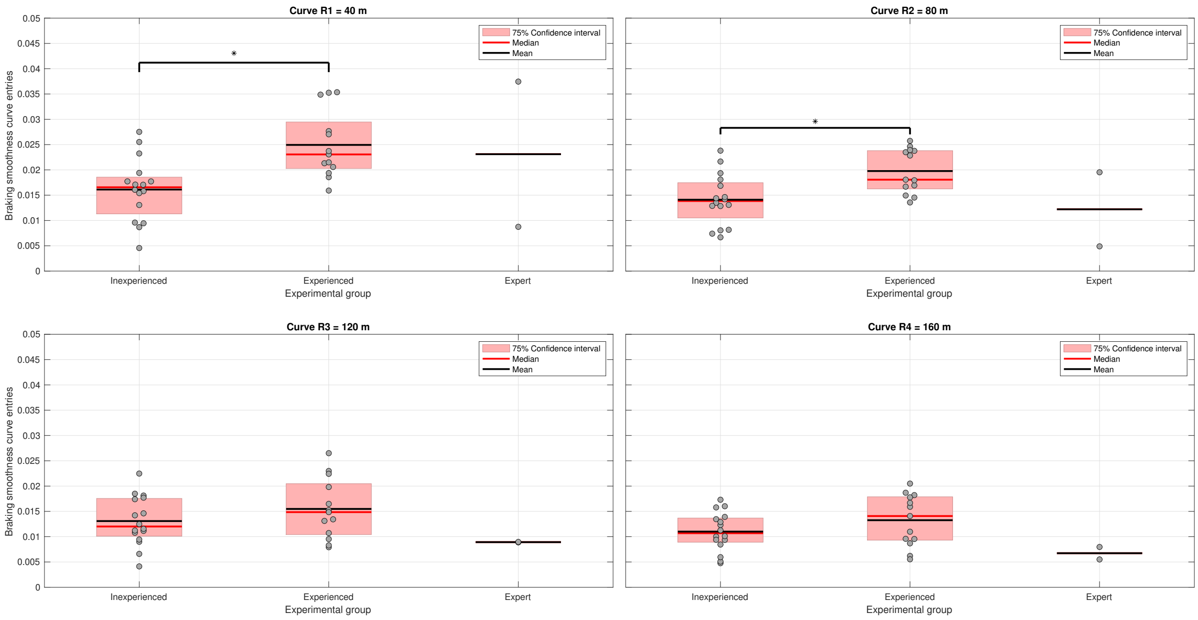

Figure C.5: Overview of the average braking smoothness curve entries per participant and arranged per experimental group. Differences between the experienced and inexperienced drivers were declared statistically significant if p<0.05 and were highlighted by: (*).

C.3. Additional visualisations: Driving line through the curves

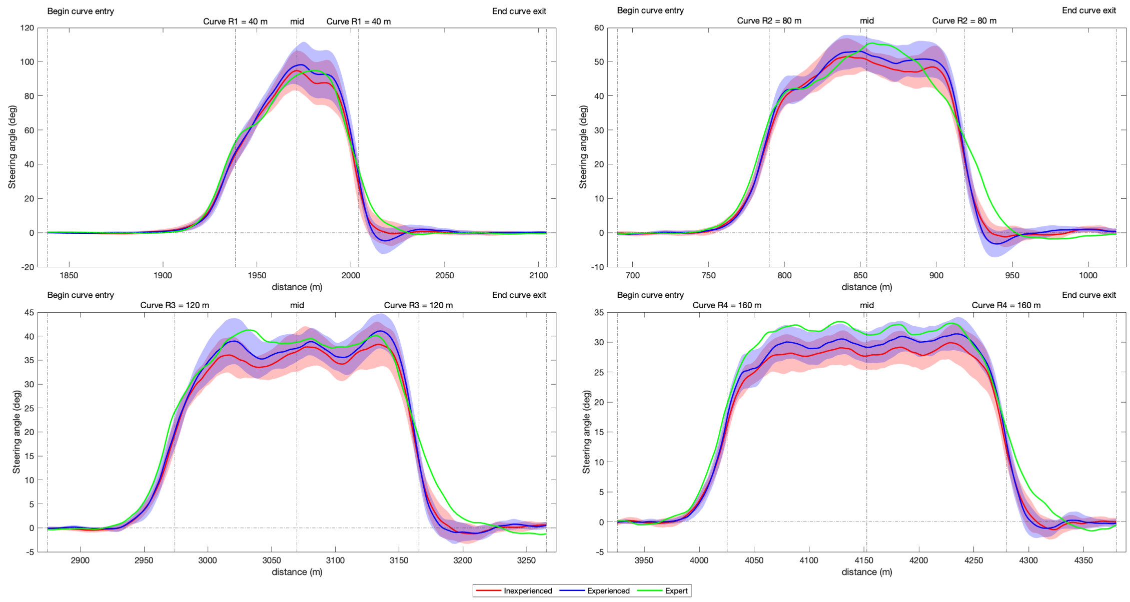

Figure C.6: Overview of steering angle as a function of travelled distance for the inexperienced, experienced and expert drivers for the four different curves. The group averages are presented by the solid lines and the standard deviation by the transparent areas. The grey dotted lines indicate the different track sections.

C.4. Additional visualisations: correlation coefficient lead time curves

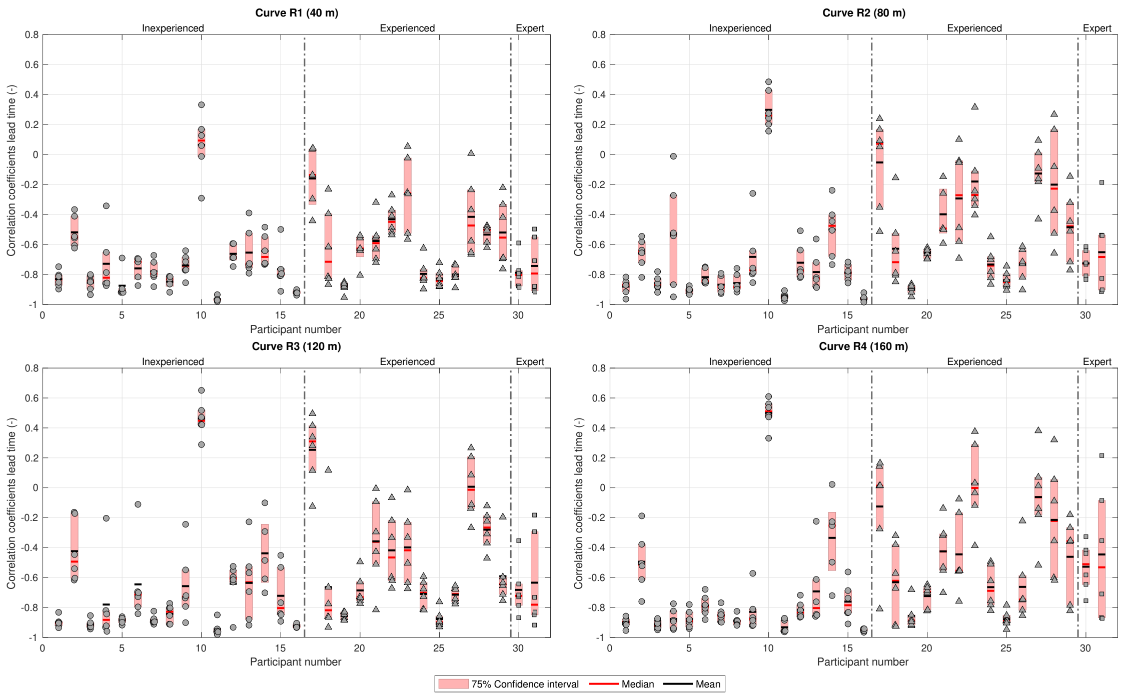

Figure C.7: Overview correlation coefficient lead time curves for each curve, participant and individual lap, separately.

D

Appendix D: Vehicle paths for all curves

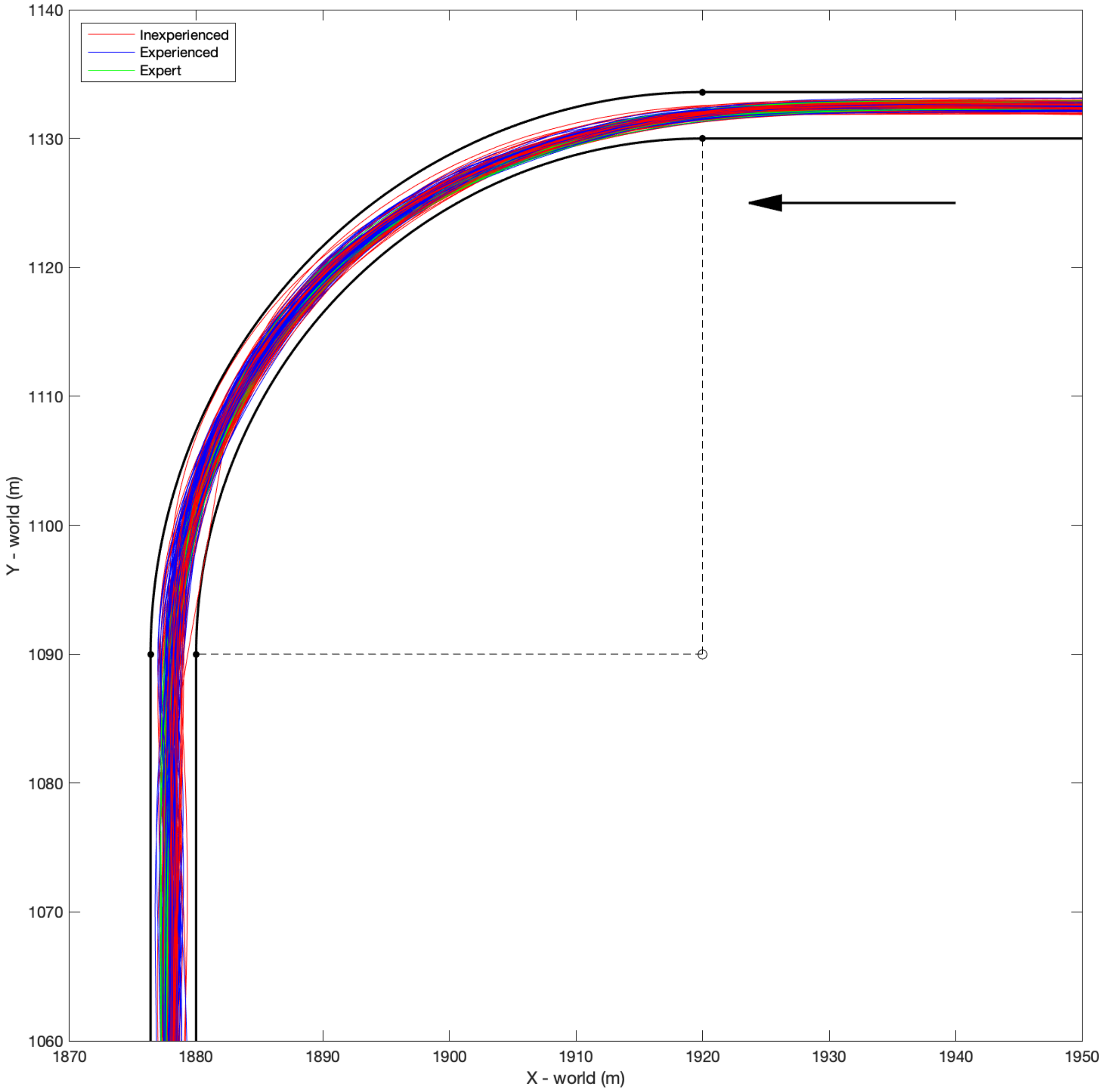

Figure D.1: Individual paths of the vehicle center through curve R1 (with an inner radius of 40 m) of the inexperienced, experienced and expert drivers, for all laps that were included in the analysis. The driving direction is indicted by the black arrow with a length of 23.75 m. The dotted line and black dots highlight the curve center and curve beginning and ending, respectively.

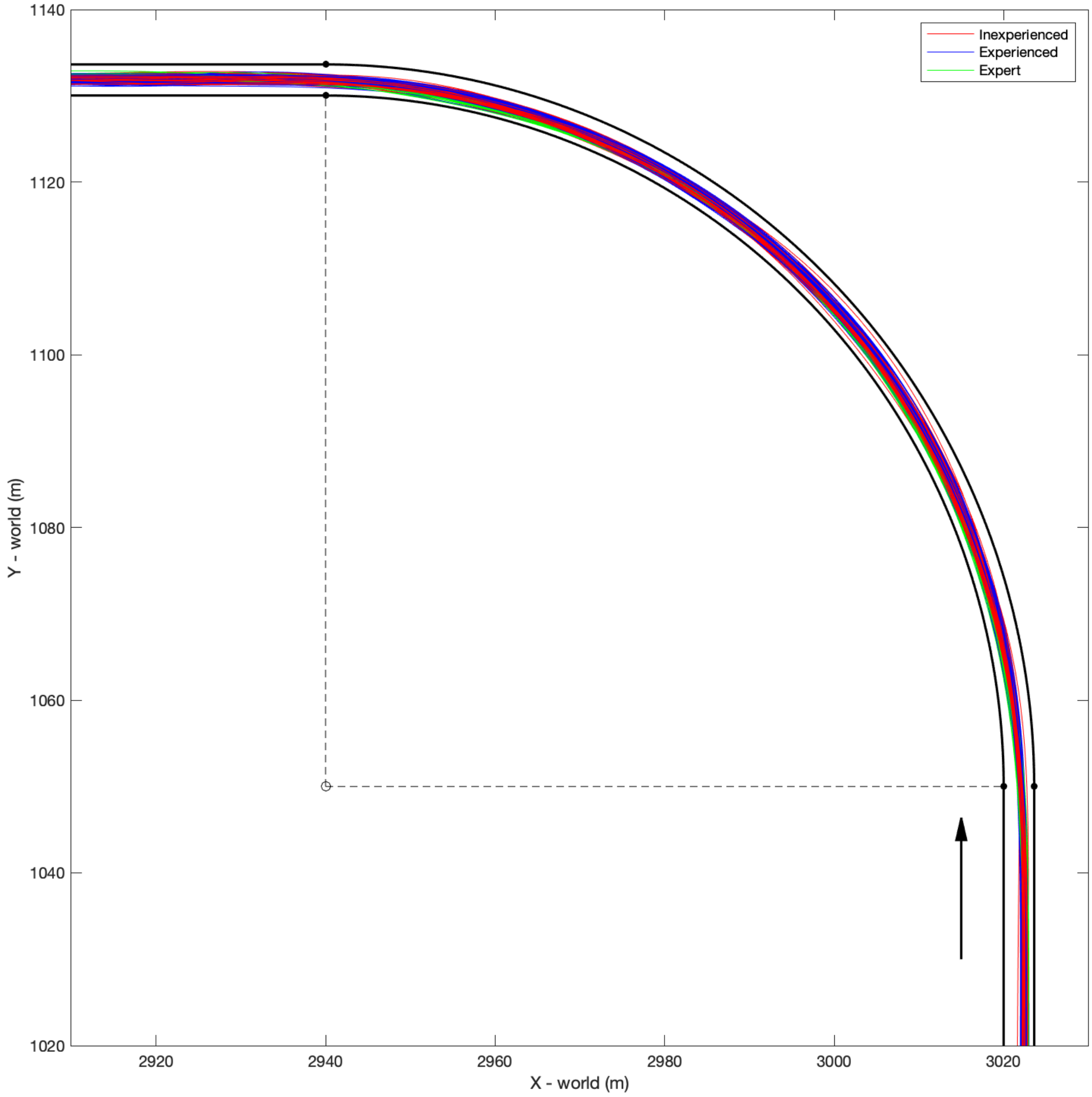

Figure D.2: Individual paths of the vehicle center through curve R2 (with an inner radius of 80 m) of the inexperienced, experienced and expert drivers, for all laps that were included in the analysis. The driving direction is indicted by the black arrow with a length of 23.75 m. The dotted line and black dots highlight the curve center and curve beginning and ending, respectively.

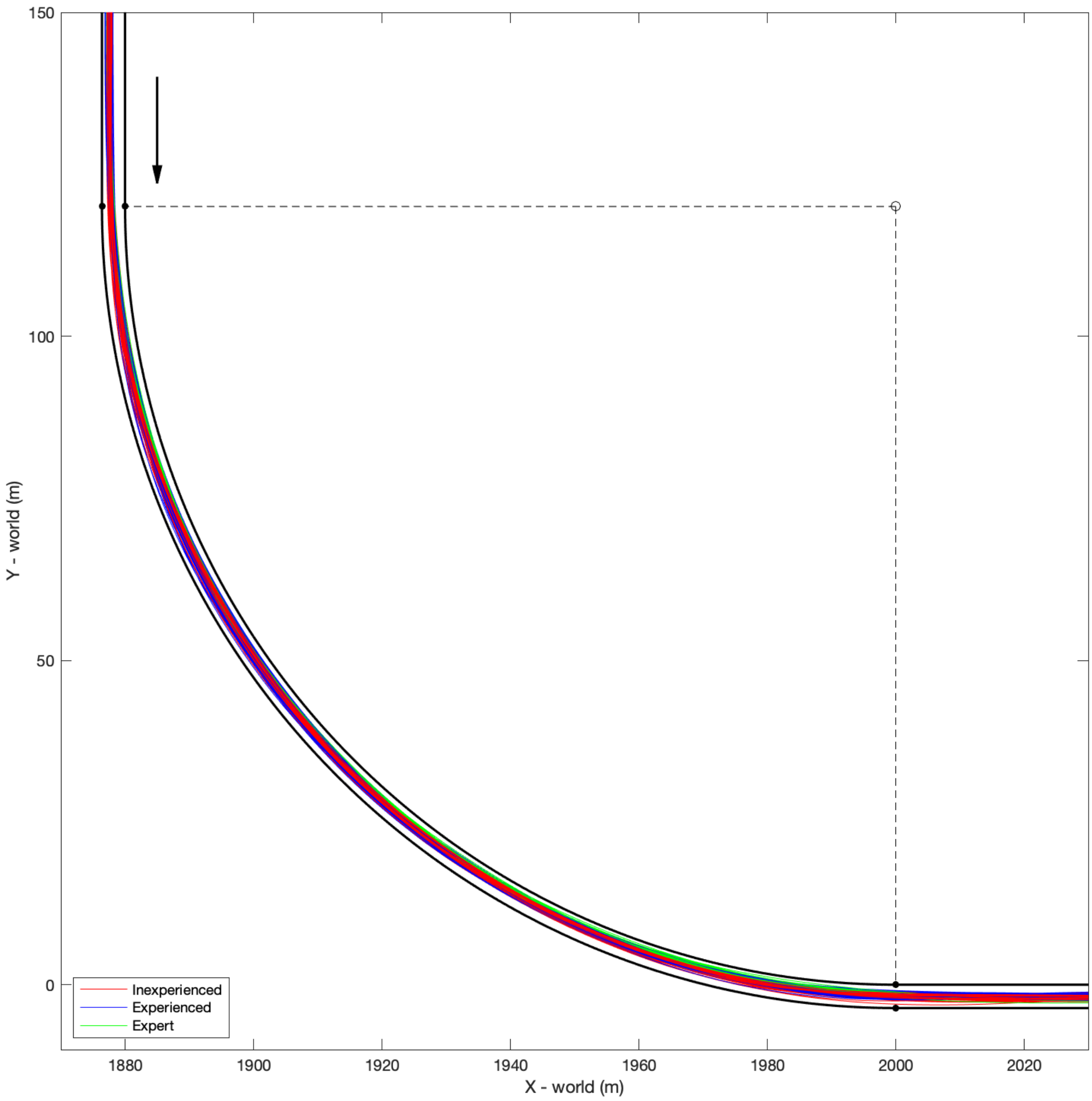

Figure D.3: Individual paths of the vehicle center through curve R3 (with an inner radius of 120 m) of the inexperienced, experienced and expert drivers, for all laps that were included in the analysis. The driving direction is indicted by the black arrow with a length of 23.75 m. The dotted line and black dots highlight the curve center and curve beginning and ending, respectively.

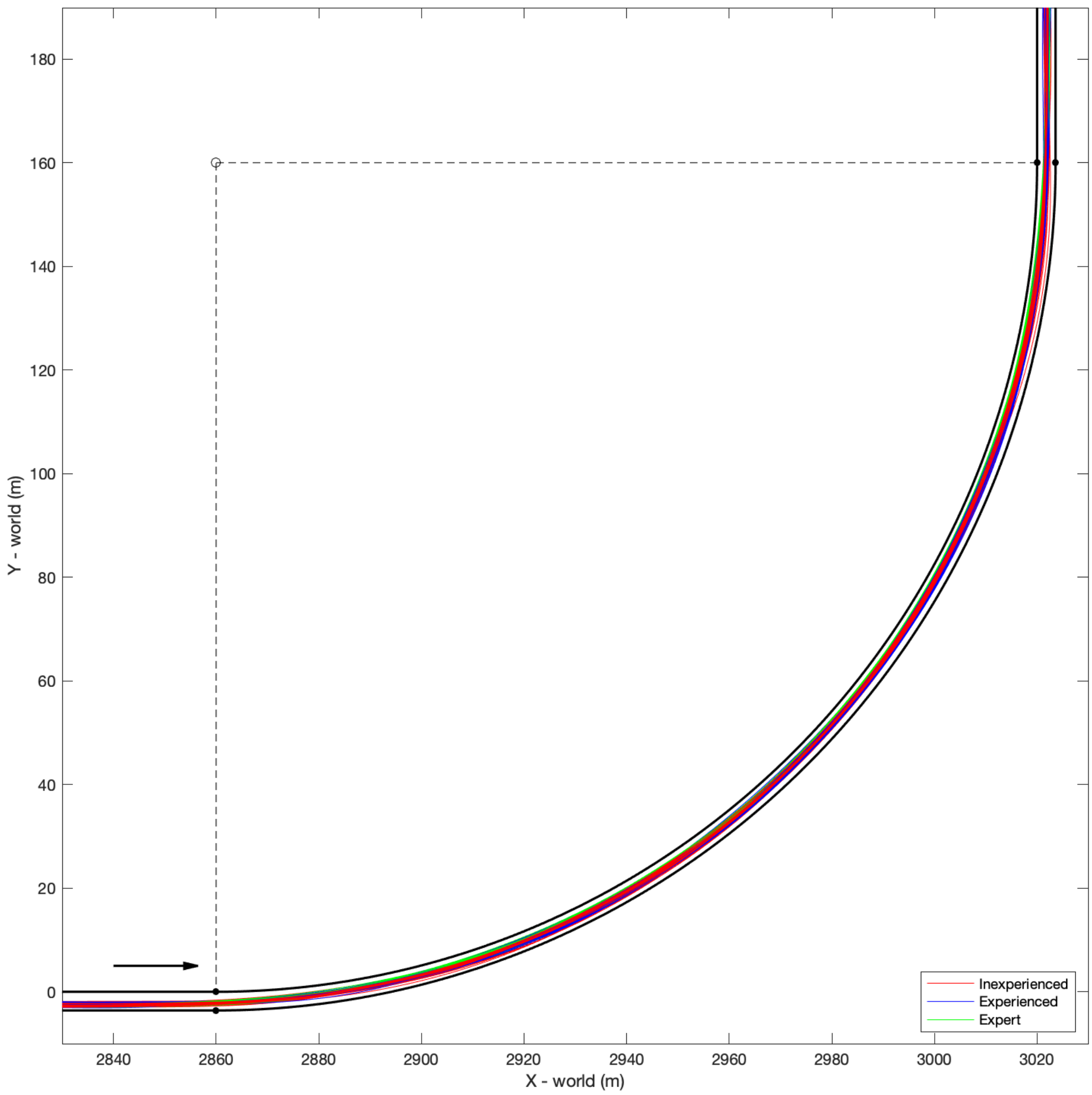

Figure D.4: Individual paths of the vehicle center through curve R4 (with an inner radius of 160 m) of the inexperienced, experienced and expert drivers, for all laps that were included in the analysis. The driving direction is indicted by the black arrow with a length of 23.75 m. The dotted line and black dots highlight the curve center and curve beginning and ending, respectively.

Appendix E: Horizontal & vertical gaze distributions

E.1. Horizontal gaze distributions: curves

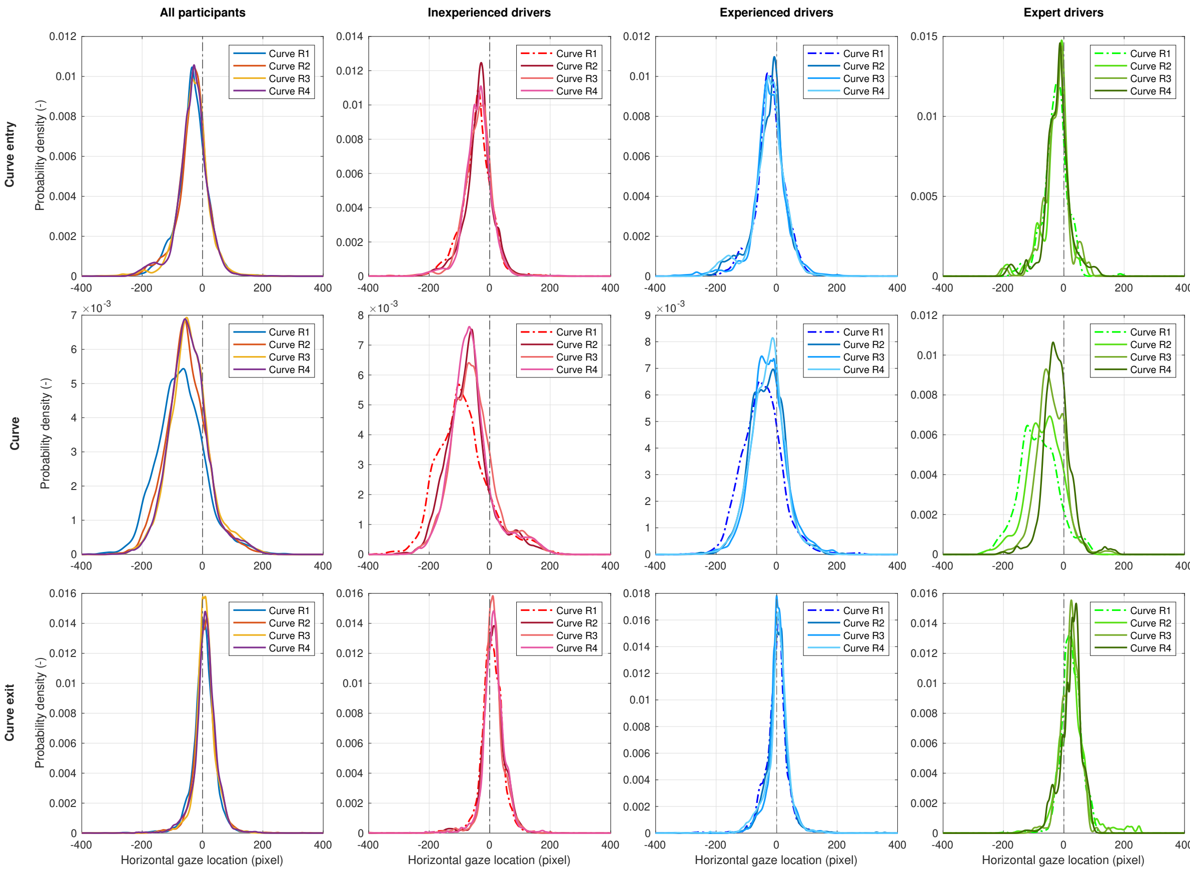

Figure E.1: Density estimates of horizontal gaze for the curves (R1-R4), curve sections (entry, curve and exit) and experimental groups (all participants, inexperienced, experienced and expert), separately. The visualised horizontal gaze location is the gaze location from the reference, in line with the rest of the report.

