

Is this the real-life? Or just virtual reality?

A head mounted display based virtual reality driving simulator study on the effect of roadside vegetation density on driving behaviour.

J. N. P. Giltay

Delft University of Technology

Condition = N/A

X = 5/5

Y = -135/-135

Z = 122/122

0 km/h



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by

J. N. P. Giltay

to obtain the degree of Master of Science in Mechanical Engineering,
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Preface

Driving a car has become a major factor in almost everyone's daily life nowadays. With the ever increasing number of cars on the road and the rise of (semi-) autonomous vehicles the study of driving behaviour is also becoming more and more relevant. In this Msc. thesis I took the first steps towards building a new Head-Mounted-Display based Virtual Reality driving simulator for driving behaviour evaluation. I did this as a cheap and portable alternative to the current driving simulator being used by the Delft-Haptics-Lab.

This thesis report is a part of the fulfillment for the Master degree of BioMechanical Design at the Delft University of Technology, a full version of this thesis is also available at the online TU-Delft repository on: <http://repository.tudelft.nl>. The different scripts used for the implementation of the simulator, the Matlab code used for data- & statistical analyses have been submitted to the BioMechanical engineering depository on a USB stick, which is available on request.

*J.N.P. Giltay
Delft, August 2019*

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Thesis Paper

The effect of roadside vegetation density on driving behaviour in a head-mounted-display based virtual reality driving simulator

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Abstract—An issue in driving simulation is that behaviour displayed in simulation does not exactly replicate behaviour in real-life. For example, roadside vegetation density impacts a driver's speed and lateral position in on-road studies, but not in driving simulator studies. In this study it is investigated if the increase in fidelity and presence that head mounted display based virtual reality bring forth, yields behavioural adaptation as shown in real-life by evaluating the effect of three different roadside vegetation density conditions in a novel head mounted display based virtual reality driving simulator. Twenty-nine participants drove a 2m wide car over a 11km long 3.5m wide winding road. Participants completed three trials driving through three different roadside vegetation density conditions per trial, the density conditions being light (one tree per 40m), medium (one tree per 20m) and dense (one tree per 5m). The effect of the density conditions was evaluated with respect to speed, lateral position, steering reversals, subjective workload and self-reported risk. Increased vegetation density increased self-reported risk, but did not affect speed or lateral positioning. This finding is congruent with findings in conventional simulator studies, which could indicate that despite the advantages of head mounted display based virtual reality regarding fidelity and presence the resulting driving behaviour still has a closer connection to conventional simulated driving than real-life driving. In future work the built and implemented simulator can be improved and optimized, furthermore the relative validity of the simulator should be investigated.

Keywords - driving behaviour, behavioural adaptation, head mounted display, virtual reality, roadside vegetation density

I. INTRODUCTION

Single-vehicle collisions resulting in injuries and fatalities are a significant part of annual road accident casualties [1]. Single-vehicle accidents include run-off-the-road accidents and head-on collisions with obstacles in the environment. These accidents are often directly related to a loss of control of the car due to for example inappropriate speed selection or failing to maintain a proper lateral position on the road, especially in curves [2].

In order to understand why accidents, including single-vehicle collisions, take place it is imperative to investigate human driving behaviour. The human driving task is a complex dynamic control task [3] that has been studied extensively over the last decades. A specifically interesting part of human driving behaviour is how drivers act in hazardous or dangerous situations that can cause single-vehicle collisions.

Since the risk of physical harm to the driver is minimal, driving simulators are a good method to evaluate driving

behaviour in dangerous situations. Driving simulations have been used to study a lot of aspects of the driving task [4]. One of the main points that needs to be taken into consideration when simulating driving is the transferability of results from simulator to real driving conditions [5], or the simulator validity. An argument of improving transferability is increasing the simulation fidelity [6]. There are state-of-the-art driving simulators that integrate motion platforms and life-sized cars in dome type simulators to reach the highest simulation fidelity [7]. However, these systems are very costly and might not always be needed to obtain valid results.

One of the situations where a difference of validity of simulated driving and real-world driving becomes apparent is the effect that roadside vegetation has on speed and lateral positioning. In a recent on-road study in Sri-Lanka by Lankathilake et al. [8] roads with varying roadside vegetation density were studied. The study included both curved road sections and straight road sections. The metrics used were mean lateral position and mean speed. At each location about 50 cars were measured. The speed was measured by radar gun while the lateral position was deduced from video analysis shot at the studied locations. It was found that in lightly vegetated roadways the subjects drove at higher speed and nearer to the edge of the road. When transitioning into more vegetated roadways drivers slowed down and drove closer to the center of the road. Another on-road study was conducted by Fitzpatrick et al. [9]. This study focused on a clear-zone, the distance between the vegetation and the edge of the road, and vegetation density combinations, evaluating both speed and lateral positioning. The field data came from around 40 cars at each chosen location. The results showed that in the densely vegetated and small clear-zone areas drivers tended to position their vehicle closer to the road center. Furthermore, with large clear-zone size and a change in vegetation density drivers slowed down as the vegetation density increased, especially in curves.

The effects of roadside vegetation on driving, specifically lateral positioning and speed, has also been studied in driving simulation environments. Calvi [10] used a fixed-base driving simulator at Roma-Tre University studying whether tree spacing affected driving performance on a two-lane rural road. It was found that tree spacing did not affect the driver's speed, however when tree spacing was decreased drivers moved further away from the road's edge. Bella [11] and

van der Horst [12] also conducted driving simulator studies and found that presence of trees alongside the road did not significantly change either the driver's chosen speed or their lateral positioning on a two-lane rural road. The results from the driving simulator studies are consistently different with respect to the previously stated on-road studies, where roadside vegetation had a significant effect on both lateral positioning and speed.

Virtual reality (VR) using head mounted displays (HMDs) is known to create a highly immersive environment improving the level of presence, at relatively low cost. Presence being defined as *"a subjective phenomenon as the sensation of being in a virtual environment"* [13], in other words the higher the presence of the simulation the more the participant feels like he/she is present in the simulated virtual environment. VR has been shown to be effective for training in different domains such as surgery [14], [15] or construction safety [16]. For construction safety the results indicated that users of an immersive virtual environment assessed higher risk levels and identified more hazards than the ones who studied videos and documents. It is expected that this increase in risk perception can also be present in driving simulation. A recent study pointed out that over 40% of driving simulation studies could have also been performed with head mounted display based virtual reality [17].

The identified inconsistency of simulator and on-road studies investigating roadside vegetation with respect to lateral positioning and speed is a cause for extra investigation and an opportunity to see whether the increase of fidelity and/or risk perception with a head mounted display based virtual reality (HMD-based VR) setting results in behavioural adaptation seen in on-road studies. Therefore the aim of this study is to investigate the effects of varying roadside vegetation density on driving behaviour in a head mounted display based virtual reality driving simulator. The research question reads:

"How does roadside vegetation density affect human driving behaviour in a head mounted display based virtual reality driving simulator?"

It was hypothesized that as roadside vegetation density increases the chosen vehicle speed decreases. Furthermore it is thought that the driver's lateral position shifts to the left with increasing vegetation density. This result for speed and lateral position would concur with the on-road experiment results [8], [9]. In order to offer a comprehensive evaluation between the different roadside vegetation density conditions, they were assessed with respect to three different measures; driving behaviour, workload, and risk.

This paper is organized as follows. The second section presents a short overview of the development of the simulator. The third section reports the experimental methodology. The results of the experiment are shown in the fourth section, followed by the discussion of the results in section five.

Lastly conclusions are drawn and acknowledgments are made in the final section.

II. HMD-BASED VR DRIVING SIMULATOR DEVELOPMENT

The head mounted display based virtual reality driving simulator setup was built and implemented in the Delft University of Technology at the Cognitive Robotics lab.



Fig. 1: The HMD-based VR driving simulator setup.

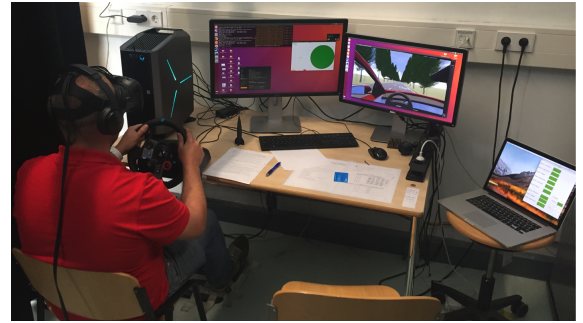


Fig. 2: The HMD-based VR driving simulator in use, the participant can be seen with the HMD and headphones on his head. The right desktop shows what the participant is currently seeing via the HMD.

The layout of the full setup is shown in Fig. 1, the setup consists of the following hardware and software components. The setup in use can be seen in Fig. 2, videos of the simulator being used can be found at: <https://www.youtube.com/playlist?list=PL4sMIj-q-UMZf0fy9peEQZRn4ybPNhDn2>.

A. Hardware

Several pieces of hardware were required for the setup shown in Fig 1.

- The computer needed to run the dedicated software was an Allienware R6 with an intel 5 processor 2.9 GHz, 16gb RAM and a NVIDIA GeForce 1080 GTX gpu.
- A Logitech G29 Driving Force racing steering wheel including pedals was used. The wheel has force-feedback capabilities & auto-centering functionality.
- A Bose quiet comfort 35 II is included for audio, the ambient car noise's volume and pitch increases as the car travels faster.
- The HTC-Vive virtual reality headset was used. The HTC-Vive can be classified as a marker-based inside-out tracking virtual reality headset. Two base stations

attached to trusses 2.5 meters above the ground, separated at a 5 meter diagonal distance sweeping the area with lasers to track the headsets orientation and relative position at a refresh rate of 120Hz [18].

B. Software

To get the appropriate scenario for testing, record the needed parameters for driving evaluation and the usage of a head mounted display based virtual reality headset, different software packages were used. Fig. 3 shows the communication between the different software aspects of the simulator.

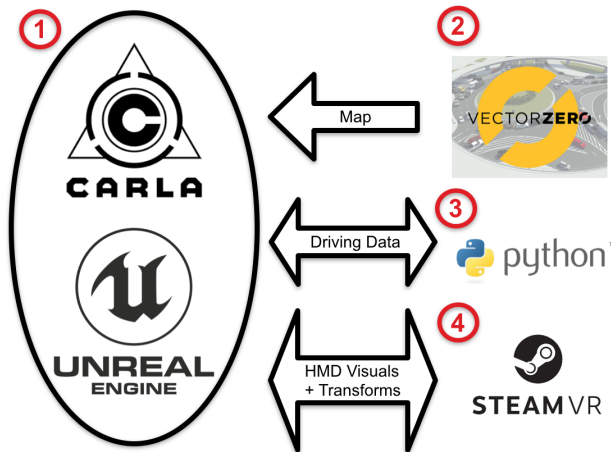


Fig. 3: Communication between software packages of the HMD-Based VR simulator.

The following enumeration pertains to the different software sections as shown in the overview in Fig 3.

- 1) The main software the simulator revolves around is CARLA, an open-source simulator for autonomous driving research [19]. CARLA was built from source on the dedicated PC running Ubuntu 16.04, utilizing the Unreal 4.21 gaming engine. Within this combination it is possible to configure both the physics and layout of your levels in the Unreal Editor via either a visual scripting language called 'Blueprint' or C++. For a full explanation of used scripts and overview of the level buildup please turn to Appendix A.
- 2) Program called 'Roadrunner' by Vectorzero IO, this software is used for generating maps and road configurations. These maps can be imported into the CARLA/Unreal combination.
- 3) One of the main strengths of the CARLA simulator is that it can be connected to via a python client, which can send and receive info from the simulation in real-time. Commands can also be sent over the python-client/CARLA-server connection changing features such as the weather, amount of traffic, autopilot settings etc. In this study the GUI for data collection and experiment initialization was written in python, see Appendix B.

- 4) The Unreal Editor comes with a plugin specifically for the Steam-VR library, which makes it possible to play created levels in a virtual reality environment making use of for example the HTC-Vive. To do so an optimization of the rendering time of the level is required, in Kemeny et al. [20] it is recommended for any driving simulation to be in the 30 to 60Hz range for acceptable visible comfort. However, when making use of a HMD-based VR setting this range goes up because of the stimulation of the peripheral vision, if the frame-rate drops below 90Hz the chance of simulation sickness and/or annoyance increases. To avoid these issues it is recommended to keep to a drawing time of the scene of around 11 ms.

III. EXPERIMENTAL METHODS

A. Participants

Twenty-nine participants (five female) between the ages of 22 and 29 ($M = 25.1$, $SD = 1.8$) volunteered in a human-in-the-loop driving simulator experiment. More than half of the participants had had their driving license for over four years ($M = 6.0$, $SD = 2.4$). One of the participants did not complete the experiment due to simulator sickness, and was therefore not included in further analysis.

B. Environment Conditions

All participants drove in three conditions, light vegetation ($L = \text{tree}/40\text{m}$), medium vegetation ($M = \text{tree}/20\text{m}$) and dense vegetation ($D = \text{tree}/5\text{m}$), shown in Fig. 4, over a winding two-lane road in three trials. The road included nine 45° right and left turns with a 400m radius of 390m in length & nine straight sections of 400m. An overview of the road configuration has been shown in Fig. 5. Six different density combinations were possible (DML, MDL, LDM, DLM, MLD & LMD). The road had two lanes both with a width of 3.5m, on the side of the road a shoulder of 0.5m was present, the trees were placed at 0.5m from the road's edge. The implemented car had an automatic transmission so the use of the clutch pedal was not needed.

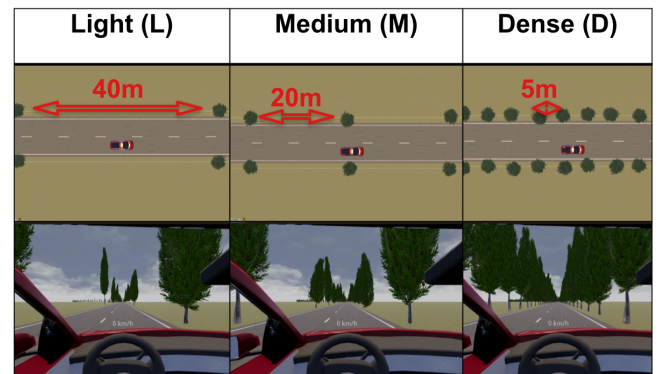


Fig. 4: Three different roadside vegetation density conditions for a straight road section shown in top-view and from the inside of the car. Light (L) meant a tree spacing of 40m, Medium (M) meant a tree spacing of 20m and Dense (D) meant a tree spacing of 5m.

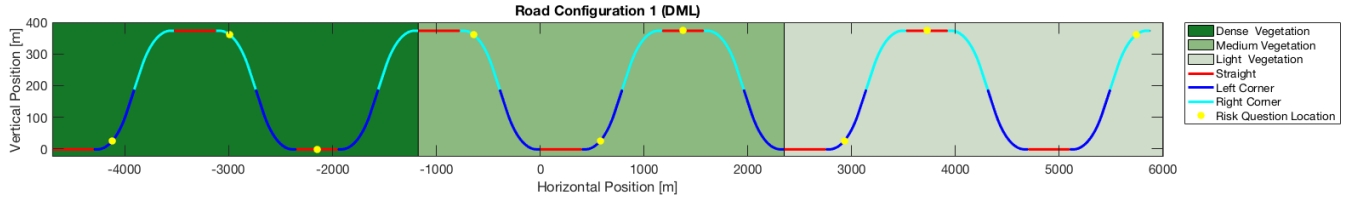


Fig. 5: One of the six possible roadside vegetation combinations (DML): Dense \rightarrow Medium \rightarrow Light. The driving direction is from left to right.

C. Experimental Design

A fully counterbalanced within-subject experimental design was used to mitigate vegetation density order effects. The participants were instructed to drive as they would if they were driving in real-life conditions. A straight section of 400m was included before the data was recorded to exclude initial acceleration, on this straight a speed sign with a maximum speed limit of 120 km/h was placed on the right side of the road. During a trial at certain points (see Fig. 5) the request: 'Please state your perceived risk on a scale of one to ten' would sound through the headphones, the participant would then call out a number between one and ten which was recorded in a Matlab GUI by the experimenter.

To have each participant end in all three density conditions the six different vegetation density orders were grouped as shown in Table I. It was necessary to have all participants end in a different density condition since a NASA Task Load Index (NASA-TLX) workload questionnaire [21] had to be filled in after each trial concerning the last four corners and two straights that were driven.

TABLE I Grouping of density orders.

	Group 1	Group 2	Group 3
Option 1	1) DML	3) LDM	5) MLD
Option 2	2) MDL	4) DLM	6) LMD

The group order was determined by a counter balanced Latin-square, to decide which option the participant would drive a coin-flip was used.

D. Experimental Procedure

Before the experiment commenced all participants were asked to sign an informed consent form, explaining the purpose, instructions, procedures and agreements of the experiment. After signing the informed consent form the participants were asked to fill in a personal driving experience form. The different forms are included in Appendix E.

After filling in the forms a training session was started to let participants get used to the dynamics of the vehicle and the sensitivity of the steering, throttle and brake. Before driving the participants were asked to put on the HTC-Vive (the HMD), the headphones and be able to reach the pedals comfortably. To make sure everybody was in a similar position in the car the participants were placed at the same

world coordinates inside the car (see Appendix A for the implementation).

The training session was done on a separate track where the start was connected to the end. The training track consisted of multiple corners and straights with varying curvatures to make sure the participants got a good feel for the vehicle handling (see Appendix F for the training-map layout). The participants were asked to drive at different velocities, 80, 100 and 120 km/h. Furthermore it was asked to crash into the roadside barrier to get a feel of how broad the car was since there were no side mirrors available. When the participants arrived back at the start of the track it was asked whether they felt comfortable with the handling of the car, if they did not they could drive on until they were. Whenever the participants deemed themselves comfortable enough the data recording sessions on the winding road shown in Fig. 5 commenced.

After each trial the participants were asked to remove both the headphones and the HMD and fill out a NASA-TLX form, this was done digitally via a Matlab GUI (Appendix B). The participants were specifically instructed to give their answers regarding the last four corners and two straights they drove. The total experiment including filling out the questionnaires and forms took approximately one hour per participant.

Although participants were specifically instructed to drive as they normally would, there were still eight participants who crashed into the vegetation (see Appendix D). Whenever this happened they were instructed to get the car back on the road and complete the session. The data for the specific section where they crashed, for example the last right corner, was not taken into account for further analysis.

E. Dependent Measures

The data was collected at a sample rate of 100Hz. The dependent measures that were calculated were categorized into driving behaviour, workload and risk.

Driving Behaviour Metrics

- *Mean speed* (km/h). One of the two primary effects of interest.
- *Mean lateral position* (m). Second of the two primary effects of interest. To see whether drivers drove further away from the roadside vegetation the mean lateral position was used with respect to the center of the

driving lane. A positive value indicates a position closer to the left lane (away from the vegetation) and a negative value vice-versa.

- *Mean Standard Deviation of Lateral Position (SDLP)* (m). The standard deviation of lateral position is a commonly used measure describing a driver's amount of swerving around a driver's mean lateral position [22], [23].

Workload Metrics

- *NASA-TLX Subjective Workload (%)*. Participants were asked to indicate their workload on six items; Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration after each trial. The items were scored on a 21-point scale from *very low* to *very high*, except for performance which ranged from *perfect* to *failure*. The overall workload was computed as the mean of the six items.
- *Steering Reversal Rate SRR* (reversals/s). SRR is defined as the number of times that the steering wheel is reversed by a magnitude greater than two degrees [24] and can be considered an objective measure for workload. [25]. The SRR was calculated by determining the local minima and maxima of the steering wheel angle, if the difference between two adjacent peaks was greater than two degrees it was considered a reversal.

Risk Metrics

- *Self-reported-risk(%)*. Represents the average risk level as indicated by responding to the risk question asked at certain positions in the winding road (see Fig. 5), similar to the metric used in Saffarian et al. [26]. The risk was normalized with respect to the total risk perceived in the respective trial, so the values for one run amount to 100%.

F. Statistical Analyses

With the exception of the results of the NASA-TLX Subjective Workload measure and the self-reported risk measure, the dependent measures were tested with a one-way repeated measures ANOVA with the three different density conditions as within-subjects factor. Homogeneity of variance was ensured by Levene's test. Mauchly's test was applied to check for sphericity (see Appendix D), if Mauchly's test was violated the Greenhouse-Geisser corrected values are reported. Bonferroni corrections were applied to the three different pairwise comparisons between the conditions for post-hoc tests.

The risk results for the corners violated Levene's test for homogeneity of variance (see Appendix D). Because the one-way repeated measures ANOVA assumes homogeneity of variance this test could not be used, therefore the risk results for the corners were subjected to the Friedman test which does not assume either sphericity or homogeneity of variance.

Because the NASA-TLX workload questionnaire is interval-based it was assumed that homogeneity of variance

would not be satisfied a-priori. Therefore the results of the NASA-TLX were also subjected to the non-parametric Friedman test.

IV. RESULTS

For analysis of the results the different road configurations, straight, left corner & right corner were all transposed to fit over each other. This resulted in nine data-sets for each road-configuration/density combination. Table II shows the means and standard deviations for all dependent measures, the results of the repeated measures ANOVA and the pairwise comparisons.

A. Driving Behaviour

The vegetation density did not significantly affect the speed of the participants in any road configuration. This is congruent when looking at Fig. 6 where the means over the x-distance for all conditions heavily overlap. When looking at the means and standard deviations in Table II also very little difference is observed. No significant effect was found with respect to any of the driving behaviour measures in any road configuration. The change in roadside configuration did not result in extra swerving of participants which would mean a change in SDLP (see Fig. 8). Drivers did also not adapt their position on the road (see Table II) which can also be deduced from Fig. 6 where both the means and standard deviations almost perfectly overlap for the three different vegetation density conditions.

B. Workload

The NASA-TLX subjective workload questionnaire did not result in any significant effect for any of the roadside vegetation density conditions (Fig. 7). A small yet significant effect was found for SRR on the straight road section $F(2,52) = 6.37, p = 0.0033$. Pairwise comparisons revealed that only a significant effect on the straight road section was found for light vs dense vegetation condition $p = 0.047$.

C. Risk

The self-reported-risk rating as given by the participants was significant for almost every road configuration for the different density conditions, see Table II. This is in concurrence with data shown in Fig. 8, where for almost every road configuration the mean risk rating goes up with an increase in roadside vegetation density. Only the result for the risk rating in right corners between medium and light vegetation was non-significant.

V. DISCUSSION

A human-in-the-loop driving simulator experiment was conducted in a novel HMD-based VR driving simulator investigating the effect of roadside vegetation density on driving behaviour. In this section the results will be discussed.

TABLE II Means (M), standard deviations (SD), and results of the repeated measures ANOVA(F, p) per dependent measure. x means $p \leq 0.05$, xx means $p \leq 0.01$, xxx means $p \leq 0.001$.

Straight		Light (1)	Medium (2)	Dense (3)	$F(2, 52)$, p-Value	Pairwise comparisons		
		M, (SD)	M, (SD)	M, (SD)		1-2	1-3	2-3
Driving Behaviour	Mean speed (km/h)	120.12, (5.09)	120.28, (6.77)	119.37, (4.87)	$F = 2.12, p = 0.15^*$			
	Mean Lateral Position (m)	0.18, (0.15)	0.17, (0.15)	0.16, (0.13)	$F = 0.22, p = 0.80$			
	Mean SDLP (m)	0.19, (0.04)	0.18, (0.04)	0.18, (0.04)	$F = 2.65, p = 0.08$			
Workload	Mean SRR (reversals/s)	0.49, (0.28)	0.50, (0.30)	0.54, (0.32)	$F = 6.37, p = 0.0033$		x	
	NASA-TLX (%)**	33.44 (15.2)	33.15 (14.79)	34.82 (14.33)	$\chi^2_F(2) = 0.78, p = 0.67$			
Risk	Mean Risk (%)	7.69, (2.13)	8.86, (1.99)	11.99, (2.36)	$F = 14.03, p = 10.8 \cdot 10^{-5}^*$	xxx	xxx	xxx
Left Corner								
Driving Behaviour	Mean speed (km/h)	117.30, (5.48)	116.66, (6.37)	118.14, (5.37)	$F = 0.010, p = 0.97^*$			
	Mean Lateral Position (m)	0.35, (0.16)	0.35, (0.15)	0.30, (0.15)	$F = 1.16, p = 0.31^*$			
	Mean SDLP (m)	0.26, (0.06)	0.25, (0.05)	0.25, (0.07)	$F = 0.35, p = 0.70$			
Workload	Mean SRR (reversals/s)	0.74, (0.28)	0.74, (0.28)	0.81, (0.31)	$F = 1.31, p = 0.28$			
Risk***	Mean Risk (%)	9.16, (1.82)	10.91, (1.45)	14.94, (3.05)	$\chi^2_F(2) = 36.35, p = 1.28e^{-8}$	x	xxx	xx
Right Corner								
Driving Behaviour	Mean Speed (km/h)	118.14, (5.04)	118.01, (5.37)	117.45, (5.78)	$F = 0.58, p = 0.56$			
	Mean Lateral Position (m)	0.07, (0.18)	0.04, (0.16)	0.03, (0.15)	$F = 0.75, p = 0.48$			
	Mean SDLP (m)	0.26, (0.06)	0.26, (0.06)	0.25, (0.05)	$F = 0.019, p = 0.98$			
Workload	Mean SRR (reversals/s)	0.69, (0.24)	0.72, (0.27)	0.72, (0.29)	$F = 2.95, p = 0.061$			
Risk***	Mean Risk (%)	9.62, (1.75)	11.01, (1.92)	15.83, (3.79)	$\chi^2_F(2) = 30.13, p = 2.86e^{-7}$		xxx	xx

* Because Mauchly's test had been violated, these p values have been corrected for via Greenhouse Geisser corrections.