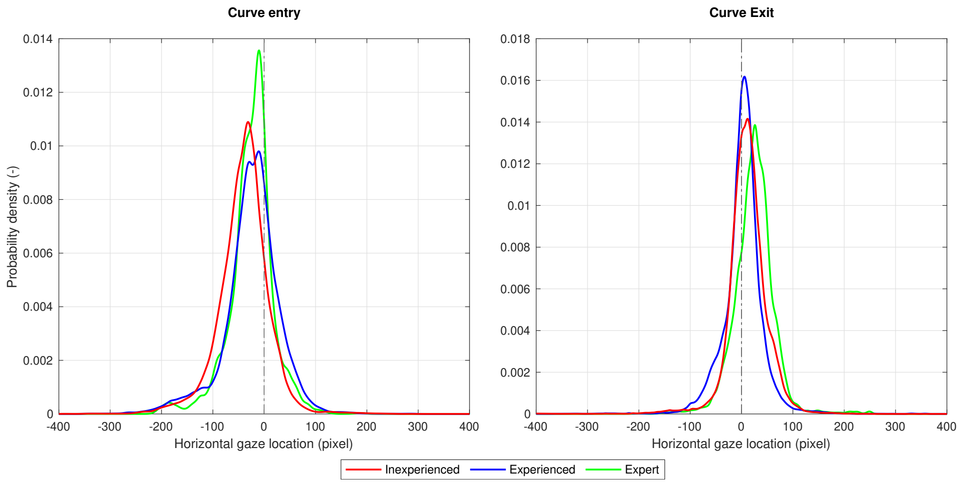

Figure E.2: Collapsed density estimates of horizontal gaze for the curve entry and exit sections using all curves. The density estimates are presented for each experimental group separately. The visualised horizontal gaze location is the gaze location from the reference, in line with the rest of the report.

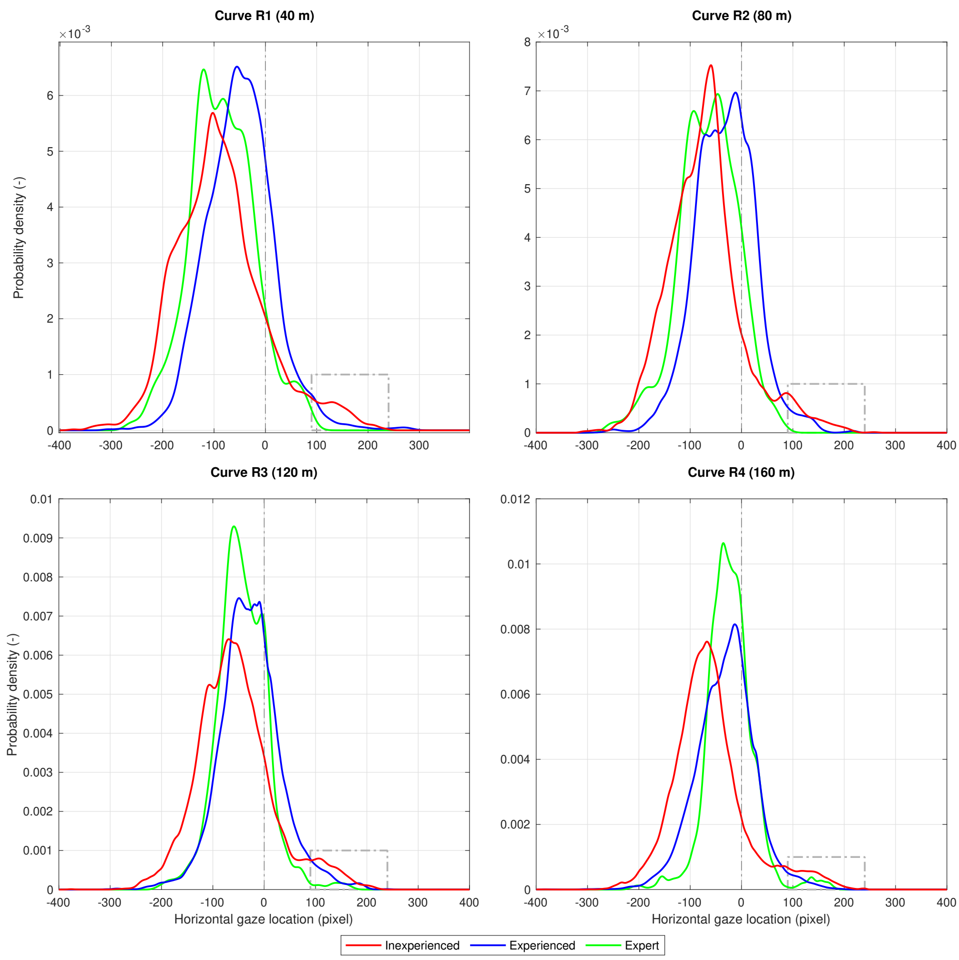

Figure E.3: Density estimates of horizontal gaze separately for novice vs. experienced vs. expert drivers, curve sections. The visualised horizontal gaze location is the gaze location from the reference, in line with the rest of the report.

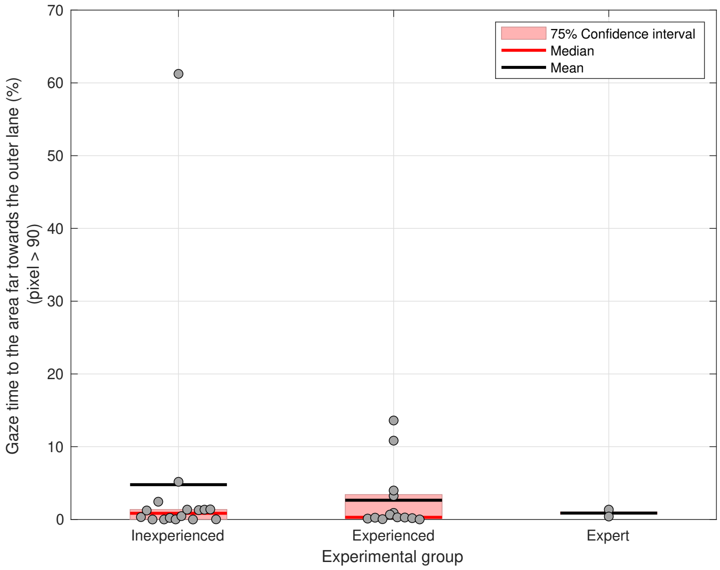

Figure E.4: Overview of the mean gaze time the drivers spent towards the outer lane of the track during curve driving, using all curves' collapsed results. The criteria for the outer lane was set to 90 pixels from the horizontal reference location.

E.2. Vertical gaze distributions: curves

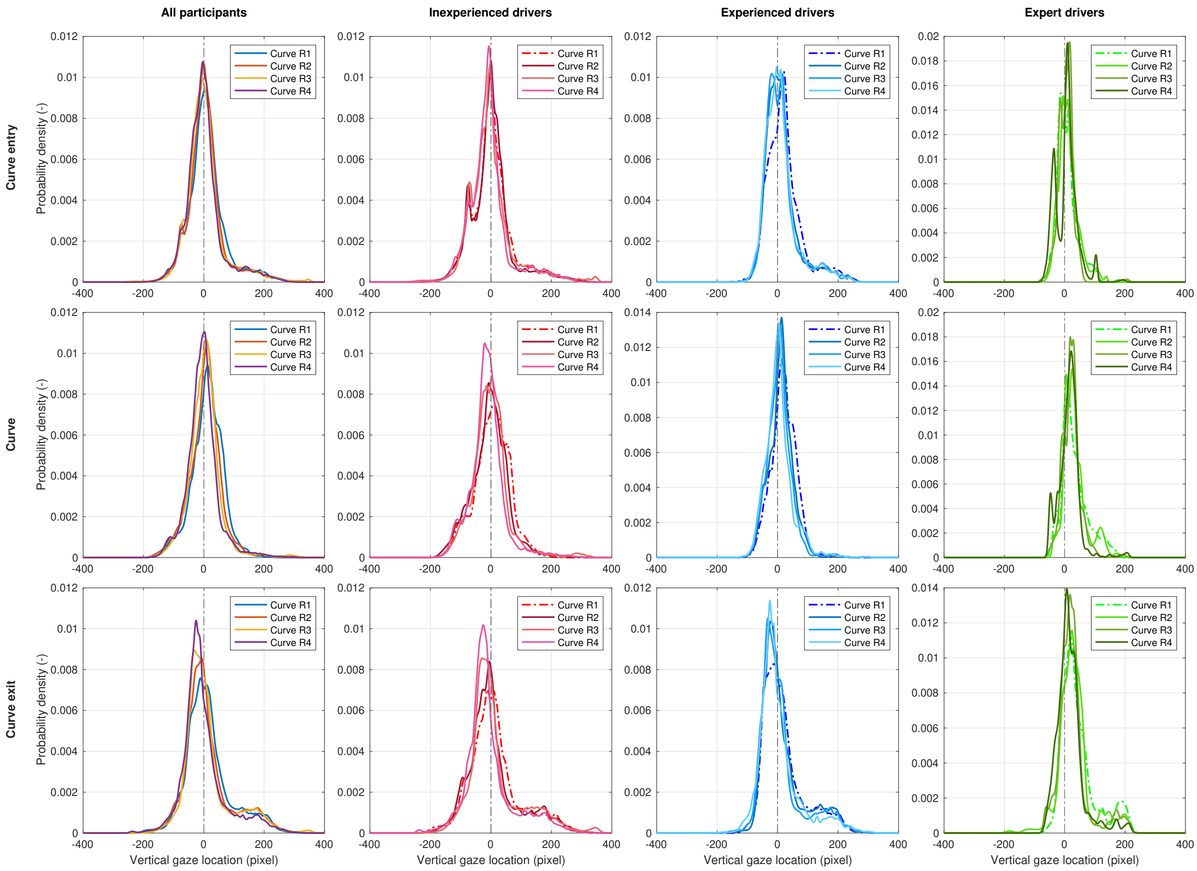

Figure E.5: Density estimates of vertical gaze for the curves (R1-R4), curve sections (entry, curve and exit) and experimental groups (all participants, inexperienced, experienced and expert), separately. The visualised vertical gaze location is the gaze location from the reference, in line with the rest of the report.

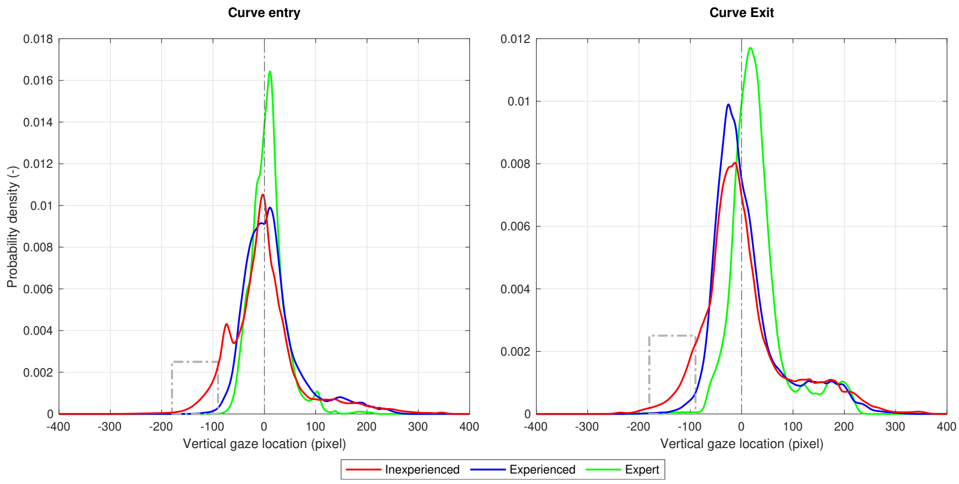

Figure E.6: Collapsed density estimates of vertical gaze for the curve entry and exit sections using all curves. The density estimates are presented for each experimental group separately. The visualised vertical gaze location is the gaze location from the reference, in line with the rest of the report.

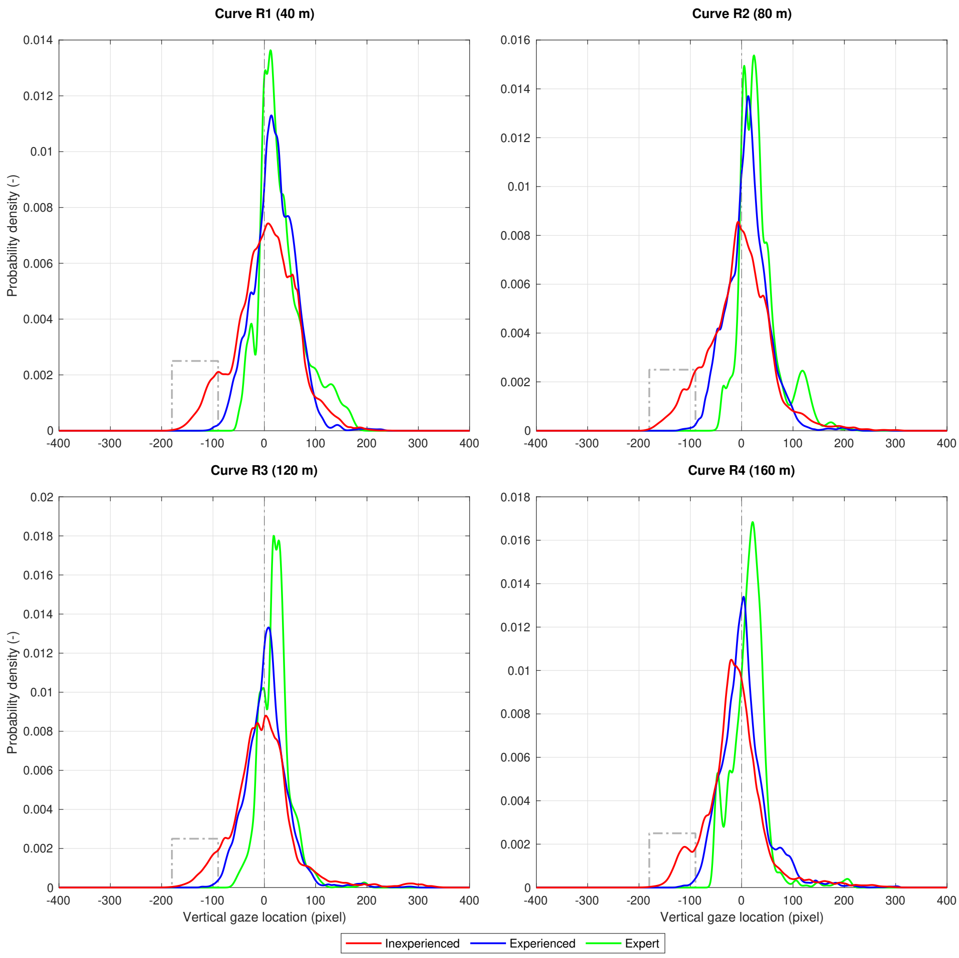

Figure E.7: Density estimates of vertical gaze separately for novice vs. experienced vs. expert drivers, curve sections. The visualised vertical gaze location is the gaze location from the reference, in line with the rest of the report.

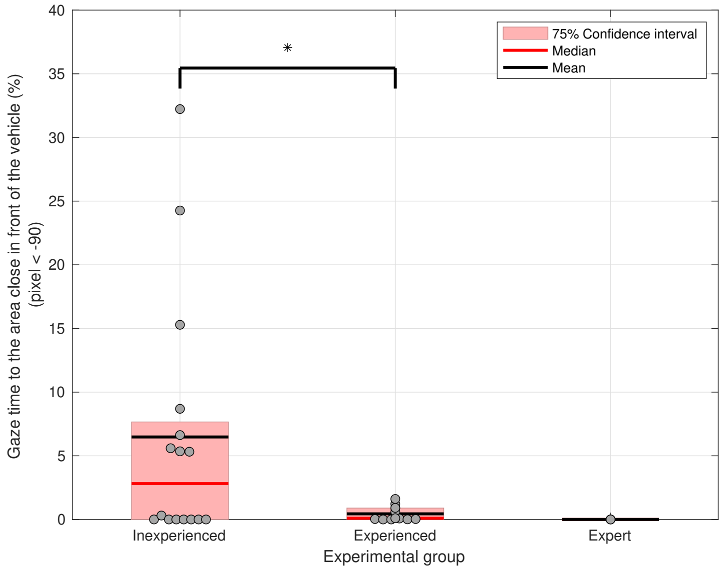

Figure E.8: Overview of the mean gaze time the drivers spent towards the area close in front of the vehicle, using all curves' collapsed results. The vertical location criteria was set to be lower than -90 pixel from the vertical reference.

E.3. Horizontal gaze distributions: straights & narrowings

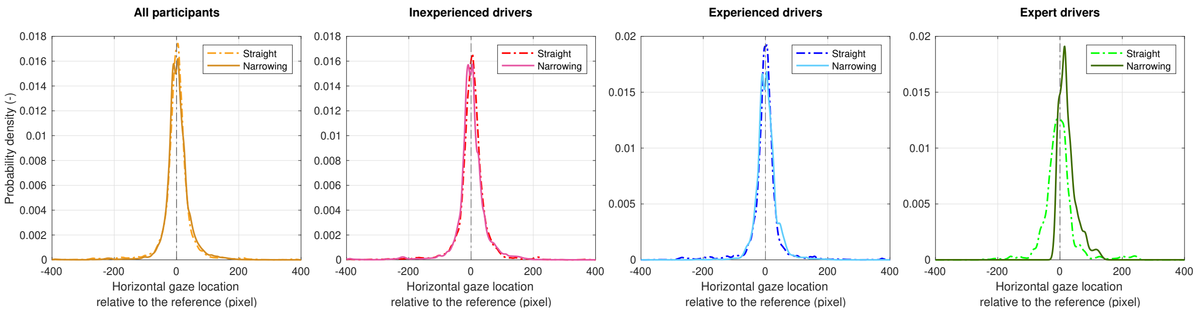

Figure E.9: Density estimates of horizontal gaze for the straights and road-narrowings, presented for experimental groups (all participants, inexperienced, experienced and expert), separately.

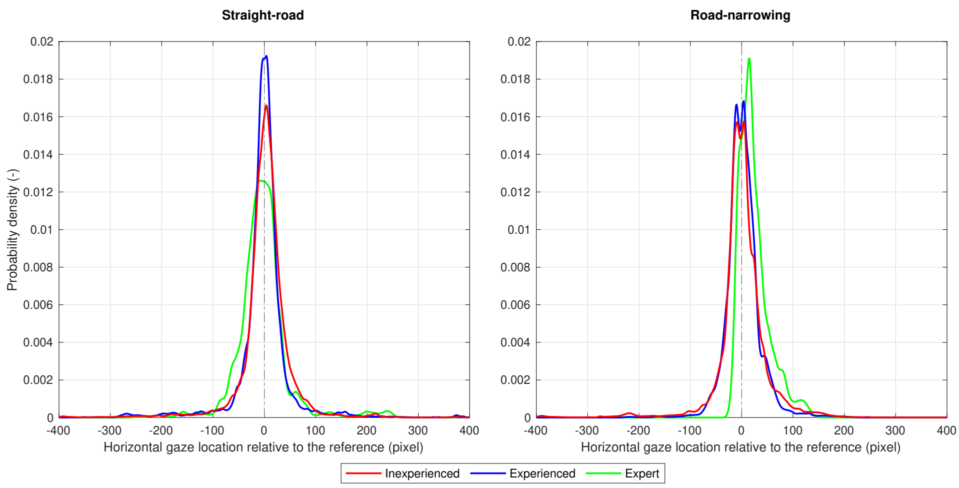

Figure E.10: Density estimates of horizontal gaze for straights and narrowings presenting the results for each experimental group.

E.4. Vertical gaze distributions: straights & narrowings

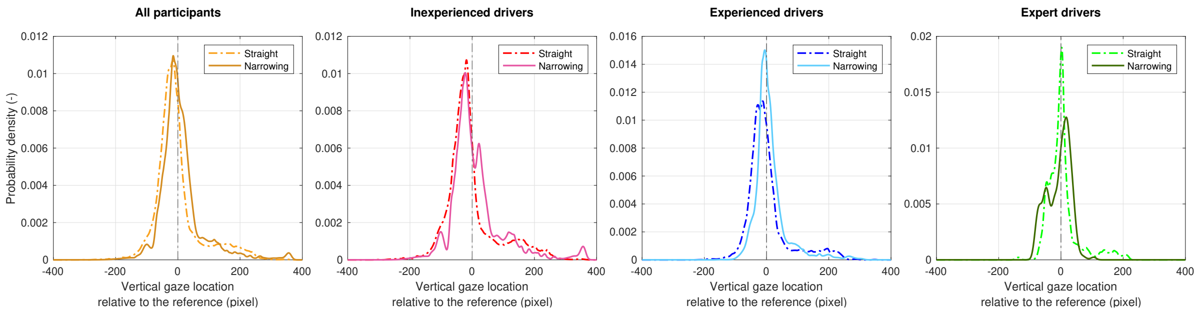

Figure E.11: Density estimates of vertical gaze for the straights, road-narrowings and experimental groups (all participants, inexperienced, experienced and expert),separately.

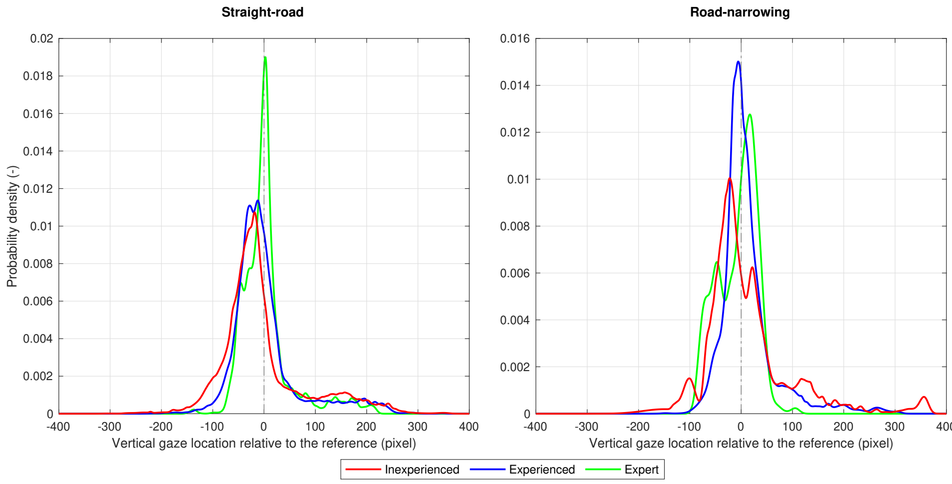

Figure E.12: Density estimates of vertical gaze for the straights and narrowings, for the different experimental groups.

F

Appendix F: Correlation matrix for the dependent measures

Table F.1 shows the correlation matrix of the dependent measures. The correlation analysis was conducted using the average performance of all participants (i.e., the inexperienced, experienced and expert drivers combined), and curves collapsed.

Table F.1: Correlation matrix of the dependent measures. Correlations were determined using the average of the all participants (N = 31) and all curves.

			1	2	3	4	5	6	7	8
	1	Mean speed curves (km/h)								
	2	Mean throttle position curves (0-1)	**0.37**							
	3	Throttle activation curves (0-1)	**0.40**	0.11						
	4	Brake activation curves (0-1)	-0.19	0.30	**-0.62**					
	5	Speed difference curves (end-begin) (Δkm/h)	-0.02	**0.58**	**0.61**	-0.30				
	6	First braking moment curve entries (s)	**-0.67**	-0.22	-0.24	-0.02	0.16			
	7	Max. brake pedal position curve entries (0-1)	0.10	0.15	**0.54**	**-0.40**	**0.51**	-0.30		
	8	Braking smoothness curve entries (-)	0.23	0.02	**0.73**	**-0.70**	**0.52**	-0.30	**0.79**	
	9	Turn-in distance (m)	0.26	0.05	-0.08	0.27	-0.28	-0.28	-0.06	-0.16
	10	Turn-in LP (m)	0.17	0.09	0.07	0.10	0.04	0.01	-0.22	-0.18
	11	Track-out distance (m)	-0.02	**0.45**	-0.09	**0.37**	0.12	-0.03	-0.19	-0.25
	12	Track-out LP (m)	-0.06	0.34	0.07	0.18	0.27	0.04	-0.13	0.01
	13	Mean LP curves (m)	-0.22	-0.29	-0.04	-0.13	0.00	0.34	-0.07	-0.01
	14	Throttle variance curves (0-1)	0.16	**0.91**	-0.19	**0.48**	**0.37**	-0.05	-0.08	-0.26
	15	Steer steady curves (0-1)	-0.31	0.35	0.03	0.28	**0.39**	0.25	0.01	0.00
	16	Steering integral curves (deg)	**0.45**	-0.02	0.23	-0.20	-0.03	**-0.46**	0.25	0.28
	17	SDLP curves (m)	**0.37**	0.30	0.08	0.06	0.08	**-0.42**	0.18	0.19
CD	18	Anticipatory steering (AS) error (deg)	**0.43**	0.22	0.26	-0.04	0.07	**-0.40**	0.12	0.16
	19	Steering integral curve recovery (deg)	0.22	-0.11	0.03	-0.11	-0.10	-0.26	0.24	0.24
	20	Steer steady curve recovery (0-1)	-0.22	-0.16	0.01	-0.15	0.00	0.24	-0.19	-0.10
	21	Mean horizontal gaze from the reference curve entries (px)	0.19	0.04	0.25	-0.19	0.12	-0.07	0.30	0.35
	22	Mean horizontal gaze from the reference curves (px)	0.22	0.12	0.17	-0.10	0.10	-0.19	0.20	0.26
	23	Mean horizontal from the reference curve exits (px)	0.12	0.16	-0.08	0.28	-0.01	0.02	-0.33	-0.25
	24	SD horizontal gaze from the reference curve entries (px)	-0.13	-0.25	0.07	-0.24	-0.07	-0.12	0.09	0.21
	25	SD horizontal gaze from the reference curves (px)	-0.14	-0.18	-0.17	0.11	-0.20	-0.21	-0.05	0.01
	26	SD horizontal gaze from the reference curve exits (px)	-0.34	0.00	-0.14	-0.10	0.19	0.28	0.21	0.15
	27	Mean vertical gaze from the reference curve entries (px)	0.01	-0.22	-0.10	-0.28	-0.21	0.08	-0.13	0.03
	28	Mean vertical gaze from the reference curves (px)	0.03	-0.12	-0.19	-0.01	-0.27	0.07	-0.13	-0.10
	29	Mean vertical gaze from the reference curve exist (px)	0.31	0.21	0.22	-0.10	0.10	-0.25	0.14	0.08
	30	SD vertical gaze from the reference curve entries (px)	**-0.55**	-0.23	-0.02	-0.03	0.19	0.16	0.16	0.11
	31	SD vertical gaze from the reference curves (px)	-0.21	-0.18	0.02	0.08	-0.05	-0.24	0.15	0.17
	32	SD vertical gaze from the reference curve exits (px)	-0.26	-0.13	0.06	0.03	0.05	-0.16	0.19	0.07
	33	Lead time curves (s)	0.00	0.23	0.06	0.21	0.18	-0.10	-0.11	-0.15
	34	Correlation coefficient lead time curves (R)	0.13	0.06	0.13	-0.12	0.10	-0.14	0.18	0.30
	35	Constrained lead time curves (s)	-0.15	0.20	0.21	0.13	**0.39**	0.13	0.06	-0.08
	36	Constrained correlation coefficient lead time curves (R)	-0.04	-0.03	-0.02	-0.04	0.05	0.12	0.15	0.05
	37	Mean speed straights (km/h)	**0.42**	**0.50**	0.19	-0.08	0.25	-0.22	**0.48**	0.34
	38	Mean LP straights (m)	0.16	0.24	0.01	-0.06	0.18	0.20	-0.05	-0.04
SD	39	Steer steady straights (0-1)	-0.15	0.12	0.12	0.07	0.22	0.16	-0.06	-0.12
	40	SDLP straights (m)	0.24	0.34	0.26	0.10	0.27	-0.26	-0.04	0.11
	41	SD horizontal gaze from the reference straights (px)	-0.23	-0.13	-0.02	-0.12	0.02	0.11	0.13	0.10
	42	SD vertical gaze from the reference straights (px)	**-0.36**	-0.15	-0.09	0.20	-0.04	-0.05	0.09	-0.07
	43	Mean speed narrowings (km/h)	**0.69**	0.34	0.25	-0.05	0.03	-0.23	0.11	0.02
	44	Delta mean speed (narrowing-straight) (Δkm/h)	**0.62**	0.19	0.21	-0.03	-0.07	-0.18	-0.07	-0.12
	45	Mean LP narrowings (m)	0.11	0.21	-0.26	0.22	-0.05	0.16	-0.15	-0.27
	46	Delta mean LP (narrowing-straight) (Δm)	-0.13	-0.15	-0.24	0.26	-0.30	-0.14	-0.05	-0.17
	47	Speed difference over narrowings (end-begin) (Δkm/h)	-0.27	0.01	0.27	-0.22	**0.44**	0.13	0.31	**0.42**
	48	Steer steady narrowings (0-1)	0.00	0.12	0.11	0.00	0.12	0.12	-0.04	-0.09
	49	Delta steer steady (narrowing-straight) (0-1)	0.21	0.05	0.03	-0.11	-0.11	-0.01	0.01	0.01
	50	SDLP narrowings (m)	-0.20	-0.03	-0.08	0.15	-0.01	-0.01	-0.04	-0.05
RO	51	Delta SDLP (narrowing-straight) (Δm)	-0.32	**-0.36**	-0.29	-0.05	-0.28	0.26	0.03	-0.13
	52	Delta mean horizontal gaze (narrowing-straight) (Δpx)	**0.58**	**0.42**	0.12	0.26	0.02	-0.33	-0.12	-0.03
	53	Delta mean vertical gaze (narrowing-straight) (Δpx)	0.01	-0.21	-0.34	0.09	**-0.41**	0.01	-0.27	-0.20
	54	SD horizontal gaze from the reference narrowings (px)	**-0.39**	-0.22	-0.24	0.10	-0.14	-0.01	-0.01	-0.05
	55	SD vertical gaze from the reference narrowings (px)	-0.29	-0.07	-0.10	0.17	-0.01	-0.12	0.09	-0.05
	56	Delta SD horizontal gaze (narrowing-straight) (Δpx)	-0.12	-0.06	-0.20	0.22	-0.15	-0.12	-0.14	-0.15
	57	Delta SD vertical gaze (narrowing-straight) (Δpx)	0.25	0.18	0.04	-0.12	0.05	-0.07	-0.04	0.05
	58	Delta mean abs. horizontal gaze (narrowing-straight) (Δpx)	**-0.39**	-0.11	-0.32	0.15	-0.05	0.15	-0.09	-0.15
	59	Delta mean abs. vertical gaze (narrowing-straight) (Δpx)	0.16	-0.08	**-0.38**	0.16	**-0.41**	-0.05	-0.28	-0.26
SR	60	NASA TLX Mental (1-20)	0.06	-0.24	-0.16	0.06	-0.33	0.01	-0.07	-0.15

Note: Correlations that are statistically significant (p<.05) are in boldface. The abbreviations SR, CD, SD, RO represent the subgroup measures self-reported, curve driving, straight-road driving and road-narrowing, respectively.

Table F.1: Correlation matrix of the dependent measures. Correlations were determined using the average of the all participants (N = 31) and all curves.

			9	10	11	12	13	14	15	16
	1	Mean speed curves (km/h)								
	2	Mean throttle position curves (0-1)								
	3	Throttle activation curves (0-1)								
	4	Brake activation curves (0-1)								
	5	Speed difference curves (end-begin) (Δkm/h)								
	6	First braking moment curve entries (s)								
	7	Max. brake pedal position curve entries (0-1)								
	8	Braking smoothness curve entries (-)								
	9	Turn-in distance (m)								
	10	Turn-in LP (m)	0.27							
	11	Track-out distance (m)	0.17	**0.16**						
	12	Track-out LP (m)	-0.12	0.31	**0.61**					
	13	Mean LP curves (m)	**-0.40**	-0.08	**-0.55**	0.12				
	14	Throttle variance curves (0-1)	0.05	**0.01**	**0.56**	**0.33**	**-0.31**			
	15	Steer steady curves (0-1)	-0.19	0.00	**0.38**	**0.39**	**-0.03**	**0.42**		
	16	Steering integral curves (deg)	**0.08**	0.06	**-0.41**	-0.13	0.09	**-0.26**	**-0.66**	
	17	SDLP curves (m)	**-0.20**	-0.20	-0.18	-0.08	0.12	**0.12**	0.10	0.31
CD	18	Anticipatory steering (AS) error (deg)	**-0.26**	-0.24	-0.31	-0.14	0.29	**0.09**	0.05	0.30
	19	Steering integral curve recovery (deg)	0.02	-0.19	**-0.58**	-0.21	0.35	-0.27	**-0.51**	**0.81**
	20	Steer steady curve recovery (0-1)	-0.19	0.31	0.23	0.09	-0.17	-0.02	0.33	**-0.65**
	21	Mean horizontal gaze from the reference curve entries (px)	0.18	-0.28	-0.10	-0.06	-0.03	-0.02	0.06	0.11
	22	Mean horizontal gaze from the reference curves (px)	0.19	0.09	-0.14	-0.02	-0.13	0.03	0.12	0.20
	23	Mean horizontal from the reference curve exits (px)	0.05	**0.42**	0.28	**0.40**	0.01	0.16	0.28	-0.09
	24	SD horizontal gaze from the reference curve entries (px)	-0.25	0.05	-0.09	-0.11	-0.11	-0.25	-0.07	0.12
	25	SD horizontal gaze from the reference curves (px)	-0.23	0.03	0.05	0.07	-0.05	-0.18	0.01	0.08
	26	SD horizontal gaze from the reference curve exits (px)	-0.20	-0.02	-0.15	0.04	0.16	0.00	0.03	0.01
	27	Mean vertical gaze from the reference curve entries (px)	-0.01	-0.25	-0.22	-0.08	0.14	-0.09	-0.28	-0.06
	28	Mean vertical gaze from the reference curves (px)	0.12	0.00	-0.18	-0.01	0.11	0.01	-0.20	-0.08
	29	Mean vertical gaze from the reference curve exist (px)	0.20	0.22	-0.05	-0.08	-0.21	0.12	-0.20	0.25
	30	SD vertical gaze from the reference curve entries (px)	**-0.13**	0.07	-0.11	0.05	0.09	-0.27	-0.08	0.18
	31	SD vertical gaze from the reference curves (px)	0.07	0.16	-0.03	0.05	-0.12	-0.27	0.05	0.21
	32	SD vertical gaze from the reference curve exits (px)	0.09	0.24	0.09	0.02	-0.20	-0.20	-0.06	0.18
	33	Lead time curves (s)	0.04	**0.51**	0.13	0.29	-0.12	0.20	0.21	0.10
	34	Correlation coefficient lead time curves (R)	0.04	0.03	-0.20	-0.06	-0.09	-0.01	0.13	0.16
	35	Constrained lead time curves (s)	0.15	**0.43**	0.20	0.17	**-0.18**	0.15	0.10	-0.09
	36	Constrained correlation coefficient lead time curves (R)	0.06	0.17	-0.06	-0.06	-0.16	-0.07	-0.16	0.21
	37	Mean speed straights (km/h)	**0.05**	**-0.01**	0.33	0.09	-0.34	**0.43**	**0.13**	-0.03
	38	Mean LP straights (m)	0.04	**0.69**	0.03	0.26	0.10	0.17	-0.05	0.17
SD	39	Steer steady straights (0-1)	-0.22	**0.47**	0.27	0.25	-0.11	0.18	**0.47**	**-0.55**
	40	SDLP straights (m)	-0.10	**0.42**	0.22	**0.42**	-0.01	0.21	**0.41**	0.04
	41	SD horizontal gaze from the reference straights (px)	-0.20	0.10	0.10	-0.03	-0.15	-0.11	-0.01	-0.04
	42	SD vertical gaze from the reference straights (px)	**0.13**	0.32	0.12	0.13	-0.09	-0.17	0.02	0.12
	43	Mean speed narrowings (km/h)	**0.01**	0.15	0.09	-0.08	-0.16	0.25	-0.08	0.04
	44	Delta mean speed (narrowing-straight) (Δkm/h)	**-0.01**	0.18	-0.03	-0.14	-0.05	0.10	-0.15	0.06
	45	Mean LP narrowings (m)	0.18	**0.47**	-0.15	0.14	0.30	0.23	0.08	0.12
	46	Delta mean LP (narrowing-straight) (Δm)	0.10	**-0.57**	-0.16	-0.24	0.12	-0.03	0.14	-0.14
	47	Speed difference over narrowings (end-begin) (Δkm/h)	0.07	-0.01	-0.11	0.06	**0.05**	-0.13	0.24	**-0.03**
	48	Steer steady narrowings (0-1)	-0.09	0.36	0.22	0.01	-0.21	0.19	**0.46**	**-0.62**
	49	Delta steer steady (narrowing-straight) (0-1)	0.15	-0.03	0.00	-0.34	-0.22	0.09	0.15	-0.34
	50	SDLP narrowings (m)	0.15	-0.05	0.08	0.22	0.11	0.00	-0.03	0.31
RO	51	Delta SDLP (narrowing-straight) (Δm)	0.16	**-0.44**	-0.19	-0.35	0.05	-0.21	**-0.43**	0.07
	52	Delta mean horizontal gaze (narrowing-straight) (Δpx)	**0.20**	**0.25**	-0.01	0.11	-0.02	0.35	0.11	0.09
	53	Delta mean vertical gaze (narrowing-straight) (Δpx)	-0.10	-0.15	-0.29	-0.13	**0.26**	-0.08	-0.25	-0.01
	54	SD horizontal gaze from the reference narrowings (px)	**0.17**	-0.08	0.03	-0.03	-0.07	-0.14	-0.29	0.19
	55	SD vertical gaze from the reference narrowings (px)	0.04	0.15	0.15	0.03	-0.16	-0.14	0.00	0.17
	56	Delta SD horizontal gaze (narrowing-straight) (Δpx)	**0.36**	-0.17	-0.07	0.00	0.09	-0.01	-0.25	0.22
	57	Delta SD vertical gaze (narrowing-straight) (Δpx)	-0.17	**-0.36**	0.00	-0.19	-0.06	0.11	-0.04	0.02
	58	Delta mean abs. horizontal gaze (narrowing-straight) (Δpx)	**0.18**	-0.19	-0.12	0.06	0.23	-0.02	-0.23	0.13
	59	Delta mean abs. vertical gaze (narrowing-straight) (Δpx)	-0.09	-0.11	**-0.09**	-0.22	**-0.04**	0.03	-0.03	-0.13
SR	60	NASA TLX Mental (1-20)	0.15	0.07	**-0.56**	**-0.40**	0.35	-0.23	-0.35	0.10

Note: Correlations that are statistically significant (p<.05) are in boldface. The abbreviations SR, CD, SD, RO represent the subgroup measures self-reported, curve driving, straight-road driving and road-narrowing, respectively.

Table F.1: Correlation matrix of the dependent measures. Correlations were determined using the average of the all participants (N = 31) and all curves.

			17	18	19	20	21	22	23	24
	1	Mean speed curves (km/h)								
	2	Mean throttle position curves (0-1)								
	3	Throttle activation curves (0-1)								
	4	Brake activation curves (0-1)								
	5	Speed difference curves (end-begin) (Δkm/h)								
	6	First braking moment curve entries (s)								
	7	Max. brake pedal position curve entries (0-1)								
	8	Braking smoothness curve entries (-)								
	9	Turn-in distance (m)								
	10	Turn-in LP (m)								
	11	Track-out distance (m)								
	12	Track-out LP (m)								
	13	Mean LP curves (m)								
	14	Throttle variance curves (0-1)								
	15	Steer steady curves (0-1)								
	16	Steering integral curves (deg)								
	17	SDLP curves (m)								
CD	18	Anticipatory steering (AS) error (deg)	**0.69**							
	19	Steering integral curve recovery (deg)	**0.42**	0.35						
	20	Steer steady curve recovery (0-1)	**-0.42**	-0.28	**-0.81**					
	21	Mean horizontal gaze from the reference curve entries (px)	0.22	0.01	**0.37**	**-0.43**				
	22	Mean horizontal gaze from the reference curves (px)	0.21	-0.01	0.30	-0.26	**0.73**			
	23	Mean horizontal from the reference curve exits (px)	-0.14	**-0.15**	-0.12	**0.07**	0.06	0.13		
	24	SD horizontal gaze from the reference curve entries (px)	0.28	0.10	0.10	0.21	0.02	0.14	-0.25	
	25	SD horizontal gaze from the reference curves (px)	0.20	0.03	0.04	0.14	-0.19	-0.19	0.21	**0.57**
	26	SD horizontal gaze from the reference curve exits (px)	-0.12	-0.20	0.03	-0.01	0.06	0.13	-0.12	0.16
	27	Mean vertical gaze from the reference curve entries (px)	-0.06	0.02	0.09	0.11	0.24	0.10	-0.24	0.15
	28	Mean vertical gaze from the reference curves (px)	-0.09	0.05	0.05	0.17	0.05	-0.03	-0.18	0.05
	29	Mean vertical gaze from the reference curve exist (px)	0.15	0.20	0.14	-0.01	0.11	0.12	-0.21	0.20
	30	SD vertical gaze from the reference curve entries (px)	**-0.02**	-0.30	0.22	-0.13	0.10	0.17	-0.17	**0.47**
	31	SD vertical gaze from the reference curves (px)	0.12	-0.16	0.23	-0.10	0.03	0.30	-0.04	**0.50**
	32	SD vertical gaze from the reference curve exits (px)	-0.03	-0.19	0.08	0.04	-0.01	0.19	-0.17	**0.50**
	33	Lead time curves (s)	-0.11	**-0.04**	-0.17	0.21	-0.21	0.31	**0.37**	0.05
	34	Correlation coefficient lead time curves (R)	0.24	0.01	0.31	-0.19	**0.67**	**0.93**	0.11	0.34
	35	Constrained lead time curves (s)	-0.24	**-0.25**	**-0.41**	0.28	**-0.43**	-0.36	-0.03	-0.21
	36	Constrained correlation coefficient lead time curves (R)	0.07	-0.27	0.17	-0.13	**0.44**	**0.74**	-0.16	0.25
	37	Mean speed straights (km/h)	**0.15**	**0.08**	-0.08	-0.04	0.29	**0.23**	**-0.06**	0.02
	38	Mean LP straights (m)	-0.05	**-0.10**	-0.01	0.08	-0.22	0.04	0.12	0.02
SD	39	Steer steady straights (0-1)	-0.20	**-0.13**	**-0.74**	**0.81**	**-0.39**	-0.15	**0.14**	**0.11**
	40	SDLP straights (m)	**0.49**	**0.31**	-0.01	**0.06**	0.08	0.28	**0.41**	0.33
	41	SD horizontal gaze from the reference straights (px)	-0.06	-0.19	-0.11	0.23	0.01	0.05	-0.12	**0.68**
	42	SD vertical gaze from the reference straights (px)	**-0.09**	-0.31	0.10	-0.06	0.04	0.25	0.02	**0.41**
	43	Mean speed narrowings (km/h)	**0.18**	0.28	-0.04	0.02	0.08	-0.06	0.22	-0.29
	44	Delta mean speed (narrowing-straight) (Δkm/h)	**0.14**	0.30	-0.02	0.04	-0.03	-0.16	0.28	-0.35
	45	Mean LP narrowings (m)	0.10	**0.06**	0.11	-0.07	-0.05	0.25	0.04	-0.22
	46	Delta mean LP (narrowing-straight) (Δm)	0.15	**0.20**	0.11	-0.18	0.27	0.15	-0.13	-0.22
	47	Speed difference over narrowings (end-begin) (Δkm/h)	-0.06	-0.21	-0.02	-0.12	**0.22**	**0.37**	-0.15	**0.05**
	48	Steer steady narrowings (0-1)	-0.10	-0.03	**-0.74**	**0.75**	-0.25	-0.16	**0.00**	**-0.02**
	49	Delta steer steady (narrowing-straight) (0-1)	0.11	0.14	-0.27	0.19	0.10	-0.07	-0.21	-0.19
	50	SDLP narrowings (m)	0.19	0.10	0.30	**-0.42**	0.16	0.10	-0.16	0.29
RO	51	Delta SDLP (narrowing-straight) (Δm)	**-0.43**	**-0.28**	0.12	-0.22	-0.02	-0.25	**-0.48**	-0.23
	52	Delta mean horizontal gaze (narrowing-straight) (Δpx)	**0.37**	**0.32**	0.09	-0.15	0.33	0.26	**0.37**	-0.18
	53	Delta mean vertical gaze (narrowing-straight) (Δpx)	0.13	0.23	0.18	0.11	**-0.02**	-0.06	-0.18	0.27
	54	SD horizontal gaze from the reference narrowings (px)	**-0.11**	-0.24	0.17	-0.13	-0.06	-0.06	**-0.39**	**0.52**
	55	SD vertical gaze from the reference narrowings (px)	0.01	-0.16	0.10	-0.12	-0.08	0.20	-0.08	0.34
	56	Delta SD horizontal gaze (narrowing-straight) (Δpx)	**-0.03**	-0.02	0.27	**-0.36**	-0.06	-0.10	-0.23	-0.24
	57	Delta SD vertical gaze (narrowing-straight) (Δpx)	0.18	**0.34**	-0.05	-0.06	-0.18	-0.16	-0.15	-0.27
	58	Delta mean abs. horizontal gaze (narrowing-straight) (Δpx)	**-0.23**	-0.21	0.20	-0.22	-0.14	-0.16	-0.33	-0.21
	59	Delta mean abs. vertical gaze (narrowing-straight) (Δpx)	-0.01	0.08	**-0.13**	0.20	**-0.19**	0.08	0.05	-0.15
SR	60	NASA TLX Mental (1-20)	-0.02	0.08	**0.31**	**-0.12**	-0.13	-0.05	-0.17	-0.19

Note: Correlations that are statistically significant (p<.05) are in boldface. The abbreviations SR, CD, SD, RO represent the subgroup measures self-reported, curve driving, straight-road driving and road-narrowing, respectively.

Table F.1: Correlation matrix of the dependent measures. Correlations were determined using the average of the all participants (N = 31) and all curves.

			25	26	27	28	29	30	31	32
CD	1	Mean speed curves (km/h)								
	2	Mean throttle position curves (0-1)								
	3	Throttle activation curves (0-1)								
	4	Brake activation curves (0-1)								
	5	Speed difference curves (end-begin) (Δkm/h)								
	6	First braking moment curve entries (s)								
	7	Max. brake pedal position curve entries (0-1)								
	8	Braking smoothness curve entries (-)								
	9	Turn-in distance (m)								
	10	Turn-in LP (m)								
	11	Track-out distance (m)								
	12	Track-out LP (m)								
	13	Mean LP curves (m)								
	14	Throttle variance curves (0-1)								
	15	Steer steady curves (0-1)								
	16	Steering integral curves (deg)								
	17	SDLP curves (m)								
	18	Anticipatory steering (AS) error (deg)								
	19	Steering integral curve recovery (deg)								
	20	Steer steady curve recovery (0-1)								
	21	Mean horizontal gaze from the reference curve entries (px)								
	22	Mean horizontal gaze from the reference curves (px)								
	23	Mean horizontal from the reference curve exits (px)								
	24	SD horizontal gaze from the reference curve entries (px)								
	25	SD horizontal gaze from the reference curves (px)								
	26	SD horizontal gaze from the reference curve exits (px)	0.02							
	27	Mean vertical gaze from the reference curve entries (px)	-0.05	0.02						
	28	Mean vertical gaze from the reference curves (px)	-0.02	0.02	**0.78**					
	29	Mean vertical gaze from the reference curve exist (px)	0.11	-0.02	0.28	**0.53**				
	30	SD vertical gaze from the reference curve entries (px)	**0.34**	0.24	-0.06	-0.21	0.01			
	31	SD vertical gaze from the reference curves (px)	**0.54**	-0.02	-0.25	-0.25	0.16	**0.61**		
	32	SD vertical gaze from the reference curve exits (px)	**0.43**	0.05	-0.26	-0.22	0.33	**0.73**	**0.80**	
	33	Lead time curves (s)	0.18	**0.00**	-0.11	0.00	0.27	0.22	**0.34**	**0.38**
	34	Correlation coefficient lead time curves (R)	0.00	0.26	0.12	-0.03	**0.14**	**0.21**	**0.41**	0.22
	35	Constrained lead time curves (s)	-0.05	**-0.10**	**-0.17**	0.03	**0.32**	0.25	0.01	0.22
	36	Constrained correlation coefficient lead time curves (R)	-0.12	0.36	0.12	0.17	**0.23**	**0.42**	0.06	0.26
SD	37	Mean speed straights (km/h)	**-0.14**	**0.14**	-0.13	-0.04	0.11	**-0.32**	**-0.15**	-0.11
	38	Mean LP straights (m)	-0.20	**0.24**	-0.14	0.00	0.06	-0.05	-0.08	-0.04
	39	Steer steady straights (0-1)	0.00	**0.02**	**-0.10**	**0.05**	**-0.01**	-0.06	**-0.11**	**0.06**
	40	SDLP straights (m)	**0.25**	**0.02**	-0.29	**-0.22**	0.06	0.06	**0.16**	0.08
	41	SD horizontal gaze from the reference straights (px)	**0.39**	**0.63**	-0.16	-0.16	0.03	0.35	0.26	**0.41**
	42	SD vertical gaze from the reference straights (px)	**0.35**	0.09	-0.35	-0.29	0.07	**0.76**	**0.77**	**0.89**
RO	43	Mean speed narrowings (km/h)	**-0.19**	**-0.41**	-0.06	0.11	0.17	**-0.65**	**-0.43**	**-0.39**
	44	Delta mean speed (narrowing-straight) (Δkm/h)	**-0.16**	**-0.54**	-0.01	0.14	0.16	**-0.62**	**-0.44**	**-0.40**
	45	Mean LP narrowings (m)	**-0.37**	**0.09**	-0.05	0.15	0.05	-0.10	-0.13	-0.10
	46	Delta mean LP (narrowing-straight) (Δm)	-0.03	**-0.27**	0.16	0.13	-0.04	-0.02	0.00	-0.03
	47	Speed difference over narrowings (end-begin) (Δkm/h)	-0.11	**0.58**	-0.18	-0.29	**-0.01**	**0.37**	0.34	**0.26**
	48	Steer steady narrowings (0-1)	-0.08	-0.13	**-0.05**	**0.10**	0.09	-0.24	**-0.20**	**-0.05**
	49	Delta steer steady (narrowing-straight) (0-1)	-0.15	-0.27	0.06	0.10	0.17	**-0.36**	-0.21	-0.18
	50	SDLP narrowings (m)	0.02	0.30	-0.03	**-0.05**	0.07	**0.41**	0.11	0.19
	51	Delta SDLP (narrowing-straight) (Δm)	**-0.25**	**0.09**	0.29	0.20	-0.03	0.09	**-0.13**	-0.02
	52	Delta mean horizontal gaze (narrowing-straight) (Δpx)	**0.00**	**-0.27**	0.04	0.21	0.22	-0.31	**-0.21**	-0.28
	53	Delta mean vertical gaze (narrowing-straight) (Δpx)	0.21	-0.03	**0.65**	**0.77**	**0.28**	-0.10	-0.17	-0.18
	54	SD horizontal gaze from the reference narrowings (px)	**0.32**	0.30	0.05	-0.04	0.08	**0.66**	**0.43**	**0.54**
	55	SD vertical gaze from the reference narrowings (px)	0.33	0.10	**-0.47**	**-0.51**	-0.02	**0.62**	**0.77**	**0.85**
	56	Delta SD horizontal gaze (narrowing-straight) (Δpx)	**-0.11**	**-0.39**	0.21	**0.13**	0.04	0.24	0.11	0.07
	57	Delta SD vertical gaze (narrowing-straight) (Δpx)	-0.18	**-0.02**	-0.02	-0.19	-0.14	**-0.51**	-0.32	**-0.43**
	58	Delta mean abs. horizontal gaze (narrowing-straight) (Δpx)	**-0.07**	0.01	0.27	0.20	0.06	**0.39**	0.12	0.16
	59	Delta mean abs. vertical gaze (narrowing-straight) (Δpx)	0.00	-0.09	**0.07**	0.09	**-0.22**	**-0.44**	-0.18	-0.33
SR	60	NASA TLX Mental (1-20)	-0.12	0.06	**0.11**	**0.16**	0.00	-0.15	-0.01	-0.19

Note: Correlations that are statistically significant (p<.05) are in boldface. The abbreviations SR, CD, SD, RO represent the subgroup measures self-reported, curve driving, straight-road driving and road-narrowing, respectively.

Table F.1: Correlation matrix of the dependent measures. Correlations were determined using the average of the all participants (N = 31) and all curves.

			33	34	35	36	37	38	39	40
	1	Mean speed curves (km/h)								
	2	Mean throttle position curves (0-1)								
	3	Throttle activation curves (0-1)								
	4	Brake activation curves (0-1)								
	5	Speed difference curves (end-begin) (Δkm/h)								
	6	First braking moment curve entries (s)								
	7	Max. brake pedal position curve entries (0-1)								
	8	Braking smoothness curve entries (-)								
	9	Turn-in distance (m)								
	10	Turn-in LP (m)								
	11	Track-out distance (m)								
	12	Track-out LP (m)								
	13	Mean LP curves (m)								
	14	Throttle variance curves (0-1)								
	15	Steer steady curves (0-1)								
	16	Steering integral curves (deg)								
	17	SDLP curves (m)								
CD	18	Anticipatory steering (AS) error (deg)								
	19	Steering integral curve recovery (deg)								
	20	Steer steady curve recovery (0-1)								
	21	Mean horizontal gaze from the reference curve entries (px)								
	22	Mean horizontal gaze from the reference curves (px)								
	23	Mean horizontal from the reference curve exits (px)								
	24	SD horizontal gaze from the reference curve entries (px)								
	25	SD horizontal gaze from the reference curves (px)								
	26	SD horizontal gaze from the reference curve exits (px)								
	27	Mean vertical gaze from the reference curve entries (px)								
	28	Mean vertical gaze from the reference curves (px)								
	29	Mean vertical gaze from the reference curve exist (px)								
	30	SD vertical gaze from the reference curve entries (px)								
	31	SD vertical gaze from the reference curves (px)								
	32	SD vertical gaze from the reference curve exits (px)								
	33	Lead time curves (s)								
	34	Correlation coefficient lead time curves (R)	0.26							
	35	Constrained lead time curves (s)	**0.73**	**-0.53**						
	36	Constrained correlation coefficient lead time curves (R)	0.17	**0.68**	0.11					
	37	Mean speed straights (km/h)	**-0.16**	**0.23**	-0.23	0.20				
	38	Mean LP straights (m)	0.21	**-0.01**	0.16	0.10	0.25			
SD	39	Steer steady straights (0-1)	**0.36**	**-0.18**	**0.45**	**-0.04**	**0.02**	0.32		
	40	SDLP straights (m)	**0.29**	**0.31**	0.01	**0.19**	0.14	0.17	**0.26**	
	41	SD horizontal gaze from the reference straights (px)	**-0.07**	**0.24**	-0.22	0.37	0.28	0.15	0.17	**0.26**
	42	SD vertical gaze from the reference straights (px)	**0.35**	0.24	0.12	0.27	-0.13	**0.10**	**0.09**	**0.12**
	43	Mean speed narrowings (km/h)	**-0.17**	**-0.15**	-0.13	-0.14	**0.53**	**0.24**	**0.16**	**0.05**
	44	Delta mean speed (narrowing-straight) (Δkm/h)	**-0.13**	**-0.27**	-0.06	-0.25	0.20	**0.17**	**0.18**	**0.01**
	45	Mean LP narrowings (m)	**0.29**	**0.09**	0.09	0.19	0.11	**0.71**	0.16	0.06
	46	Delta mean LP (narrowing-straight) (Δm)	-0.04	**0.09**	-0.14	0.03	-0.25	**-0.79**	-0.31	-0.18
	47	Speed difference over narrowings (end-begin) (Δkm/h)	0.14	**0.43**	0.18	0.28	**-0.07**	**-0.01**	-0.08	**0.07**
	48	Steer steady narrowings (0-1)	0.14	-0.21	**0.32**	**-0.10**	0.18	0.25	**0.84**	**0.13**
	49	Delta steer steady (narrowing-straight) (0-1)	-0.27	-0.13	-0.03	-0.14	0.30	**0.00**	0.08	-0.13
	50	SDLP narrowings (m)	0.01	0.08	0.04	**0.32**	-0.17	**0.03**	-0.30	0.23
RO	51	Delta SDLP (narrowing-straight) (Δm)	**-0.29**	**-0.29**	0.01	-0.07	-0.20	-0.16	**-0.37**	**-0.94**
	52	Delta mean horizontal gaze (narrowing-straight) (Δpx)	**0.12**	**0.16**	-0.01	0.02	0.19	0.18	**0.09**	0.33
	53	Delta mean vertical gaze (narrowing-straight) (Δpx)	-0.07	0.04	**-0.20**	**0.19**	**-0.12**	-0.24	-0.10	-0.06
	54	SD horizontal gaze from the reference narrowings (px)	**0.00**	0.06	0.10	0.26	-0.19	**-0.15**	**-0.29**	**-0.07**
	55	SD vertical gaze from the reference narrowings (px)	0.31	0.24	**0.01**	**0.11**	-0.05	**0.00**	**-0.06**	**0.07**
	56	Delta SD horizontal gaze (narrowing-straight) (Δpx)	**0.07**	**-0.19**	0.32	**-0.13**	**-0.46**	-0.29	**-0.44**	-0.33
	57	Delta SD vertical gaze (narrowing-straight) (Δpx)	-0.19	**-0.09**	-0.19	-0.35	0.15	**-0.19**	-0.25	**-0.12**
	58	Delta mean abs. horizontal gaze (narrowing-straight) (Δpx)	**0.12**	-0.19	0.37	0.02	**-0.45**	**-0.21**	**-0.36**	**-0.44**
	59	Delta mean abs. vertical gaze (narrowing-straight) (Δpx)	0.08	0.13	**-0.20**	0.04	**0.10**	**-0.19**	-0.06	-0.12
SR	60	NASA TLX Mental (1-20)	-0.12	0.04	**-0.04**	**-0.19**	-0.18	0.05	-0.20	-0.18

Note: Correlations that are statistically significant ($p<.05$) are in boldface. The abbreviations SR, CD, SD, RO represent the subgroup measures self-reported, curve driving, straight-road driving and road-narrowing, respectively.