** With the NASA-TLX metric no differentiation was made between the road configurations, the shown values are means from the questionnaire which was concerned with the whole last section per trial run, concerning the total workload. Furthermore the Friedman test was used for this metric, which is why the χ^2_F test statistic is reported.

*** For these measures Levene's test of homogeneity of variance had been violated, therefore a Friedman test was used which does not assume either sphericity or homogeneity of variance.

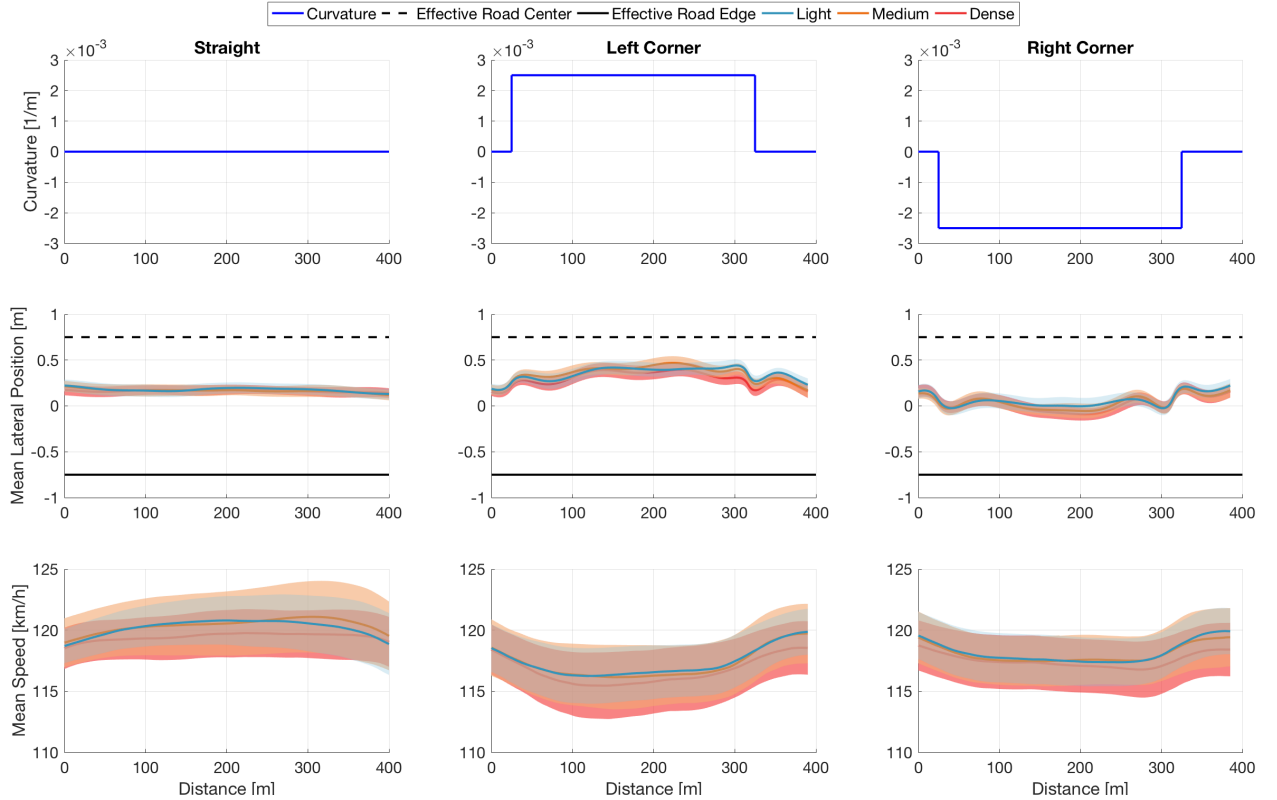


Fig. 6: Top: Curvature (1/curve radius) of the different sections, straight, left corner and right corner. **Middle:** mean lateral position across all participants per condition. The shaded area represents 2σ , so 95% of the interpersonal variability. The road plotted is the effective road width, half of the car width (car-width/2 = 1m) was subtracted from the lane width (3.5m). The bumps in the lateral position can be explained by the start and end of the respective turn. **Bottom:** mean speed across all participants per condition, shaded area representing 2σ .

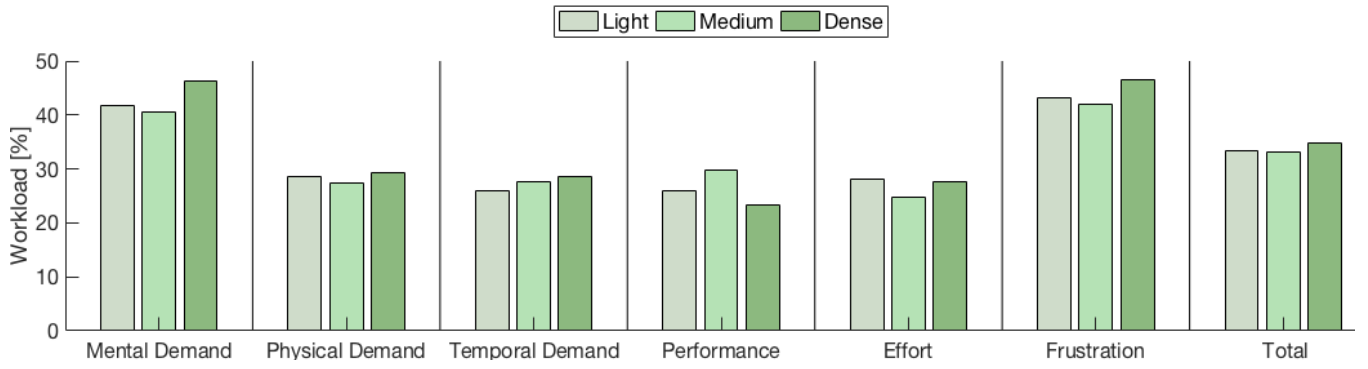


Fig. 7: Mean scores of the NASA-TLX subjective workload questionnaire.

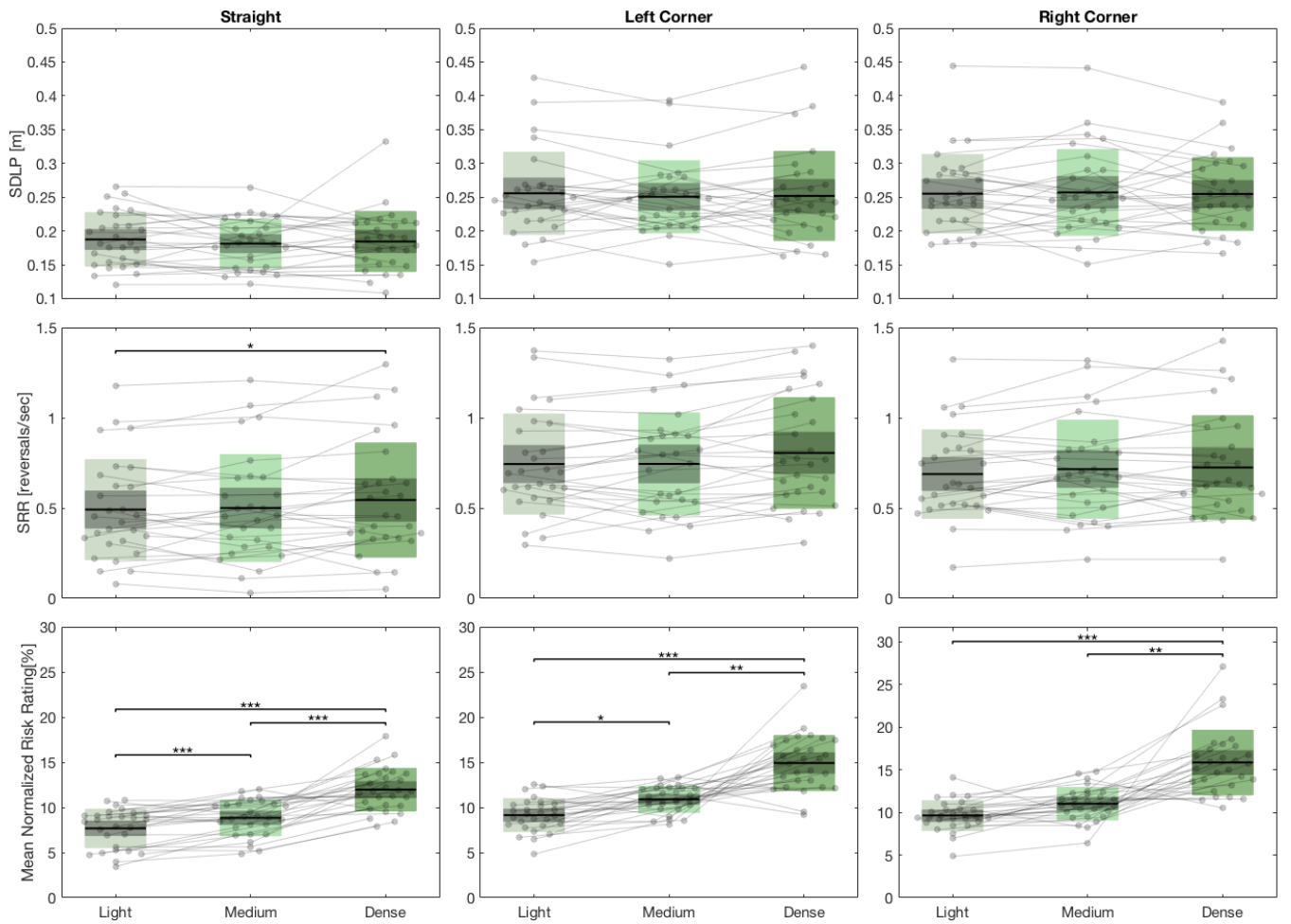


Fig. 8: Results for the dependent measures SDLP, SRR and normalized risk rating shown by row 1,2 and 3 respectively. The columns represent the different road sections; straight, left corner and right corner. The black line in the middle of the shaded areas represents the total mean (reported in Table II), the light shaded boxes the standard deviation (also reported in Table II) and the darker shaded box is the standard error of the mean (SEM). The individual data points are the different participants, the lines between them indicating the individual difference between the density conditions. Any significant results are shown with asterisks where * means $p \leq 0.05$, ** means $p \leq 0.01$ and *** means $p \leq 0.001$

A. Main Results

Mean speed was not significantly affected by roadside vegetation density in this study, which is consistent with other simulator studies [10], [11], indicating that the increased presence, increased perception of depth and increased engagement in the simulation in a HMD-based Virtual Reality environment [27], [28], [29] does not cause different speed selection as is observed in real-life driving [8], [9].

The non-significant effect on participants mean speed does not necessarily mean that mentioned advantages of HMD-based VR simulation did not translate to the behaviour of the drivers, other factors could also have been of influence. For example, the decision was made to place a 120 km/h maximum speed sign at the beginning of the track to give the participants a target speed. Although the participants were specifically instructed that it was an upper speed limit and they could also drive slower if they wanted, it is possible that the participants cognitively associated this set speed limit to be inherently 'safe' thus did not adapt their speed in any circumstance. Another option could be that participants might have mistaken the speed target for a measure of performance and actively tried to keep their speed constant as much as possible to perform well.

Mean lateral position was not significantly affected by roadside vegetation density either. Drivers kept their position on the road more or less constant throughout the different densities. When looking at the means for different vegetation densities in Table II the biggest difference between densities is only five centimeters (on a road with a width of 3.5 meters this is a minimal difference). This is consistent with findings in a thorough simulator study by Van Der Horst et al. [12], where if trees were introduced solely (without guardrail) no effect on lateral positioning was found. It can therefore be questioned whether drivers understand the risk that roadside trees form to their safety fully. One effect that can be distinguished from Fig. 6 is 'corner cutting', specifically in the left corners, this is a common phenomenon in driving behaviour studies. Rather than staying perfectly in their own lane (optimizing control strategy) drivers chose a satisficing control strategy [30], [31]. Since corner cutting posed a higher risk for the right corners (due to the presence of roadside vegetation) we see this shift of lateral positioning less in the right corners. An explanation of the difference in corners is that drivers were seated on the left side and could therefore judge the safety margins better in left corners than in right corners.

Drivers were placed at the exact middle of the lane at the start of every trial, however the mean lateral position shown the second row in Fig. 6 shows a small bias to the left of the lane, mainly on the straight road sections. An explanation for this bias could be perception related. As mentioned earlier the drivers were seated on the left side of the vehicle, it is a well-known issue in HMD-based VR that absolute distances are consistently underestimated, especially for low distances [32]. If drivers perceived their position of the right side of

the road as closer than it actually was (underestimation) it could result in the shift towards the left lane.

The results discussed above do not confirm the hypotheses that drivers slow down and move away from the road edge when confronted with higher roadside vegetation density in a HMD-based VR driving simulator. As an additional analysis, potential changes in SDLP were investigated, which reflects the amount of swerving around a driver's mean lateral position. As can be seen in the first row in Fig. 8 the SDLP does not change with different roadside vegetation density. When looking at the individual differences (the light grey lines) on the straight road section, only one person swerved more in the dense condition. No evidence was found that vegetation density affected driving behaviour in terms of speed, lateral position or SDLP.

B. Self-reported-risk

An often mentioned limitation of driving simulator studies is the absence of perceived risk, or perhaps a very low one linked to the possibility of a virtual crash [33], [11]. Due to the fact this study is using a newly implemented simulator the perceived risk is an important factor to consider. For almost every roadside configuration and roadside vegetation density condition the self-reported risk significantly increased (see Fig. 8 and Table II), which can be seen as a verification that the simulator conveys risk.

Not only can risk be seen as a verification that the simulator works, perceived risk is also a significant part of driving behaviour which can help explain why there was no significant effect found in the driving behaviour measures. Perceived risk is the main factor behind the 'Risk Homeostasis Theory' (or 'Risk Compensation Theory') [34]. According to this model the driver is inclined to react to changes in the road environment and this reaction occurs in accordance with his/her motives. The driver will only adjust his/her behaviour when a certain risk threshold is exceeded or expected to be exceeded. With regards to the driving behaviour (mean speed, mean lateral positioning and mean SDLP) found in this study, the risk threshold was apparently not exceeded or expected to exceed. Looking closer at speed adaptation with respect to the risk homeostasis theory, a recent paper linked the risk homeostasis theory to two other theories; task difficulty and safety margins [35]. It was concluded it was neither risk, task difficulty or safety margins that governed speed adaptation, which could help explain that in this HMD-based VR driving simulation study the increase of self-reported risk did not show itself in a different speed selection either.

A factor that can influence self-reported risk is how far away from the vehicle the treeline is presented. In this study it was decided to present the treeline 1m away from the lane boundary (of which half was a road shoulder, and the other half grass). Given a lane-width of 3.5m and a car-width of 2m, this meant the distance between the treeline and the right car side was 1.75m. It is possible that the trees were too far away from the car to present a sufficiently high risk

to the driver to change their behaviour, according to the risk homeostasis theory. Furthermore, it has been argued that a lining of trees is helpful to drivers for estimating curves and distances, seeing the treeline as 'guidance' rather than a risk [10], [12].

Another factor which might have influenced the fact that the supposed risk threshold was not exceeded is that there was no oncoming traffic included. This was decided because it would be difficult to regulate the velocity of the oncoming traffic in such a way that the participants met the traffic at the exact same point so that the results of the separate sections could still be easily compared. The participants were not told they would not encounter traffic but it is possible that after a while they assumed this would not be the case and therefore this decreased their overall perceived risk, making it less likely to exceed the threshold as described in the risk homeostasis theory.

An interesting finding in this study is the significant increase in SRR on straight road sections between the light and dense vegetation density condition (see Fig. 8). In the dense condition the participants adopted a higher SRR, meaning that they had higher steering activity. Together with the results of the higher perceived risk it indicates participants did recognize that the risk was higher but they did not adopt a larger safety margin (by for example slowing down or moving to away from the vegetation as hypothesized) instead the drivers put in more steering action. The lack of significance of this effect in curves might be because the steering activity in curves is higher anyway, making the difference smaller.

An explanation for the significant effect between the light and dense vegetation condition with respect to SRR could be that with the addition of trees the drivers had a better understanding of where they were positioned on the road and therefore adopted a higher adjustment rate. A reason for this effect showing up in the SRR and not the SDLP is that the vehicle dynamics are in between the steering movement and lateral position on the road, one could see this as the vehicle dynamics acting as a low-pass-filter which filters out the relatively high frequent SRR.

C. Workload

Subjective workload has been shown to be closely related to driving performance [36]. Subjective workload in this study was evaluated by the Raw NASA-TLX (RTLX) questionnaire, the prefix raw indicating that no two-pass process with paired comparisons was used, but rather a simple average of the six TLX scales. This measure has been shown to work as a simple alternative to the full NASA-TLX questionnaire [37]. The results for the RTLX workload in this study show no significant difference with regards to roadside vegetation (see Table II), further analysis showed that no significant difference was found regarding the six scales of the RTLX (see Fig. 7) either (see Appendix D for the statistics). The lack of evidence for an effect on workload is complimentary to the finding that no evidence was found

for a change driving behaviour as drivers did not find the driving task to become more demanding when the roadside vegetation density increased.

The steering reversal rate (SRR) is considered an objective metric for driver workload [25]. Therefore the significant effect of SRR on straight road sections seems to be inconsistent when cross-referenced with the subjective workload. However, the subjective workload questionnaire was regarding the last four corners and two straights the participants drove. No distinction was made between roadside geometries in the NASA-TLX questionnaire, furthermore the NASA-TLX measures perceived workload of the whole driving task, whereas SRR mainly focuses on steering activity, which does not necessarily have to be perceived as more demanding.

Another factor that might have played a roll with regards to the difference between the objective SRR and subjective NASA-TLX measure of workload is the steering wheel characteristics (see Appendix C). The maximum steering angle needed to initiate the curve was about 12 degrees, however the auto-centering force feedback functionality only starts to work from a steering angle of 20 degrees, making the steering wheel very light in the steering bandwidth of this study. A very light steering wheel could be perceived as not demanding since hardly any steering input will turn the wheel. On the other hand a very light steering wheel could also be perceived as very demanding because any input torque by the driver is converted to steering action. The exact reason for the inconsistency in workload with regards to the steering characteristics is debatable. The supposed 'dead-band' of the steering wheel around the center could have also had some implications regarding the fidelity of simulation as some participants indicated that the steering did not really feel like steering in a real car.

D. Effects of experimental design choices and limitations

When preparing the experiment several choices and simplifications were made due to time and resource constraints. In this section the impact of these simplifications and limitations on the results will be discussed.

Due to time constraints no mirrors (neither rear-view mirrors nor side-mirrors) were implemented in this study. It can be argued that these are of crucial importance to the driving task, specifically the absence of side-mirrors could have an influence on driver's lateral positioning. When driving in a new car, not having a perfect mental model of the width of the car can be compensated by checking your side mirrors more frequently. The absence of side-mirrors was also sometimes mentioned by the participants after the experiment. On top of the discussed perceptual explanation, the absence of side-mirrors might also be a reason why there was a tendency of drivers to drive to the left of the lane center especially in the straight road sections.

To ensure the highest possible fidelity one ideally wants to achieve the highest resolution possible, however due to this simulator exploring a HMD-based VR application the

resolution was down-scaled to make sure the frame-rate was kept in acceptable bounds to counter simulation sickness occurrence [20]. Another reason for resolution adjustment was that the used hardware had limitations regarding the graphical computing power. Some participants indicated that they began to see 'lines' as if the resolution was not perfect, reminding them they were in a simulated environment. Another possibility of these 'lines' could be due to the usage of Fresnel lenses in the HMD. [38].

E. Future Work

In future work the relative validity of the developed simulator should be investigated. A way of doing so is by creating a scene which mimics a real-life scenario as close as possible, driving this scenario in the HMD-based VR simulator and on the real road in an instrumented car, and check how comparable the resulting behaviour is. Secondly the developed simulator can still be improved upon, for example by including a high fidelity steering wheel and implementation of both side- and rear view mirrors. Furthermore, to avoid resolution and latency issues a system with more computational power and a later version of head mounted display is recommended.

VI. CONCLUSION

In a newly implemented and built HMD-based VR driving simulator at the TU-Delft, a human factors driving simulation experiment investigated the effect of three different roadside vegetation density conditions on driving behaviour. Conclusions can be drawn for both the development of the simulator and the performed human factors experiment.

For the developed simulator the following conclusions can be drawn:

- The developed HMD-based VR simulator is able to gather relevant driving data at a refresh rate of 100Hz.
- The drawing time of the driving scene is kept around 11ms (90Hz), reducing the chance of simulation sickness.
- Increasing roadside vegetation density consistently resulted in higher self-reported risk ratings indicating that the simulator reproduces behaviour, which is in accordance with other types of simulators.

For the experimental conditions studied in the human-factors experiment, the following conclusions can be drawn:

- Contrary to the hypotheses, the increased roadside vegetation density presented in the developed HMD-Based VR driving simulator did not affect mean lateral position or mean speed of the subjects.
- The increase of roadside vegetation density increased self-reported risk ratings, however participants did not act on this risk increase since neither speed nor lateral positioning were affected as hypothesized.
- Additional analysis showed that the increase of roadside vegetation density had an effect on SRR for the straight road sections between the light and dense vegetation

condition, indicating a tendency for drivers put in more steering action as roadside vegetation density increased.

The implication of this study is that the developed HMD-based VR driving simulator offers an affordable, easily manipulable environment that can replicate behaviour in conventional projection-based simulators, but not real-life driving. Further research could expand on investigating the relative validity and improving the developed simulator.

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Unreal Editor Blueprints

The built HMD-based VR driving simulator mainly revolves around CARLA which was built in the Unreal editor environment. CARLA is mainly used for autonomous driving research, therefore it had to be expanded with the capability to also drive around in the car and gather the necessary parameters. To build the scenario used for testing in this study the Unreal Editor's visual scripting language called 'Blueprint' was used. In this section the main implementation of these blueprints will be shown and shortly discussed.

The overarching architecture of the built scenario is called the 'level blueprint', it is shown in Figure A.1. The main 2 things in the level blueprint when created are the following:

- 'Event begin play', this will execute whenever the level is started
- 'Event Tick' which will execute every clock-tick or at a set interval.

Other events can also be set by for example key presses or whenever somethings happens inside the level like passing through a certain location. The different blueprints denoted by numbers in Figure A.1 are discussed in the same order of sections in this chapter. So A.1 would refer to the number 1 on the left top in Figure A.1.



Figure A.1: Overall Level Blueprint, the blue numbers pertain to the different functionalities explained more in the different sections in this chapter.

A.1. Attaching spawned car to pawn

The car spawning is done by the Python API, since there was no functionality to attach an extra player camera via the API this was done via the blueprint environment. Whenever a car was spawned the 'pawn' with the player camera was attached to it by pressing x. Figure A.2 shows the different used actors and first person view of the shown camera.

1. Pawn + Camera
2. Spawn point
3. Ambient audio
4. Speedometer widget
5. Positioning widget

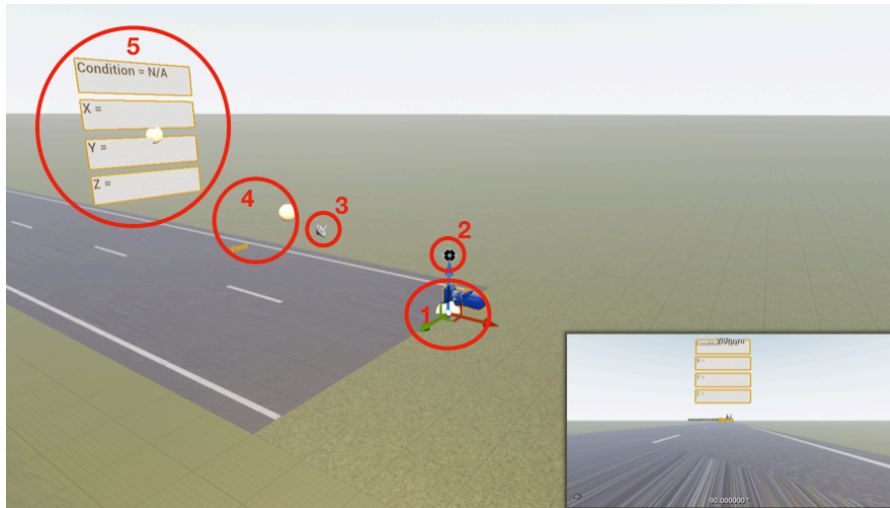


Figure A.2: The different actors placed prior to connecting to it with the python client and spawning the car.