Table F.1: Correlation matrix of the dependent measures. Correlations were determined using the average of the all participants (N = 31) and all curves.

			41	42	43	44	45	46	47	48
	1	Mean speed curves (km/h)								
	2	Mean throttle position curves (0-1)								
	3	Throttle activation curves (0-1)								
	4	Brake activation curves (0-1)								
	5	Speed difference curves (end-begin) (Δkm/h)								
	6	First braking moment curve entries (s)								
	7	Max. brake pedal position curve entries (0-1)								
	8	Braking smoothness curve entries (-)								
	9	Turn-in distance (m)								
	10	Turn-in LP (m)								
	11	Track-out distance (m)								
	12	Track-out LP (m)								
	13	Mean LP curves (m)								
	14	Throttle variance curves (0-1)								
	15	Steer steady curves (0-1)								
	16	Steering integral curves (deg)								
	17	SDLP curves (m)								
CD	18	Anticipatory steering (AS) error (deg)								
	19	Steering integral curve recovery (deg)								
	20	Steer steady curve recovery (0-1)								
	21	Mean horizontal gaze from the reference curve entries (px)								
	22	Mean horizontal gaze from the reference curves (px)								
	23	Mean horizontal from the reference curve exits (px)								
	24	SD horizontal gaze from the reference curve entries (px)								
	25	SD horizontal gaze from the reference curves (px)								
	26	SD horizontal gaze from the reference curve exits (px)								
	27	Mean vertical gaze from the reference curve entries (px)								
	28	Mean vertical gaze from the reference curves (px)								
	29	Mean vertical gaze from the reference curve exist (px)								
	30	SD vertical gaze from the reference curve entries (px)								
	31	SD vertical gaze from the reference curves (px)								
	32	SD vertical gaze from the reference curve exits (px)								
	33	Lead time curves (s)								
	34	Correlation coefficient lead time curves (R)								
	35	Constrained lead time curves (s)								
	36	Constrained correlation coefficient lead time curves (R)								
	37	Mean speed straights (km/h)								
	38	Mean LP straights (m)								
SD	39	Steer steady straights (0-1)								
	40	SDLP straights (m)								
	41	SD horizontal gaze from the reference straights (px)								
	42	SD vertical gaze from the reference straights (px)	**0.40**							
	43	Mean speed narrowings (km/h)	**-0.25**	**-0.40**						
	44	Delta mean speed (narrowing-straight) (Δkm/h)	**-0.40**	**-0.41**	**0.93**					
	45	Mean LP narrowings (m)	**-0.22**	**0.06**	0.12	0.10				
	46	Delta mean LP (narrowing-straight) (Δm)	**-0.39**	**-0.09**	-0.23	-0.16	-0.13			
	47	Speed difference over narrowings (end-begin) (Δkm/h)	0.26	**0.24**	**-0.59**	**-0.65**	**-0.07**	**-0.04**		
	48	Steer steady narrowings (0-1)	0.01	-0.09	**0.36**	**0.35**	0.19	-0.19	**-0.18**	
	49	Delta steer steady (narrowing-straight) (0-1)	-0.21	-0.29	**0.43**	**0.37**	0.11	**0.10**	-0.21	**0.61**
	50	SDLP narrowings (m)	0.25	0.28	**-0.55**	**-0.57**	0.12	**0.06**	0.28	**-0.47**
RO	51	Delta SDLP (narrowing-straight) (Δm)	**-0.17**	**-0.02**	-0.26	-0.21	-0.02	0.21	**0.03**	**-0.30**
	52	Delta mean horizontal gaze (narrowing-straight) (Δpx)	**-0.32**	**-0.20**	**0.52**	**0.52**	0.34	0.04	**-0.26**	0.22
	53	Delta mean vertical gaze (narrowing-straight) (Δpx)	-0.01	-0.26	**-0.03**	**0.01**	**0.02**	0.35	**-0.36**	-0.12
	54	SD horizontal gaze from the reference narrowings (px)	**0.49**	**0.48**	**-0.73**	**-0.77**	-0.18	**0.05**	**0.27**	**-0.43**
	55	SD vertical gaze from the reference narrowings (px)	**0.37**	**0.83**	**-0.41**	**-0.45**	-0.05	**-0.05**	**0.32**	**-0.17**
	56	Delta SD horizontal gaze (narrowing-straight) (Δpx)	**-0.60**	**0.02**	**-0.41**	**-0.28**	**0.07**	**0.46**	**-0.02**	**-0.41**
	57	Delta SD vertical gaze (narrowing-straight) (Δpx)	-0.20	**-0.65**	0.15	0.11	-0.18	**0.10**	0.01	**-0.08**
	58	Delta mean abs. horizontal gaze (narrowing-straight) (Δpx)	**-0.34**	0.09	**-0.61**	**-0.52**	**0.11**	**0.39**	**0.16**	**-0.41**
	59	Delta mean abs. vertical gaze (narrowing-straight) (Δpx)	-0.15	**-0.40**	**0.11**	0.09	**0.10**	**0.35**	-0.20	0.02
SR	60	NASA TLX Mental (1-20)	-0.13	-0.17	**0.04**	**0.12**	0.14	0.05	-0.04	-0.05

Note: Correlations that are statistically significant (p<.05) are in boldface. The abbreviations SR, CD, SD, RO represent the subgroup measures self-reported, curve driving, straight-road driving and road-narrowing, respectively.

Table F.1: Correlation matrix of the dependent measures. Correlations were determined using the average of the all participants (N = 31) and all curves.

			49	50	51	52	53	54	55
	1	Mean speed curves (km/h)							
	2	Mean throttle position curves (0-1)							
	3	Throttle activation curves (0-1)							
	4	Brake activation curves (0-1)							
	5	Speed difference curves (end-begin) (Δkm/h)							
	6	First braking moment curve entries (s)							
	7	Max. brake pedal position curve entries (0-1)							
	8	Braking smoothness curve entries (-)							
	9	Turn-in distance (m)							
	10	Turn-in LP (m)							
	11	Track-out distance (m)							
	12	Track-out LP (m)							
	13	Mean LP curves (m)							
	14	Throttle variance curves (0-1)							
	15	Steer steady curves (0-1)							
	16	Steering integral curves (deg)							
	17	SDLP curves (m)							
CD	18	Anticipatory steering (AS) error (deg)							
	19	Steering integral curve recovery (deg)							
	20	Steer steady curve recovery (0-1)							
	21	Mean horizontal gaze from the reference curve entries (px)							
	22	Mean horizontal gaze from the reference curves (px)							
	23	Mean horizontal from the reference curve exits (px)							
	24	SD horizontal gaze from the reference curve entries (px)							
	25	SD horizontal gaze from the reference curves (px)							
	26	SD horizontal gaze from the reference curve exits (px)							
	27	Mean vertical gaze from the reference curve entries (px)							
	28	Mean vertical gaze from the reference curves (px)							
	29	Mean vertical gaze from the reference curve exist (px)							
	30	SD vertical gaze from the reference curve entries (px)							
	31	SD vertical gaze from the reference curves (px)							
	32	SD vertical gaze from the reference curve exits (px)							
	33	Lead time curves (s)							
	34	Correlation coefficient lead time curves (R)							
	35	Constrained lead time curves (s)							
	36	Constrained correlation coefficient lead time curves (R)							
	37	Mean speed straights (km/h)							
	38	Mean LP straights (m)							
SD	39	Steer steady straights (0-1)							
	40	SDLP straights (m)							
	41	SD horizontal gaze from the reference straights (px)							
	42	SD vertical gaze from the reference straights (px)							
	43	Mean speed narrowings (km/h)							
	44	Delta mean speed (narrowing-straight) (Δkm/h)							
	45	Mean LP narrowings (m)							
	46	Delta mean LP (narrowing-straight) (Δm)							
	47	Speed difference over narrowings (end-begin) (Δkm/h)							
	48	Steer steady narrowings (0-1)							
	49	Delta steer steady (narrowing-straight) (0-1)							
	50	SDLP narrowings (m)	**-0.42**						
RO	51	Delta SDLP (narrowing-straight) (Δm)	**-0.02**	**0.12**					
	52	Delta mean horizontal gaze (narrowing-straight) (Δpx)	**0.28**	**-0.11**	**-0.38**				
	53	Delta mean vertical gaze (narrowing-straight) (Δpx)	-0.07	0.02	**0.06**	**0.16**			
	54	SD horizontal gaze from the reference narrowings (px)	**-0.37**	**0.63**	**0.30**	**-0.41**	0.18		
	55	SD vertical gaze from the reference narrowings (px)	**-0.21**	**0.15**	**-0.01**	**-0.37**	-0.35	**0.47**	
	56	Delta SD horizontal gaze (narrowing-straight) (Δpx)	**-0.12**	**0.31**	**0.45**	**-0.05**	**0.17**	**0.41**	**0.04**
	57	Delta SD vertical gaze (narrowing-straight) (Δpx)	0.22	**-0.29**	0.01	-0.14	-0.02	**-0.22**	-0.12
	58	Delta mean abs. horizontal gaze (narrowing-straight) (Δpx)	**-0.22**	0.32	**0.56**	**-0.30**	**0.22**	**0.55**	**0.11**
	59	Delta mean abs. vertical gaze (narrowing-straight) (Δpx)	0.12	**-0.38**	**-0.01**	-0.01	**0.40**	**-0.16**	-0.12
SR	60	NASA TLX Mental (1-20)	0.18	-0.29	**0.07**	**0.01**	0.21	-0.02	-0.09

Note: Correlations that are statistically significant (p<.05) are in boldface. The abbreviations SR, CD, SD, RO represent the subgroup measures self-reported, curve driving, straight-road driving and road-narrowing, respectively.

Table F.1: Correlation matrix of the dependent measures. Correlations were determined using the average of the all participants (N = 31) and all curves.

			56	57	58	59
	1	Mean speed curves (km/h)				
	2	Mean throttle position curves (0-1)				
	3	Throttle activation curves (0-1)				
	4	Brake activation curves (0-1)				
	5	Speed difference curves (end-begin) (Δkm/h)				
	6	First braking moment curve entries (s)				
	7	Max. brake pedal position curve entries (0-1)				
	8	Braking smoothness curve entries (-)				
	9	Turn-in distance (m)				
	10	Turn-in LP (m)				
	11	Track-out distance (m)				
	12	Track-out LP (m)				
	13	Mean LP curves (m)				
	14	Throttle variance curves (0-1)				
	15	Steer steady curves (0-1)				
	16	Steering integral curves (deg)				
	17	SDLP curves (m)				
CD	18	Anticipatory steering (AS) error (deg)				
	19	Steering integral curve recovery (deg)				
	20	Steer steady curve recovery (0-1)				
	21	Mean horizontal gaze from the reference curve entries (px)				
	22	Mean horizontal gaze from the reference curves (px)				
	23	Mean horizontal from the reference curve exits (px)				
	24	SD horizontal gaze from the reference curve entries (px)				
	25	SD horizontal gaze from the reference curves (px)				
	26	SD horizontal gaze from the reference curve exits (px)				
	27	Mean vertical gaze from the reference curve entries (px)				
	28	Mean vertical gaze from the reference curves (px)				
	29	Mean vertical gaze from the reference curve exist (px)				
	30	SD vertical gaze from the reference curve entries (px)				
	31	SD vertical gaze from the reference curves (px)				
	32	SD vertical gaze from the reference curve exits (px)				
	33	Lead time curves (s)				
	34	Correlation coefficient lead time curves (R)				
	35	Constrained lead time curves (s)				
	36	Constrained correlation coefficient lead time curves (R)				
	37	Mean speed straights (km/h)				
	38	Mean LP straights (m)				
SD	39	Steer steady straights (0-1)				
	40	SDLP straights (m)				
	41	SD horizontal gaze from the reference straights (px)				
	42	SD vertical gaze from the reference straights (px)				
	43	Mean speed narrowings (km/h)				
	44	Delta mean speed (narrowing-straight) (Δkm/h)				
	45	Mean LP narrowings (m)				
	46	Delta mean LP (narrowing-straight) (Δm)				
	47	Speed difference over narrowings (end-begin) (Δkm/h)				
	48	Steer steady narrowings (0-1)				
	49	Delta steer steady (narrowing-straight) (0-1)				
	50	SDLP narrowings (m)				
RO	51	Delta SDLP (narrowing-straight) (Δm)				
	52	Delta mean horizontal gaze (narrowing-straight) (Δpx)				
	53	Delta mean vertical gaze (narrowing-straight) (Δpx)				
	54	SD horizontal gaze from the reference narrowings (px)				
	55	SD vertical gaze from the reference narrowings (px)				
	56	Delta SD horizontal gaze (narrowing-straight) (Δpx)				
	57	Delta SD vertical gaze (narrowing-straight) (Δpx)	0.01			
	58	Delta mean abs. horizontal gaze (narrowing-straight) (Δpx)	**0.86**	-0.02		
	59	Delta mean abs. vertical gaze (narrowing-straight) (Δpx)	0.01	**0.56**	**0.02**	
SR	60	NASA TLX Mental (1-20)	0.12	0.20	**0.15**	**0.29**

Note: Correlations that are statistically significant (p<.05) are in boldface. The abbreviations SR, CD, SD, RO represent the subgroup measures self-reported, curve driving, straight-road driving and road-narrowing, respectively.

G
Appendix G: Self-reported results

In addition to the aforementioned MISC and NASA TLX mental workload, drivers were also asked to rate their own driving skill [106], style [106], and safety [107]. These measures were excluded from the main body to reduce complexity. Table G.1 shows an overview of the results of the self-reported scores. For more details about the exact phrasing for the questions, review Appendices I.1 and I.6.

In summary, the experienced drivers rated noted a statistically significant higher driving skill and driving safety than the inexperienced drivers. Furthermore, no significant differences were found in the self-reported driving style and perceived TLX mental workload scores of the experienced and inexperienced drivers. The expert drivers rated their driving skill, safety and style the highest of all three experimental groups and noted the lowest score for perceived TLX mental workload compared to the inexperienced and experienced drivers.

Table G.1: Overview of the self-reported scores for each experimental group, including a group comparison between the experienced and inexperienced drivers.

Measure	Experimental group						Group comparison	
	Inexperienced		Experienced		Expert		Inexperienced vs. Experienced	
	mean	std	mean	std	mean	std	p-value	Cohen's d
Self-reported driving skill (0-10)	6.19	1.22	7.15	1.28	9.50	0.71	**0.05**	-0.77
Self-reported driving safety (0-10)	6.13	1.20	7.23	1.24	9.00	0.00	**0.02**	-0.91
Self-reported driving style (1-5)	3.31	0.79	3.46	1.05	4.00	1.41	0.68	-0.16
NASA TLX Mental (1-20)	8.44	3.65	8.58	3.90	3.50	0.71	0.92	-0.04
MISC score (0-10)	1.44	1.09	1.33	1.44	1.50	0.71	0.84	0.08

Appendix H: Other two manual driving scenario's

This appendix covers the additional two driving scenarios that the drivers performed as part of the experiment. More information about the exact instructions the drivers received can be found in Appendix I.

H.1. Manual driving scenario 1: Overtaking a slow trucks on the highway

The first driving scenario intended to capture a driver's trajectory planning and manoeuvring and operational skills and control. The drive took place on a triple-lane highway with a road width of 3.6m. The participants were instructed to follow a lead vehicle that controlled the pace at 130 km/h. The lead vehicle had small speed fluctuations to mimic more naturalistic driving conditions. The participants were also instructed to perform a lane-change when this was done by the lead vehicle. During the drive, the participants had to perform eight double lane changes to overtake a slow truck that drove 80 km/h on the rightmost lane (see Figure H.1). The double lane change actions were alternated with small highway sections that contained high radial curves (see Figure H.3). Other traffic was included to create a more realistic environment and was intended to motivate drivers to do more extensive scanning of the environment. During the double-lane changes, traffic drove on the leftmost lane to not interfere with the driver's action. Figure H.2 gives an illustration of how the double lane change looked like from the driver's front eye-tracking camera frame of reference.

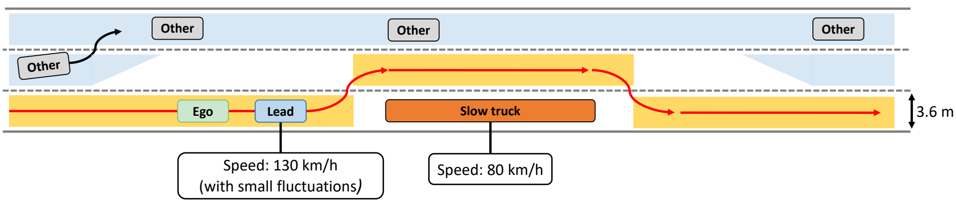

Figure H.1: Schematic visualisation of the first manual driving scenario: overtaking a slow truck on the highway.

H.2. Manual driving scenario 2: Merging rural roads

The second driving scenario intended to capture if and how much drivers adapted their gaze [25, 42, 43, 45] and driving behavior when confronted with alternating low and high demand driving sections. The drive took place on a single-lane rural road with a road width of 3.6m. The participants were instructed to follow a lead vehicle that controlled the pace (see Figure H.4). The lead vehicle had small speed fluctuations during the connecting single-lane rural road segments to mimic more naturalistic driving conditions and was programmed to reduce its operating speed if the following distance became too large. During the scenario, the participants encountered six merging road sections. Thus, the lead vehicle was operating at a constant speed during each merging road section. With each merging road section, a high-density traffic lane merged the initial single-lane from the left and right simultaneously (see Figure H.5). Different preset vehicles were programmed to make lane changes in front of the lead

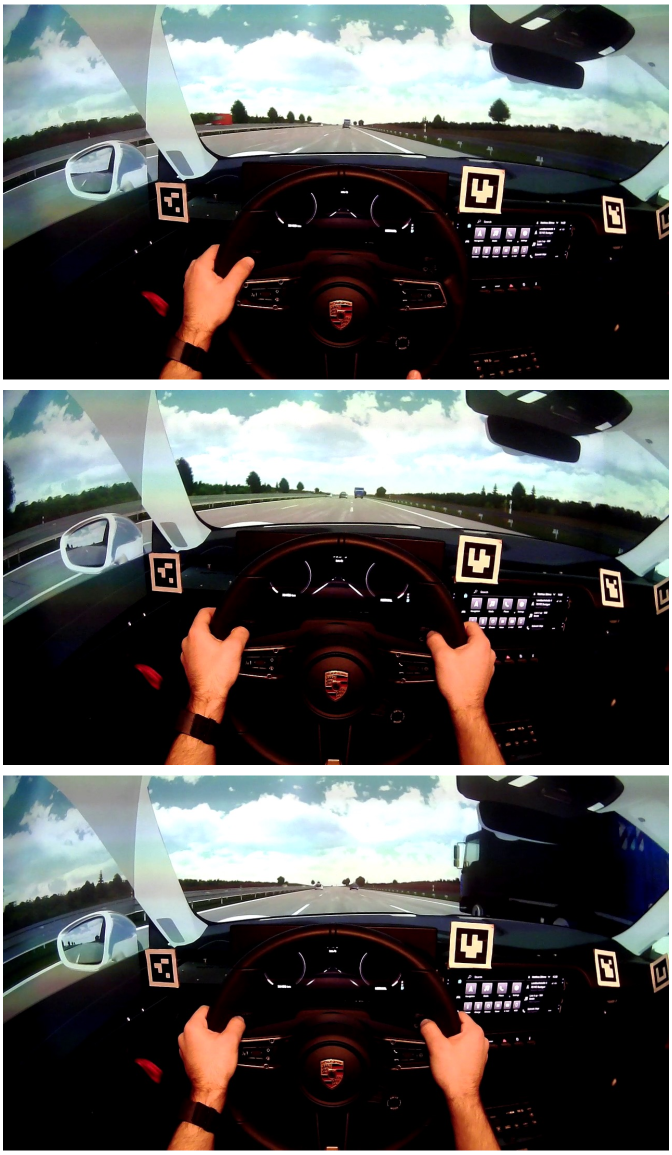

Figure H.2: Top: The lead and ego vehicle approach the slow driving truck on the rightmost lane. Middle: the lead vehicle made a lane change to overtake the slow truck, followed by the ego vehicle. Down: the ego vehicle is overtaking the slow truck, and the lead vehicle made a lane change back to the rightmost lane.

vehicles for each merging road section (see Figure H.6). This traffic interaction should give drivers the impression that traffic might interfere with their driving task, potentially influencing their following distance.

The different road segments should motive drivers to adapt their visual scanning behavior. It is expected that the experienced and expert drivers will effectively increase their scanning during the merging road sections, with this effect being more pronounced for the expert drivers [25, 42, 43]. Furthermore, it is expected that novice/inexperienced drivers will not show this sensitivity to road complexity caused by their underdeveloped hazard detection, therefore, failing to identify potential dangers involving the behaviour of other road users [25, 42, 43]. Additional measures of interest were the number of mirror fixations and minimum/mean following distance (based on [108]) during the different track sections. Figure H.7 gives am impression of how such a driving scenario would approximately look like in reality.

Figure H.3: Small highway sections with high radial curves encountered by the driver between the different overtaking the slow truck sections.

Figure H.4: The single-lane rural road of manual driving scenario two including the lead vehicle that controlled the pace taken from the front eye-tracking camera frame of references.

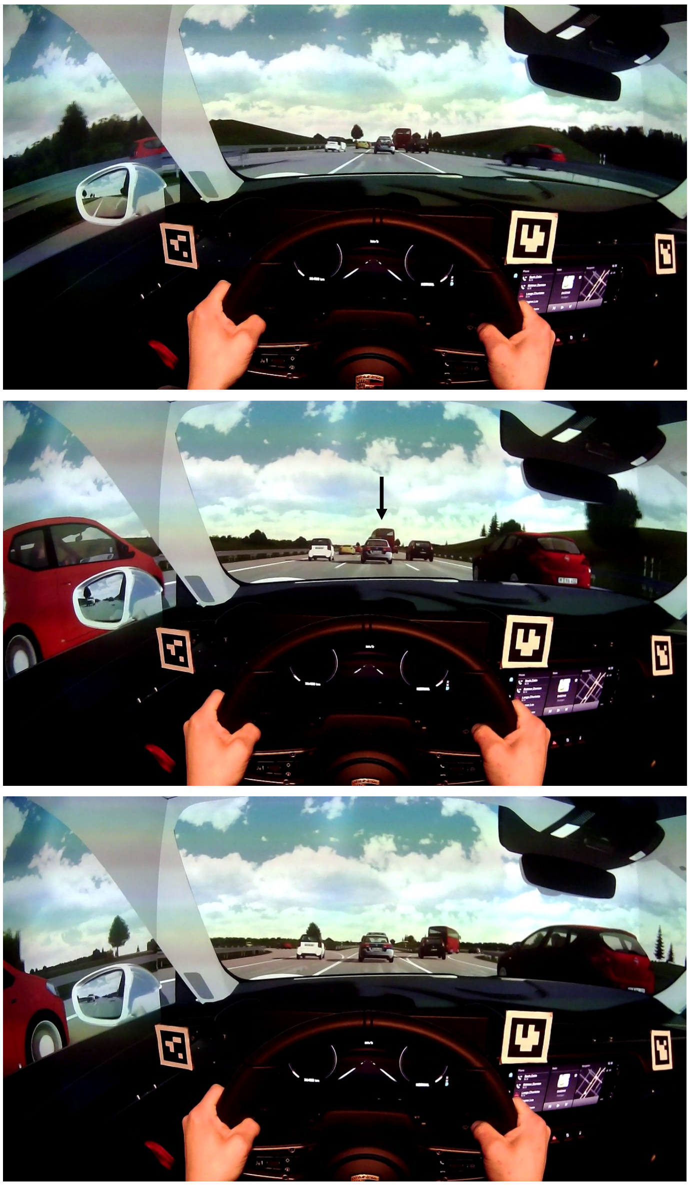

Figure H.5: Top: Entering the road merging section. Middle: the black arrow highlights a vehicle that made a lane change in front of the lead vehicle during the road merging section. Down: Exiting the road merging section. All figures were taken from the front eye-tracking camera frame of reference.

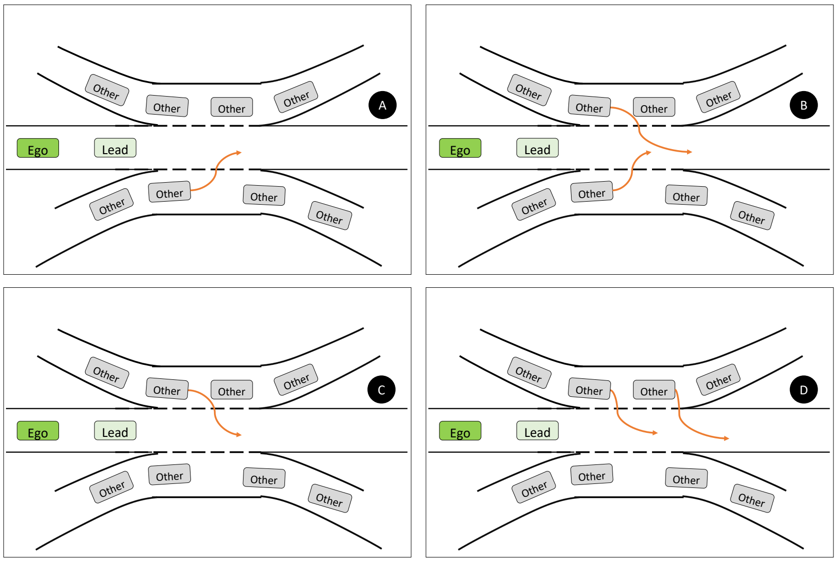

Figure H.6: Overview of the different merging road section configurations.

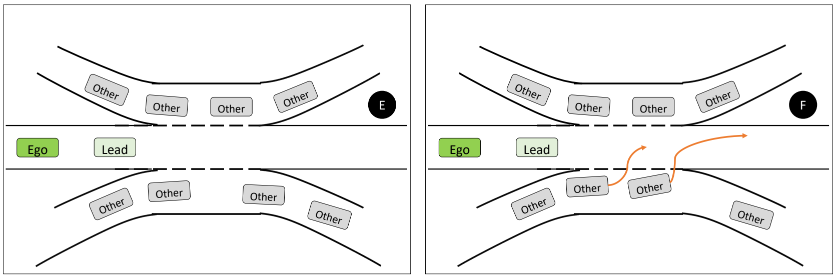

Figure H.6: Overview of the different merging road section configurations (continued).

Figure H.7: Illustrative picture showing how such a merging road section would approximately look like in the real world (taken from [4]).

Appendix I: Additional study related documents

Recap: the entire conducted experiment consisted of two sessions. At the beginning of the first session the participants filled in a consent form (see I.4) and a demographic questionnaire (see I.1), and received an instruction sheet (see I.2). During the transitions from the first to second and second to the third manual driving scenario, the participants were asked to rate their sickness [72], and the perceived mental workload [73] of the last driving task (see I.6). This subjective questionnaire can be digitally accessed via the Porsche Dropbox account. At the end of the first session, the participants were asked to provide feedback (see I.5) and were offered something to eat and drink.
The second session also started with an instruction sheet (see I.3), which was followed by a training session (of approximately 7 minutes) for the delayed Digital Recall task. The instructions and audio files for the 2-back task can be found on the Porsche Dropbox account. After calibration of the equipment, the participants got an approximately 2 minutes familiarization drive to get used to the simulator and controls, directly followed by the 2-back task driving scenario. Afterwards, the participants ran the automated driving simulation identical to [66]. Besides the MISC scores, the participants were asked to give a subjective rating of the perceived mental demand, criticality, comfortable, complexity and perceived time budget of the take-over scenario's (see I.7). Lastly, the same feedback form as for the first session was given to the participants (see I.5).

I.1. Demographic questionnaire

Demographischer Fragebogen

Proband - Nr:

Simulation:

Datum:

Uhrzeit:

Demographie

Folgend einige Fragen zu Ihrer Person. Die Daten werden selbstverständlich anonymisiert und ausschließlich zu wissenschaftlichen Zwecken analysiert. Die Daten werden keinesfalls an Dritte weitergegeben.

1. Alter

Zu welcher Altersgruppe gehören Sie?

Mark only one oval.

- < 20
- 21 bis 30
- 31 bis 40
- 41 bis 50
- 51 bis 60
- > 60

2. Geschlecht

Mark only one oval.

- Weiblich
- Männlich
- Keine Angabe

3. Führerschein

Wie viele Jahre haben Sie schon einen PKW-Führerschein?

Mark only one oval.

- < 5
- >5 bis 10
- >10 bis 20
- >20 bis 40
- >40

Figure I.1: The demographic questions that all participants filled at the beginning of the first session of the study (page: 1/4).

11/9/2020 Demographischer Fragebogen

4. Fahrtfrequenz

Wie oft sind Sie in den letzten zwölf Monaten im Durchschnitt Auto gefahren?

Mark only one oval.

- Täglich
- 4 - 6 Tage pro Woche
- 1 - 3 Tage pro Woche
- 1 - 4 Tage pro Monat
- Weniger als einmal pro Monat
- Nie

5. Fahrtlänge

Wie viele Kilometer sind Sie in den letzten zwölf Monaten im Durchschnitt Auto gefahren?

Mark only one oval.

- Ich bin gar nicht Auto gefahren
- 1km - 1000km
- 1001km - 5000km
- 5001km - 10.000km
- 10.000km - 20.000km
- 20.000km - 50.000km
- Mehr als 50.000km

6. Fahrkünste bewerten

Bewerten Sie Ihre eigene Fahrfähigkeit im Vergleich zu anderen deutschen Autofahrern. Der Wert 5 entspricht dem durchschnittlichen Fahrer in Deutschland.

Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
Schlechtester Fahrer												Perfekter Fahrer

7. Fahrsicherheit

Bewerten Sie Ihre eigenen Fahrsicherheit im Vergleich zu anderen deutschen Fahrern. Der Wert 5 entspricht den durchschnittlichen Fahrer in Deutschland.

Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
Gefährlichster Fahrer												Sicherster Fahrer

https://docs.google.com/forms/d/1StFkmwxXg7O5PvfPmrUTIuqJkbr31iwBsUKw5A5hCaY/edit 2/4

Figure I.1: The demographic questions that all participants filled at the beginning of the first session of the study (page: 2/4).

11/9/2020 Demographischer Fragebogen

8. Selbsteinschätzung Fahrweise

Mark only one oval.

	1	2	3	4	5	
Defensiv/ruhig	⬭	⬭	⬭	⬭	⬭	Sportlich/dynamisch

9. Sehhilfe

Benutzen Sie zum Autofahren eine Sehhilfe?

Mark only one oval.

- Ja (Brille o. Kontaktlinsen)
- Nein

10. Falls ja, tragen Sie diese momentan?

Mark only one oval.

- Ja
- Nein
- Nicht zutreffend

Vorerfahrung

Im Folgenden einige Fragen zu Ihrer bisherigen Erfahrung mit Simulatorstudien und Fahrerassistenzsystemen.

11. Simulatorstudien

Haben Sie bereits an Studien im Fahrsimulator teilgenommen? Wenn ja, an wie vielen?

Mark only one oval.

- Nein
- 1
- 2
- 3
- Mehr als 3

https://docs.google.com/forms/d/1StFkmwxXg7O5PvfPmrUTIuqJkbr31iwBsUKw5A5hCaY/edit 3/4

Figure I.1: The demographic questions that all participants filled at the beginning of the first session of the study (page: 3/4).

12. HAF-Versuche

Haben Sie bereits an Simulatorstudien zum hochautomatisierten Fahren (HAF) teilgenommen? Wenn ja, an wie vielen?

Mark only one oval.

- ◯ Nein
- ◯ 1
- ◯ 2
- ◯ 3
- ◯ Mehr als 3

13. HAF-Kenntnis

Wie gut schätzen sie Ihre HAF-Kenntnis ein?

Mark only one oval.

	1	2	3	4	5	
Totale Unkenntnis	◯	◯	◯	◯	◯	Experte

Fertig!

Bitte wenden Sie sich nun an den Versuchsleiter.

Figure I.1: The demographic questions that all participants filled at the beginning of the first session of the study (page: 4/4).

I.2. Instruction sheet: session 1

PORSCHE

Instruktionen Teil 1

Einführung
Willkommen zum ersten Teil unserer Fahrsimulatorstudie. Wir möchten uns herzlich bei Ihnen bedanken, dass Sie sich die Zeit genommen haben, uns zu unterstützen. Zu Beginn einige Informationen zum Ablauf und der Vorgehensweise. Wir bitten Sie, die Instruktionen sorgfältig durchzulesen. Bei Fragen wenden Sie sich jederzeit an den Versuchsleiter. Während des Experiments werden Ihr Blickverhalten mittels eines „Eye-Trackers", sowie physiologische Daten mittels eines Armbands erfasst. Während des Experiments fahren Sie einen Porsche Taycan Turbo. Die Erfahrung kann von der Realität abweichen, dies geht jedoch über den Rahmen dieser Studie hinaus.

Komponenten
Der heutige Ablauf besteht aus vier Teilen:

1. Instruktionen und Einverständniserklärung
2. Kalibrierung der Messgeräte
3. Manuelle Fahrten auf drei unterschiedlichen Strecken

Manuelles Fahren
Das manuelle Fahren besteht aus drei Szenarien, die nachstehend erläutert werden. Bitte fahren Sie alle Szenarien *wie Sie normalerweise auch fahren* würden und halten Sie sich an die Verkehrsregeln.

Manuelles Fahrszenario 1
Sie fahren auf einer dreispurigen Autobahn. Sie werden gebeten, dem Auto vor Ihnen zu folgen. Wenn das Auto, dem Sie folgen, die Spur wechselt, bitten wir Sie dies auch zu tun. Auch für dieses Fahrszenario gilt, fahren Sie so, wie Sie normalerweise fahren würden. Das erste Segment mit zwei Spurwechseln zählt nicht für Ihre Performance. Auch hier dienen die ersten beiden Fahrspurwechsel der Gewöhnung und werden nicht ausgewertet.

Manuelles Fahrszenario 2
Sie fahren auf einer 1-spurigen Fahrbahn. Sie werden gebeten, dem Auto vor Ihnen zu folgen. Auch für dieses Fahrszenario gilt, fahren Sie so, wie Sie normalerweise fahren würden.

Manuelles Fahrszenario 3
Sie werden gebeten, auf einer 1-spurigen Strecke zu fahren. Verlassen Sie nicht die Fahrspur und treffen Sie idealerweise keinen Pfosten neben der Straße. Die Höchstgeschwindigkeit beträgt 100 km/h. Versuchen Sie, diese Geschwindigkeit beizubehalten, aber passen Sie Ihre Geschwindigkeit wie gewohnt an (z.B. für Kurven oder Ähnlichem). Wir informieren Sie sobald die erforderte Strecke erreicht wurde. Die ersten acht Kurven zählen nicht zu Ihren Ergebnissen und ermöglichen es Ihnen, sich an Fahrdynamik des Fahrsimulators zu gewöhnen. Zu Beginn des ersten Fahrszenarios können noch offene Fragen über das Mikrofon geklärt werden.

Bei jedem Übergang zwischen den verschiedenen Simulationsstrecken werden Sie gebeten, zwei Fragen zu beantworten. Die Fragen und Skalen werden Ihnen auf einem Tablet unterhalb des Center-Displays angezeigt. Die Antwort können Sie einfach laut aussprechen. Nach dem Experiment haben Sie die Möglichkeit, Rückmeldung zur Fahrsimulatorstudie zu geben. Dies können allgemeine Angaben oder positive und/oder negative Erfahrungen sein.

Vielen Dank

Figure I.2: The instruction sheet handed over to the participants with the first session contained information about the following simulator study.

I.3. Instruction sheet: session 2

PORSCHE

Instruktionen Teil 2

Einführung
Willkommen zum zweiten Teil unserer Fahrsimulatorstudie. Wir möchten uns herzlich bei Ihnen bedanken, dass Sie sich die Zeit genommen haben, uns zu unterstützen. Zu Beginn einige Informationen zum Ablauf und der Vorgehensweise. Wir bitten Sie, die Instruktionen sorgfältig durchzulesen. Bei Fragen wenden Sie sich jederzeit an den Versuchsleiter. Während des Experiments werden Ihr Blickverhalten mittels eines „Eye-Trackers“, sowie physiologische Daten mittels eines Armbands erfasst. Während des Experiments fahren Sie einen Porsche Taycan Turbo. Die Erfahrung kann von der Realität abweichen, dies geht jedoch über den Rahmen dieser Studie hinaus.

Komponenten
Der heutige Ablauf besteht aus sechs Teilen:

1. Instruktionen
2. Training 2-Back Task
3. Kalibrierung der Messgeräte
4. Trainingsfahrt
5. 2-Back Task
6. Hochautomatisiertes Fahren

(Training) 2-Back Task
Die Anweisungen hierfür werden in einem separaten Dokument (unter Anleitung die Versuchsleiter) erläutert.

Trainingsfahrt
Eine 5-minütige Trainingsfahrt dient zur Gewöhnung an die Fahrdynamik des Fahrsimulators und das hochautomatisierte Fahrsystem. Weitere Informationen zur Funktionalität des hochautomatisierten Fahrens finden Sie weiter unten. Während oder nach der Trainingsfahrt können noch offene Fragen geklärt werden.

Hochautomatisiertes Fahren
Das Fahrzeug ist mit einer hochautomatisierten Fahrfunktion ausgestattet. Das bedeutet, das Fahrzeug kann selbstständig bremsen, beschleunigen und die Spur halten. Sobald die Automatisierung verfügbar ist, können Sie diese über einen Knopf am Lenkrad aktivieren. Bitte beachten Sie, dass die Funktion des hochautomatisierten Fahrens nur auf der rechten Fahrspur verfügbar ist. Der aktuelle Status der Automatisierung wird durch ein Icon im oberen Bereich des Kombiinstruments dargestellt. Mögliche Ausprägungen und die entsprechenden Bedeutungen der Icons sind wie folgt:

Nicht verfügbar *Verfügbar* *Aktiv* *Übernahmeaufforderung*

Sind alle Fragen geklärt, folgt die Versuchsfahrt, welche auf einer zweispurigen Autobahn stattfinden wird. Zu Beginn ist der Autopilot noch nicht verfügbar. Bitte beschleunigen Sie auf eine Geschwindigkeit von 130 km/h und fahren Sie auf der rechten Fahrspur. Sobald der Autopilot verfügbar ist, bitten wir Sie, die Automatisierung zu aktivieren. Nach der Aktivierung bewegt sich das Fahrzeug im automatisierten Modus mit einer Geschwindigkeit von 130 km/h. Während der hochautomatisierten Fahrt können Sie sich voll und ganz der Nebenaufgabe widmen. Als Nebenaufgabe steht eine Folge der US-Sitcom „Brooklyn-nine-nine“ auf dem Bildschirm neben dem Lenkrad zur Verfügung.

Seien Sie sich jedoch bewusst, dass Sie stets der verantwortliche Fahrer bleiben. Die Automatisierung kann nicht jede Situation meistern. Sobald Sie an eine Systemgrenze stoßen, werden Sie visuell und auditiv aufgefordert die Fahrzeugführung zu übernehmen. Bitte beachten Sie, dass es Ihre oberste Priorität sein sollte, das Fahrzeug sicher und gemäß den Regeln der Straßenverkehrsordnung zu steuern.

Im Falle einer Übernahmeaufforderung, bitten wir Sie, die Automatisierung danach wieder zu aktivieren sobald dies risikofrei möglich ist. Sollte eine derartige Situation auftreten, würden wir Sie bitten, nach der Reaktivierung, vier Fragen auf dem Tablet rechts neben Ihnen zu beantworten. Nachdem Sie die Fragen beantwortet haben, können Sie sich wieder voll und ganz der Serie widmen. Nach dem Experiment haben Sie die Möglichkeit, die Studie zu kommentieren. Dies können allgemeine Angaben oder positive und/oder negative Erfahrungen sein.

Vielen Dank

Figure I.3: The instruction sheet handed over to the participants with the second session contained information about the following simulator study.

I.4. Consent form

PORSCHE

Einverständniserklärungen der Teilnehmer/-innen

Wer nimmt an der Untersuchung teil?
An der Untersuchung nehmen ca. 30 Versuchspersonen im Alter zwischen 18 – 65 Jahren teil. Ausschlusskriterien sind krankhafte degenerative Veränderungen des Bewegungsapparates, Verletzungen bzw. Operationen am Bewegungsapparat, die in den letzten 12 Monaten auftraten, sowie akute oder chronische Erkrankungen des Herzkreislaufsystems. Des Weiteren sind Personen unter Einfluss von Alkohol, Drogen oder wahrnehmungs- oder bewegungs-beeinträchtigenden Medikamenten die Teilnahme untersagt.

Wer führt die Untersuchung durch?
Die Untersuchung wird vom EEC4 durchgeführt. Zuständiger Mitarbeiter ist Herr Koen Verschoor (Betreuer Fabian Doubek).

Bitte vor dem Versuch ausfüllen:

1. Einwilligung zur Teilnahme am Versuch und Verpflichtung zur Geheimhaltung der Versuchsinhalte:

Ich bin mit der Teilnahme am Versuch einverstanden. Die Teilnahme erfolgt freiwillig, d.h. der Versuch kann jederzeit abgebrochen werden. Zudem ist es möglich die Einwilligung zur Auswertung der Daten im Nachgang des Versuchs zu widerrufen. Die Inhalte des Versuchs werde ich geheim halten.

____
Bitte den Namen nochmals lesbar in Druckbuchstaben eintragen

____
Datum und Unterschrift des Testteilnehmers / der Testteilnehmerin

2. Einwilligung zur Erfassung und Speicherung von Daten und Bildmaterial:

Ich bin damit einverstanden, dass Versuchsdaten aufgezeichnet und gespeichert werden. Insbesondere bin ich auch damit einverstanden, dass Bildmaterial vom Versuchsablauf erstellt und gespeichert wird.

____
Datum und Unterschrift des Testteilnehmers / der Testteilnehmerin

3. Risiko-Nutzen-Abwägung
Das gesundheitliche Risiko für Sie ist minimal. Ab und zu treten bei vereinzelten Probanden Unwohlsein während des Versuchs auf. Dies hängt damit zusammen, dass Bewegungen visuell wahrgenommen aber haptisch nicht gefühlt werden. Sollten Sie sich nicht gut fühlen, können Sie den Versuch jederzeit ohne Konsequenzen abbrechen.

____
Datum und Unterschrift des Testteilnehmers / der Testteilnehmerin

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Figure I.4: The consent form that all participants filled in before starting the study (page 1/3).

PORSCHE

Bitte erst <u>nach</u> dem Versuch ausfüllen:

3. Einwilligung zur Auswertung der Versuchsdaten:

Ich bin damit einverstanden, dass Versuchsdaten und das während der Versuchsfahrten gewonnene Bildmaterial zur Versuchsauswertung und zur anonymisierten Ergebnispräsentation verwendet werden können.

____

Datum und Unterschrift des Testteilnehmers / der Testteilnehmerin

Optional:

4. Einwilligung zur Verwendung von Bildmaterial für Präsentationen:

Ich bin damit einverstanden, dass Ausschnitte des während der Versuchsfahrten gewonnenen Bildmaterials oder anderen bildhaften Daten aus dem Versuch bei internen und externen Präsentationen gezeigt werden.

____

Datum und Unterschrift des Testteilnehmers / der Testteilnehmerin

Wir freuen uns über Ihre Teilnahme an der Untersuchung und nehmen den Schutz Ihrer Privatsphäre und Ihrer persönlichen Daten, die Sie uns zur Verfügung stellen, sehr ernst. Alle im Rahmen der Versuche anfallenden Daten unterliegen einer Datenschutz- / Vertraulichkeitsverpflichtung der Versuchsleiter und Auswerter, die Sie auf Wunsch einsehen können.

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Figure I.4: The consent form that all participants filled in before starting the study (page 2/3).

Anlage 1 zur Probandenstudie – Hochautomatisiertes Fahren

Datenschutzrechtliche Einwilligungserklärung

Einwilligung in die Datenverarbeitung zur Durchführung und Auswertung des Probandenversuchs:

Ich bin damit einverstanden, dass im Rahmen des Probandenversuchs personenbezogene Daten zu folgenden Zwecken

- Grundlagenforschung und angewandten Forschung
- Produkt- und Diensteentwicklung und –verbesserung

erhoben und verarbeitet werden.

Diese Einwilligung umfasst folgende im Rahmen dieses Versuchs relevanten personenbezogenen Daten:

- Demographische Daten (insbesondere Name, Alter, Geschlecht)
- Gesundheitsdaten (Brillenträgereigenschaft, Hautleitfähigkeit, Puls, Pupillometrie (Größenveränderung der Pupille bei Stresseinwirkung))
- Fahrerfahrungen bzgl. des Hochautomatisierten Fahrens

Folgende Verarbeitungstätigkeiten werden mit diesen Daten durchgeführt:
Da uns die Perfektion unserer Fahrzeuge am Herzen liegt, sind wir bestrebt diese immer weiter zu verbessern. Dies kann uns nur gelingen, wenn wir immer neue Mittel und Wege finden bestehende Funktionen zu verbessern. Mit Hilfe dieser Studie soll bei einer manuellen Fahrt die Übernahmequalität bei einer systemseitigen Aufforderung betrachtet werden. Hierzu werden Sie im Fahrsimulator im ersten Schritt auf einer Landstraße/Autobahn bei einer manuellen Fahrt unterschiedliche Verkehrssituationen erleben. Danach werden Sie als Proband gebeten eine Autobahnfahrt durchzuführen, nun jedoch unter Einfluss des Automationssystems. Während dieser Fahrt werden Sie zusätzlich durch die Lösung einer Zweitaufgabe abgelenkt sein. In diesem Zeitraum wird Sie das System sechsmal auffordern aktiv in die Fahrsituation einzugreifen. Hierbei wird Ihr Stresslevel beim Eingriff über Sensoren auf Ihrer Haut, dem Eye-Tracking und Ihrem Puls kontrolliert. Ziel der Studie ist Parameter und Kriterien des manuellen Fahrens zu identifizieren, die einen signifikanten Einfluss auf die Übernahmequalität beim automatisierten Fahren haben.
Ihre personenbezogenen Daten werden im Rahmen des Probandenversuches durch Kameraaufnahmen und ein intelligentes Armband (physiologische Daten) erhoben. Wir pseudonymisieren personenbezogene Daten der Versuchspersonen so früh wie möglich anhand eines zufällig generierten Zeichencodes. Eine Zuordnung der Versuchspersonen zu den anderen persönlichen Daten können nur Versuchsleiter und Auswerter vornehmen. Die Daten werden zu den obenstehenden Zwecken ausgewertet und aufbereitet.

_______________ ____

Datum /Unterschrift des Probanden/der Probandin

____

Bitte den Namen nochmals lesbar in Druckbuchstaben eintragen

Wir freuen uns über Ihre Teilnahme an der Untersuchung und nehmen den Schutz Ihrer Privatsphäre und Ihrer persönlichen Daten, die Sie uns zur Verfügung stellen, sehr ernst. Alle im Rahmen der Versuche anfallenden Daten unterliegen einer Datenschutz- / Vertraulichkeitsverpflichtung der Versuchsleiter und Auswerter, die Sie auf Wunsch einsehen können.

Die Einwilligung kann – auch nur teilweise – gegenüber der Porsche AG ohne Angabe von Gründen mit Wirkung für die Zukunft widerrufen werden. Dazu wenden Sie sich bitte an Nikolai von Janczewski (nikolai.paersch@porsche.de).

Figure I.4: The consent form that all participants filled in before starting the study (page 3/3).

I.5. Feedback form (session 1 & 2)

11/9/2020 Nachbefragung

Nachbefragung

Proband - Nr:

Simulation:

Datum:

Uhrzeit:

Simulator

1. "Ich empfand den Fahrsimulator als sehr realistisch in Bezug auf die Visualisierung und Fahrdynamik"

Mark only one oval.

	1	2	3	4	5	
trifft nicht zu	◯	◯	◯	◯	◯	trifft zu

Anmerkung

2. Haben Sie weitere negativen oder positiven Anmerkungen zum Versuchsaufbau und -ablauf?

____

____

____

____

____

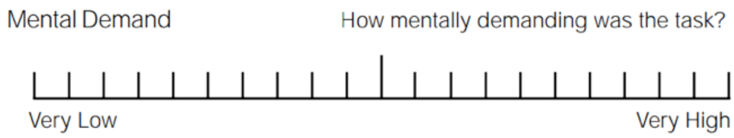
Ende

Vielen Dank für Ihre Teilnahme

Figure I.5: The feedback form that gave participants the possibility to give feedback on the study, used for sessions one and two.

I.6. Subjective questionnaire: session 1

Wie mental anstrengend war die Aufgabe für Sie (z. B. Denken, Entscheiden, Berechnen, Erinne
Schauen, Suchen usw.)? Bitte nennen Sie uns hierfür jetzt laut und deutlich eine Zahl zwischen 1
(gar nicht anstrengend) und 20 (sehr anstrengend).



Fahrerzustand nach Manuelles fahrzenario 2

Bitte teilen Sie uns laut und deutlich mit, wie Sie sich gerade auf einer Skala von 0 - 9 (siehe Ska
unten) fühlen.

Symptom		Bewertung
Keine Probleme		0
Leichtes Unbehagen, aber keine spezifischen Symptome		1
Schwindel, Hitzegefühl, Kopfschmerzen, Magenprobleme, Schwitzen, usw.	vage	2
	etwas	3
	mittel	4
	heftig	5
Übelkeit	etwas	6
	mittel	7
	heftig	8
	würgend	9

Figure I.6: Section of the subjective questionnaire as filled out on the tablet, used to measure the driver's sickness and perceived mental workload (TLX) during the first session.

I.7. Subjective questionnaire: session 2

10. Wie sicherheitskritisch empfanden Sie diese Übernahmesituation?

Mark only one oval.

	0	1	2	3	4	5	6	
Sehr unkritisch	◯	◯	◯	◯	◯	◯	◯	Sehr kritisch

11. Wie kompliziert empfanden Sie diese Übernahmesituation?

Mark only one oval.

	0	1	2	3	4	5	6	
Sehr unkompliziert	◯	◯	◯	◯	◯	◯	◯	Sehr kompliziert

12. Wie komfortabel empfanden Sie Ihre Ausführung des Übernahmemanövers?

Mark only one oval.

	0	1	2	3	4	5	6	
Sehr komfortabel	◯	◯	◯	◯	◯	◯	◯	Sehr unkomfortabel

13. Wie empfanden Sie die zur Verfügung gestellte Zeit zur Übernahme?

Mark only one oval.

	0	1	2	3	4	5	6	
Mehr als ausreichend	◯	◯	◯	◯	◯	◯	◯	Viel zu wenig

Vierte Übernahmesituation

Figure I.7: Section of the subjective questionnaire as filled out on the tablet, used to rate each take-over scenario.

J

Appendix J: Ethical approval Porsche AG

In order to perform the intended experiment at the Porsche Research and Development Facility in Weissach, the study had to be approved by the company's ethical committee. Due to the worldwide Covid-19 pandemic, additional measures were set up to assure the safety of the Porsche employees. The final approval can be found in Figure J.1.

PORSCHE

Antrag auf Durchführung eines Probandenversuches bwz. Datenloggereinsatzes im EZW Intern

Von	Personalnummer	Abteilung	Datum
Koen Verschoor	384741	EEC4	17.06.2020
Standort	Telefon	Fax	Mobil
Werk 8			
	E-Mail		
	koen.verschoor@porsche.de		

Dr. Ing. h.c. F. Porsche Aktiengesellschaft

Hiermit wird

☒ die Durchführung eines Probandenversuches (gemäß RBV über Probandenversuche)

☐ der Einsatz von Messwerterfassungssystemen (Datenlogger) in Fahrzeugen (gemäß RBV über den Einsatz von Messwerterfassungssystemen und Online-Diensten in der Fahrzeugentwicklung)

mit folgenden Rahmenbedingungen beantragt:

Begründung (warum ist der Versuch bzw. der Datenloggereinsatz notwendig)

Es soll der Effekt des Fahrverhaltens während einer manuellen Fahrt auf die Übernahmequalität bei systeminitiierten Übernahmeaufforderungen bestimmz werden. Ein Datenlogger wird zur Analyse der Fahrdaten (Fahrsimulator) aufzeichnen. Daten die aufgezeichnet werden:

Fahrzeugposition (keine GPS/Standort Daten, sondern in Realtion zur Fahrbahnmitte, -Rand oder einem Hindernis, etc.), Beschleunigungsparameter, Lenk- und Bremsaktivität und Fahrzeugdynamik (z.B.: Gierwinkel). Über Eye-Tracking soll das Blickverhalten und das Stresslevel durch Pupillometrie (Größenveränderung der Pupille) bestimmt werden. Zur Verfizierung des Stresslevels soll mittels des E4 Armbands (Empatica) der Puls, die Hautleitfähigkeit und Hauttemperatur erhoben werden.