The blueprint to attach all the shown actors and (speedometer) widget to the car, (so it will move with the car) is shown in Figure A.3. It is also shown in Figure A.1, where it is referenced by number 1.

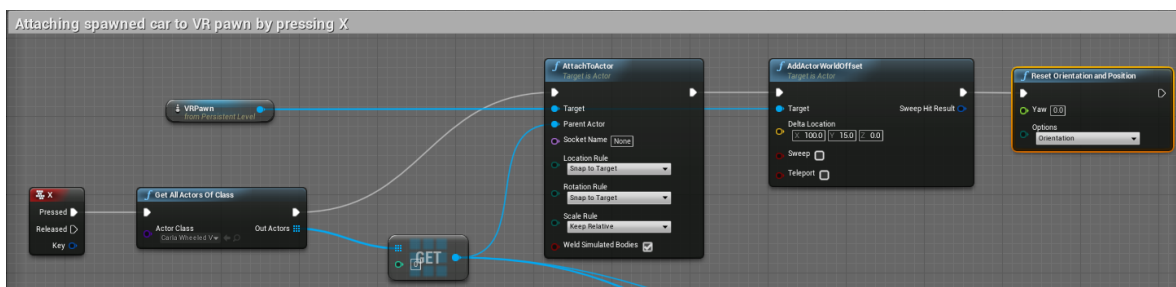


Figure A.3: The blueprint of attaching the shown components to a spawned car when X is pressed.

A.2. HMD-positioning

In order to let all participants sit in the same position the coordinates in worldspace of the HMD were needed and cross referenced with set coordinates. If the coordinates were in the right range the coordinates widget changes from red to green. The way this was done is also via blueprint shown in Figure A.4 below.

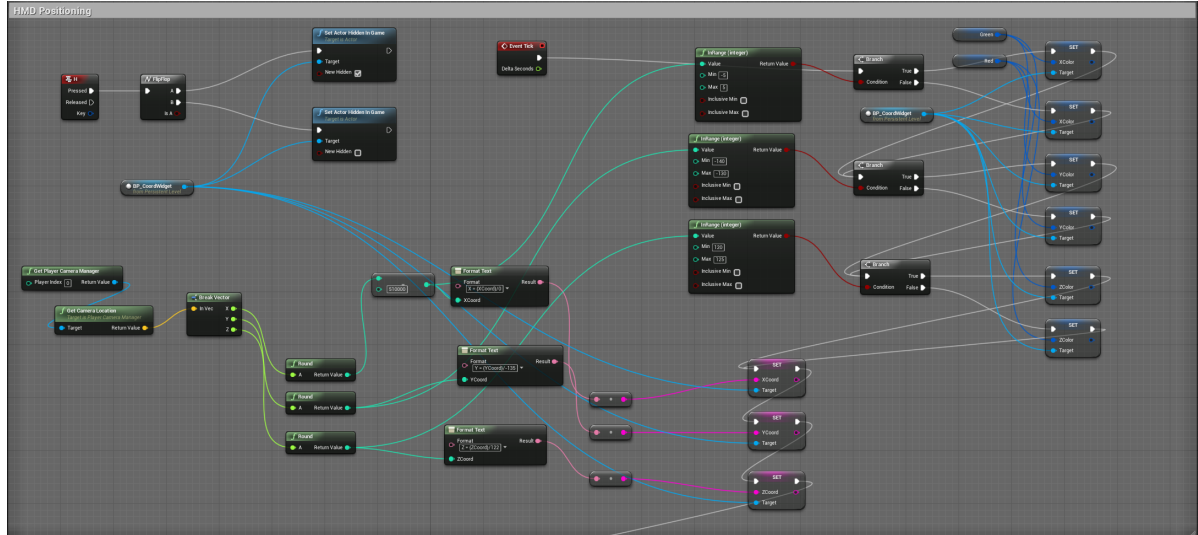


Figure A.4: Displaying world and HMD coordinates

A.3. FPS settings

To ensure that the simulation runs smoothly there are certain parameters of the engine that can be set to optimize the drawing time of the scene. This can be done by changing the generated 'engine.ini' file at startup, but also by blueprint which is shown in Figure A.5 below:

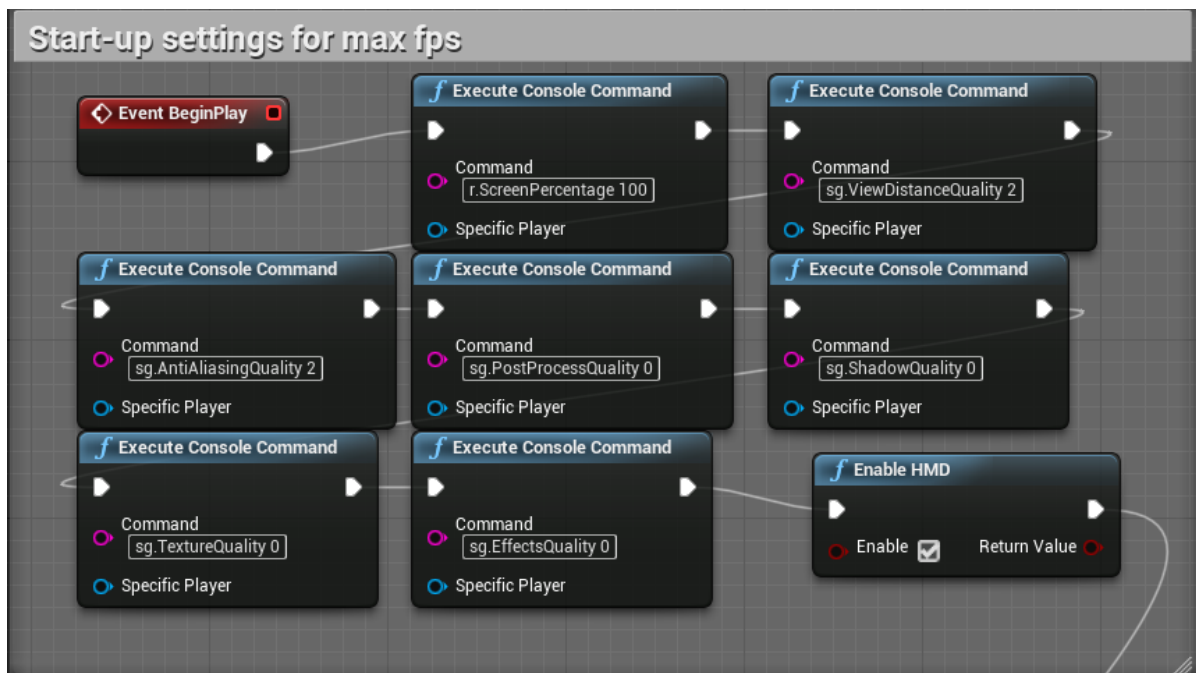


Figure A.5: Start-up settings to ensure acceptable framerate.

A.4. Attaching speedometer

Right after the settings for the FPS are done the speedometer is attached to the VR-pawn, see Figure A.6 (which can be attached to the spawned car by pressing X). The speedometer is a widget which will move with the car and is 'floating' in front of the car which makes it look like its like a sort of head-up-display. Furthermore the visibility of all vegetation is set to 0 and the volume of the sound is set to 0 as initialization.

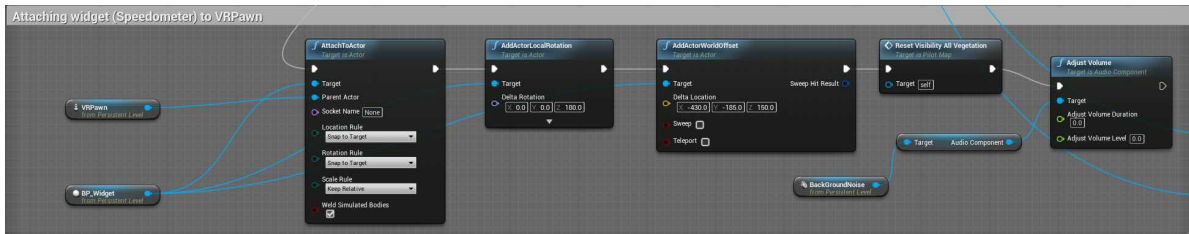


Figure A.6: Attaching speedometer to VR-pawn and initialization of sound and vegetation.

A.5. Updating Speedometer

The speedometer needs to display the correct value, therefore it need sto be linked to the velocity of the player (VR-pawn). This is done in the blueprint shown in Figure A.7. It is attached to the 'event tick', so the speedometer gets updated with each rendered frame.

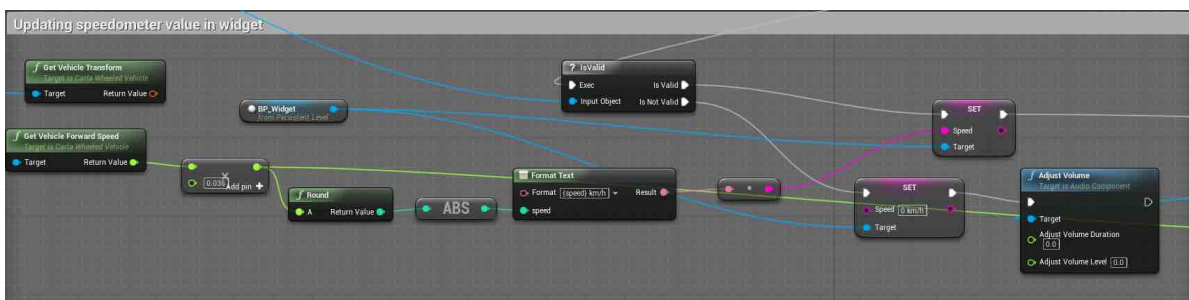


Figure A.7: Updating the speed.

A.6. Setting volume of ambient noise

The volume of the sound, which is a loop of inside car noises of a real Tesla taken from youtube, changes in volume and pitch when speed increases. Which is done in the blueprint shown in Figure A.8.

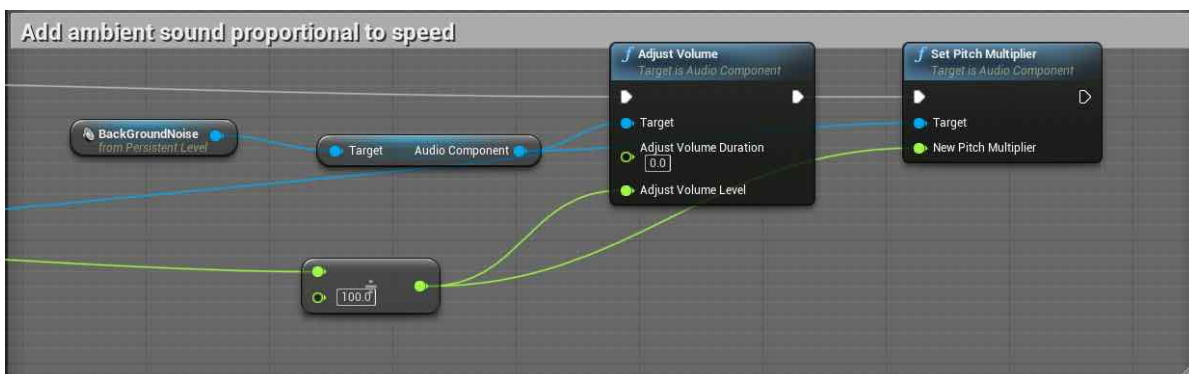


Figure A.8: Adjusting pitch and volume of ambient car noise.

A.7. Moving speedometer

Although this functionality is not necessary during the final simulation this feature was implemented to see where the speedometer widget can be placed in such a way it looks most like a head up display. With the different numpad keys the location and rotation of the speedometer widget can be changed, see Figure A.9.

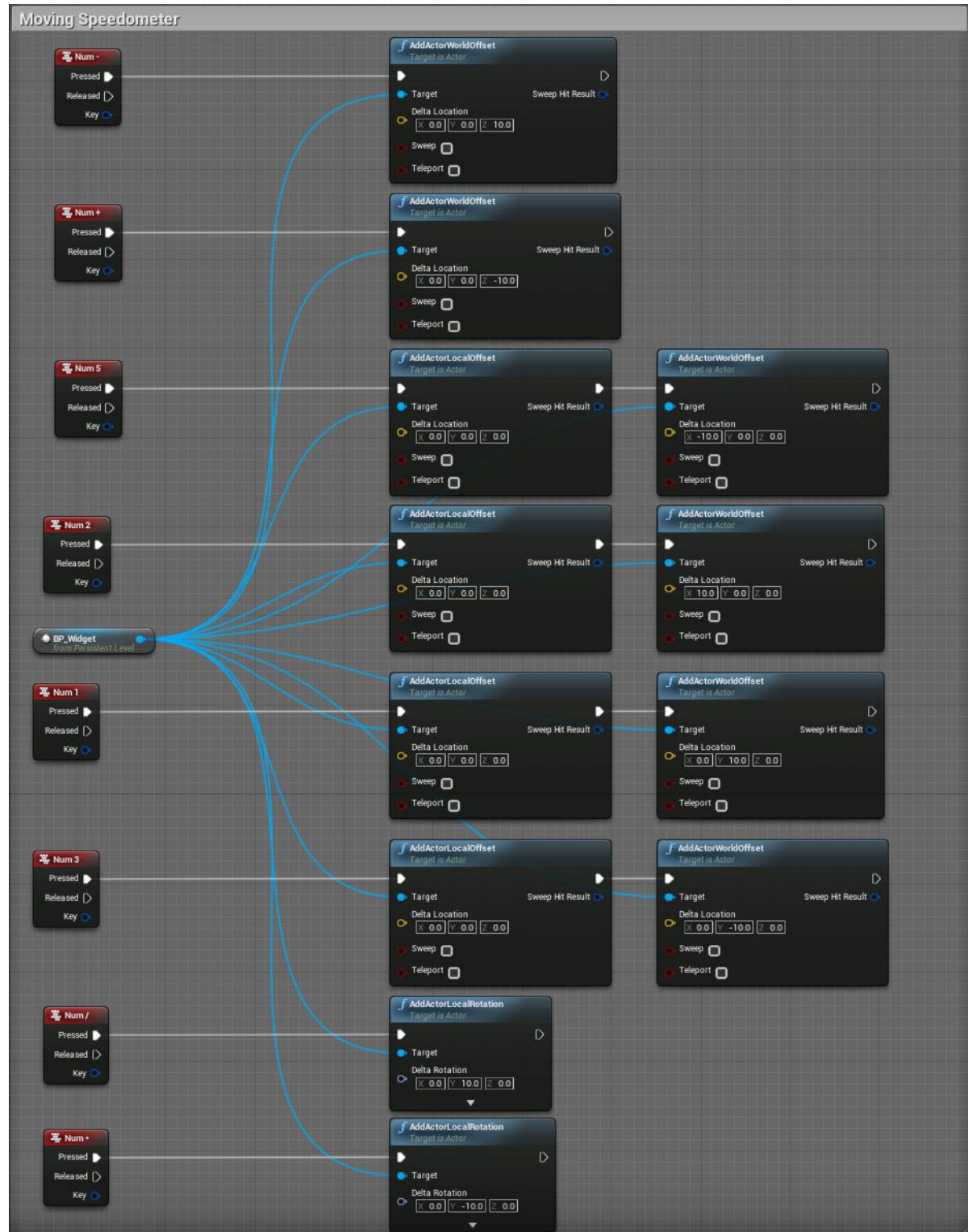


Figure A.9: Moving the speedometer widget.

A.8. Moving player inside the car

To make sure every participant is in the same exact spot inside the car, VR-pawn can be moved around using the arrow keys and w & s. As the coordinates change the widget is updated as was shown in Figure A.4.

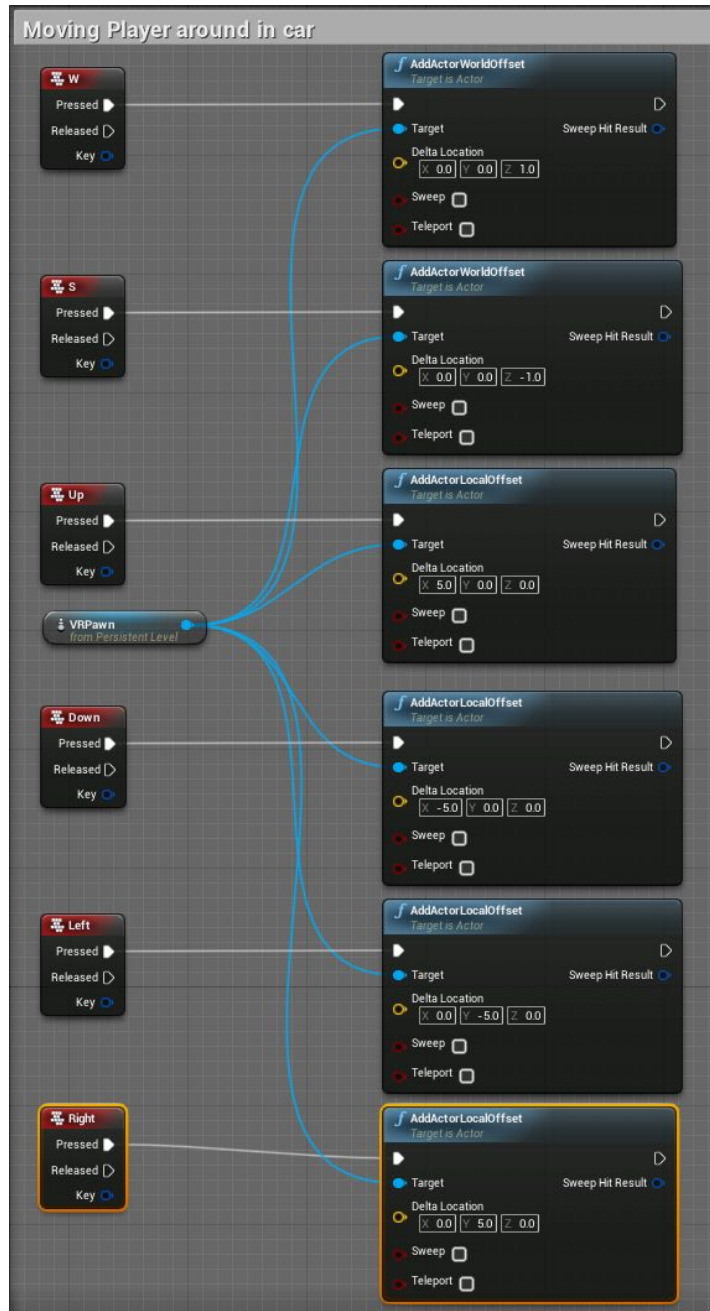


Figure A.10: Moving player inside car.

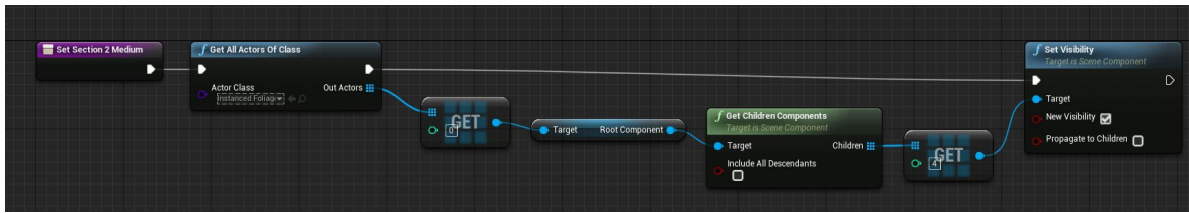


Figure A.13: One of the implemented functions to set the vegetation density, this particular one sets medium vegetation in section 2. It basically just sets the visibility of the trees.

A.11. Setting spectator mode

To see what is going on inside the HMD one can set the spectator mode on or off. If it is on the visuals that are shown in the hmd will also be shown in the desktop, if not vice versa.

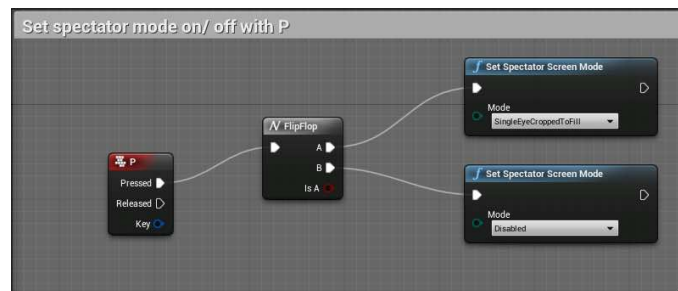
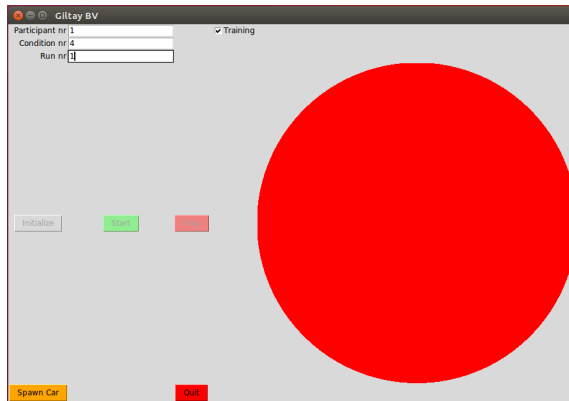


Figure A.14: Setting spectator mode on & off.

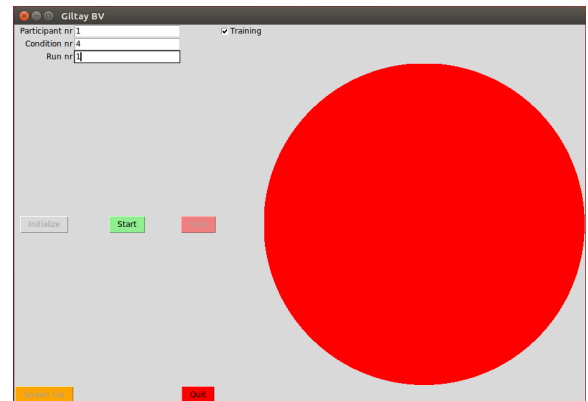
B

GUI's for data collection

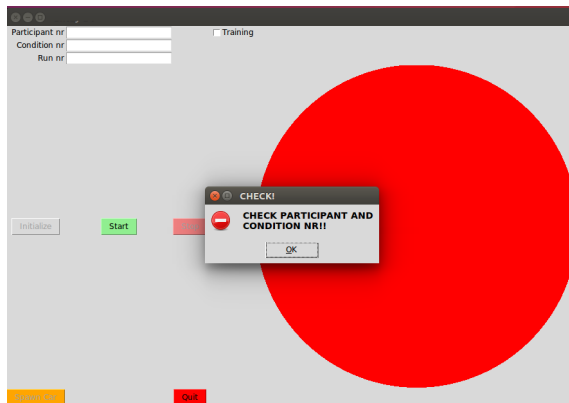
B.1. Python GUI



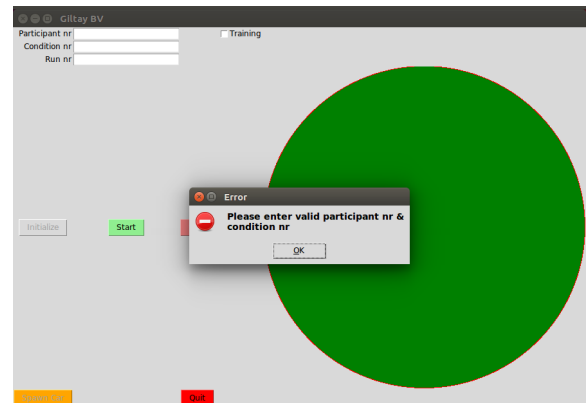
(a) After clicking initializing button the python GUI is connected to Carla, now the spawn car (orange) button will be clickable.



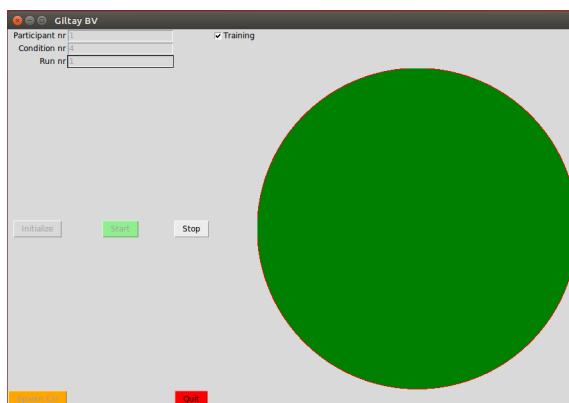
(b) After a car is spawned the start button will be clickable, indicating you can start collecting data.



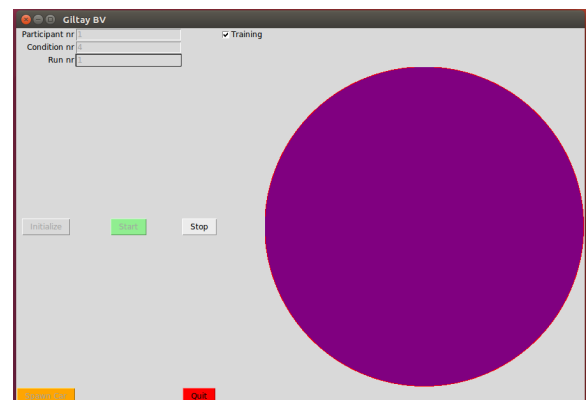
(c) Whenever you press 'start' the pop-up for extra check of the participant, condition and run number will appear. This was done to minimize errors.



(d) If still no values were inserted the above error message will show, pausing the program until you have filled in correct values.



(e) When everything has been put in correctly and you press 'start' the giant circle on the right will change from red to green, indicating that you are collecting data. Please note that you will only write data to a file when the 'training' checkbox on the topleft is unchecked.



(f) Whenever the giant circle changes from green to purple the risk question would sound through the headphones, this was implemented to remind the experimenter to fill in the result or remind the participant if he/she did not respond.

Figure B.1: The figure above shows the workflow of the implemented Python GUI that records data at a 100Hz and writes it away in a textfile.

B.1.1. Recorded Data with Python GUI

Table B.1: The text file that is generated for each run contains the following information (gathered at 100Hz). The values are separated by comma's making it easy to convert it to a CSV file as well.

Column	1	2	3	4	5	6
Data	Run Number	Timestamp	X-Pos	Y-Pos	Z-Pos	Yaw
Column	7	8	9	10	11	12
Data	Pitch	Roll	X-Velocity	Y-Velocity	Z-Velocity	X-Acceleration
Column	13	14	15	16	17	18
Data	Y-Acceleration	Z-Acceleration	Steering Angle	Throttle Input	Brake Input	Participant Nr
Column	19	20	21			
Data	Condition Nr	Lateral Position *	Zeroes			

* The lateral position was calculated using the square root of the dot product of the vector defined by the car position and the nearest waypoint. To calculate the angle the Atan2 with the determinant and the dot product of the distance vector & the direction vector (secondnearestwaypoint - nearestwaypoint) was used. Whenever the angle was bigger than 0 the calculated distance was positive (left side of the middle of the lane) if it was negative the distance was negative (right side of the middle of the lane).

B.2. NASA TLX GUI

The screenshot displays the NASA TLX GUI, which is used for collecting workload measures. The interface is divided into two main sections: 'Workload' on the left and 'NASA Task Load Index' on the right.

Workload Section: This section contains six horizontal sliders, each representing a different aspect of workload. Each slider has a scale from 'Very Low' to 'Very High' and a central blue bar indicating the current value.

- Mental Demand:** How mentally demanding was the task?
- Physical Demand:** How physically demanding was the task?
- Temporal Demand:** How hurried or rushed was the task?
- Performance:** How successful were you in accomplishing what you were asked to do? (Scale: Perfect to Failure)
- Effort:** How hard did you have to work to accomplish your level of performance?
- Frustration:** How insecure, discouraged, irritated, stressed, and annoyed were you?

NASA Task Load Index Section: This section contains a form for entering subject information and a 'First Run' button. Below the 'First Run' button are three buttons: 'Finish', 'Comparisons', and 'Save'.

Figure B.2: The GUI shown above was used for the collection of the workload measure NASA TLX.

B.3. Risk Question Result GUI

The screenshot shows a window titled "RiskGUI" with a light gray background. On the left, there is a list of nine risk questions, each followed by a green rectangular box representing the result. The questions are grouped into three sections:

- Section 1: Left Corner, Right Corner, Straight
- Section 2: Right Corner, Left Corner, Straight
- Section 3: Left Corner, Straight, Right Corner

On the right side of the window, there are two input fields labeled "Participant Nr" and "Condition Nr". The "Condition Nr" field is filled with a green box. Below these fields are two buttons: "Next Run" and "Save". The text "Run 1" is displayed in red below the "Condition Nr" field.

Figure B.3: The GUI shown above was used for the risk perception measure. This GUI was filled in by the experimenter during the trials.

C

Dynamics

C.1. Steering Wheel Characteristics

The measured steering characteristics of the steering wheel have been shown in Figure C.1. The data gathered for this plot was done by using a spring scale 10 times for the different angles and holding the steering wheel steady. The data was then interpolated using cubic interpolation.

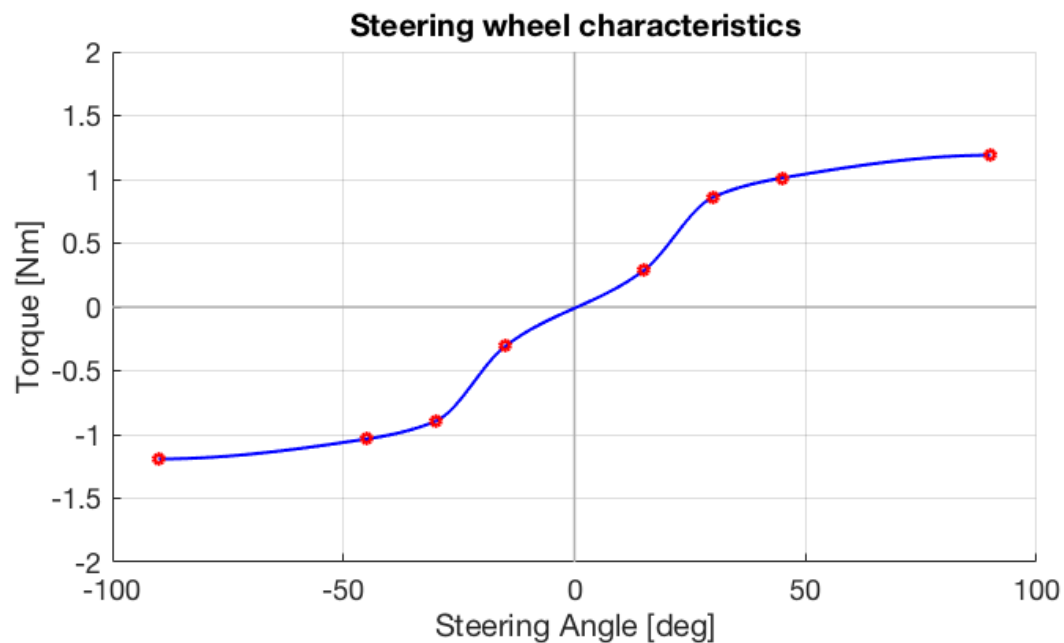


Figure C.1: Steering characteristics of the used Logitech G29 Driving Force steering wheel. Red points indicating the mean of 10 measurements, blue line the interpolation between the measured points.

D

Extensive Results

D.1. Scatterplots of Mean Velocity & Lateral Position

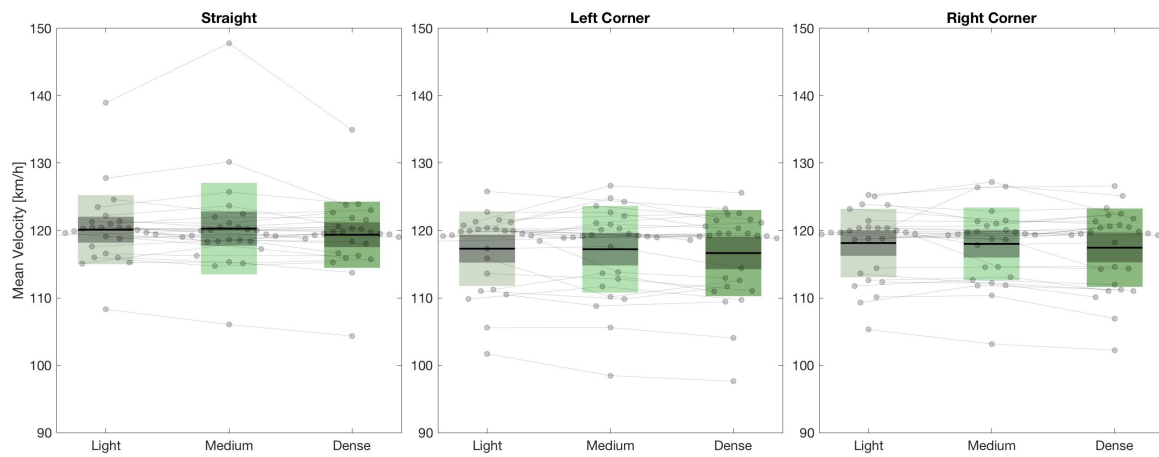


Figure D.1: Scatterplot of the mean velocity for the different road configurations and density conditions. Black line represents the total mean, darker shaded area the Standard error of the mean (SEM) and the lightly shaded area 2 times the 95% confidence interval. The scatter dots represent the participants.

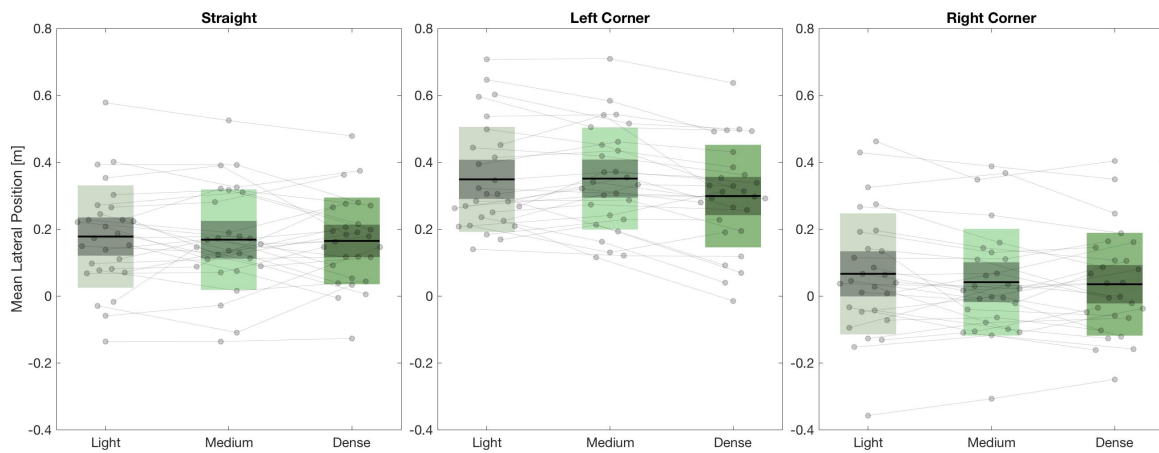


Figure D.2: Scatterplot of the mean lateral position for the different road configurations and density conditions. Black line represents the total mean, darker shaded area the Standard error of the mean (SEM) and the lightly shaded area 2 times the 95% confidence interval. The scatter dots represent the participants.

D.2. Statistical Test Results for Sphericity and Homogeneity of Variance

Table D.1: Results for Mauchly's test of sphericity for the different measures, whenever $p < 0.05$ Mauchly's test was violated.

Measure	Road Geometry		
	Straight	Left Corner	Right Corner
	$\chi^2, (p)$	$\chi^2, (p)$	$\chi^2, (p)$
<i>Speed</i>	14.49, ($7.14e^{-4}$)	8.46, (0.015)	2.32, (0.31)
<i>Lateral Position</i>	4.90, (0.086)	8.81, (0.012)	3.91, (0.14)
<i>SDLP</i>	4.74, (0.093)	0.22, (0.90)	2.03, (0.36)
<i>SRR</i>	0.23, (0.89)	0.73, (0.69)	1.18, (0.55)
<i>Risk</i>	12.28, (0.0022)	22.5, ($1.29e^{-5}$)	21.18, ($2.51e^{-5}$)

Table D.2: Results for Levene's absolute test of homogeneity of variance for the different measures, whenever $p < 0.05$ Levene's test was violated.

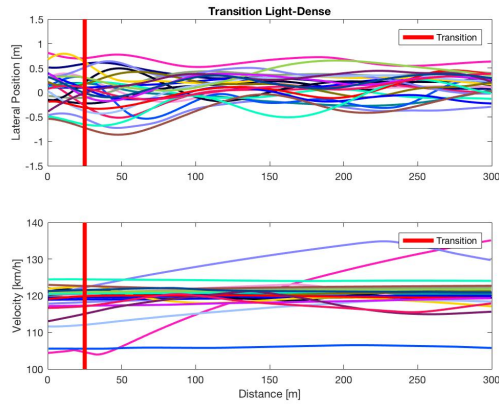
Measure	Road Geometry		
	Straight	Left Corner	Right Corner
	$F, (p)$	$F, (p)$	$F, (p)$
<i>Speed</i>	0.24, (0.79)	0.59, (0.54)	0.49, (0.61)
<i>Lateral Position</i>	0.28, (0.76)	0.21, (0.81)	0.20, (0.82)
<i>SDLP</i>	0.22, (0.80)	0.41, (0.66)	0.21, (0.81)
<i>SRR</i>	0.20, (0.82)	0.37, (0.69)	0.23, (0.79)
<i>Risk</i>	0.33, (0.72)	6.90, (0.0017)	4.3, (0.016)

D.3. Extensive subjective workload results

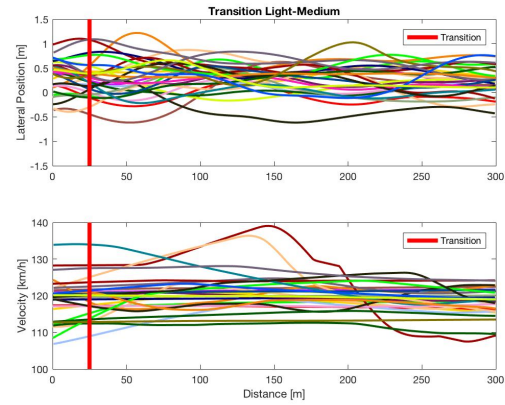
Table D.3: Statistical results of Friedman tests of the six different items and total NASA TLX workload.

	NASA TLX items						Total
	Mental	Physical	Temporal	Performance	Effort	Frustration	
$\chi^2(2)$	3.26	1.63	1.42	1.17	0.27	3.67	0.78
p	0.20	0.44	0.49	0.56	0.88	0.16	0.68

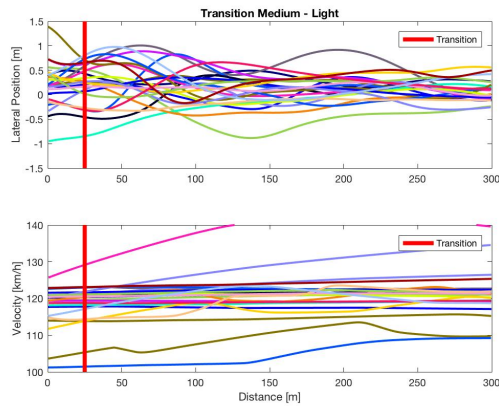
D.4. Roadside Vegetation Density Transitions



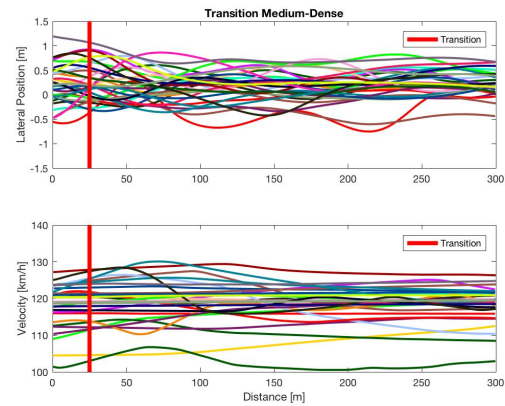
(a) Transition from Light to Dense Vegetation.



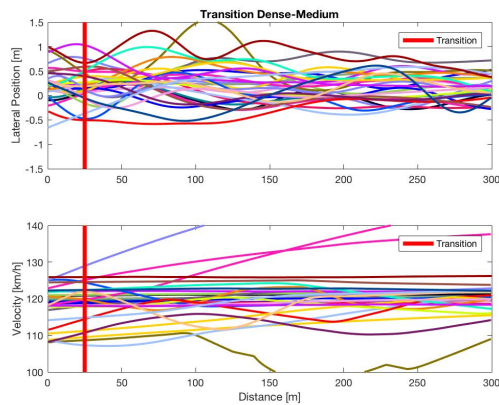
(b) Transition from Light to Medium Vegetation.



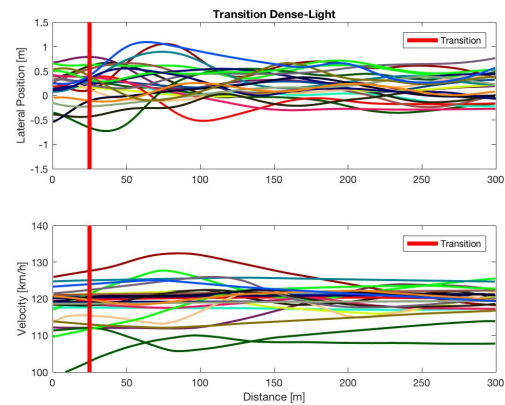
(c) Transition from Medium to Light Vegetation.



(d) Transition from Medium to Dense Vegetation.



(e) Transition from Dense to Medium Vegetation.



(f) Transition from Dense to Light Vegetation.

Figure D.3: The above plots show the lateral positioning and velocity of the different participants. The color coding is the same in all plots, so 1 color is the same participant in each plot, due to these plots not showing any sort of clear change in either position or velocity, it was decided to not look further into whether transitioning from density conditions lead to different behaviour.

D.5. Entrance of vegetation

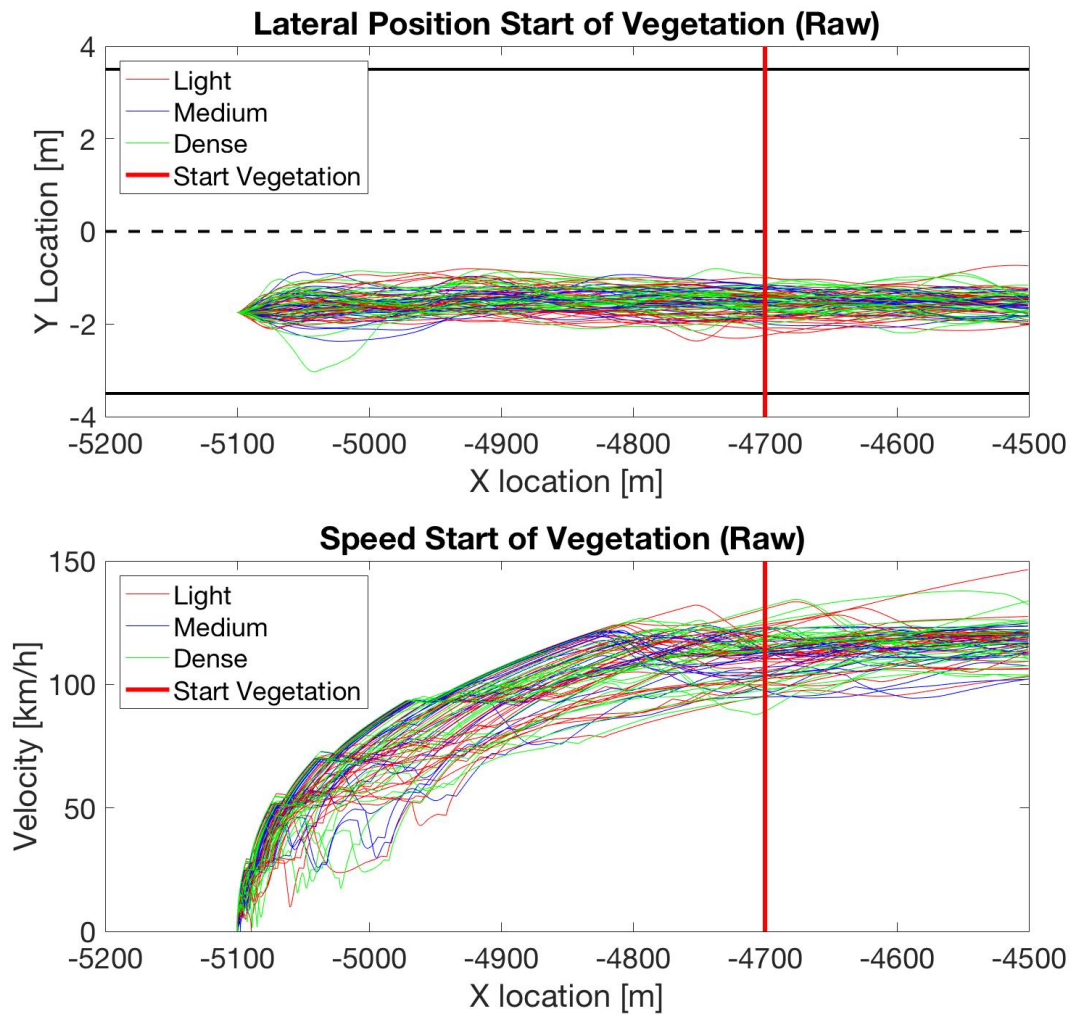


Figure D.4: To check whether the beginning of the vegetation had any effect on lateral position and velocity these are plotted above. As there is no clear difference it was decided to not look further into the entrance of the vegetation.

D.6. Investigation of learning effects

Although the participants were subjected to an extensive training period and were only allowed to start the trials when they thought they had a total understanding of the vehicle handling learning effects could still be present. Therefore in this section several plots are shown that were used to investigate whether learning occurred or not. In the following plots no distinction was made w.r.t. vegetation density due to the lack of significance between vegetation density conditions.

D.6.1. Difference in trials

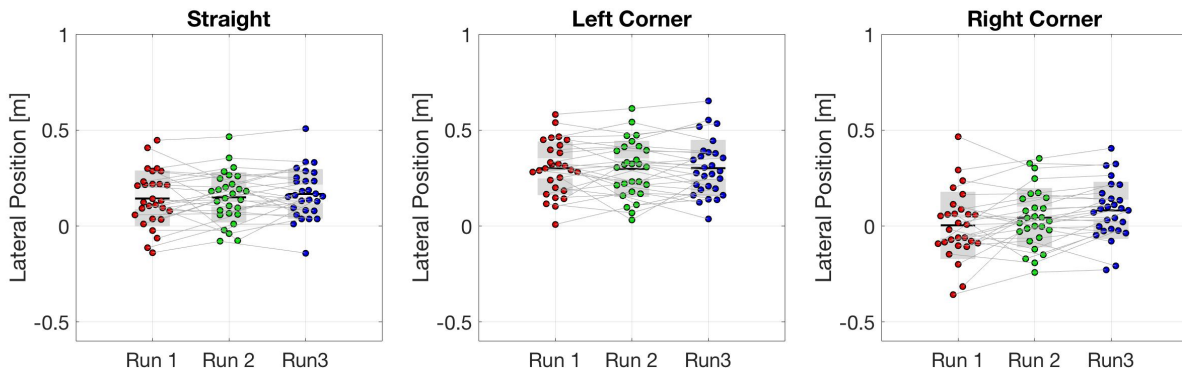


Figure D.5: Result for the mean lateral position over the different runs (trials).

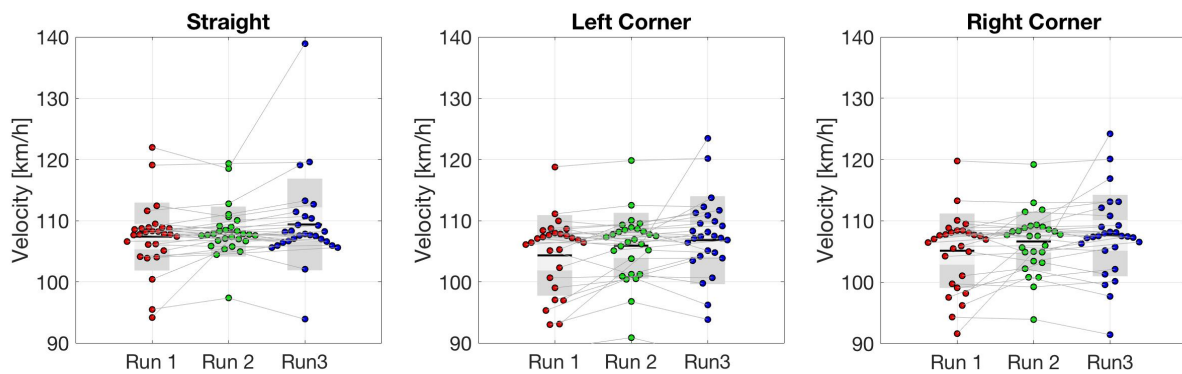


Figure D.6: Result for the mean velocity over the different runs (trials).

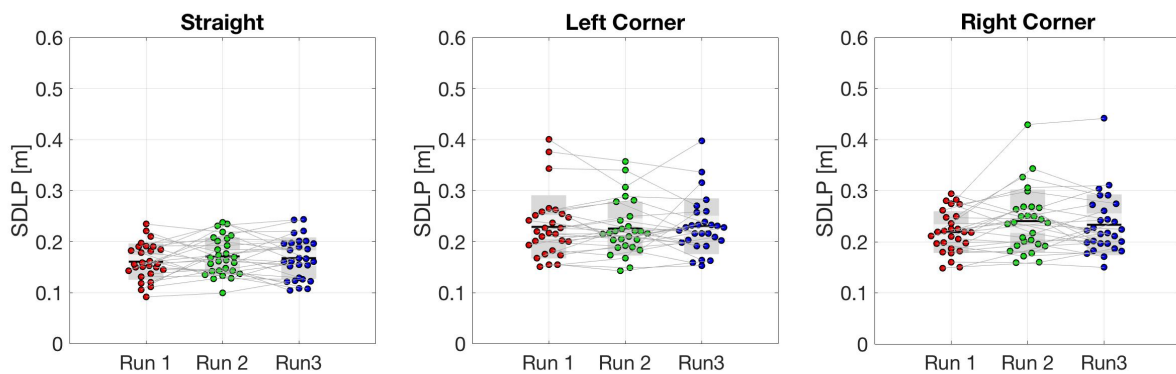


Figure D.7: Result for the mean SDLP over the different runs (trials).