Zweck und Ablauf (was wird erprobt und wie)

Im virtuellen Fahrerplatz (Fahrsimulator), werden die Probanden, in einer ersten manuellen Fahrt, unterschiedliche Verkehrssituationen auf einer Landstraße erleben. Nach einer kurzen Pause und Einführung in das Automationssystem, folgt eine automatisierte Fahrt in der die Probanden einer Zweitaufgabe (Video auf dem Centerdisplay) nachgehen. Während der automatisierten Fahrt wird der Fahrer insgesamt sechsmal aufgefordert die Fahraufgabe zu übernehmen, um einem Hindernis durch einen Spurwechsel auszuweichen. Die Übernahmeszenarien variieren in Bezug auf Übernahmezeiten und Verkehrskomplexität.

Ablauf:

- Begrüßung und Erklärung zum Versuchablauf
- Einverständniserklärungen der Teilnehmer/-innen & Allgemeiner Fragebogen
- Einführungsfahrt
- Manuelle Fahrt ikl. verbaler Rückmeldung (warum haben Sie die Situation so gelöst?)
- Hochautomatisierte Fahrt
- Fragebogen zur subjektiven Bewertung

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24.08.2020 Seite 1 von 16 Koen Verschoor - Antrag auf Durchführung eines Probandenversuches_v2.docx

Figure J.1: The ethical approval granted by the ethical committee of Porsche AG and signed by the Head of Development Electronics Electronics Software (page 1/16).

PORSCHE

Antrag auf Durchführung eines Probandenversuches bzw. Datenloggereinsatzes im EZW   Intern

Erprobungsort(e)	**Labor im EZW**
Virtueller Fahrerplatz 2	

Versuchsverantwortliche Personen		
Abteilung	Name	Funktion
EEC4	Koen Verschoor	Projektleitung
EEC4	Fabian Doubek	Betreuer
EEC4	Nikolai von Janczewski	Betreuer

Versuchsteilnehmer bzw. Fahrer (vorgesehene Zielgruppe und Auswahlverfahren)
Projektferne Mitarbeiter des EWZ

Starttermin und Ende der Studie / der Erprobung
KW46/KW47 2020

Datenerhebung (welche personenbezogenen Daten und welche wesentlichen Fahrdaten werden erfasst) Bitte fügen Sie den jeweiligen Fragebogen als Anlage bei.
Alter (Spanne), Geschlecht Fahrerfahrung (Spanne) Erfahrung mit automatisierten Fahrsystemen im Fahrsimulator Subjektive Bewertung der manuellen Fahrt und der Übernahmesituationen Eye Tracking, Hautleitfähigkeit, Hauttemperatur und Puls

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24.08.2020   Seite 2 von 16   Koen Verschoor - Antrag auf Durchführung eines Probandenversuches_v2.docx

Figure J.1: The ethical approval granted by the ethical committee of Porsche AG and signed by the Head of Development Electronics Electronics Software (page 2/16).

PORSCHE

Antrag auf Durchführung eines Probandenversuches bzw. Datenloggereinsatzes im EZW Intern

Erprobungsort(e)	**Labor im EZW**
Virtueller Fahrerplatz 2	

Versuchsverantwortliche Personen		
Abteilung	Name	Funktion
EEC4	Koen Verschoor	Projektleitung
EEC4	Fabian Doubek	Betreuer
EEC4	Nikolai von Janczewski	Betreuer

Versuchsteilnehmer bzw. Fahrer (vorgesehene Zielgruppe und Auswahlverfahren)
Projektferne Mitarbeiter des EWZ

Starttermin und Ende der Studie / der Erprobung
KW46/KW47 2020

Datenerhebung (welche personenbezogenen Daten und welche wesentlichen Fahrdaten werden erfasst) Bitte fügen Sie den jeweiligen Fragebogen als Anlage bei.
Alter (Spanne), Geschlecht
Fahrerfahrung (Spanne)
Erfahrung mit automatisierten Fahrsystemen im Fahrsimulator
Subjektive Bewertung der manuellen Fahrt und der Übernahmesituationen
Eye Tracking, Hautleitfähigkeit, Hauttemperatur und Puls

F.G.2224-15.08 24.08.2020 Seite 2 von 16 Koen Verschoor - Antrag auf Durchführung eines Probandenversuches_v2.docx

Figure J.1: The ethical approval granted by the ethical committee of Porsche AG and signed by the Head of Development Electronics Electronics Software (page 3/16).

PORSCHE

Antrag auf Durchführung eines Probandenversuches bzw. Datenloggereinsatzes im EZW Intern

Erprobungsort(e)	**Labor im EZW**
Virtueller Fahrerplatz 2	

Versuchsverantwortliche Personen		
Abteilung	Name	Funktion
EEC4	Koen Verschoor	Projektleitung
EEC4	Fabian Doubek	Betreuer
EEC4	Nikolai von Janczewski	Betreuer

Versuchsteilnehmer bzw. Fahrer (vorgesehene Zielgruppe und Auswahlverfahren)
Projektferne Mitarbeiter des EWZ

Starttermin und Ende der Studie / der Erprobung
KW46/KW47 2020

Datenerhebung (welche personenbezogenen Daten und welche wesentlichen Fahrdaten werden erfasst) Bitte fügen Sie den jeweiligen Fragebogen als Anlage bei.
Alter (Spanne), Geschlecht Fahrerfahrung (Spanne) Erfahrung mit automatisierten Fahrsystemen im Fahrsimulator Subjektive Bewertung der manuellen Fahrt und der Übernahmesituationen Eye Tracking, Hautleitfähigkeit, Hauttemperatur und Puls

F.G.2224.15.08 24.08.2020 Seite 2 von 16 Koen Verschoor - Antrag auf Durchführung eines Probandenversuches_v2.docx

Figure J.1: The ethical approval granted by the ethical committee of Porsche AG and signed by the Head of Development Electronics Electronics Software (page 4/16).

PORSCHE

Antrag auf Durchführung eines Probandenversuches bzw. Datenloggereinsatzes im EZW Intern

Erprobungsort(e)	**Labor im EZW**
Virtueller Fahrerplatz 2	

Versuchsverantwortliche Personen		
Abteilung	Name	Funktion
EEC4	Koen Verschoor	Projektleitung
EEC4	Fabian Doubek	Betreuer
EEC4	Nikolai von Janczewski	Betreuer

Versuchsteilnehmer bzw. Fahrer (vorgesehene Zielgruppe und Auswahlverfahren)
Projektferne Mitarbeiter des EWZ

Starttermin und Ende der Studie / der Erprobung
KW46/KW47 2020

Datenerhebung (welche personenbezogenen Daten und welche wesentlichen Fahrdaten werden erfasst) Bitte fügen Sie den jeweiligen Fragebogen als Anlage bei.
Alter (Spanne), Geschlecht
Fahrerfahrung (Spanne)
Erfahrung mit automatisierten Fahrsystemen im Fahrsimulator
Subjektive Bewertung der manuellen Fahrt und der Übernahmesituationen
Eye Tracking, Hautleitfähigkeit, Hauttemperatur und Puls

F.G.2224-15.08

24.08.2020 Seite 2 von 16 Koen Verschoor - Antrag auf Durchführung eines Probandenversuches_v2.docx

Figure J.1: The ethical approval granted by the ethical committee of Porsche AG and signed by the Head of Development Electronics Electronics Software (page 5/16).

PORSCHE

Antrag auf Durchführung eines Probandenversuches bzw. Datenloggereinsatzes im EZW Intern

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EEC4	Nikolai von Janczewski	Betreuer

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Antrag auf Durchführung eines Probandenversuches bzw. Datenloggereinsatzes im EZW   Intern

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K

Appendix K: Reproducibility and MATLAB script

K.1. Reproducibility

The figures presented in chapter 2.6 were used as templates for programming the digital simulator environment. The programming of the simulator environment was performed by Ingo Krems, Claus-Heiko Winkler, and Niklas Bohne, at the Porsche *Virtueller Fahrerplatz 2* in Weissach, Germany. All study results are stored and kept offline on a hard drive in the possession of Fabian Doubek and Joost de Winter. The hard drive also contains all video files of all manual and automated driving scenarios recorded by the front camera of the eye-tracker.

K.2. MATLAB script

The data processing and analysis for this research were entirely performed in MATLAB (version 2020b). The complete script, including all function files, are stored offline on a hard drive in possession of Joost de Winter. The code has been written with the goal to make it (1) easy to read and (2) allow editors to adapt the settings for the analysis without rewriting the code. The code was divided into three main m-files to enhance readability. These three main m-files were responsible for: (1) data pre-processing, (2) running the analysis and exporting the results to Excel and (3) generating and saving the figures. Moreover, the code is primarily built out of function files to (again) enhance readability. The three main m-files were responsible for controlling the required function files. All settings needed for each main m-file are stated at the top of the concerned main m-file script. Table K.1 gives an overview of the structure of the MATLAB code used for this report. All self-written code was stored in the folder *Function_files*. The imported function files were stored in the *Imported_Function_files* folder.

K.3. Data structure

The raw .txt-files exported from the D-Lab behavioural research software were stored in the *Raw data* folder. The first main m-files (Thesis_V1) gives the option to use the raw files, convert them to .mat-files and store them in the *Converted data* folder; or directly use the converted files by selecting the *load* option. Afterwards, the code remains the same independent of the selected option (*load* or *import data*) and will perform all data processing steps. When completed, the .mat-files are stored in the *Participant data for analysis* folder. The data for each driving scenario and participant is stored separated. The files are named according to driving task (A) Manual/Automated, (B) the driving scenario/the take-over number and lastly, the participant number in the sequence of A_B_pp_#. So, for example, the data of manual driving scenario 3, of participant 6, is saved as Manual_03_pp_6. A password protects the raw data that contains privacy-sensitive information. If required to access these files, contact Fabian Doubek.

K.4. Analysis settings and exporting the results

The first and second main m-files, *Thesis_V1* and *Thesis_V1_data_analysis*, allow the editor to adjust the settings for the analysis. An example of such an adjustment could be the lap settings, participant selection, road-departure definition, or distance settings for the different track sections. Furthermore, the last two main m-files allow the editor to determine to which Excel file the results are exported to.

K.5. Analysis conventions

Figure K.1 gives an overview of the conventions used for the analysis. As stated in chapter 2.3, the vehicle cabin had QR-markers needed to localise the participant's gaze direction. Figure K.2 shows the names used for the different QR-markers. Lastly, Table K.2 lists the sequence of straight, narrowings and curves for each lap. As

Table K.1: Overview of the coded MATLAB files used for this report.

Main m-files	Description	Function files*
Thesis_V1.m	Responsible for pre-processing the data needed for the analysis.	• Thesis_start_load_data • Thesis_start_import_and_update_data • Thesis_Oval_track_layout_info • Thesis_extract_txt_filenames • Thesis_extract_mat_filenames • Thesis_data_preprocessing • Thesis_part_group_information • Thesis_create_additional_structs • Thesis_det_mean_speed_curves • Thesis_correct_lane_offset_measure • Thesis_road_departures • Thesis_add_abs_diff_steering_wheel_angle • Thesis_heading_angle_vehicle_track_and_relative • Thesis_long_lat_acceleration • Thesis_analysis_section_labels • Thesis_add_brake_pedal_speed • Thesis_filter_gaze_locationXY • Thesis_overview_speed_fig
Thesis_V1_data_analysis.m	Responsible for the data analysis and exporting the results to Excel.	• Thesis_remove_track_departures_section_labels • Thesis_determine_mean_median_gaze_XY_straights • Thesis_store_outputs_excel • Thesis_store_outputs_MATLAB • Thesis_determine_output_curves_Excel • Thesis_determine_AS_CSEI_error • Thesis_determine_output_excel_mean_deviation • Thesis_calc_lead_times_horizontal • Thesis_determine_output_straight_road_Excel • Thesis_determine_output_narrowing_Excel
Thesis_V1_final_figures.m	Responsible for generating the figures and saving the figures.	• Thesis_generate_curve_figure_data • Thesis_determine_output_curves_Excel • Thesis_calc_lead_times_horizontal • Thesis_cohens_d

(*): Not all function files are included. For the complete overview, review the MATLAB code.

stated in chapter 2.3, the narrowings were presented in a counterbalanced order using a Latin-square method to eliminate order and sequence effects.

Table K.2: Overview of the road-narrowing sequence per lap.

Lap	Sequence	Number of narrowings
1*	Straight →R2 →Straight →R1 →Straight →R3 →Straight →R4	0
2	Straight →R2 →Narrow →R1 →Straight →R3 →Narrow →R4	2
3	Narrow →R2 →Straight →R1 →Narrow →R3 →Straight →R4	2
4	Narrow →R2 →Narrow →R1 →Straight →R3 →Straight →R4	2
5	Straight →R2 →Straight →R1 →Narrow →R3 →Narrow →R4	2
6	Narrow →R2 →Straight →R1 →Narrow →R3 →Straight →R4	2
7	Straight →R2 →Narrow →R1 →Straight →R3 →Narrow →R4	2
8**	Narrow →R2 →Straight →R1 →Narrow →R3 →Straight →R4	2

(*): test lap, (**): back-up lap.

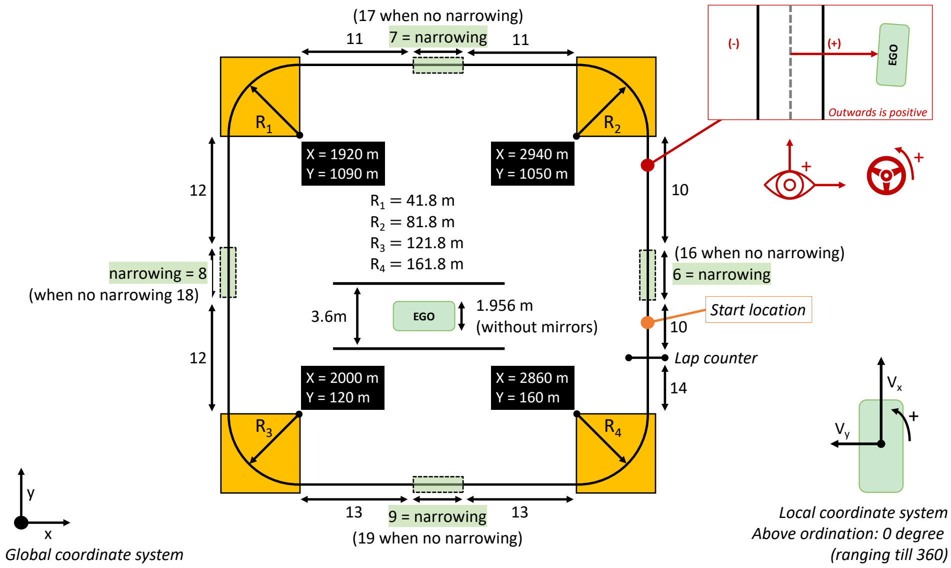

Figure K.1: Overview of the conventions and track labels used for the analysis.

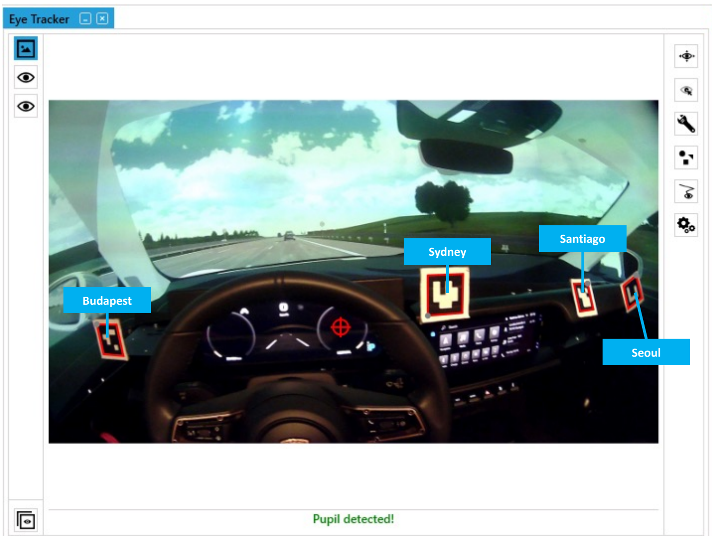

Figure K.2: Screenshot taken from the D-Lab behavioural research software (version 3.5) showing the names for the different QR-markers.

L

Appendix L: Driving simulator system specifications

Table L.1 presents the system's specification, eMove eM6-640-1800, moving base driving simulator used for this study [63–66]. Figures L.1 to L.3 visualizes the simulator apparatus end its surrounding.

Table L.1: Overview of the eMove eM6-640-1800 moving base platform as used for this research.

	Excursions		Velocity	Acceleration
	Single DOF	Non-single DOF		
Surge	-0.48 to 0.60 [m]	-0.64 to 0.63 [m]	0.8 [m/s]	7 [m/s2]
Sway	0.50 to 0.50 [m]	-0.66 to 0.66 [m]	0.8 [m/s]	7 [m/s2]
Heave	-0.41 to 0.41 [m]	-0.41 to 0.41 [m]	0.6 [m/s]	10 [m/s2]
Roll	23.8 to 23.8 [deg]	-29.2 to 29.2 [deg]	35 [deg/s]	250 [deg/s2]
Pitch	23.7 to 26.0 [deg]	-28.2 to 32.9 [deg]	35 [deg/s]	250 [deg/s2]
Yaw	-25.4 to 25.4 [deg]	-28.7 to 28.7 [deg]	40 [deg/s]	500 [deg/s2]

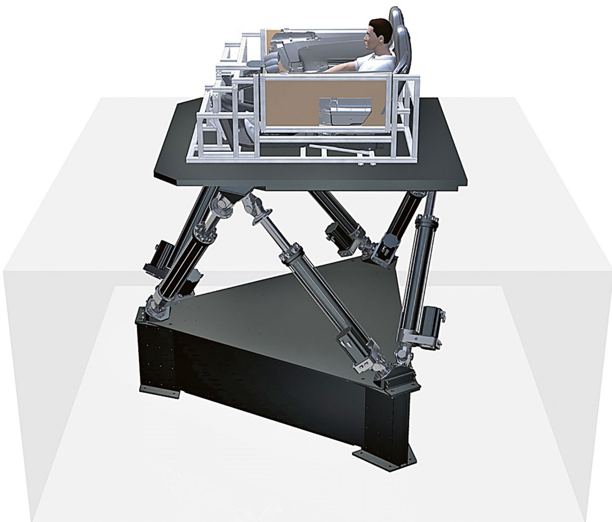

Figure L.1: Visualisation of 6-DOF moving base hexapod driving simulator [5].

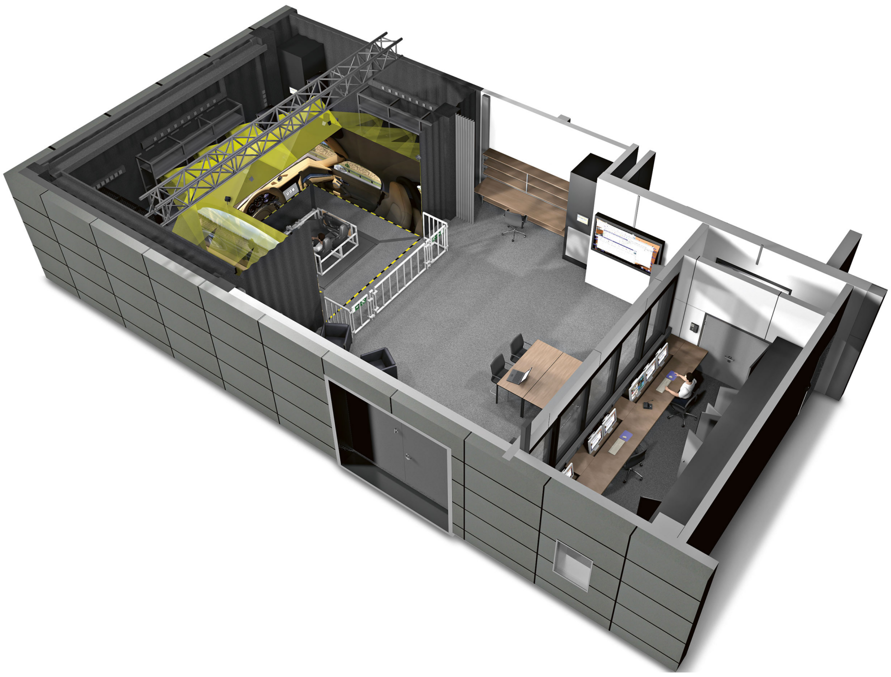

Figure L.2: Visualisation of the *Virtueller Fahrerplatz 2* in Weissach, Germany [5].

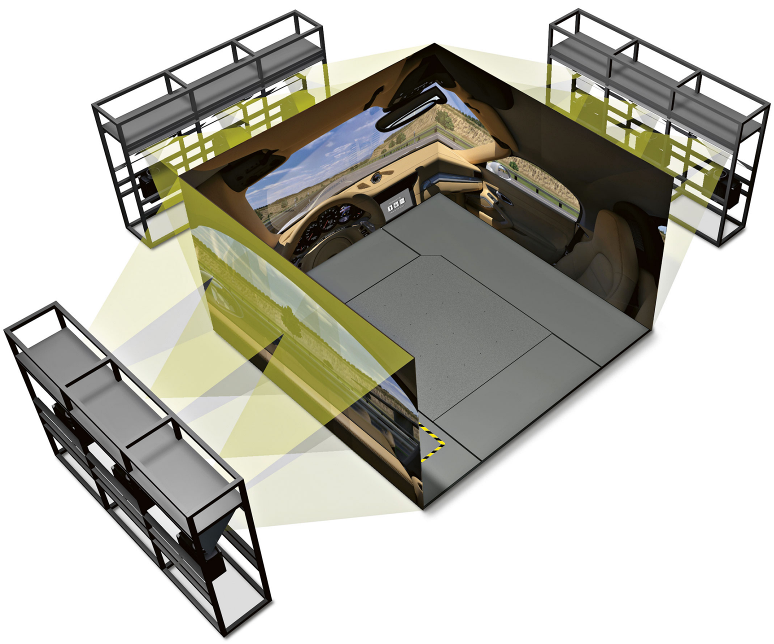

Figure L.3: Visualisation of the projectors displaying the 180 deg test environment [5].

M

Appendix M: Vehicle model specifications

The vehicle dynamics software was based on the all-electric Porsche Taycan Turbo. Table M.1 presents the vehicle specifications as used for the conducted experiment. The vehicle understeer gradient was determined by running various steady-state curve driving simulations. Table M.1 shows that the vehicle has a two-speed automatic transmission. However, for the study, the vehicle model was restricted to using only one gear to improve overall smoothness, intended to reduce the change of motion sickness and eliminate undesired vehicles' vibrations that could affect the operators' behavior. Moreover, the restriction of using one of the two gears had a negligible effect on the car's overall performance. Figure M.1 gives a top view visualisation of the vehicle.

Table M.1: Porsche Taycan Turbo vehicle model specifications.

	Specification
Wheelbase	2.90 m
Length	4.96 m
Width	1.96 m
Height	1.38 m
Weight	2234.7 kg
Steering ratio	15.448
Maximum power	626 hp
Maximum torque	850 Nm
Transmission	2-speed automatic
Drivetrain	4-wheel drive
Understeer gradient	Classified*

(*): The understeer gradient can not be presented since it is confidential information.

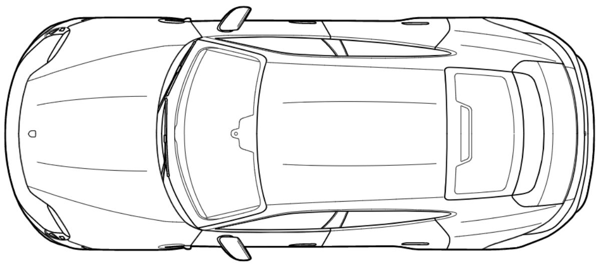

Figure M.1: Top view visualisation of the Porsche Taycan Turbo ([6]).

N

Appendix N: Mathematical expressions & calculation methods

N.1. Equations

The equation for Cohen's d (ds) used to describe the standardized mean difference of an effect [90]:

$$d_s = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{(n_1-1)SD_1^2+(n_2-1)SD_2^2}{n_1+n_2-2}}} \tag{N.1}$$

where:

- d_s = Cohen's d.
- $\bar{X}_1$ / $\bar{X}_2$ = mean of group one and two, respectively.
- n_1 / n_2 = group sizes.
- SD_1 / SD_2 = standard deviations.

The equation for the estimated 95% Cohen's d confidence interval (CI), according to [109]:

$$CI = [d_s - 1.96 \times \sigma(d_s), d_s + 1.96 \times \sigma(d_s)] \tag{N.2}$$

$$\sigma(d_s) = \sqrt{\frac{n_1 + n_2}{n_1 \times n_2} + \frac{d_s^2}{2\,(n_1 + n_2)}} \tag{N.3}$$

The equation for the required steering wheel angle for a particular curve can roughly be characterized as [1, 2]:

$$\delta_\mathrm{s} = \frac{\mathrm{Gl}\left(1 + \mathrm{Ku}^2\right)\mathrm{c_r}}{1000} \tag{N.4}$$

where:

- δ_s = required steering wheel angle (rad).
- G = steering ratio (-).
- l = wheelbase length (m).
- K = understeer gradient (-).
- u = longitudinal velocity (m/s).
- $\mathrm{c_r}$ = track curvature (1/km)

N.2. Calculation method: lead time and corresponding correlation coefficient

To obtain the eye-steering correlation, the horizontal gaze location relative to the reference and steering wheel rotation were analyzed. The recordings were taken from the start of the curve entry to the end of the curve exit section. Table N.1 lists the mean and standard deviation of the epoch length for the different curves. The lead time and corresponding correlation coefficient (R) were calculated on an individual basis for each curve and lap separately. Figure 2.6 shows the cross-correlogram of the horizontal gaze location relative to the reference and steering wheel rotation for one random individual, curve and lap. The y-axis value indicates the degree of covariation between the two signals. The x-axis value indicates the time interval by which the eye and steering signal offset. A negative offset means that the horizontal eye movements led the steering signal, which is expected to be ca. 1-2 seconds [74, 87, 88]. The peak value identifies the correlation coefficient and the corresponding time shift, i.e., lead time (see Figure 2.6). Thus, for this example, the correlation coefficient was 0.86, and the lead time was 1.54 seconds. For the constrained lead time and correlation coefficient, the correlation coefficients and corresponding lead times were excluded if the correlation size was smaller than 0.7, as indicated by the red line in Figure 2.6.

Table N.1: Mean and standard deviation of the recording durations of the different curves using all participants.

Curve	Epoch length (s)	
	mean	std
R1	13.14	1.71
R2	14.72	1.49
R3	16.27	1.52
R4	17.88	1.66

O

Appendix O: Participant data listing

Table O.1 gives an overview of the completeness of the data recordings for each participant. All participants received a fixed number at the beginning of the study that remained the same for all recordings. The itemization below elaborates on why specific participants were excluded from the analysis or highlights (minor) technical complications:

- **Participant 5**: The settings of the sky were incorrect. However, this effect can be ignored.
- **Participant 8**: The recording of the right eye of the eye-tracker did not work. As a result, the eye-tracking data could be slightly less accurate. The decision was made to not exclude the participant from the analysis.
- **Participant 13**: The data of this participant got corrupted due to a crash in D-Lab. As a result, the participant was excluded from the analysis.
- **Participant 15**: The eye-tracker recordings showed glitches throughout the recording. This was often an indicator that the program would crash. Therefore, the recording was divided to prevent all data loss. This participant was not included in the analysis due to the glitches in the eye-tracking data and because the recording was fragmented.
- **Participant 17**: The eye-tracker was not operating at all. So, all vehicle data is present, but all eye-tracking data is missing. As a result, the participant was excluded from the analysis.
- **Participant 24**: D-Lab lost connection with the eye-tracking halfway through the manual driving scenario. The eye-tracking data was not complete, but the vehicle performance data was.
- **Part. 31**: Completed 6.5 laps out of 7 due to lack of time. The decision was made to include this participant in the analysis still.
- **Participant 36**: The participants had to stop the experiment due to simulator sickness and was therefore not included in the analysis.
- **Participant 37**: The eye-tracker was not operating at all. So, all vehicle data is present, but all eye-tracking data is missing. As a result, the participant was excluded from the analysis.