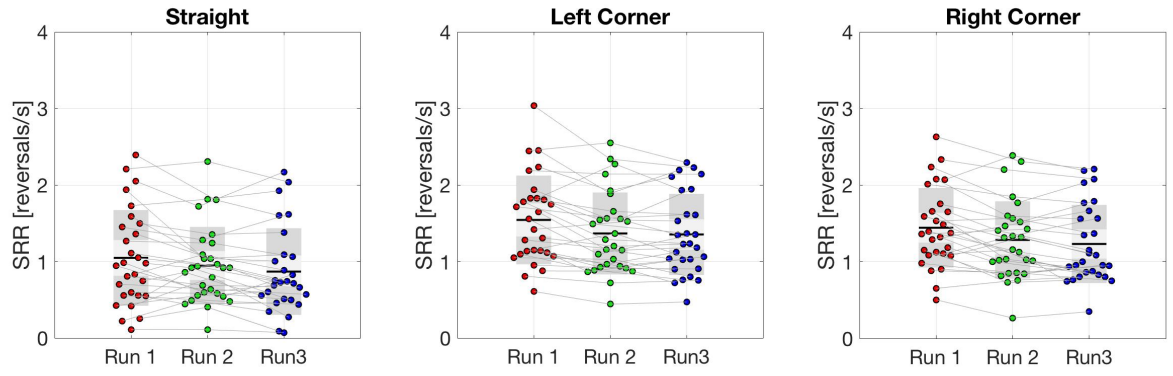


Figure D.8: Result for the mean SRR over the different runs (trials).

D.6.2. Difference in first trial only

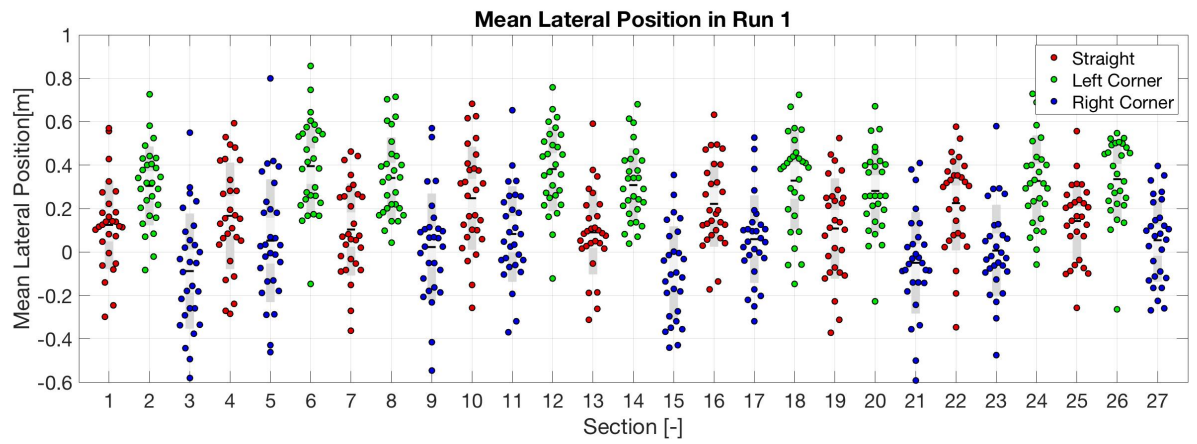


Figure D.9: Result for the mean lateral position for run 1 (trial 1). The x axis shows the road section, the total road existed of 27 sections.

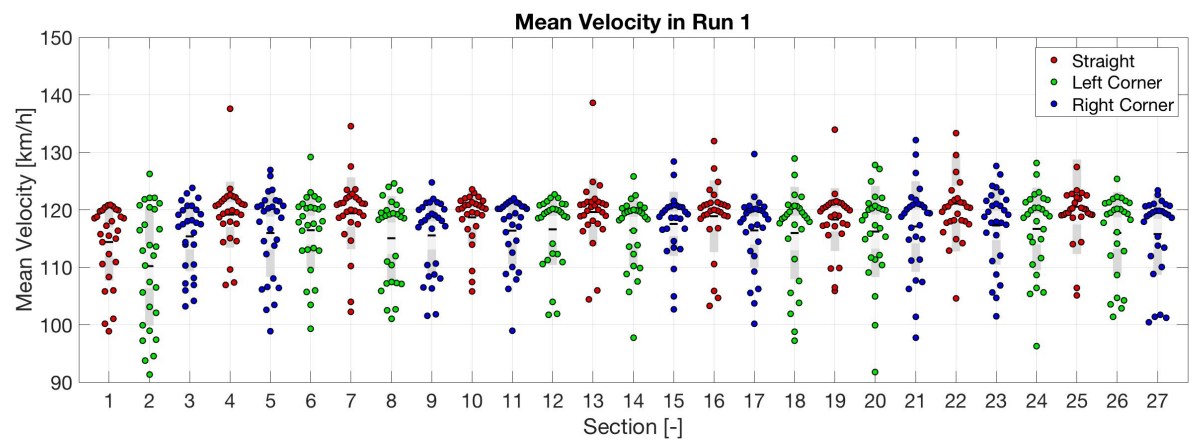


Figure D.10: Result for the mean velocity for run 1 (trial 1). The x axis shows the road section, the total road existed of 27 sections.

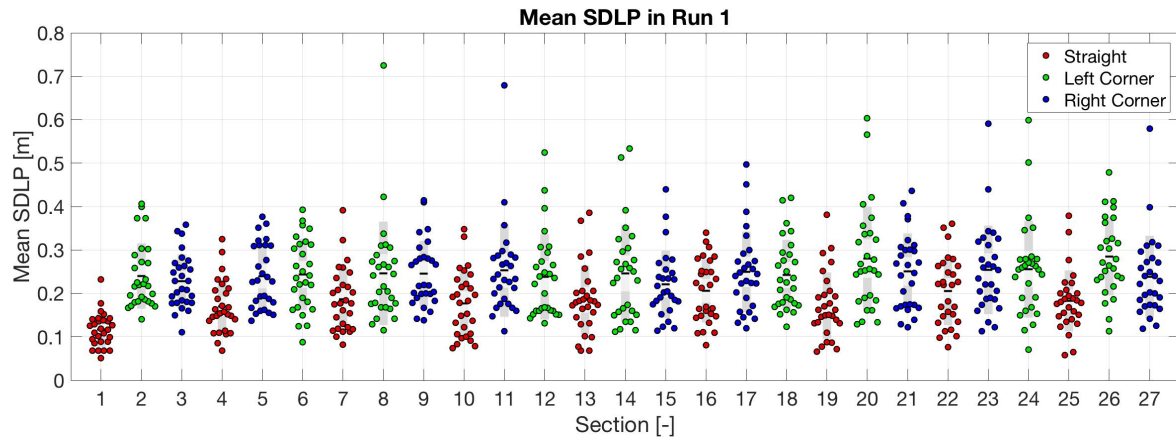


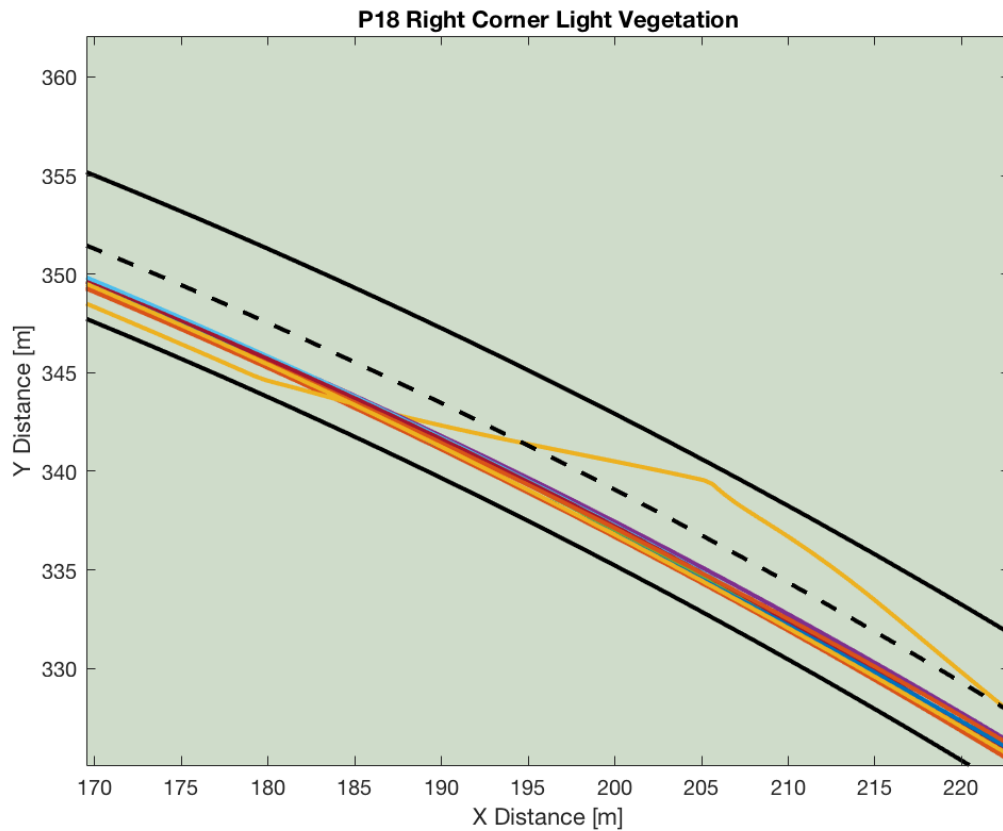
Figure D.11: Result for the mean SDLP for run 1 (trial 1). The x axis shows the road section, the total road existed of 27 sections.

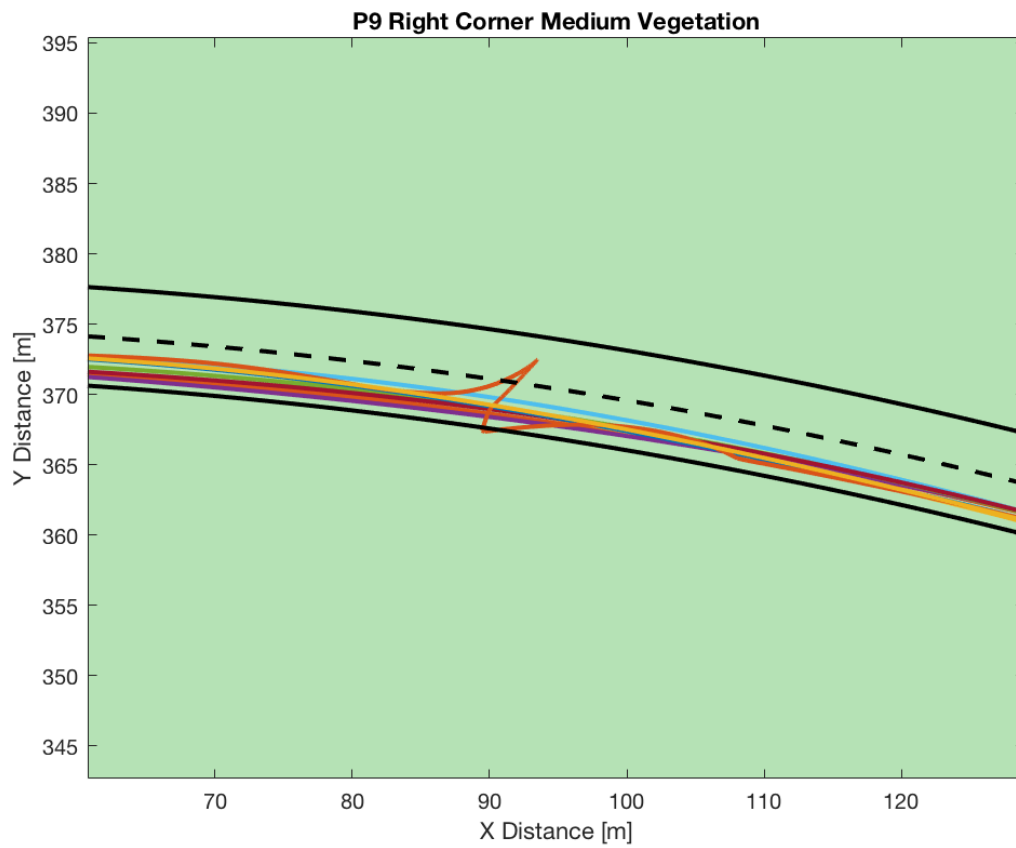
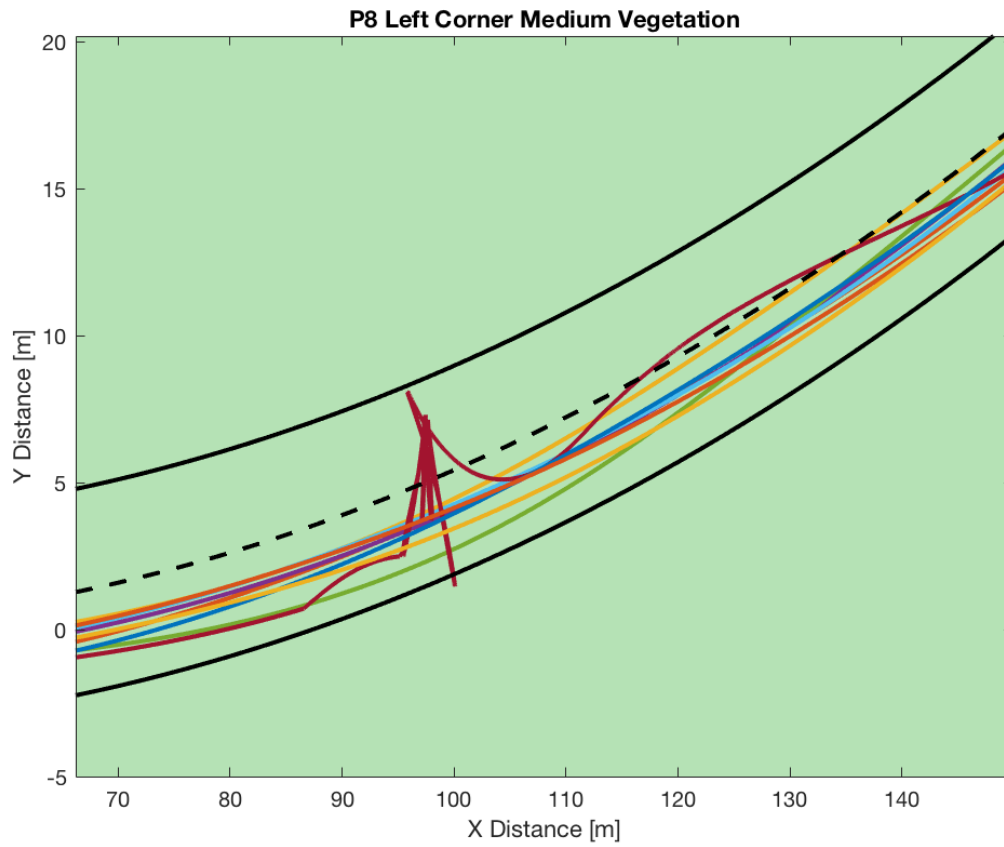


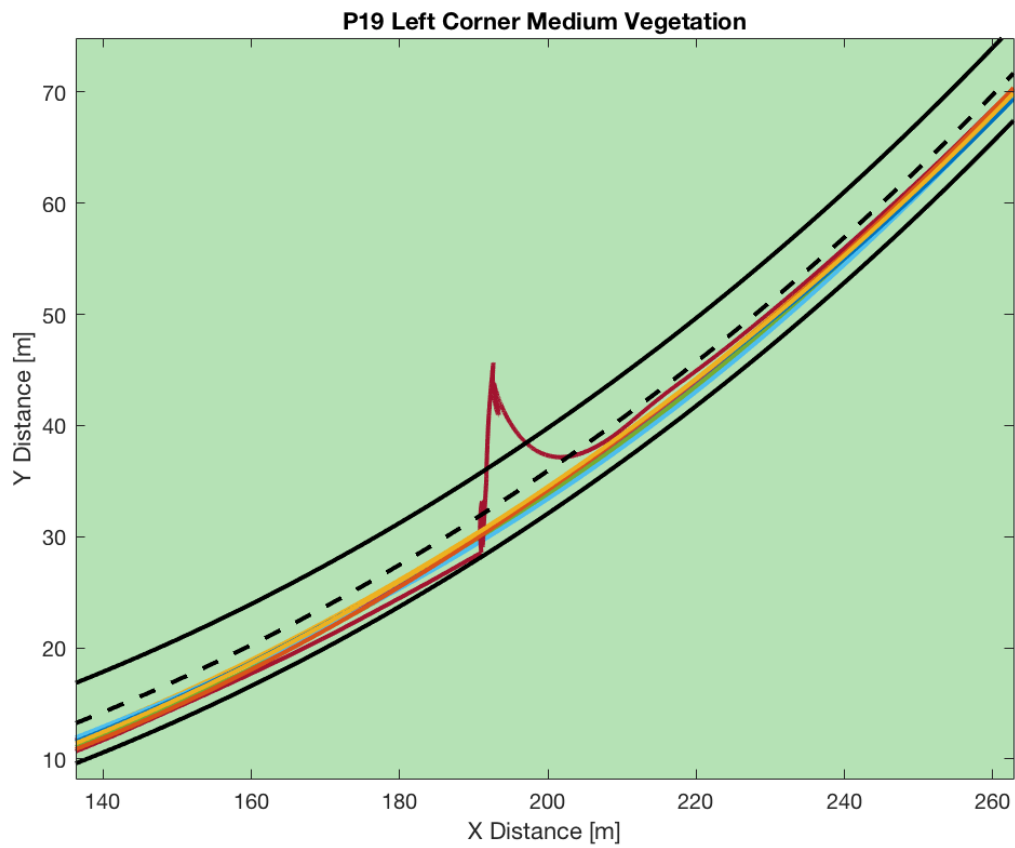
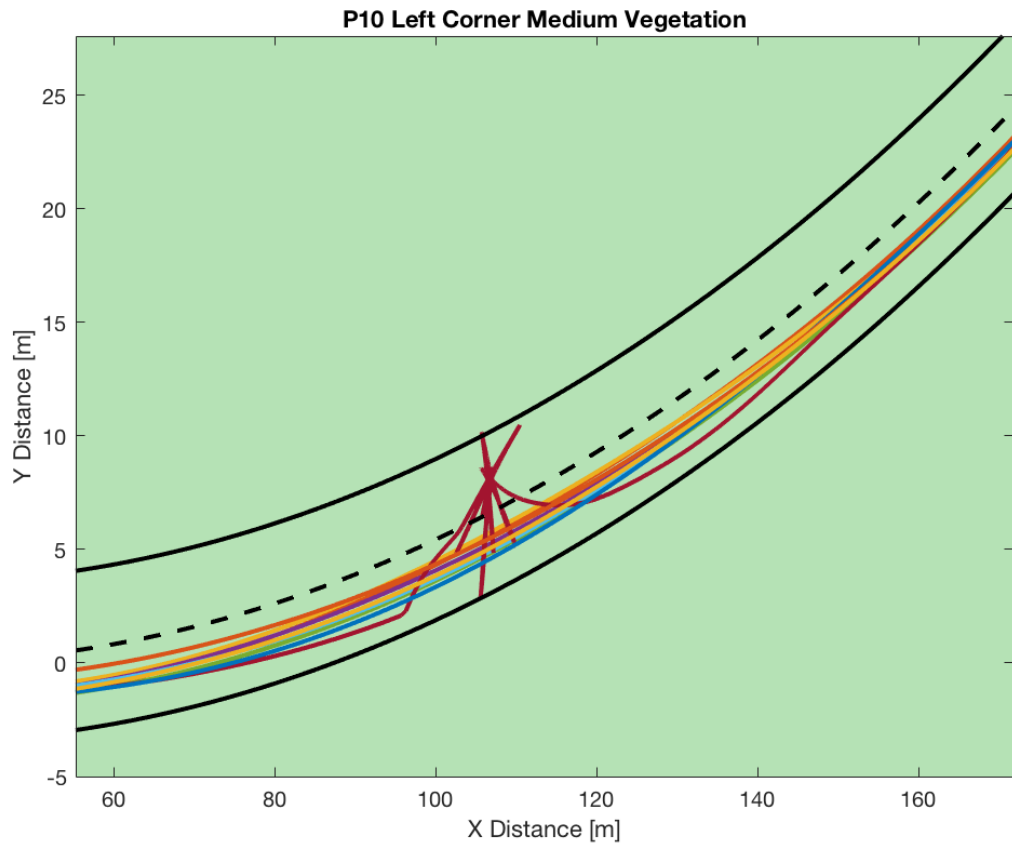
Figure D.12: Result for the mean SRR for run 1 (trial 1). The x axis shows the road section, the total road existed of 27 sections.

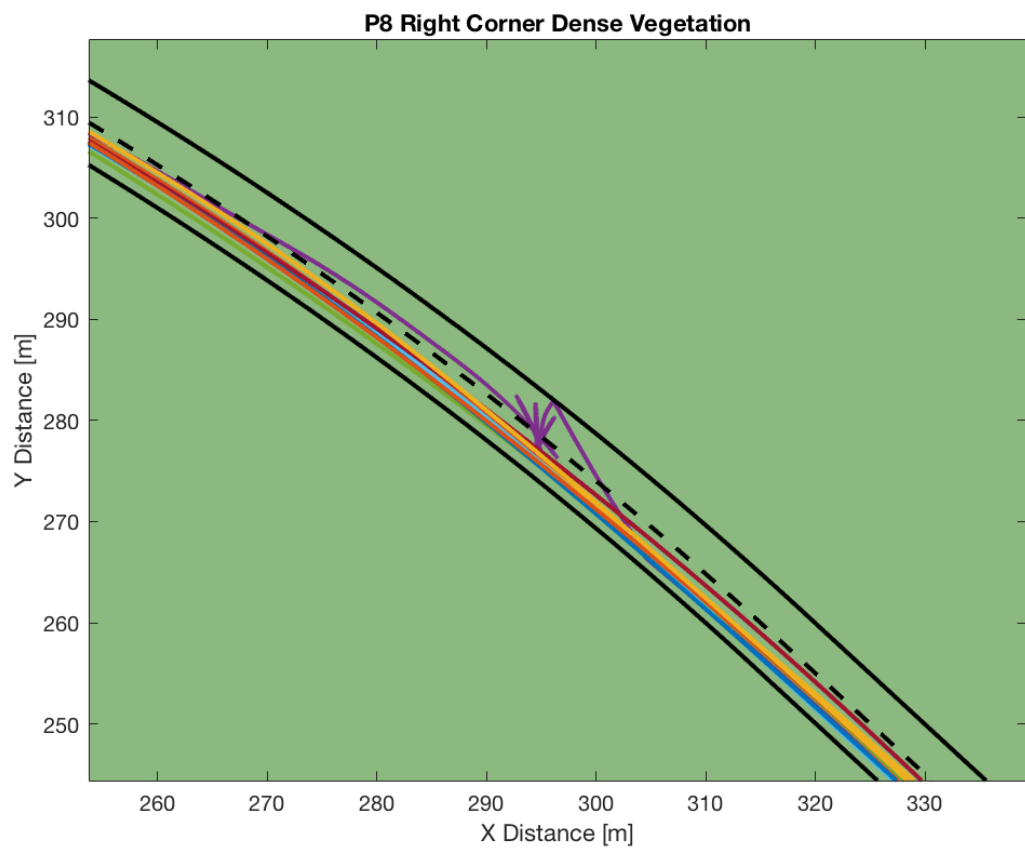
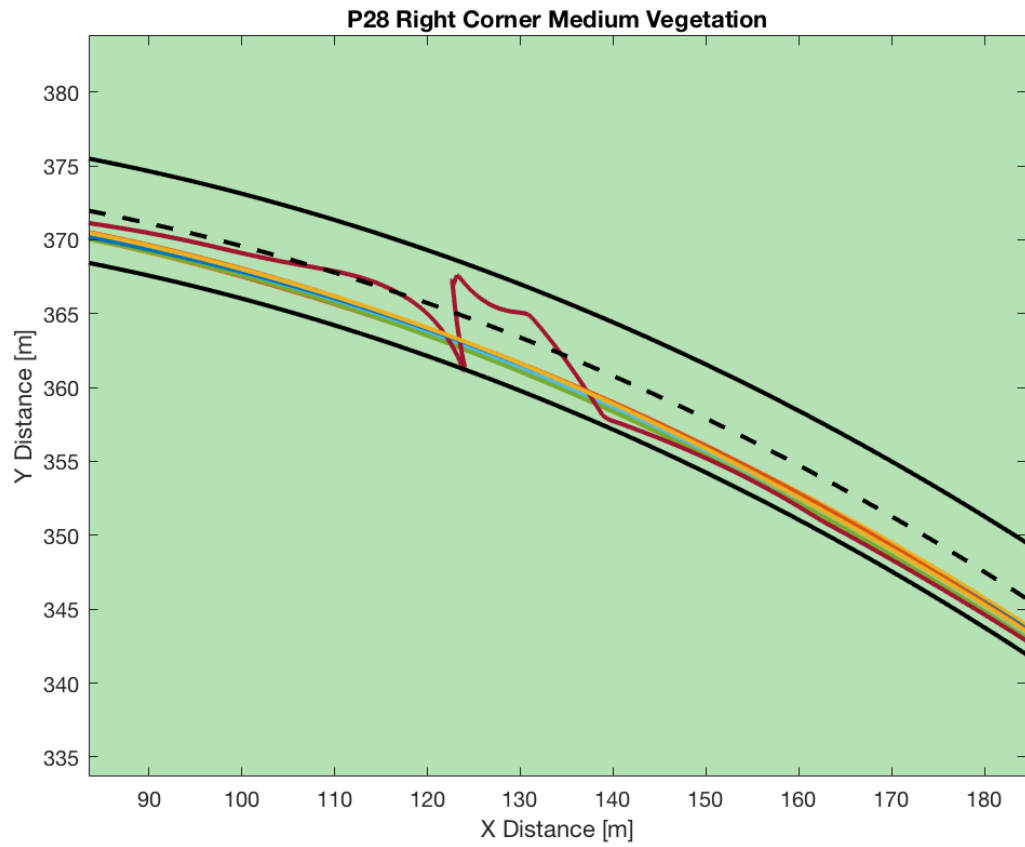
D.7. Crashes

In this section the trajectories of the participants who crashed into the roadside vegetation have been shown. The same color coding as in the paper has been used for Light, Medium and Dense Vegetation. Please note that it might seem that no crash occurred for example in the first figure, P18 right corner light vegetation, however the line shown is the middle of the car, so another meter should be added. Furthermore the road isn't exactly as it is drawn, for example one lane might seem wider), this is due to zooming in in Matlab and the offset curve deforms a little bit.

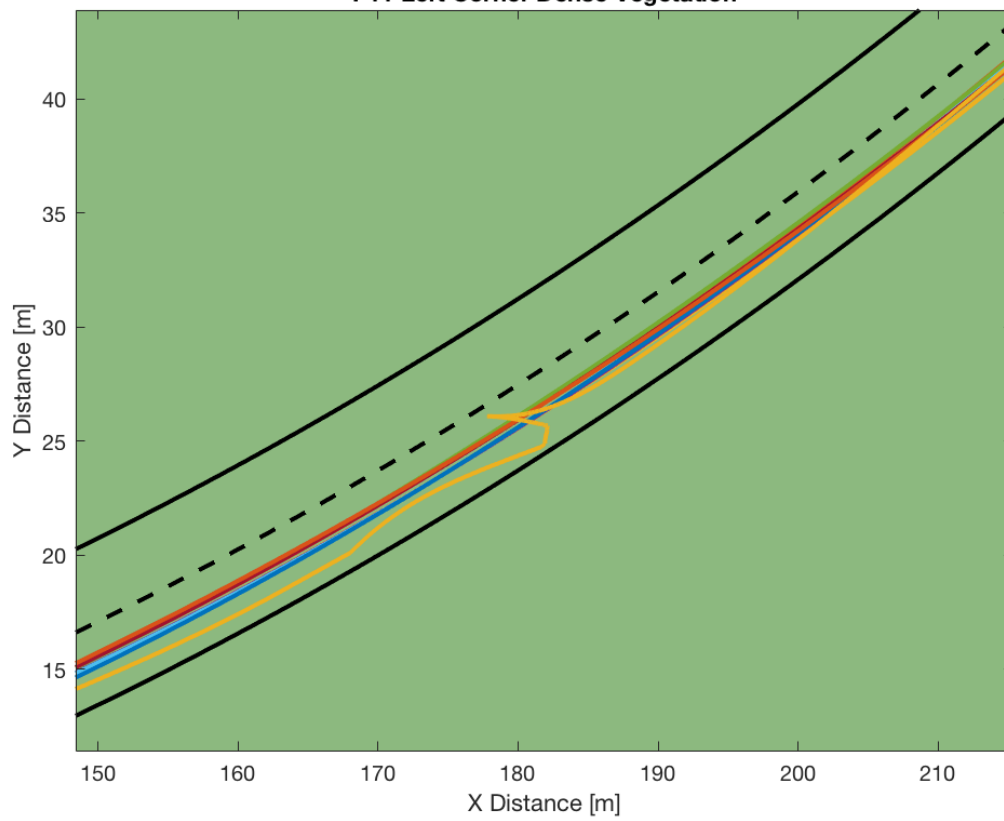




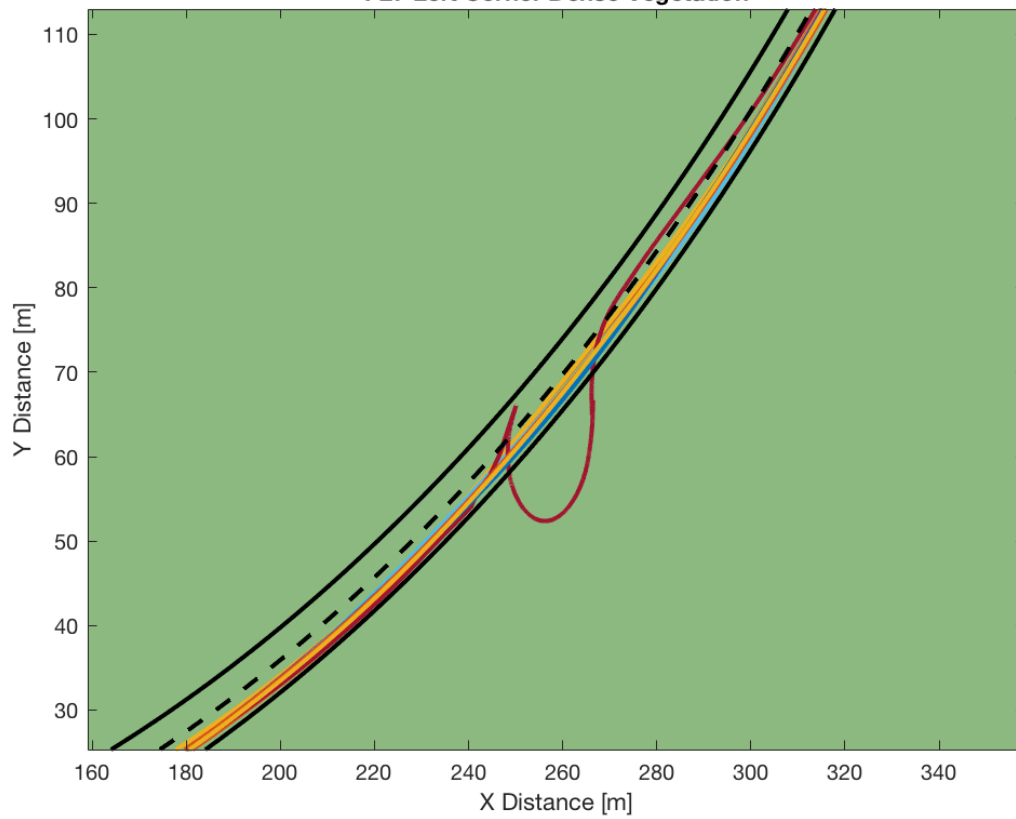




P11 Left Corner Dense Vegetation



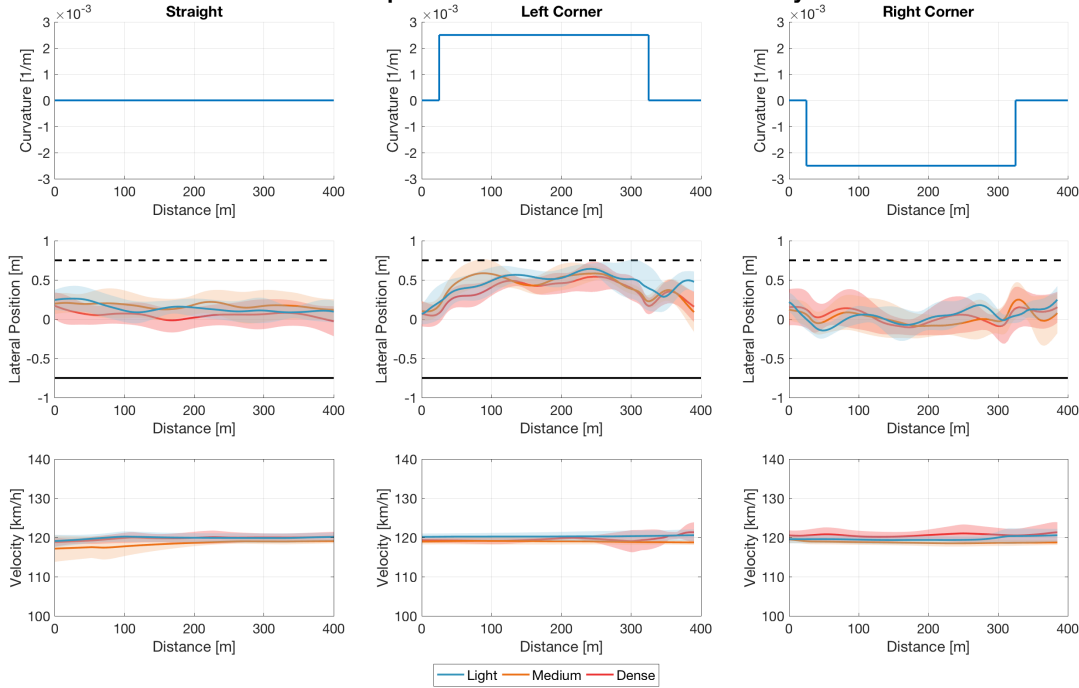
P27 Left Corner Dense Vegetation



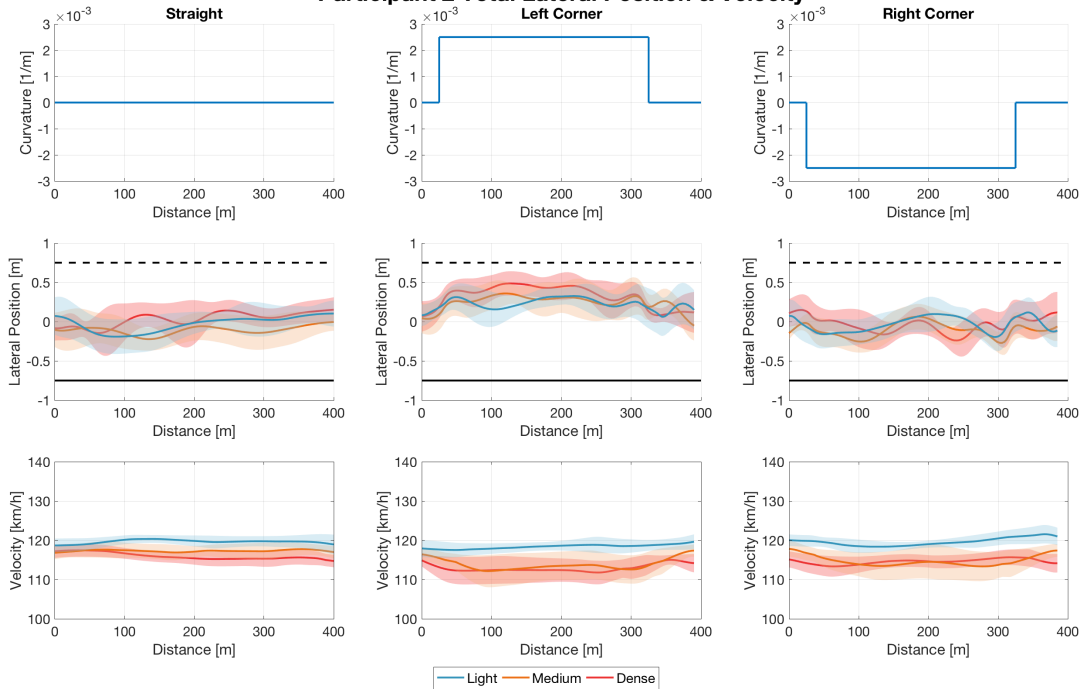
D.8. Individual Results

In this section the participants individual 'raw' results are presented. The mean of ~ 9 individual datasets is shown (depends on whether there had been a crash) and 2 times the standard deviation (2σ) in a shaded area. The road layout represents the effective lane width in the lateral position plots. Note that participant 23 is absent because this person did not want to go through with the experiment after the training session.

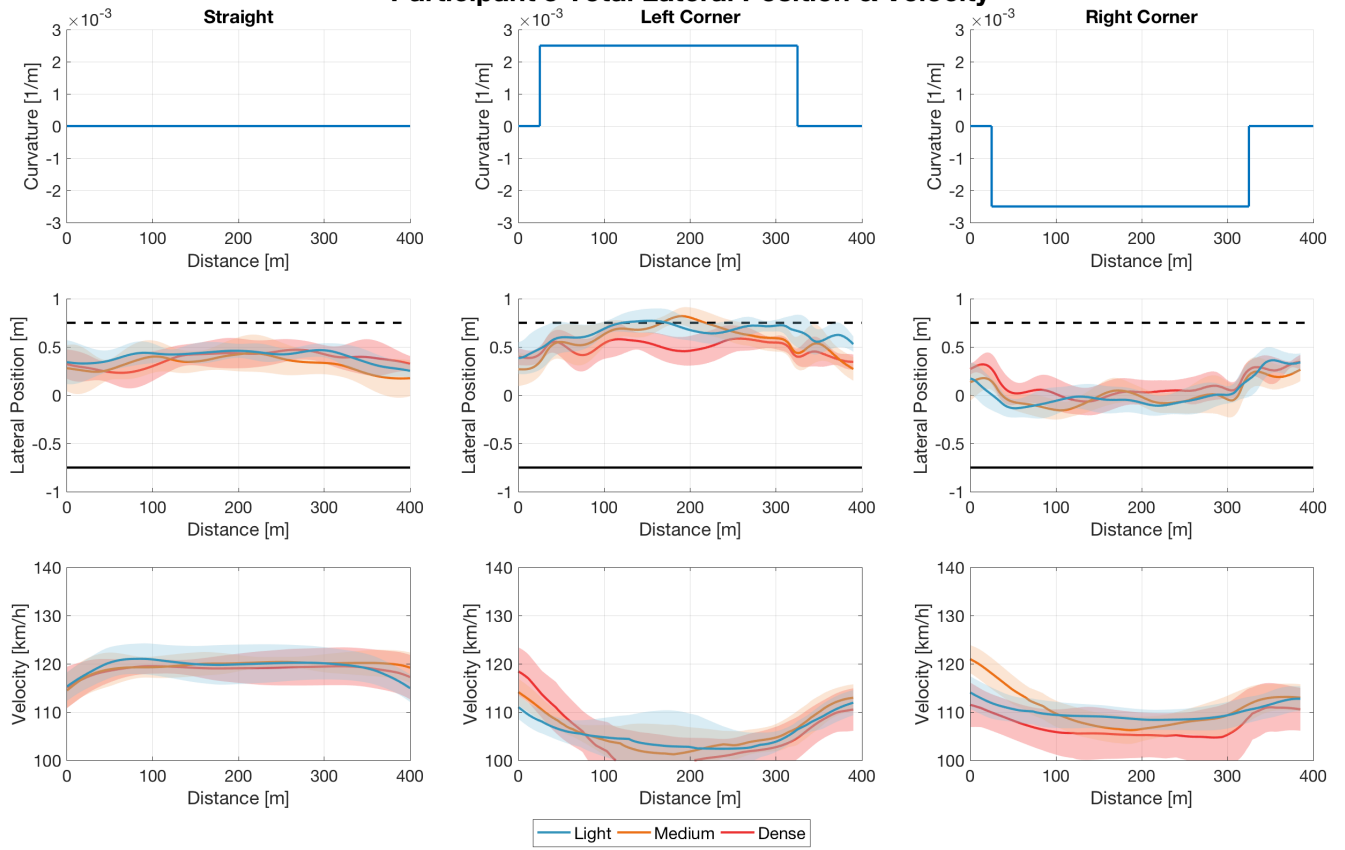
Participant 1 Total Lateral Position & Velocity



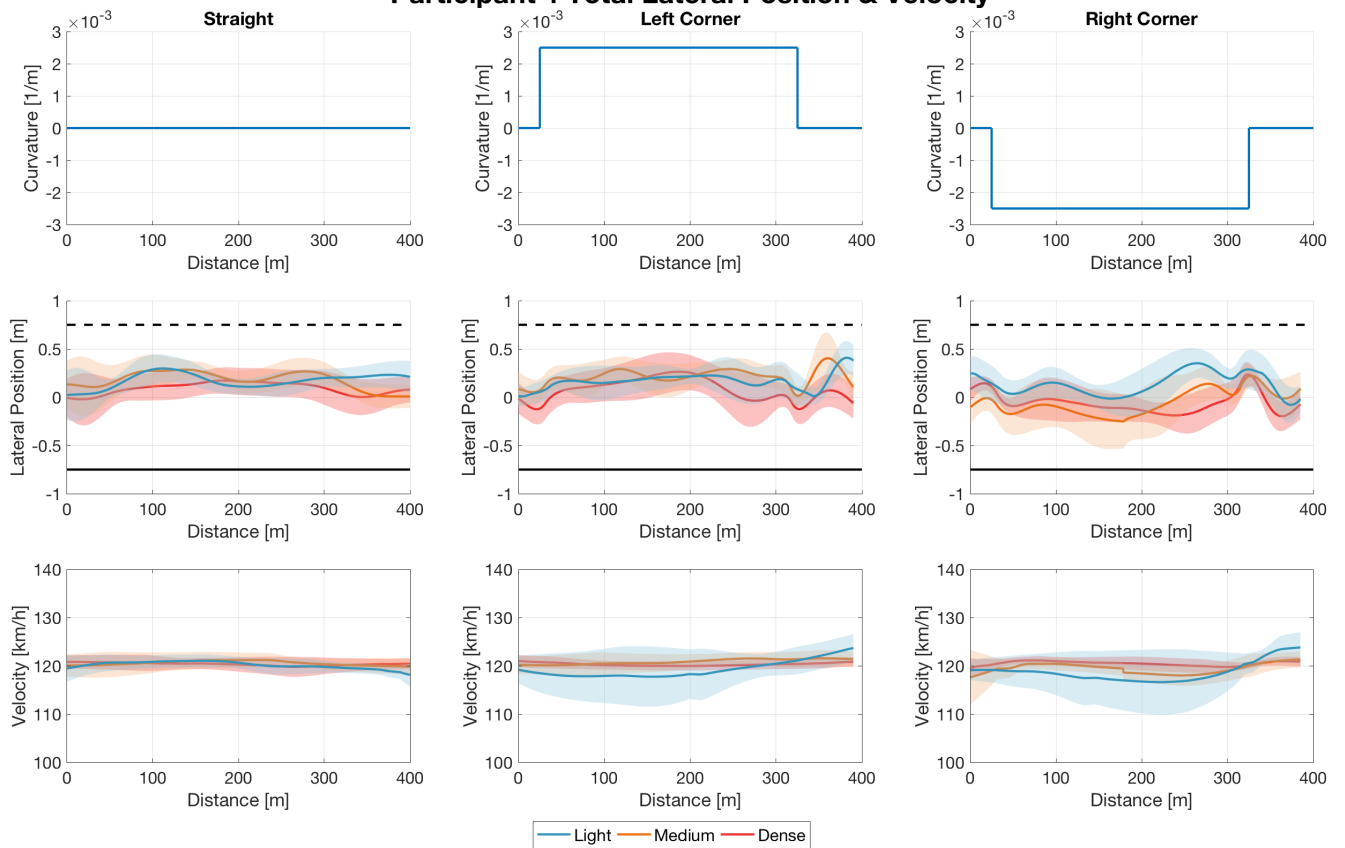
Participant 2 Total Lateral Position & Velocity



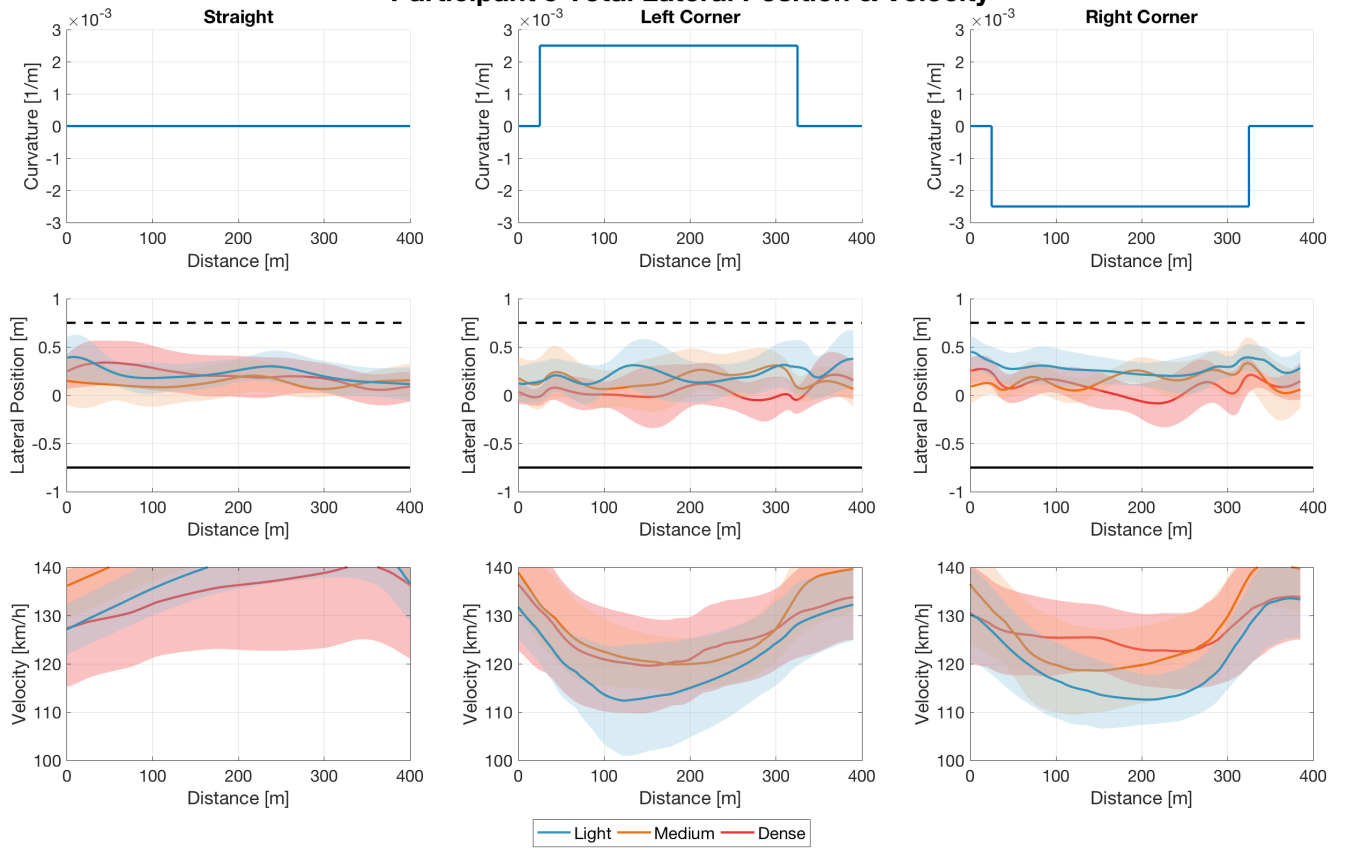
Participant 3 Total Lateral Position & Velocity