An identical overview as covered above can be found on the hard drive in the folder *Data quality inspection*. This overview provides the information for the other two manual driving scenarios and the automated driving recordings.

Table O.1: Overview of the completeness of the recordings for manual driving scenario 3 (oval track).

Part. #	Manual 03	MISC 3 score	NASA-TLX 3 score	All data complete	Used
	0 = ok, 1 = all data missing, 2 = segment data missing/(minor) tech. comp.			0 = all, 1 = without eye-tracking data	
1	0	0	0	0	x
2	0	0	0	0	x
3	0	0	0	0	x
4	0	0	0	0	x
5	2	0	0	0	x
6	0	0	0	0	x
7	0	0	0	0	x
8	2	0	0	0	x
9	0	0	0	0	x
10	0	0	0	0	x
11	2	0	0	0	x
12	0	0	0	0	x
13	1	0	0		
14	0	0	0	0	x
15	2	0	0		
16	0	1	1	0	x
17	2	0	0	1	
18	0	0	0	0	x
19	0	0	0	0	x
20	0	0	0	0	x
21	0	0	0	0	x
22	0	0	0	0	
23	0	0	0	0	x
24	2	0	0		
25	0	0	0	0	x
26	2	0	0	0	x
27	0	0	0	0	x
28	0	0	0	0	x
29	0	0	0	0	x
30	0	0	0	0	x
31	2	0	0		x
32	0	0	0	0	x
33	0	0	0	0	x
34	0	0	0	0	x
35	0	0	0	0	x
36	2	0	0		
37	2	0	0	1	
38	0	0	0	0	x
				total:	31

P

Appendix P: Literature study

This appendix presents the conducted literature study: *Towards a suitable take-over request*. It should be mentioned that this part has already been graded. The literature study has been included because it outlines how the findings of this study could be used for predicting take-over performance and how the driver's characteristics can be integrated into automated driving systems. In summary, the study explores three topics:

- A review on the definition of manual driving skill including an analysis on which components are expected to be most critical for the take-over performance;
- An overview of the state-of-the-art automated data-driven methods to predict the driver's ability to take over control;
- A framework that can be used to identify and structure adaptive take-over systems.

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Towards a suitable take-over request:

A Literature Review

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***Abstract*—The development of conditionally automated driving systems enables drivers to engage in non-driving related tasks. However, drivers are requested to get back into the control loop during potentially hazardous circumstance (i.e. take-over request (TOR)), which could induce safety-critical situations. Recent studies analysing driver behavior have shown that many factors influence the driver's ability to regain control safely. A part of these individual differences might be a result of manual driving skill differences. Predictive tools for driver take-over readiness are considered the next step, allowing designers to adapt the design of a TOR to account for influencing factors, creating a more suitable take-over situation. A new framework is introduced to identify and structure developments into the design of adaptive take-over systems. Overall, this contribution explores three complementary topics: (1) a comprehensive assessment of driving skill to investigate which elements are expected to be most critical for a successful take-over and which metrics are used to determine driving skill; (2) a literature overview of currently available automated data-driven predictive tools to assess driver take-over readiness and (3) the state-of-the-art in adaptive take-over systems. The results suggest that driver-vehicle-interaction tasks are most critical for a successful take-over and that predictive tools for driver take-over readiness can serve as a valuable input for adaptive take-over systems. Based on the findings, it is expected that replacing static take-over system by adaptive take-over systems helps to diminish adverse effects, and thereby resulting in safer and more comfortable automated vehicles. Future research can use the presented framework to explore new design concepts for adaptive take-over systems.**

***Index Terms*—Automated driving; Transition of control; Driving skill; Predicting driver take-over readiness; Adaptive take-over systems**

I. INTRODUCTION

In the last few decades, automation has gained a noticeable grip on the automotive industry [1]. Developments such as advanced driver assistance systems (ADAS) have proven to enhance road safety [2] and allow for the reduction of traffic congestion and carbon emissions [3]. According to the Society of Automotive Engineers (SAE), six levels of automated driving can be identified, ranging from no automation (SAE L0) to full automation (SAE L5) [4]. Partial automation (SAE L2) requires drivers to permanently monitor the system (in order for them to act in critical situations), while the vehicle is in control of longitudinal and lateral motion. These systems are already available by several car manufacturers (e.g. [5]). For both conditional automation (SAE L3) and high automation (SAE L4), the responsibility to permanently monitor is transferred to the automation, which allows drivers to engage in non-driving-related tasks (NDRTs). However, the driver is forced to intervene when the vehicle leaves the operation design domain (ODD) or malfunctions in the case of an SAE L3 system and is requested to take-over control when the system reaches its ODD for an SAE L4 system. Such a take-over request (TOR) could be triggered due to, e.g., adverse weather or a road-work obstruction [6], [7]. The available time budget for the driver to intervene is limited by the vehicle sensors' capabilities and their ability to predict the ODD boundaries [8]. A situation arises in which the driver is temporarily out-of-the-loop due to limited driver-vehicle interaction and has to take over responsibility when a TOR is issued. Scientific research has shown that these scenarios introduce new challenges [9]–[11] and could lead to safety-critical situations [12], [13]. Having a seamless transition from automated driving back to manual driving will be crucial to the successful deployment of SAE L3 automation.

A. Take-over scenario

A take-over procedure is composed of different stages, as illustrated in Figure 1. In this study, the time budget refers to the time between a TOR and the moment when the vehicle reaches its system limits (i.e. the ODD boundary). Within this time period, the driver is expected to resume motor readiness (by relocating hands and feet to the driving position), regain situation awareness (by cognitive processing of the perceived stimuli from the environment), and finally select and execute the actual action (i.e. controlling the vehicle input) [14]–[16]. If the driver cannot execute all these actions within the available time budget, it may lead to an unsafe situation.

B. Take-over performance

In recent years, many studies have been conducted to analyse human performance and behavior during take-over scenarios (e.g. [15]). A broad range of metrics is used to evaluate take-over performance. These metrics can be divided into time, and quality aspects [17], or a combination of both [18]. Table I provides an overview of frequently used metrics that are found in the literature. In general, these metrics evaluate the manual driving performance of the operator during a take-over procedure. In the remainder of this paper, take-over

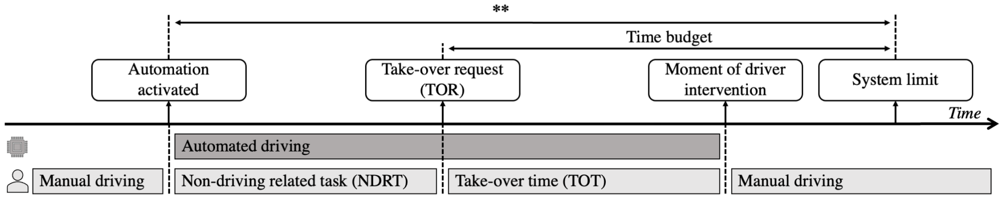

Figure 1. Schematic visualisation of a take-over procedure.

performance will be used as a generalised term to represent all three types of metrics, as shown in Table I.

C. Factors affecting driver take-over performance

It has been reported that during a TOR, drivers often respond similarly to how they would respond in an emergency situation in manual driving, albeit having a delay compared to manual vehicle operation [19]. Therefore, it is expected that many factors responsible for influencing manual driving performance are identical to those that affect take-over performance (e.g., fatigue [20], alcohol [21], ageing [16] or complexity of the driving scene [22], [23]). However, automated driving allows changes in the operational conditions (e.g. [24]–[26]), which introduces new influencing factors that are typical for automated driving, including interaction with NDRTs [27], [28], the available time budget [29] and the HMI-design utilized [15], [30], [31]. Overall, it can be concluded that the safety aspect of the take-over process is governed primarily by two constraints: the time budget and the effectiveness of the action of the driver [19]. Eriksson et al. [32] found in their study that the reported take-over time (TOT) in the literature ranges from 1.14 to 15 seconds. These results emphasise the strong effect of influencing factors on take-over performance.

D. Driver factors: required skills for taking over control

In addition to the factors mentioned in the previous Section, research has identified other driver-related factors that affect take-over performance. For instance, repeated exposure to takeover situations [16], and training [35], which positively impair take-over performance. This positive effect of repeated exposure/training is also observed with emergency situations for manual driving [40]–[42]. Elander et al. [43] mentioned that driving skill is mostly concerned with the limits to performance on aspects of the driving task, which refer to the driver's ability to maintain control and respond adaptively to complex situations. Based on these findings and the similarities in response between manual emergencies and automated take-over situations, raise the question of whether individual differences may be partially a result of manual driving skill differences and if this could provide a basis to capture a driver's competence range for take-over performance. Currently, work is limited to a study performed by Chen et al. [44], who investigated the effect of driving style (during braking and acceleration) on take-over performance and concluded that normal drivers' good driving habits do not make their take-over performance better. The study adopted a simple method to classify driving style and did not assess driving skill. How do driving skill and style relate to each other? Moreover, which elements of this framework are expected to be most critical for a successful take-over? This report covers a comprehensive assessment of driving skill to answer these questions.

E. Creating a suitable design

To make SAE L3 vehicle automation available for everyone, designers need to cope for all variations in the driving conditions and drivers' characteristics. Creating such a generalised design envelope that suits all these criteria would highly compromise the availability of the automation. In other words, the design would be optimised for the most critical events (within the design criteria) even though the system might be primarily dealing with less urgent situations. An alternative approach would be to not take all variations into account at the expense of allowing a certain amount of risk into the design. In the ideal case, the automated system would only account for situation-specific factors, generating a suitable take-over template that matches the driver's ability to tackle the required demands. For instance, the automated system can adapt the internal take-over settings if it observes that the driver is sleeping and undo these adjustments when assessed to be awake again, thereby only accounting for this factor when relevant.

To enable the automation to make such an effective adaptation, the system should be able to predict the operator's take-over performance or model their driving behavior during a take-over scenario, depending on the present circumstances. These adaptive systems could enhance comfort and allow safer transitions between different levels of automation. Additionally, these systems could be used to monitor and attend the driver to their impairments [45], such as drowsiness [46], as well as to account for drivers' preferences and attitudes, e.g., the preferred TOT [47]. Kidwell et al. [48] stated that a growing body of scientific literature proposes that the implementation of adaptive automation may alleviate the problems of static automation. Likewise, adaptive ADAS has already proven to provide benefits over regular ADAS [49]. It is expected that replacing a static take-over system by adaptive take-over systems helps to diminish adverse effects on take-over performance and thereby becomes more important for the development of safe and comfortable automated vehicles. At the moment, there is no clear definition for adaptive take-over systems in the literature. Therefore, this study will examine

Table I
OVERVIEW OF VARIOUS METRICS FOUND IN LITERATURE USED FOR THE ASSESSMENT OF TAKE-OVER PERFORMANCE.

Reaction time	Take-over quality	Integrative metrics
Gaze response time ([15], [33], [34])	Max. long. acceleration ([8], [14], [35])	Take-over performance score (TOPS) ([18])
Eyes-on-road time ([15], [33], [34])	Max. lat. acceleration ([8], [14], [35])	
Hands-on-wheel time ([15], [33], [34])	Time to collision (TTC) ([16], [36], [37])	
Take-over reaction time ([15], [33], [34])	Crash rate ([16], [38], [39])	

this design philosophy, including predictive methods for take-over performance, which are considered a valuable input for these systems.

F. Research objectives

Firstly, this paper will review the definition of manual driving skill to analyse which elements are expected to be most critical for the take-over performance. The main findings are presented in a framework used to classify metrics found in scientific literature to quantify manual driving skill. The goal is to generate a basis for future research investigating if manual driving performance could potentially be used to predict take-over performance.

Secondly, an overview is given of the state-of-the-art automated data-driven methods to predict the driver's ability to take over control during a TOR. These predictions can be used to derive the expected take-over performance, allowing designers to account for situation-specific influencing factors. Methods that provide a direct prediction of take-over performance are also included in this overview. These predictive tools will be analysed based upon their architecture.

The last part introduces a framework (with associated criteria) to identify and structure adaptive take-over systems. As pointed out above, such an overview is currently missing in the literature. In addition, a psychophysiology outline covering the design direction is discussed. The goal is to provide a guideline for developments into adaptive take-over systems for SAE L3 (or SAE L4) automation.

II. BACKGROUND

This Chapter covers additional content needed to further specify the scope used for this paper. First, an analysis is made on the available methods for predicting the driver's ability to take-over control, including the architecture of data-driven methods. Lastly, an overview is given of how adaptive take-over systems can be designed and structured depending on the design approach.

A. Data-driven predictive tools

Predicting the driver's ability to regain control could be done by means of two methods, namely: model-driven and data-driven [50]. In contrast to a model-driven approach, a data-driven approach allows finding direct relationships between the human state variables (input and output) without explicit knowledge of the behavior of the human operator [51]. A study performed by Mcdonald et al. [19] provides a review of empirical studies into the modelling of human behavior during a TOR. It was found that existing manual driving models provide a suitable starting point for take-over models. Current developments were limited, and future work was needed to integrate various factors that significantly influence take-over performance, e.g., the impact of NDRTs or other factors, as mentioned in Section I-C. However, their study did not cover data-driven predictive methods, which allow for a direct classification of the driver's ability to regain control. In 2017, it was noted that little work had yet been done into this approach [52]. It is expected that the trend towards data collection [53], including new regulation [54], will boost the developments of data-driven predictive methods for vehicle use. Moreover, data-driven approaches have proven to be powerful tools, e.g., for the development of fully adaptive cruise control systems, which allows adapting to the driver on demand [55]. The system's input, from which the features are extracted, should be a data stream proven to affect take-over performance to enable a robust classification. Research has been conducted into automatically extracting features from the surrounding, e.g., eye tracking (e.g. [56]) or more advanced algorithms like driver fatigue detection (e.g. [57]). A more conventional approach would be to use human evaluation to extract information, e.g., human observation to rate the driver's awareness (e.g. [58]). The overall architecture of data-driven methods is visualised in Figure 2.

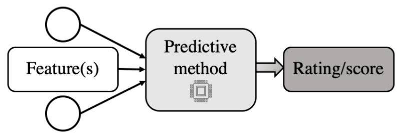

Figure 2. Overall architecture of automated classification tools for take-over performance.

B. Design directions for adaptive automation

As described in Section I, the development of SAE L3 and L4 automation allows drivers to be temporarily out-of-the-loop. These conditions could cause a non-optimal driver state, leading to a reduction in the efficiency of the operator's actions, possibly resulting in a mismatch between the operator's current state and the required state to safely regain control [59], [60]. Hockey's model [61] provides a psychophysiology outline for how this mismatch could be addressed: (1) change the cognitive state of the operator to match the environment; (2) change the target state to match the current cognitive state of the operator; (3) change factors in the environment impeding the cognitive state of the operator [62]. In the case of a take-over situation, the mismatch could be addressed by, e.g., adjusting the system's safety buffer to change the time budget (i.e. the target state) to match the task demand of a take-over to the state of the operator. The given outline, as mentioned above, illustrates the possible design directions for adaptive automation. The stimuli that allow adaptive automation to incorporate the operational environment's context into the design will be covered in the following Section (II-C).

C. Framework for adaptive take-over systems

According to Hancook et al. [63], human-centered adaptive systems can involve: (1) static adaption; (2) generalized dynamic adaption; and (3) idiosyncratic dynamic adaption. The latter two belong to so-called dynamic adaptive systems, which, in contrast to static adaptive systems, account for external (i.e. generalised) stimuli or driver state-based (i.e. idiosyncratic) stimuli. Parasuraman et al. [64] identified a categorisation that allows to further distinguish between different stimuli to generate dynamic adaptive automation, namely (1) a critical event, (2) an operator performance measurement, (3) an operator physiological assessment, (4) modeling, or (5) a hybrid method which is a combination of one or more of these techniques. In the context of automated driving, a critical event is defined as an external stimulus [65], which can arise from the vehicle or the environment [66]. These findings can be combined into a framework, as shown in Figure 3. This framework can be used to structure and identify developments into adaptive take-over systems. An alternative approach would be to use the adjustments that are adopted by the automation or the design directions (see Section II-B) to structure the literature findings. These two approaches are outside the scope of this paper.

III. Method

The remainder of the paper is organised using the three research directions (III-A, III-B and III-C) as outlined in this Chapter.

A. Scope for the analysis of driving skill

To get a better understanding of the definition of driving skill, it is important to identify and describe the processes necessary for safe vehicle operation, how they are constructed, and how humans process these tasks. This paper will elaborate on these points and covers metrics currently found in scientific literature to determine manual driving skill. The assessment of driving skill can be based on vehicle operation or non-driving tasks that serve as an indicator for driving skill. An example of the latter approach is work performed by Stokx et al. [67], who states that reaction time appears to have a predictive value for driving skill. It is argued that such a skill assessment is less applicable to be integrated into the functionality of an automated driving system since the driver is forced to execute a well-defined task which would impede normal vehicle operation or the interaction with NDRTs. Therefore, this study will only cover driving skill assessment based on vehicle operation.

B. Eligibility criteria: predicting driver's take-over ability

To be included in this review, studies had to meet the following four criteria:

1) The overall architecture of the predictive tool needs to include the following three elements: feature(s), a predictive method and a rating/score for the driver's ability to take-over control or take-over performance (as shown in Figure 2).
2) The predictive tool should be data-driven.
3) The predictive tool should operate automatically.
4) The study had to be written in English.

The working principle of the feature extraction tools is left out of the scope of this paper. Systems that require human input to process the features from the incoming data stream were also included in this study. Although intrusive feature extraction would diminish the benefits of automated driving systems, the decision was not to exclude these studies. The predictive tool's output, the score/rating, was allowed to be both a discrete or continuous score. Thus, the study was not limited to classification tools only. The structure presented in Figure 2 is used to cover the eligible papers in the following Chapter (V).

C. Eligibility criteria: adaptive take-over systems

To be included in this review, studies had to meet the following four criteria:

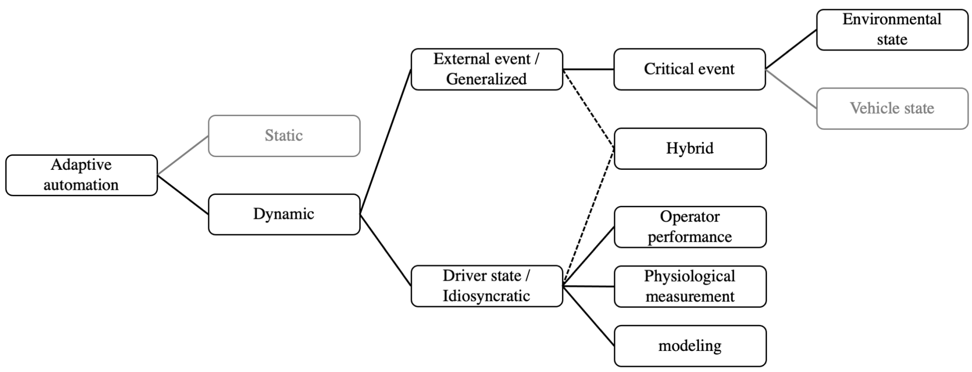

Figure 3. Framework used to structure adaptive take-over systems. The boxes in light grey are not covered in this paper.

1) The adaptive systems should be a dynamic adaptive systems, as shown in Figure 3. Systems that rely on stimuli coming from the vehicle state are excluded.
2) The system should operate between the moment the automation is activated and the instant the vehicle reaches its system limits, as visualized by the ** symbol in Figure 1. However, the stimuli that trigger the adaptation are allowed to occur before the instant the automation activated.
3) The system should adapt something measurable to the automated vehicle setup (both software or hardware are allowed).
4) The study had to be written in English.

The adaptive take-over systems will be categorized based on the framework presented in Figure 3. Adaptive task allocation to enhance overall performance are not included in this study as this would question the existence of an SAE L3 or L4 system. Systems that adapt the moment of a TOR are included. It is debatable how to define vehicle state-based stimuli, and therefore, it is questionable if these design concepts should be included in this overview. For instance, Kerschbaum et al. [68] introduced a steering wheel that changes shape depending on the state of the automation. Depending on the definition used, this system could be classified as an adaptive take-over system utilizing vehicle state stimuli or a static adaptive take-over system since it does not require measurable inputs from its surroundings. It is argued that this system should not be labelled as an adaptive take-over system. However, the question is whether, e.g., concepts that adapt the design based on a physical vehicle state input or issue a monitor request when a critical situation was likely to occur [69] also need to be excluded from the overview. Hence, the decision was made to exclude studies that utilize vehicle state-based stimuli from this literature overview (as shown in Figure 3).

IV. Review of relevant driving skill components for taking over control

A. Driving skill-style

In scientific literature, a broad range of definitions is used to define driving skill. In general, it boils down to how effective an operator can execute a predefined (driving) task [70]. In many studies, certain elements of a driving task are used as an indicator for driving skill. For instance, in [71], drivers were instructed to maintain a constant speed while remaining in the centre of the right lane. The driving scenario included a course of winding two-lane road through a rural setting. The standard deviation of lane position was used as the primary measure for driving skill. Yet, there is no clear boundary between driving skill and driving style. As stated by [72], the dichotomy between driving skill-style corresponds to driving performance and driving behavior. Driving style is frequently referred to as the way drivers choose to drive, in contrast to driving skill reflecting a person's capabilities to drive [43], [73], [74]. In addition, this dichotomy between driving skill-style is linked to lower-order and higher-order driving skills (and errors and violations), respectively [43], [73]–[76]. However, as we shall see later in this Chapter, there is an interplay between the higher- and lower-order driving skill components, making it hard to regard both factors as completely independent.

B. Human operator

The human operator needs to process information in order to perform the driving tasks. Human-information processing is often clustered into three or four stages [77]. Kantowitz et al. proposed three stages: the perceptual stage, cognitive stage, and action stage [78]. The perceptual stage is responsible for information acquisition. This includes sensing the surrounding and comparing it with domain-related knowledge (e.g. traffic rules) from memory to give meaning [77]. For driving, the eyes supply most of the information for this stage [79]. The cognitive stage is responsible for processing all incoming information. The brain will compare the perceived information with current goals and memories, make inferences and consider the best possible responses to the situation [77]. Lastly, the action stage is responsible for the selection and execution of the response action. All these stages require cognitive processing resources in order to function effectively. If a processing stage requires more processing resources, it will be taken from the remaining processing block [77]. This may result in an incomplete or faulty performance of the task due to lack of cognitive resources [79]. The resources a driver uses to execute the driving task depend amount others on the driver's driving skill [80].

C. Driving task

The driving task (i.e. operating a vehicle) is a complex task that requires the driver to perform several tasks simultaneously. The driver-vehicle interaction can be described by 65 main tasks and 1799 elementary tasks [79]. The vehicle control can be generalized by three levels of skills and control [81], [82]:

- strategic level (also known as planning, navigation and macro-performance)
- manoeuvring level (also known as tactile, guidance, and situational-performance)
- and control level (also known as operational, stabilization and micro-performance)

The strategic level involves the general planning of the trip, meaning the selection of the route from A to B. This task is often done before driving or is generally executed by the onboard computer, requiring almost no new information [83]. The manoeuvring level is responsible for the driver-behavior selection to match the environment for the upcoming 5 to 10 seconds [79]. The control level is responsible for converting the desired goals, set by the other two levels, to the driver-control input. These actions are considered to require only milliseconds to execute [82]. Both the manoeuvring and control level together are responsible for the driver-vehicle-environment interaction, which includes the longitudinal and lateral vehicle motion [79]. In other words, the manoeuvring level sets out the desired reference values, while the control level will regulate the throttle angle, brake force and steering wheel angle. Since these actions are mainly dependent on the environment, they can be considered as data-driven [83]. Based on the work of [84] and [85], [79] reported six different task groups:

- Strategic tasks (choice of route, time of departure)
- Navigational tasks (adherence to the chosen route during travel)
- Traffic related tasks (interacting with other road users in such a way that the traffic is not obstructed and collisions with other road users are avoided)
- Adherence to rules (traffic signs, signals etc.)
- Tasks relating to the road (chosen position within traffic)
- Speed control (choice of speed according to situation)

An overlap seems to be present between both structures. The first two levels are elements of the strategic level, the third and fourth are elements of the manoeuvring level, and the last two levels are elements of the control level. Similar results were found by [70].

D. Motivational and attitudinal factors

Research in traffic psychology has shown that, in addition to performance factors, there are also motivational and attitudinal factors that should be considered [86], [87]. This statement seems to be coherent with the distinction between errors and valiance in driving behavior [88]. Hatakka et al. [89] presented a four-level conceptualisation of driving behavior, in which these factors were included. The four levels consist of:

- Goals for life and skills for living (importance of cars and driving on personal development. Skills for self-control)
- Goals and context of driving (purpose, environment, social context, company)
- Mastery of traffic situations (adapting to demands of present situation)
- Vehicle manoeuvring (controlling speed, direction and position)

The vehicle manoeuvring and mastery of traffic situation levels are comparable to the control and manoeuvring level, respectively [89]. The second-highest level, goals and context of driving, refers partly to the navigational and planning tasks of the driver [89]. However, this level is extended to also include trip-related goals, driving context and the social context of the driving. It is argued that these factors are affected by higher-level goals [89]. An example of such a factor was found in [90], showing that *"pleasure in driving"* had the highest relative contribution to driver's attitude towards speeding. The highest level in the hierarchy, goals for life and skills for living, refers to the motivations and goals of the operator in a rather broad sense [89]. This level is not limited to vehicle operation only. For instance, lifestyle studies have shown that there is a correlation between lifestyle and driving behavior [91]. Similar observations were found for age [72], and different genders [92]. Overall, on-road behavior is the end product of a balance between competing goals, which can differ depending on the driver [93]. It is considered that the performance at higher levels affects the demand on skills at the lower levels in the hierarchy. However, the opposite is also true: if drivers overestimate their driving skill, they could interpret a dangerous situation as not being dangerous, thereby adapting their operating strategy, which would probably result in higher accident involvement [75].

E. Rasmussen taxonomy

As discussed above, the different driving control levels can be linked to Rasmussen's taxonomy. According to Rasmussen, human behavior can be divided into three levels: skill-based behavior, rule-based behavior, and knowledge-based behavior [95]. Table II provides an mapping of driving tasks to human cognitive levels [96]. This representation allows making a distinction between different skill levels for vehicle operation, depending on the nature of the task. For experienced drivers, most driving task cluster along the diagonal from the top left to right bottom [96]. According to [97] "Experienced drivers can generally use skill-based behavior for navigating along highly familiar routes or for negotiating familiar intersections, reflecting the fact that automaticity can operate at all levels of control". The driver will rely on rule-based behavior in situations for which previous experience can be applied and will only fall back to knowledge-based behavior regarding situations for which no applicable rules can be located. Notice drivers who lack driving experience mainly rely on knowledge-based behavior [96]. For instance, shifting gears is not yet an automated action for notice drivers. In general, it can be concluded that, as drivers become more skilled, more conscious activities become unconscious ones [98], meaning more driving tasks are becoming part of skill-based behavior. As a result, cognitive resources are released, which can be used for other tasks [99]. According to Zeeb et al. [27], motor processes are performed by reflectively and take-over quality is mainly governed by the driver's cognitive comprehension of the situation. Similarly, it was found that cognitive load had hardly any effect on the actions during a braking manoeuvre [28]. Thus, reflexive actions are expected to be not affected by cognitive load. These facts also suggest that driving experience would contribute to obtaining driving skills since fewer situations will be classified as previously unknown. This seems to be in line with the findings of Duncan et al. [93]. The benefits of experience are mainly seen in control level skills. Although driving skill allows the enhancement of skills in some areas, it could result in the development of bad habits in others [93]. In addition, it was found that the level of feedback is a key component for if experience will bring expertise.