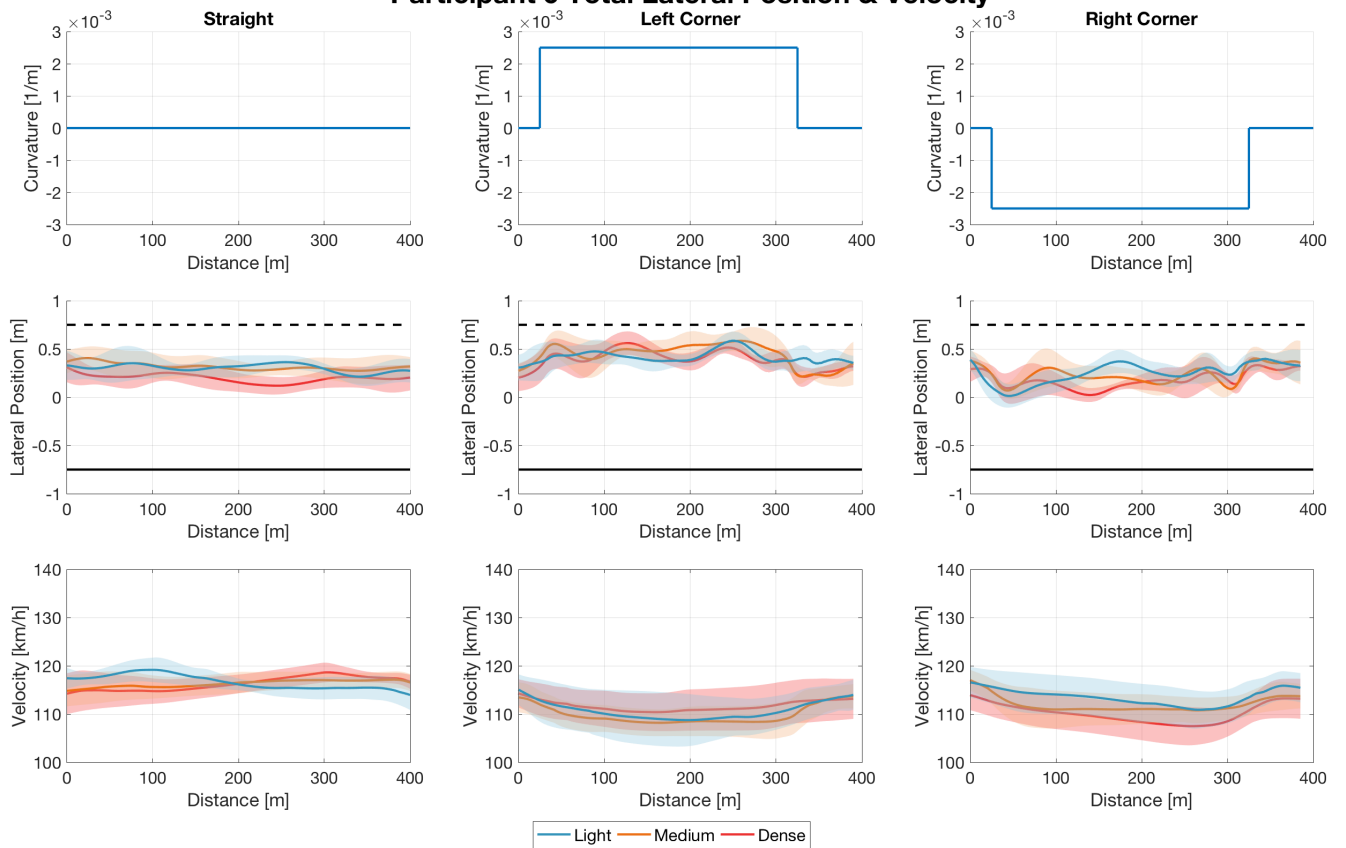
Participant 4 Total Lateral Position & Velocity



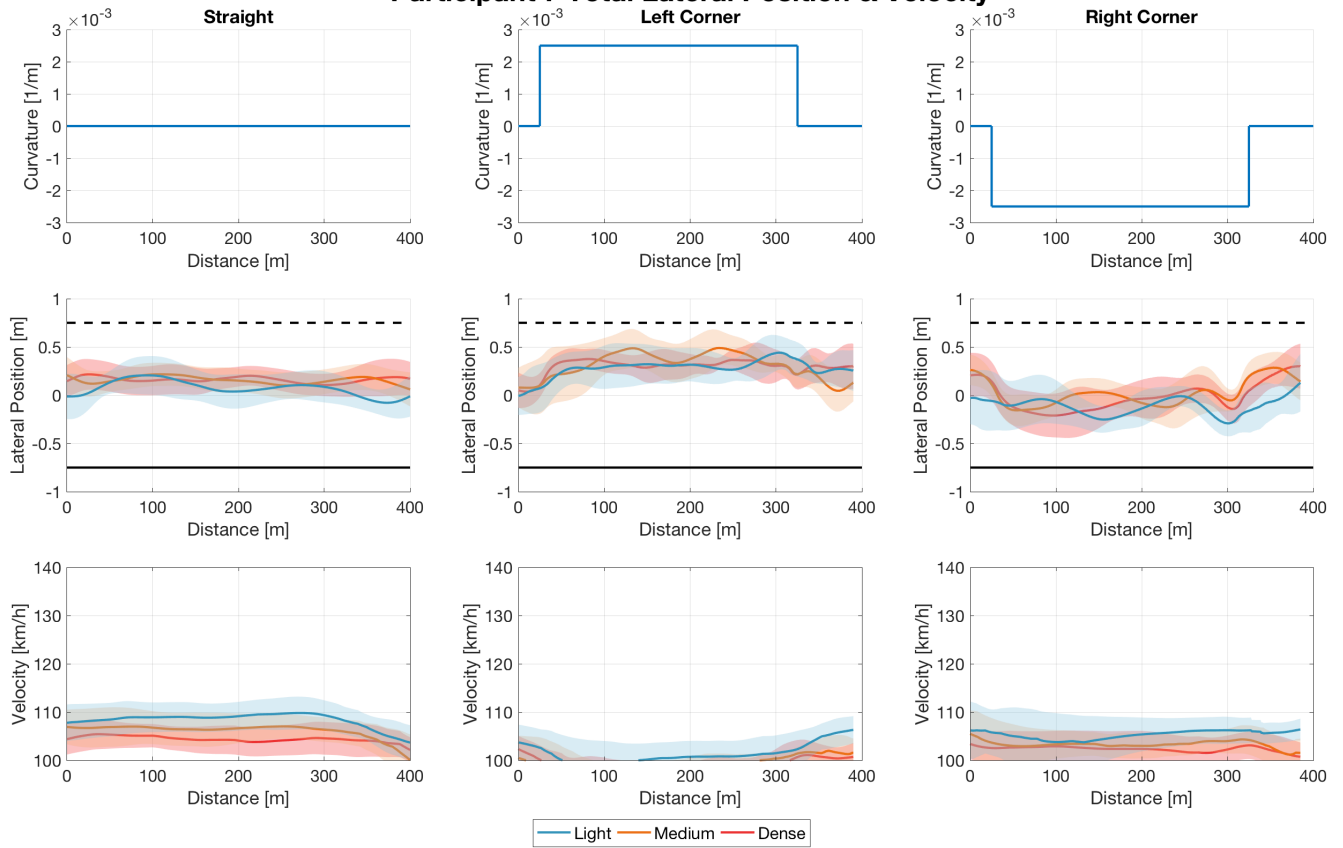
Participant 5 Total Lateral Position & Velocity



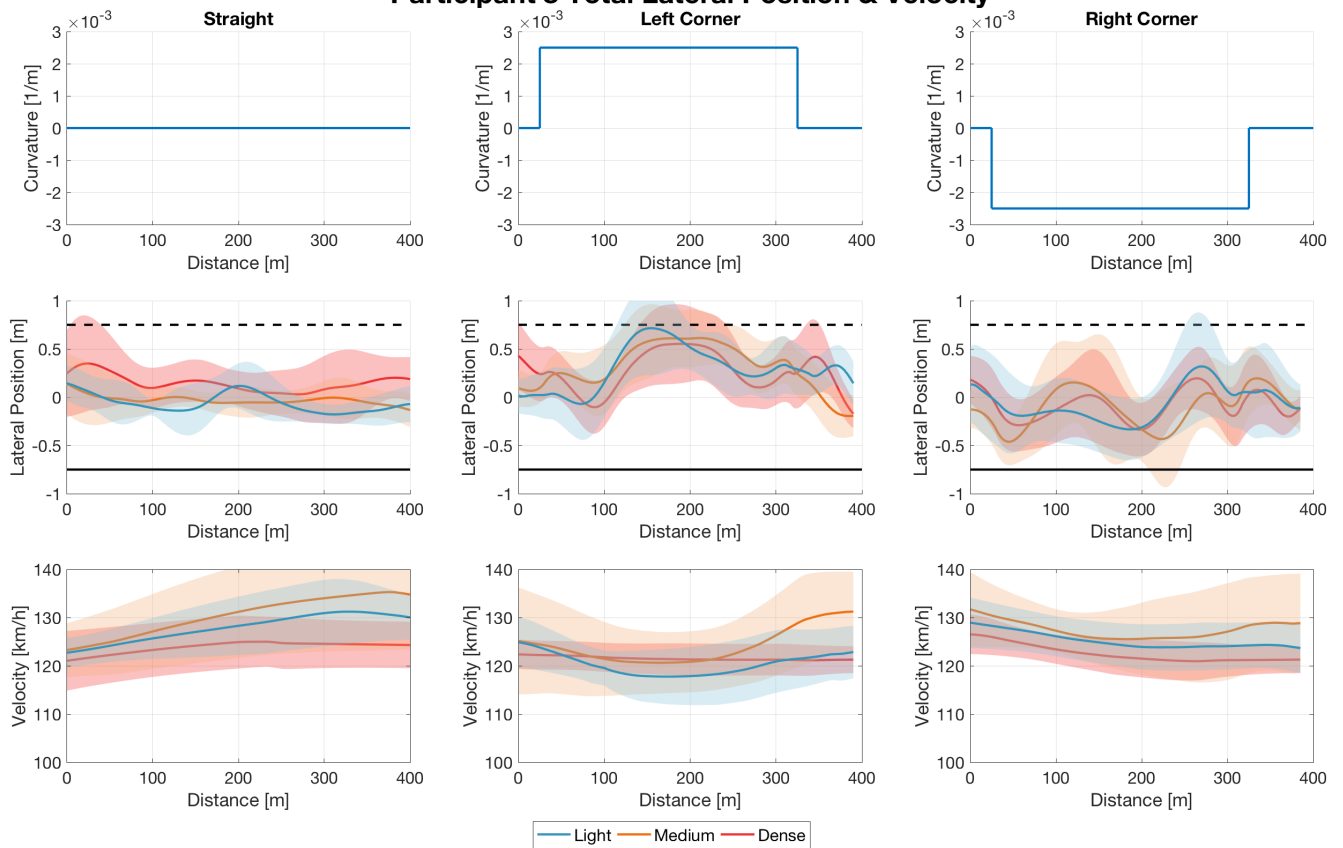
Participant 6 Total Lateral Position & Velocity



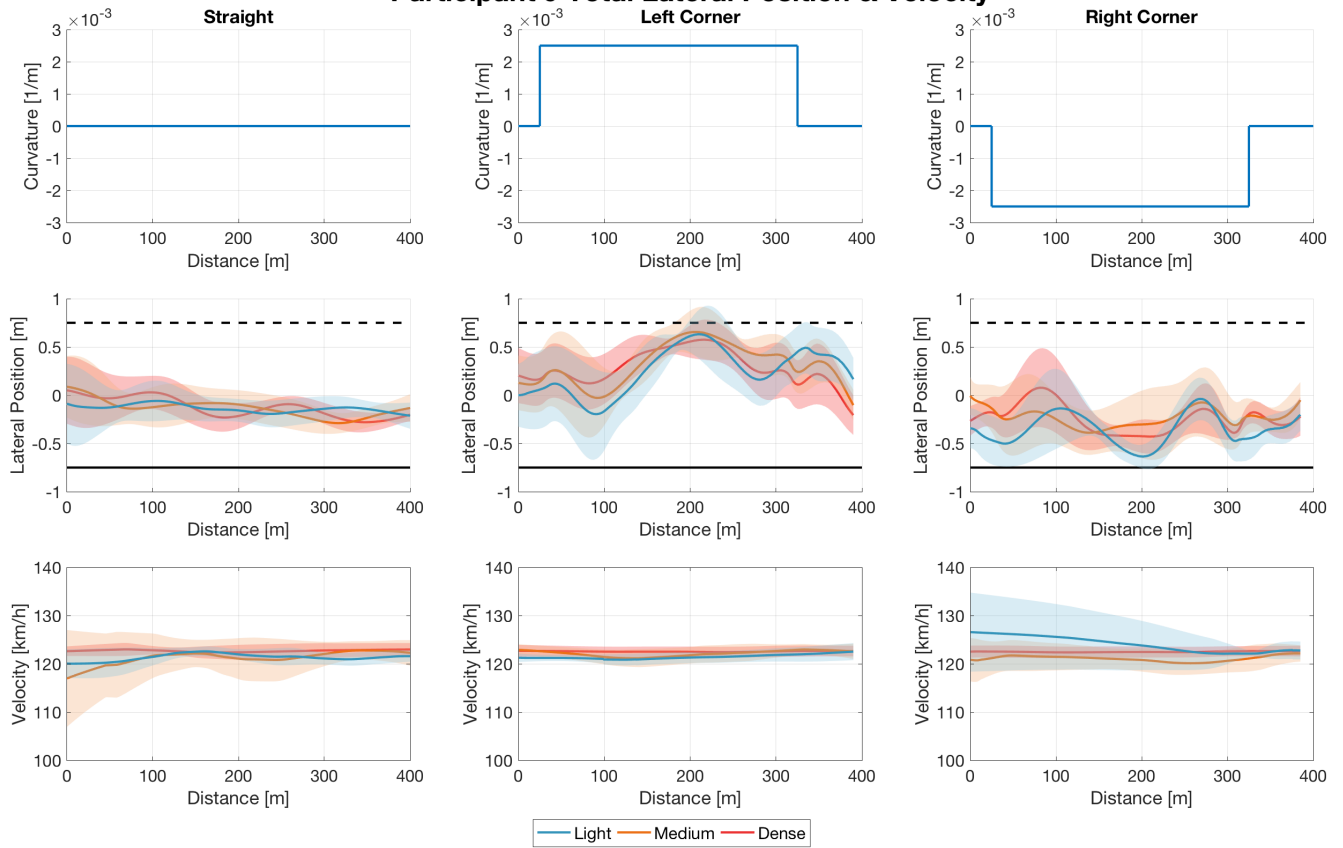
Participant 7 Total Lateral Position & Velocity



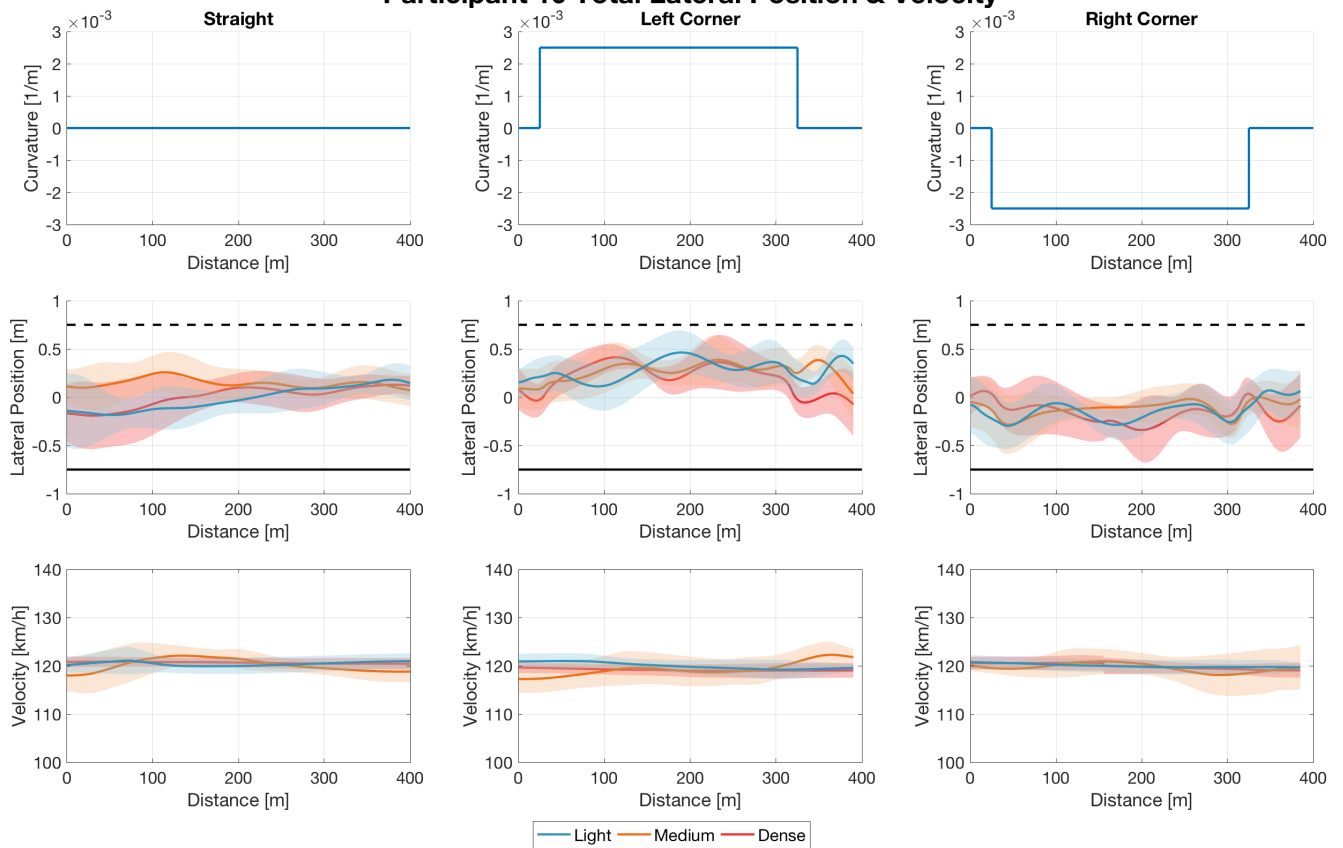
Participant 8 Total Lateral Position & Velocity



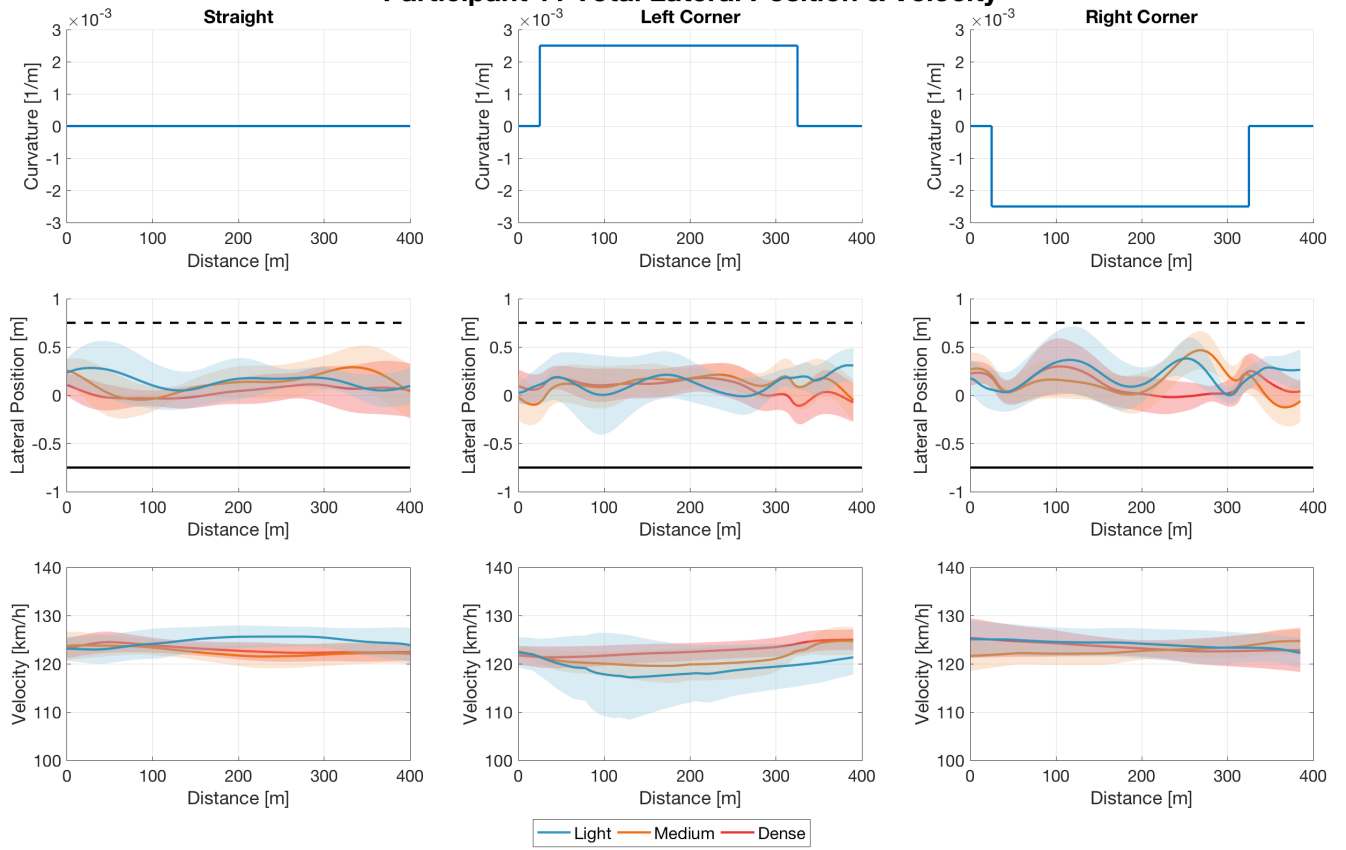
Participant 9 Total Lateral Position & Velocity



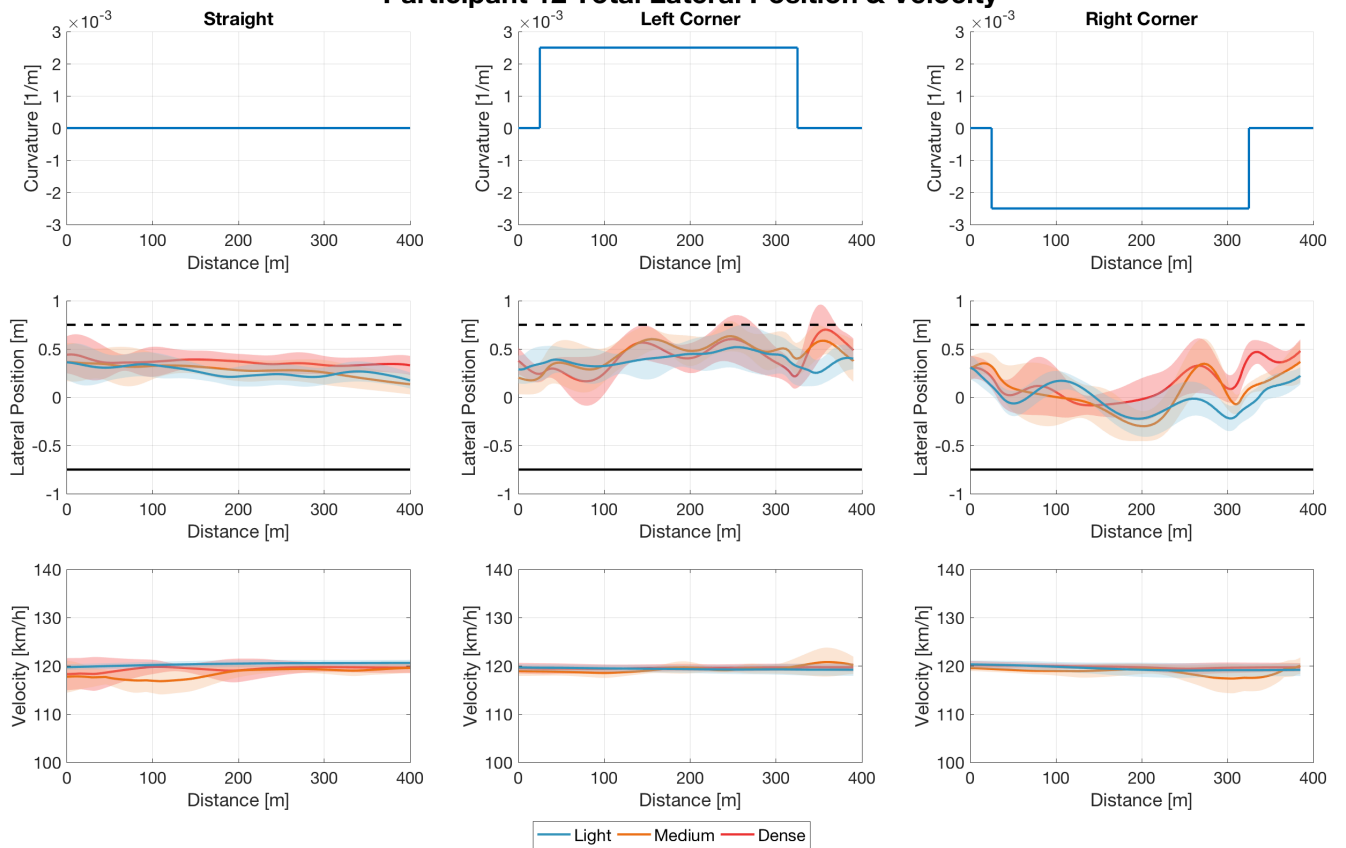
Participant 10 Total Lateral Position & Velocity