Table II
TASK MATRIX ADAPTED FROM [97]. CLASSIFICATION OF DRIVING TASKS BY MICHON'S CONTROL HIERARCHY AND RASMUSSEN'S TAXONOMY [82], [95]

	Strategic	Manoeuvring	Control
Knowledge	Navigation in unfamiliar area	Controlling skid	Novice on first lesson
Rule	Choice between familiar routes	Passing other vehicles	Driving unfamiliar vehicle
Skill	Route used for daily commute	Negotiating familiar intersections	Vehicle handing on curves

F. Framework to capture driving skill components

Figure 4 provides a multilevel structure of driver-vehicle interactions based on the work discusses above [79], [81], [82], [89], [94]. The framework highlights different aspects of controlling a vehicle. It can be a useful tool to structure different elements related to driving skill. It should be noted that Figure 4 does not include NDRT and tasks that are performed before or after operating the vehicle. There are studies which do include these task into their driving model [100]. It is debatable whether these tasks should be included; therefore, the decision was made not to include these into the framework. Appendix A will further elaborate on the framework's limitations and how they would affect its design.

G. Take-over related driving skills

The remaining question is which elements of the framework (see Figure 4) are expected to be most critical for successfully executing the actions for a take-over. There are a few characteristics that need to be kept in mind. First of all, the time frame for the driver to react is a matter of seconds. In literature, 7 seconds is often considered as a standard for the minimal time budget necessary for a fully distracted driver to successfully take over control [101]. Given the time frame, it is expected that the tasks from the manoeuvring and control level are most critical. Secondly, the type of action the drivers need to perform with a TOR. These driving tasks often include, e.g., a lane change or braking manoeuvre [39]. To perform this task, the driver mainly relies on driver-vehicle-environment related skills. Thirdly, as mentioned earlier on in this Section, many of the tasks that are part of the strategic level are already taken over by the automation. Builtin infotainment systems or external tools like a smartphone are regularly used for navigation. It is expected that these systems will become more integrated into the automation (e.g. [102]). Fourthly, the automation is operating the vehicle from the moment it is activated up until a TOR is triggered and the driver takes over control. During this entire period the control strategy is determined by the architecture designed by the designers, indirectly determining the motivations and attitude of the automation. Different factors like sensor limitation, safety margins, or even the assessed driver state could be taken into account for this architecture. As a result, the system design (limitations) are responsible for creating a situation in which the driver needs to respond with a TOR. This is different in comparison with manual driving, where motivational factors are to a larger extent decisive for situations that occurs.

To conclude, it is argued that driver-vehicle-interaction tasks are most critical for performing a successful take-over. It is expected that motivational factors will play an important role but to a smaller extent compared to manual driving since certain operations (as mentioned above), which are related

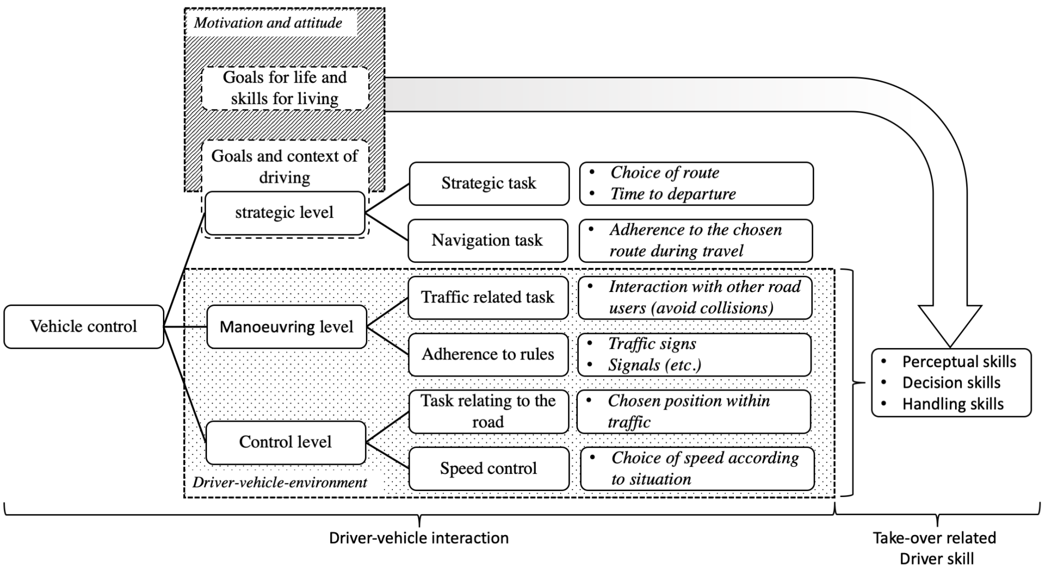

Figure 4. Framework of the driver-vehicle interaction based on the work of [79], [81], [82], [89], [94].

to higher-level goals, are taken over by the automation. The higher-level goals seem to be mainly responsible for when and why the operator has turned on the automation and how it would behave when the automation is in control. It is expected that during a TOR, most drivers will be focused on re-establishing a safe situation, being the most dominant motivational factor. It is expected that these motivational factors will have a stronger effect on certain metrics than others. Further research has to be done to provide more insight into the effect of the higher-level goals and motives on take-over performance. More details about this will be covered in the following Chapter. Lastly, it is noteworthy to mention that most scientific literature seems to assess driver-vehicle-interaction task to determine driving skill.

H. Metrics for take-over related driving skills

In [94], Wilde et al. provided a Risk Homeostasis Theory, which states that the level of accepted subjective risk is more or less a stable personal parameter. In this study, three types of skills are identified that have their effect upon driving behavior:

- Perceptual skills;
- Decisional skills;
- Vehicle handling skills.

The levels are responsible for risk perception, the driver's ability to decide what should be done to reach the desired risk level, and how effectively the driver can carry out the goal, respectively [94]. It is argued that this categorization is a suitable method to classify metrics for the assessment of driving skill related to the manoeuvring and control level, as shown in figure 4. In their study, it is proposed that motivational factors are responsible for the construction of the target level of risk [94]. The driver needs to balance their evaluation of the advantages and disadvantages of action alternatives. This statement emphasizes that these skill levels are core elements for vehicle control but are not suitable for identifying the higher goals related to vehicle control. Table III provides an overview of a selection of metrics found in scientific literature to define driving skill. The metrics are classified using the three skills types mentioned above.

V. Review of predictive tools for driver take-over ability

A. Terminology

In scientific literature, there are many terms used to indicate the driver's ability to take-over control. These differences are generally a result of the features used for the classification. Names include: driver take-over readiness (e.g. [52]), driver availability (e.g. [112]), driver state (e.g. [58]), observable readiness index (ORI) ([58]), activeness of the drive (e.g. [113]), reaction ability (e.g. [12]), driver alertness (e.g. [27]). For the remainder of this study, driver readiness will be used to indicate the driver's ability to regain control with a TOR.

B. Driver take-over readiness

Braunagel et al. [52] suggested an automated method able to predict take-over performance directly. The classifier extracts five features from three information sources: engagement in NDRTs, eyes-on-road gazes, and traffic situation (based on the classification scheme of [114]). The concept utilized a Support Vector Machine (SVM) (with a linear kernel) machine learning (ML) algorithm for the classification. In 63% of the situations with low take-over performance, the

Table III
Categorization of various metrics used in literature to assess different elements of driving skill

Study	Metric	Description
Perceptual skills		
[103], [104]	Hazard perception	Driving experience improves drivers' awareness of potential hazards and guides drivers' eye movements to locations that might embed potential risks.
[99], [105]–[107]	Variance of search along the horizontal plane	The variability of scanning being more extensive for the experienced drivers when they watched scenes recorded on both of the demanding sections of dual-carriageway. Notice drivers do not seem to adapt their search along the horizontal meridian (depending on the circumstances).
[106], [108]	Search area	Novice drivers concentrate their search in a smaller area, closer to the front of the car.
Decisional skills		
[93]	Safety margin	In a pulling out to overtake manoeuvre, novices commonly adopted very long following distances, while extreme close following was observed only in the normal and experienced group.
[67]	Reaction time	Drivers with large delays in reaction time turn out to make much more errors when they are driving a car in real traffic (i.e. lower driving skills).
[109]	Speed choice	Poorer steering competence are compensated by choosing a lower speed for cornering, such that the safety margin to the inner lane boundary is unaffected by steering competence.
Vehicle handling skills		
[109]	Steering integral	A larger steering integral is an indication of poorer steering performance which results in larger steering errors.
[110]	Path tracking skill	Drivers have to perform a cone tracking task. Depending on the test, expert drivers were able to reach higher velocities and hit less cones on average.
[50], [111]	Discrete fourier transform of the steering wheel angle	Compared to the expert driver, low-skilled driver do not produce the high-frequency steering movements.

driver would have been warned shortly before the situation occurred, and 90% of the drivers who would have performed an adequate take-over would not have been interrupted [52]. Overall, the proposed system can detect take-over readiness with an accuracy of 79%. A control group's take-over performance, which did not perform a secondary task, including a subjective validation, was labelled as high take-over performance and considered as the ground truth. The validation part is based on eyes-on-road gazes and secondary tasks for the 60 s-interval. Du et al. [115] introduced a comparable method that utilized physiological and environmental data to predict take-over performance directly. In comparison to [52], drivers were instructed to perform visual N-back to mimic different levels of demanding cognitive NDRTs. In total, 36 features, consisting of gaze behaviors, galvanic skin response (GSR), heart rate (HR), and traffic density and TOR lead time, were fed into the developed random forest ML algorithm. The metrics were gathered over 40 seconds before a TOR. The drivers subjectively rated their take-over performance. Their scores were divided into two groups (using the cut-off median) and were treated as the ground truth. The ML algorithm could predict drivers' take-over performance with the accuracy and F1-score, both around 70%, depending on the time window used. Results show that both the performance and accuracy benefit from an increasing time window, up until 36 seconds.

Deo et al. [58], proposed a concept to rate the human readiness to take-over control. Four high-resolution cameras observe the driver's face, hands, body pose and feet. A computer vision ML algorithm was used to analyze the driver's gaze activity, hand activity, objects held and body posture. The entire feature-set was put in a long short-term memory ML algorithm, which was trained to minimize the mean absolute error between the predicted and assigned driver readiness rating. The assigned driver readiness were subjective ratings provided by multiple human raters observing sensor feed. The rating reached from 1 to 5 and was treated as the ground truth. The concept was capable of predicting the take-over readiness with a mean absolute error of 0.449. Lotz et al. [116] introduced a concept that can predict the TOT. The reaction time was subdivided into four-time regions. A multivariate analysis of variances was used to identify the features which showed the highest correlation with the TOT. The thirty best physiological measures were used. The linear SVM ML classifier was able to classify 62.3% correctly. Lastly, Zeeb et al. [14], proposed that gaze behavior can be used to classify drivers into risks groups consisting of low, medium and high. The classifier was based on a k-means ML algorithm. The classification tool was only used upon a training data-set. Future research needs to point out the final performance and accuracy of the method.

VI. Review of adaptive take-over systems

This Section covers studies labelled as adaptive take-over systems based upon the criteria set up in Section III-C. The found literature will be discussed using the categorizing presented in Figure 3.

A. Environmental state

Borojeni et al. [7] proposed a light bar, placed behind the steering wheel, highlighting the location of the roadblock or hazard. The light display provides information about the action the driver should be taken for a safe take-over. Results indicate that the light cues led to shorter reaction times and longer TTC without increasing the experienced workload by the driver [7]. Yang et al. [117] proposed a comparable design, also utilizing a light bar to convey contextual information. In their study, five different modes were developed, of which two meet the criteria set up in Section III-C. Again, this research aimed to guide the visual attention of the driver to a specific hazard. Since all strategies were used together, it hard to pinpoint the exact effects of the two adaptive systems on the performance. The results show an increased trust in automation and an increased visual search of the operator. Although there were no significant differences in the take-over performance metrics, the adaptive concept showed improvements in take-over performance [117].

An alternative approach is to convey visual cues using augmented reality (AR). Lorenz et al. [33] proposed a method where graphical information is presented to the driver when a TOR is issued. Two strategies were introduced: highlight the restricted corridor ("AH red") or highlight the safe corridor ("AR green"). The AR information does not have a significant effect on take-over performance [33]. However, both AR concepts influenced the kind of reaction the drivers chose while taking over control. The AR red concept caused some participants to bring the vehicle to a full stop on a double-lane highway, which can be considered as undesired behavior for most cases [33]. The AH green trajectory promoted the drivers to use the braking pedal to reduce speed. In the experiment, all participants managed to follow the recommended trajectory. These type of systems could be beneficial to promote certain driving behavior during a TOR while the driver is responsible [33]. In [118], a haptic shared control concept was proposed, which also tries to promote a certain take-over trajectory. Although this study seemed to provide safety benefits, it is questionable why the automation would not pull off the manoeuvre by itself in the first place. Other methods proposed to convey contextual information are a changing steering wheel shape [119], vibrotactile [119], [120], auditory [120] or a combination of visual, tactile and auditory cues [120]. The changing steering wheel shape and the vibrotactile cues did not seem to enhance reaction time or the take-over performance [119], [120]. It was found that visual cues were superior compared to the other cues and that elderly benefit from bimodal warnings as compared to unimodal [120]. However, a possible explanation for this superiority is that in many of the studies, the simulator interior is relatively dark, which lends a benefit to the light cues [7], [117], [120]. The control of the amount of light in the cabin will be restricted with on-road automation usage, therefore, possibly reducing some of these benefit.

B. Hybrid

As mentioned earlier on (see V-B), Braunagel et al. [52] proposed automated classification for the drivers take-over readiness. The ML algorithm utilizes information coming from the driver's engagement in NDRTs (i.e. operator performance stimuli), eyes-on-road gazes (i.e. physiological stimuli) and the complexity of traffic situation (i.e. environmental state stimuli). Therefore, the design concept is classified as a hybrid approach. If a low take-over performance was expected, the drivers were requested to monitor the road to regain situational awareness. Such an advanced classifier could also be used to implement other adaptations to the automated vehicle setup. More details about this in the following Chapter (VII).

VII. Discussion

In the following, the examined scientific literature of the latter three Chapters (IV, V and VI) are discussed, respectively. This includes an analysis of the findings, the identified limitations and future work.

A. Findings from the review on take-over relevant driving skill components

All findings have been elaborated into a framework (see Figure 4) to provide a better overview of the related scientific literature. It was argued that driver-vehicle interaction tasks are expected to be most critical for a successful take-over performance. These skills are applied under the guidance of higher-level goals and motives. It argued that these influences are expected to be to a smaller extent compared to manual driving. However, more empirical research is needed to: (1) identify if there is a correlation between manual driving skill and take-over performance; (2) validate the effect of both higher-level goals and lower-level skills on the take-over performance.

In manual vehicle operation, there is a clear difference between males and females in traffic risk, which can be traced back to motivational factors [89]. However, no research has yet been done to identify if there is a correlation between gender and take-over performance (besides [121] which found only minor differences in brake-movement time). Based on these findings, it is expected the differences in take-over performance as a result of gender should be less pronounced compared to manual driving. However, in this case, it might be decisive which metrics are used to define take-over performance. There might be differences in safety margin (which is part of the driver-vehicle-interaction level [89]) but no differences in crash rate. More research is required on this topic.

The findings of [93] suggest that it would be beneficial to provide drivers with feedback about their take-over performance in order to allow experience with take-overs to grow into skill development. Therefore, it might be valuable to provide the driver with feedback on their take-over performance. Such feedback could be integrated into the design of future take-over systems.

Ultimately, it is likely that a major motivation for humans to use automated driving is to engage in NDRT [122]. It was found that the motivational appeal of NDRTs negatively affected the driver's performance [123]. Furthermore, according to Marberger et al. [122], NDRT characteristics may also affect driver's motivational conditions, which could result in a delayed task interruption with a TOR. It might be the case there is an interplay between motivation factors, driving skill and driver readiness state. On paper, it would be expected that driving skill will positively correlate with take-over performance. However, given that drivers seek to have a stable risk level [94], might diminish their advantage. In other words, higher-skilled drivers might be less motivated to attain a high level of driver readiness, therefore, allowing more distraction compared to less-skilled drivers, with, as a result, a lower driver readiness state ([27]), which could potentially diminish their benefits. Future research needs to point out if this will be the case.

B. Findings from the review on predictive tools for driver take-over ability

The results show that today, only a limited amount of automated tools are presented in scientific literature to predict take-over readiness or directly predict take-over performance. It was observed that many different terms are used to represent the driver's ability to regain control during a TOR. In this paper, the suggestion is made to use driver take-over readiness to group these different definitions to increase awareness for this emerging application. Even with a limited amount of data, these studies manage to showcase the potential for accurate driver take-over readiness predictions; however, challenges remain. Many of these tools are limited to driver-related factors. Future work should pursue integrating the various factors, including their interaction, which have shown to significantly impact take-over performance (as mentioned in Section I-C). Based on related work, it is expected that visual cues will be a powerful feature to include [62], [124]. Another area of focus will be to increase the performance of these predictive tools. Furthermore, it will be important to limit the false alarm rate to suppress possible adverse effects on the effectiveness and the acceptance of highly automated driver support systems [125]. Research needs to point out which level of detail is required for future implementations. It is argued that the type of design application most likely dominates the required level of detail and performance of these predictive tools.

C. Findings from the review on adaptive take-over systems

The review identified a small range of studies that investigate the possibilities for adaptive systems for a TOR. The vast majority of the studies propose concepts that mainly focus on providing the driver with contextual information (i.e. the environmental state). These concepts can be divided into two groups based on the time interval they operate. The first group provide the driver with contextual information to increase situational awareness when automation is operational, and no TOR has yet been triggered. The second group provides the driver with contextual information during a TOR to reduce cognitive workload, allowing the drivers to regain situational awareness more quickly, needed to regain control safely. Studies like [7], [52], shown that adaptive take-over systems could indeed lead to the enhancement of take-over performance and safer transitions. However, the diversity of the proposed concepts in literature are rather limited and require very restricted operating conditions (e.g., the amount of light in the car cabin). Besides, all studies covered in Section VI were conducted in a driving simulator, often lacking physical motion cues. Research has shown that the absence of physical motion cues in a simulator may affect braking behavior, thereby influencing the take-over performance [126]. Future work should show how the results will translate to real-world vehicle operation during a TOR. Lastly, current studies often lack a clear assessment of comfort; something recommended to include in future work.

Since the conditions of a take-over scenario can be highly diverse, there are also many different factors that affect the take-over performance. Therefore, it is expected that each of strategies (except the hybrid approach) will have its limitations depending on the circumstances. Subsequently, it is expected that the hybrid approach will allow the best overall performance. More research is required on this topic. It is also expected that the development of new predictive methods for take-over readiness will contribute to the expansion of adaptive take-over systems. With future developments, designers will be challenged to decide how these adaptive take-over systems should be integrated into the automated vehicle. For example, given the system observes the driver is sleepy or sleeping: "Should the system prevent the driver from falling asleep or adapt the safety buffer when detecting a sleepy driver?" [6]. It is argued that this decision will be a trade-off of many factors, including system limitations, the ability to accurately predict take-over performance (depending on the circumstances), driver preferences and attitudes, estimated risk levels, regulation and/or design preferences.

By making the take-over systems more adaptable, in which the automation itself invokes the adaptations to the system, raises the concern of unpredictability of the system for the driver's [127]. According to Billings et al. [128] users may be unwilling to accept system-driven adaptation. Although hybrid approaches are expected to have the highest potential for delivering the best performance, they are also most vulnerable to being unpredictable. Studies like [129] could help designers further to address this problem for future adaptive take-over system concepts, resulting in more comfortable automation. Overall, acceptance and trust is a crucial factor to take in consideration for future studies.

In general, this study is limited to one approach to structuring adaptive take-over systems. In Chapter II, two alternative approaches are mentioned that could also be used. Also, vehicle state-based stimuli (see Figure 4) have not been labelled as adaptive take-over systems because their existence as an adaptive take-over system can be questioned. Again, this is also something that can be analyzed in future work.

VIII. Conclusion

This work reviewed three separate topics expected to (indirectly) contribute to safer and more comfortable automation (SEA L3 and L4). Based on the analysis of driving skill, it is concluded that driving tasks which belong to the control and manoeuvring level are most critical for a successful take-over with higher-level goals playing a less pronounced role compared to manual driving. The metrics used to define driving skill can be classified into three groups: perceptual skills, decision skills and handling skills. A framework was introduced to structure all processes and skills involved with vehicle control during a TOR.

Both automated data-driven tools to predict driver take-over readiness and adaptive take-over systems were found to be expanding bodies of literature. Together these two elements are considered fundamental components to address the limitations of a static take-over design by introducing a dynamic take-over template that only accounts for situation-specific factors. However, today, only a limited amount of work has yet been done into these topics. It was observed that (depending on the operating conditions) many different terms are used to refer to the driver's ability to regain control during a TOR (i.e. take-over readiness). Overall, these data-driven predictive tools showed high potential, despite being able to only account for a limited amount of factors. The evaluation of take-over readiness can be fed into an adaptive take-over system. The decision was made to structure the adaptive take-over systems based on the stimulus that triggers the adaptation: (1) a critical event, (2) an operator performance measurement, (3) a physiological measurement, (4) modeling, or (5) hybrid method. Current developments into adaptive take-over systems seem to be mainly focused on conveying contextual information of the surrounding (i.e. the critically of the situation/event) to enhance take-over performance. The results illustrate that adaptive take-over systems can help to create a safer take-over transition, however, there is still much room for future design concepts. Since the automation itself triggers the adaptations of adaptive take-over systems, it will be key to look into how unpredictability could result in lack of trust and, therefore, suppress possible comfort benefits. Researchers can use this work as a guideline to develop new adaptive take-over systems to allow a more suitable transition of control between the automation and the human operator.

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Appendix A

This Chapter will further elaborate on the framework as introduced in Section IV-F (or see Figure 4). Additional literature is covered used to highlight the limitations of the original framework and showcase how these observations would impact the design of the framework. All findings are covered in a structured manner. At the end of this Chapter, a new framework is introduced. The goal is to provide a better understanding for how different work positions itself with respect to the framework.

Complement to the framework capturing driving skill components

1) Missing components:
The original framework, see Figure 4, is mainly intended to capture and structure the driver-vehicle interactions. As mentioned in Section IV-F, the first limitation of the framework is that NDRTs are not included into the overview. Based on work of Kiencke et al. [79] and Li et al. [130], it was observed that in addition to NDRTs, also situation awareness, the environmental state and vehicle state can be added to the framework. The vehicle state is a direct output of the control level [79]. Therefore, this block should be located below the control level. The vehicle state and its interaction with the environment are cognitively processed by the driver in order to establish situation awareness. The situation awareness state is considered as an input for the maneuvering and strategic level [130]. Although the interaction with NDRTs are not part of the driving task, they do require visual and cognitive processing resources, thereby, impacting the driver's situation awareness state and thus vehicle operation. The interaction with NDRT can also directly interfere with the vehicle controls. Consider e.g. the use-age of phone or eating while driving. In line with [130], this would mean there is a link between NDRTs and the vehicle controls. However, it is questionable if it is relevant to include such a connection to a a framework intended to capture driving skill components. The decision was made to include the connection to the new framework anyway.

2) Interaction between the levels:
The results from Section IV-D show that there is an interaction between the different control levels. It should be noted that this interaction is both top-down and bottom-up. The original framework does not very clearly indicate how the levels interact with each other. This interplay between the levels can be added to the framework to make it more complete. It is important to mention that Michon [82] does not include the interaction from the control level to the manoeuvring level.

3) Interaction between higher-level goals and situation awareness:
It is argued that motivational and attitudinal factors, i.e. higher-level goals, play an important role to what extent drivers will actively engage in updating their situation awareness. For instance, Romoser et al. [131] stated that "... healthy older drivers are redefining their driving task, possibly because of fears of declining capabilities rather than actual declining capabilities". In line with this statement, differences were found between scanning behavior between older and young experienced drivers. This example shows how, in this case, older drivers consciously choose to adapt their behavoir, indicating there is a connection between higher-level goals and the situation awareness state.

4) Interaction between higher-level goals and NDRTs:
Lastly, it is also expected that there is a connection between higher-level goals, an the level in which drivers will engage in NDRTs. An illustration of this relationship was found in the a study performed by Hergeth et al. [132]. It was observed that there is a negative relationship between drivers' self-reported automation trust and monitoring frequency during NDRT. It demonstrates that higher-level goals affect till which extent drivers will engage in the NDRT.

Reflexive actions:
As stated in Section IV-E, reflexives are expected to be not affected by cognitive load, indicating there is also a direct relation between the vehicle/environment state to driver-vehicle-environment levels. In line with this latter finding, Zeeb et al. [27] stated that "motor processes are performed by reflectively and takeover quality is mainly governed by the driver's cognitive comprehension of the situation". In addition, Zeeb et al. [28] found that cognitive load had hardly any effect on the actions during a braking manoeuvre. To conclude, these findings stress that reflexive actions play a role with the initial reaction of the driver during a TOR. It is argued that it is important to recognize the existence of the reflexive actions. However, they are not considered skill components and are therefore not included into the new framework.

Revised framework for capturing driving skill components

All comments discussed have been added to the new framework, see Figure 5.

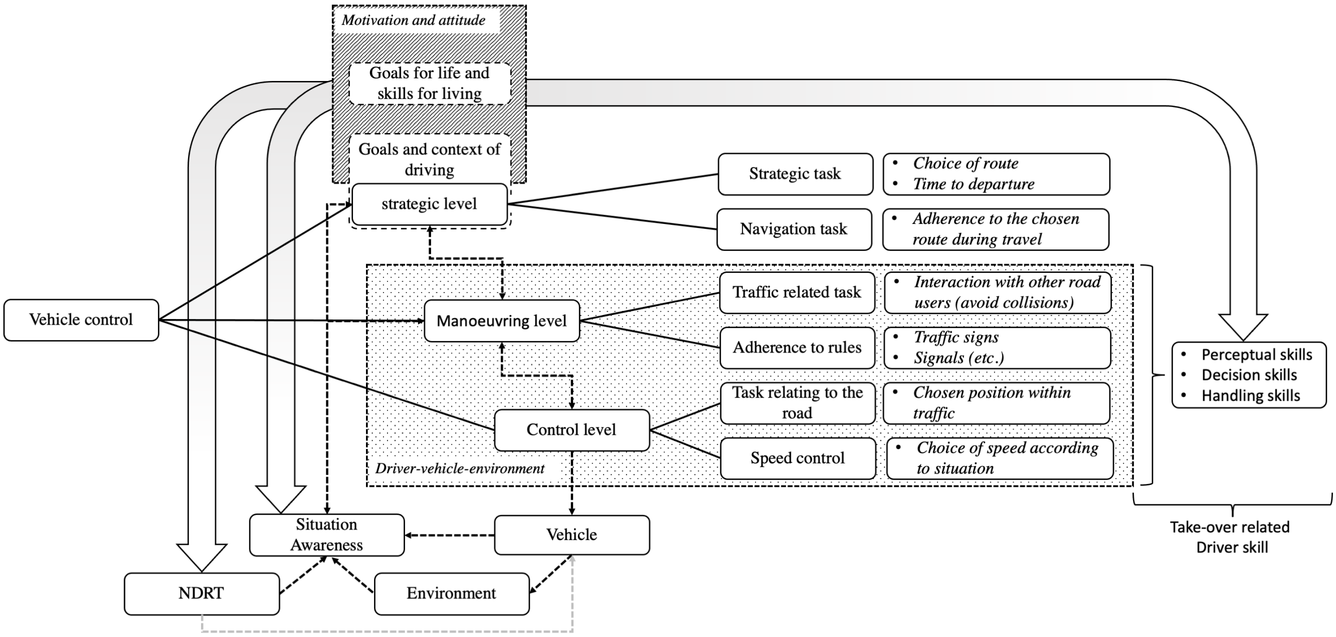

Figure 5. Revised framework of the driver-vehicle interaction based on Figure 4.

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