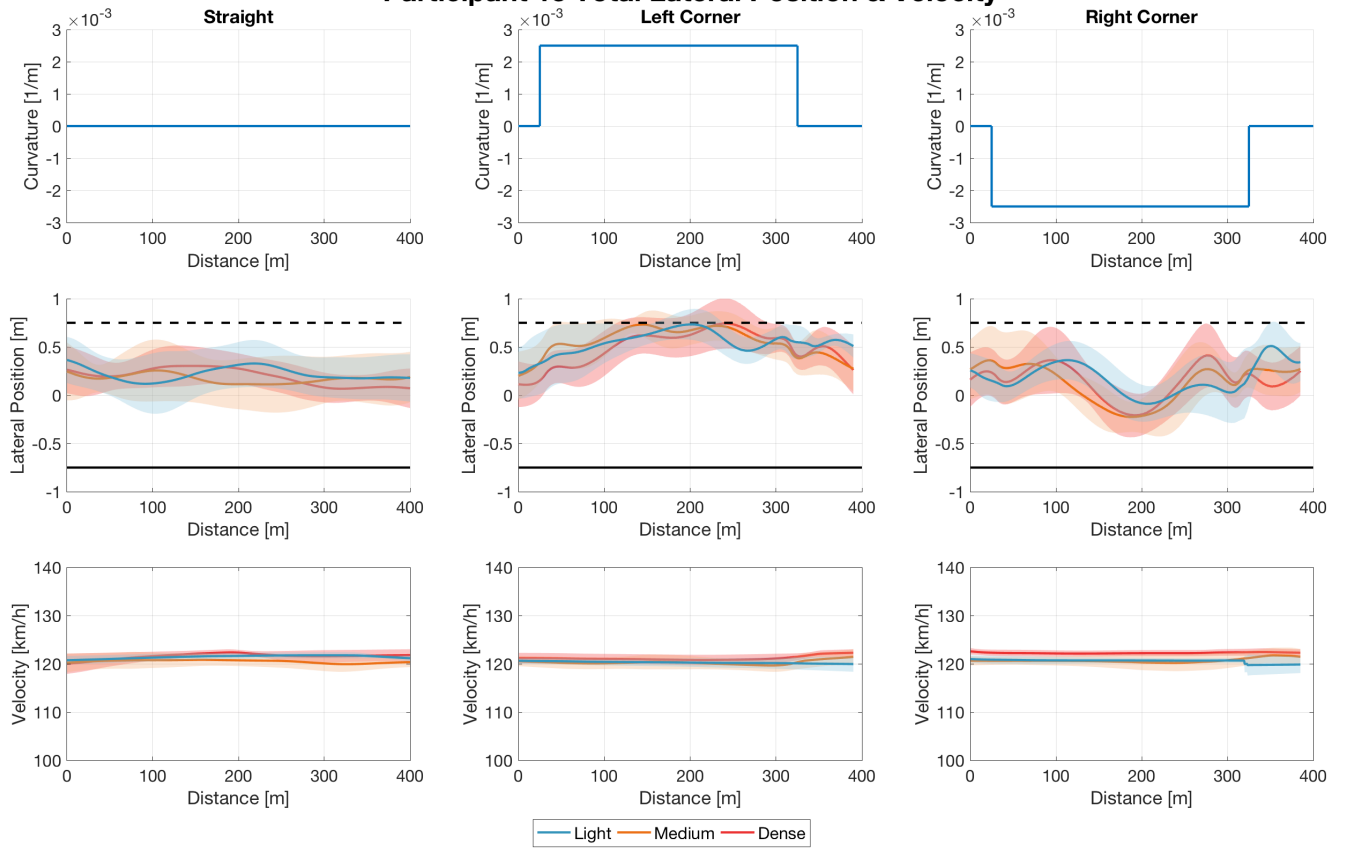
Participant 11 Total Lateral Position & Velocity



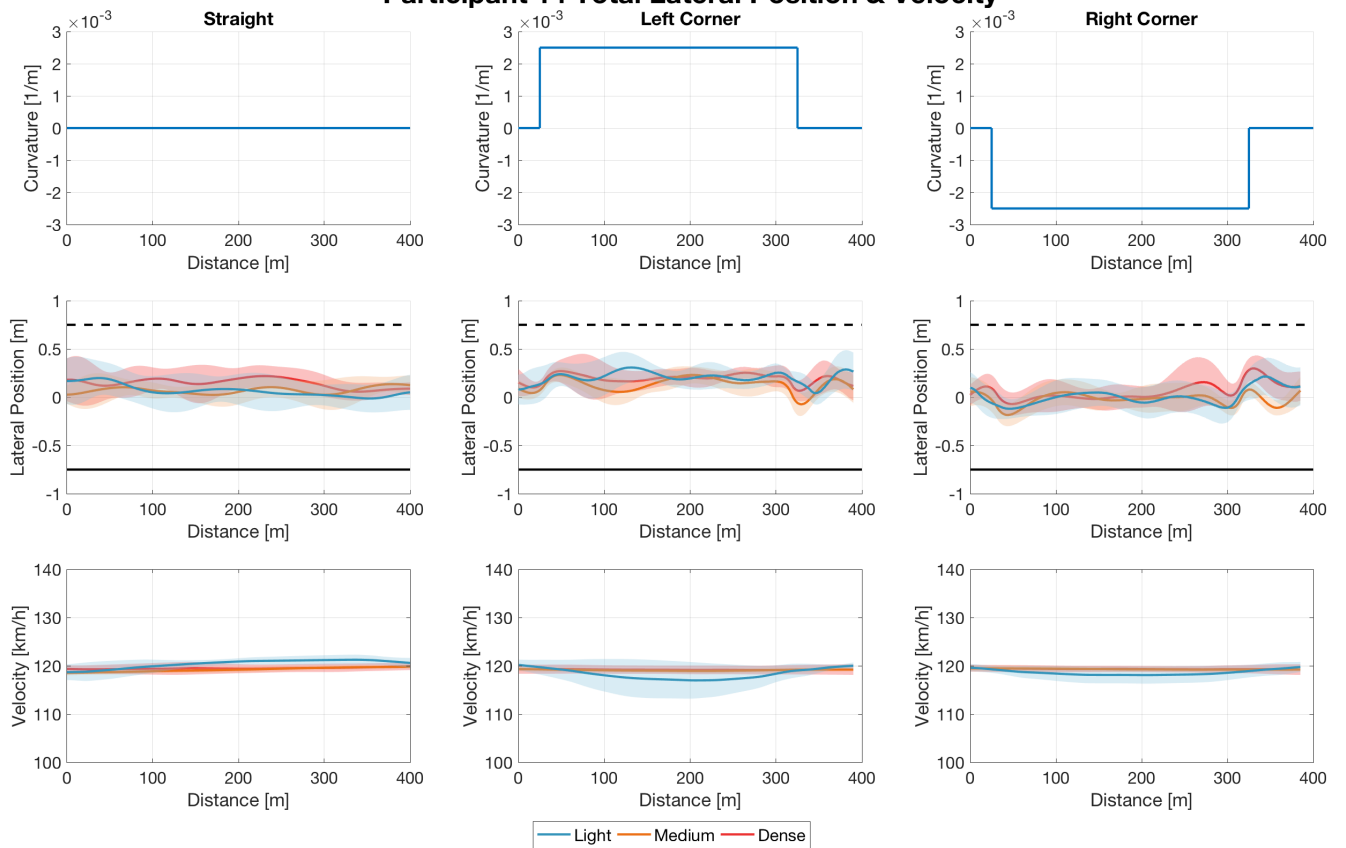
Participant 12 Total Lateral Position & Velocity



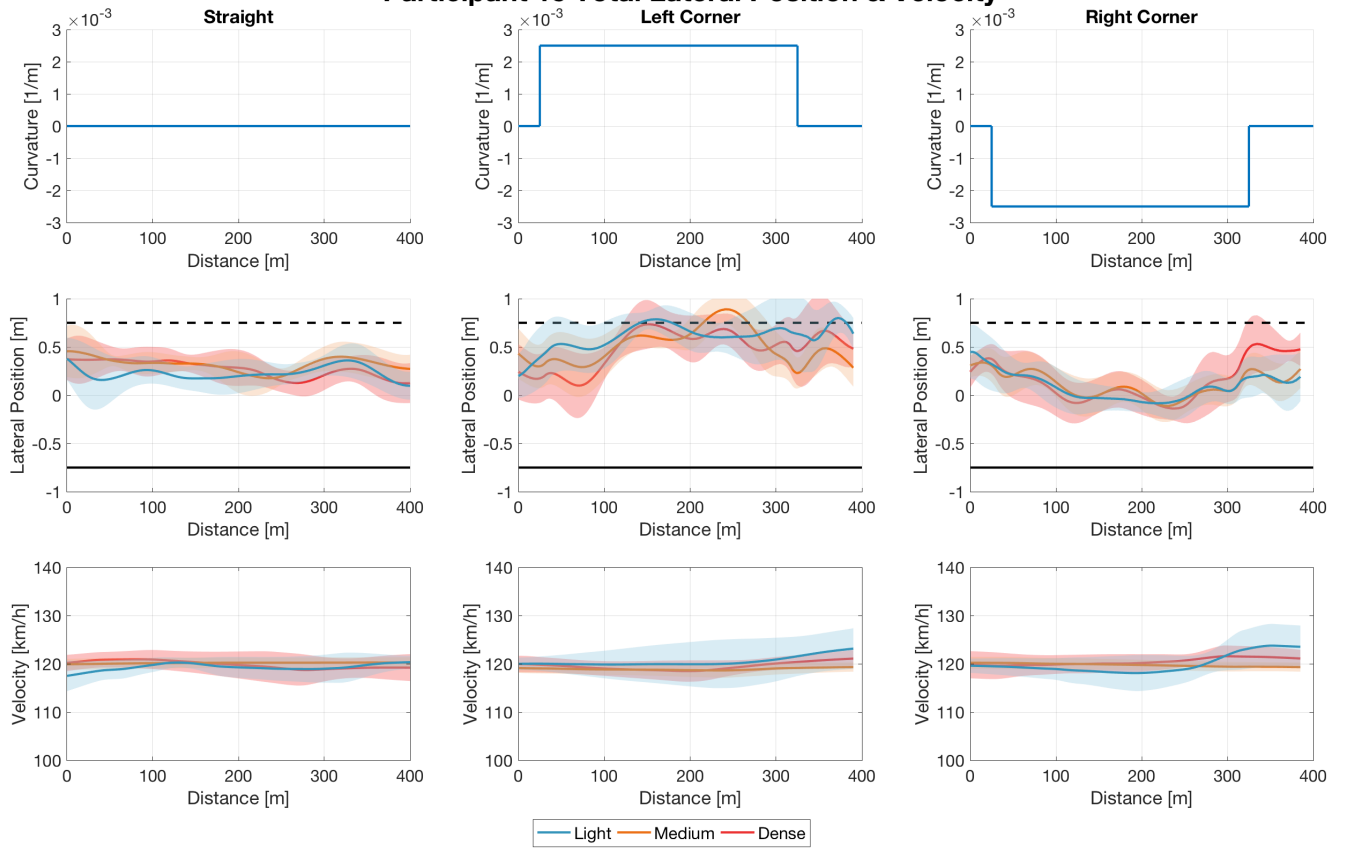
Participant 13 Total Lateral Position & Velocity



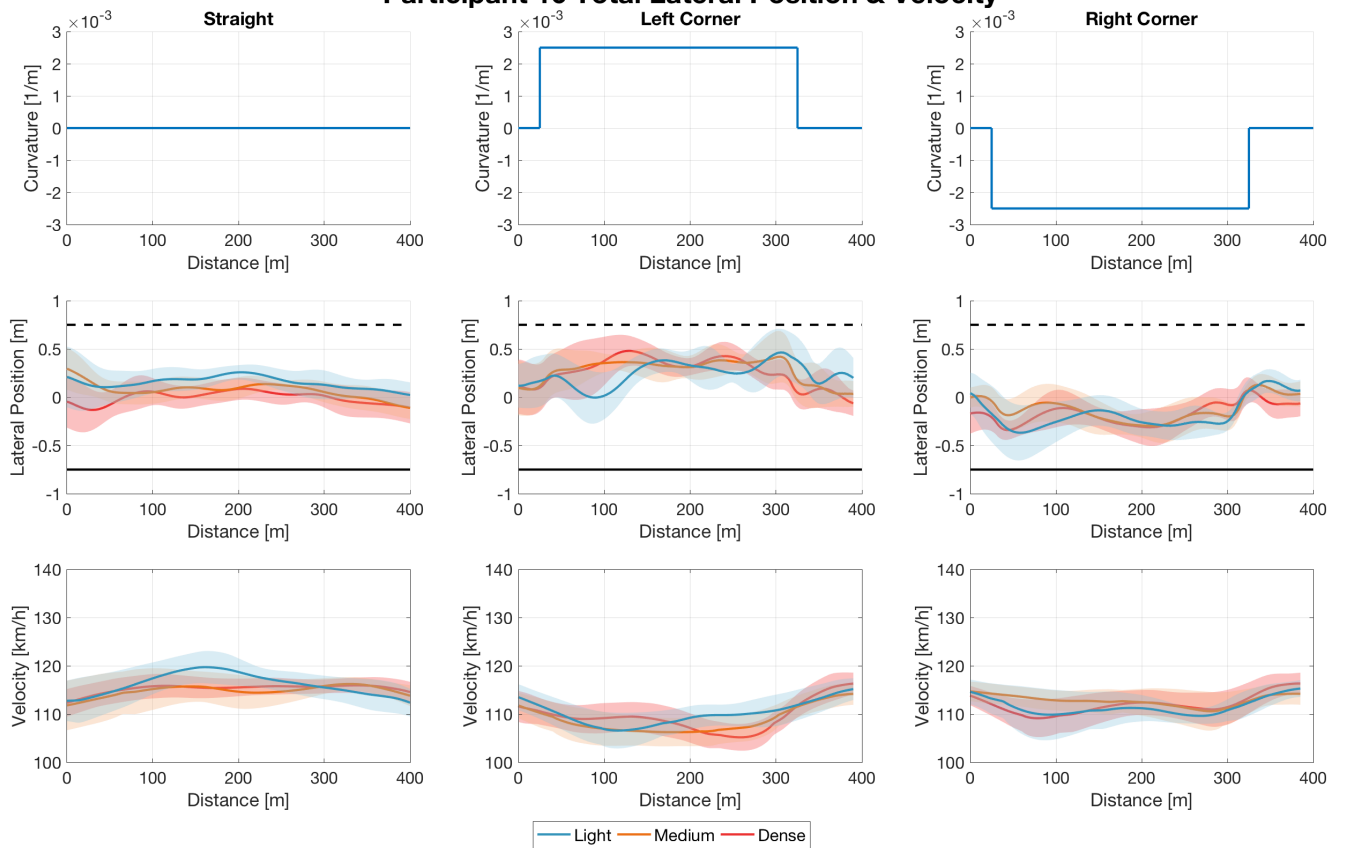
Participant 14 Total Lateral Position & Velocity



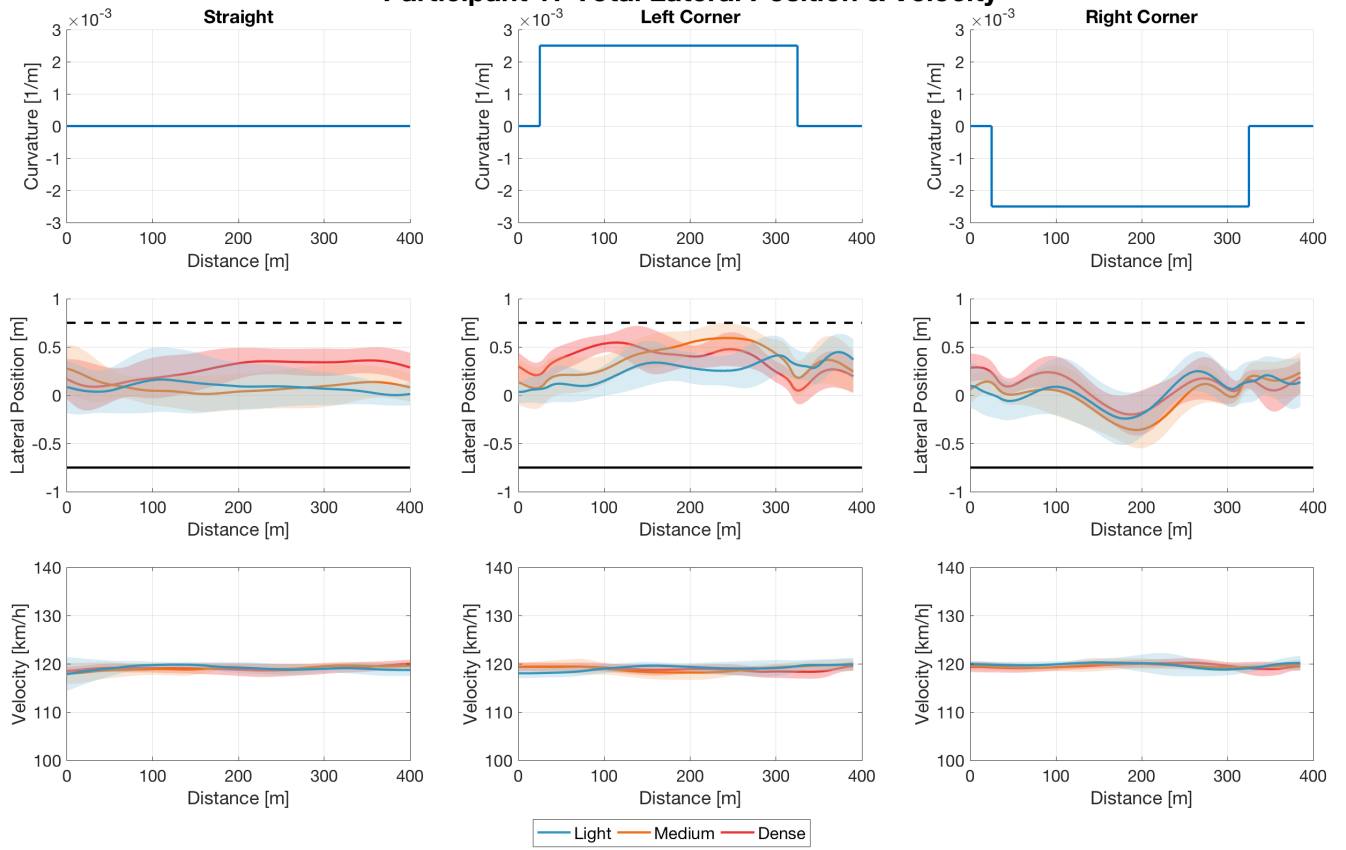
Participant 15 Total Lateral Position & Velocity



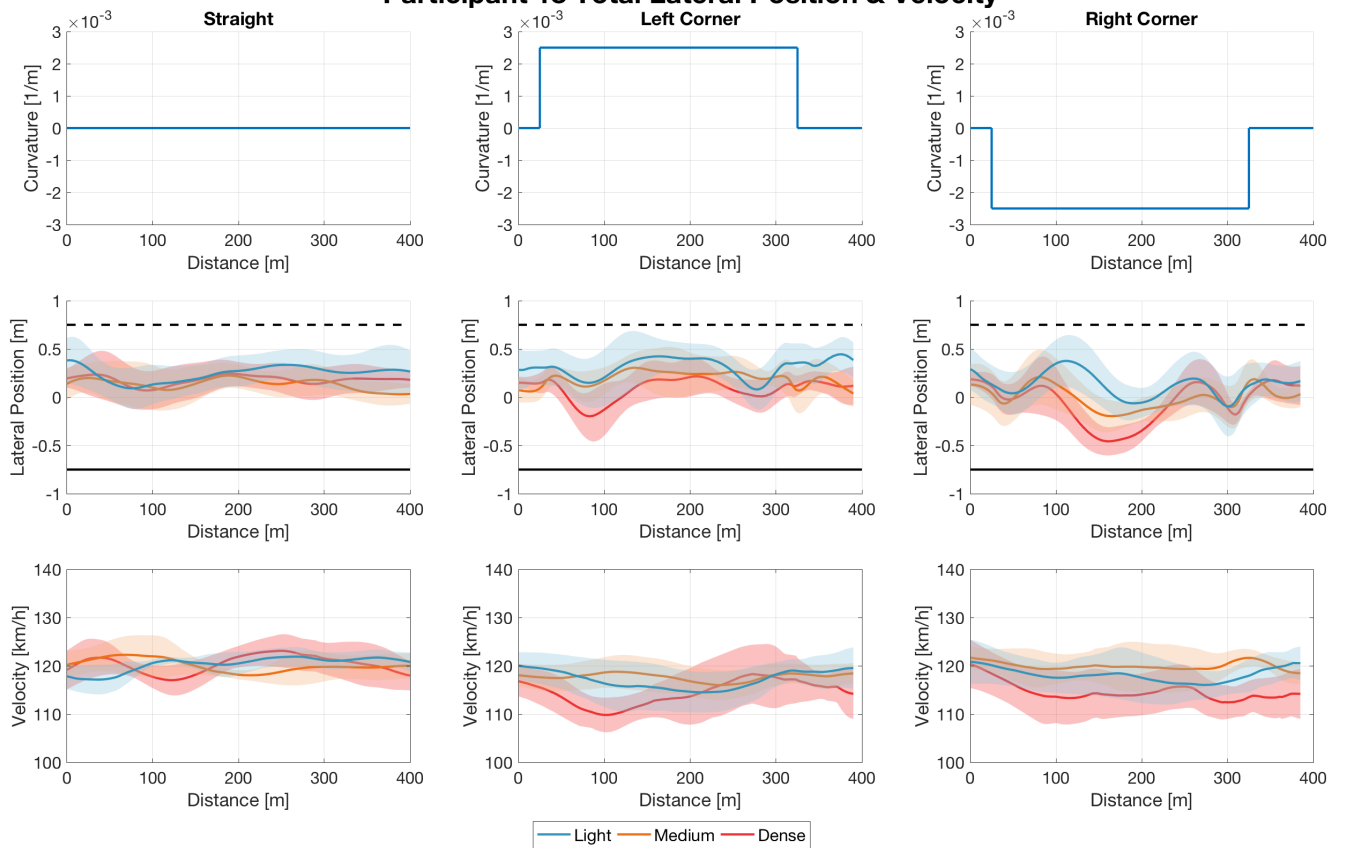
Participant 16 Total Lateral Position & Velocity



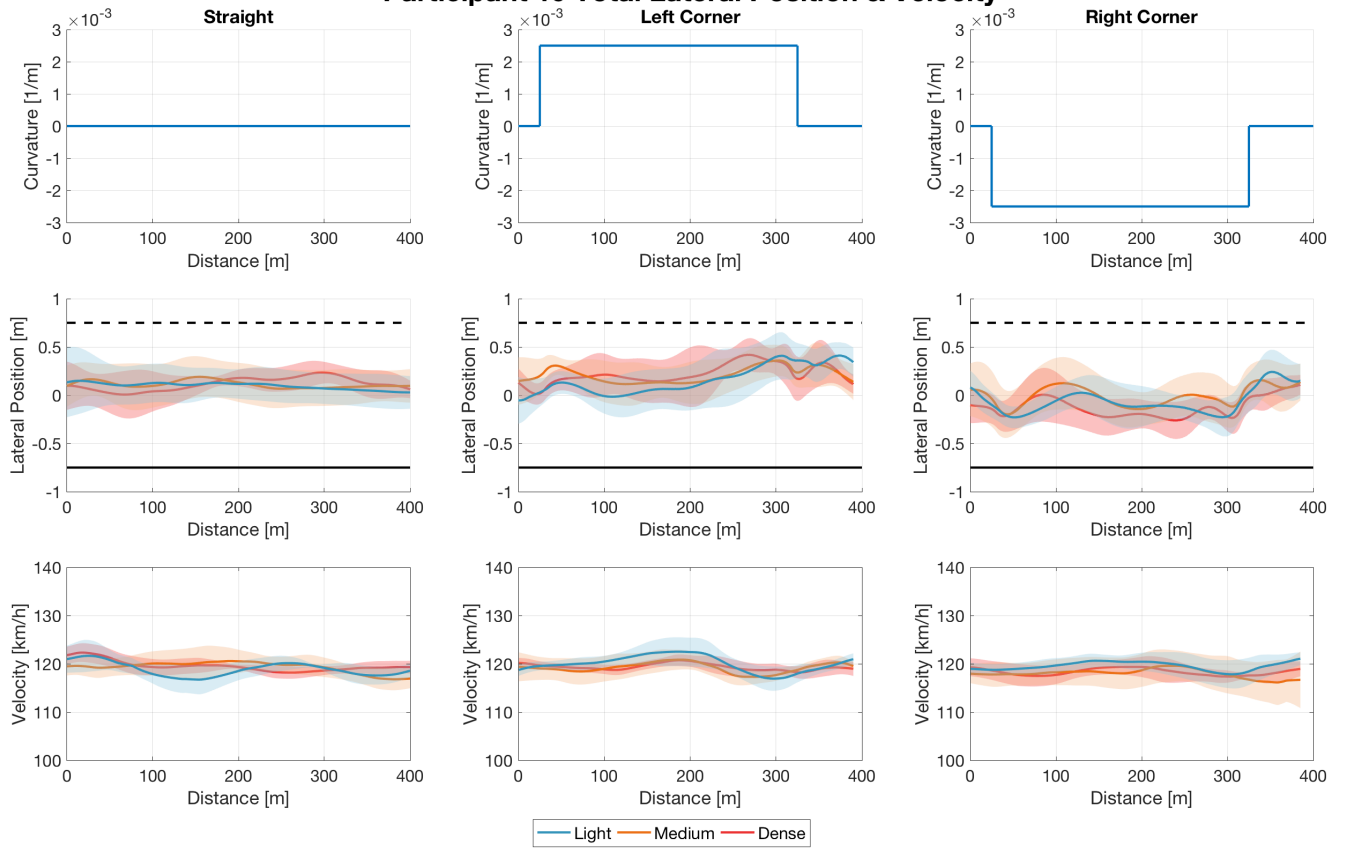
Participant 17 Total Lateral Position & Velocity



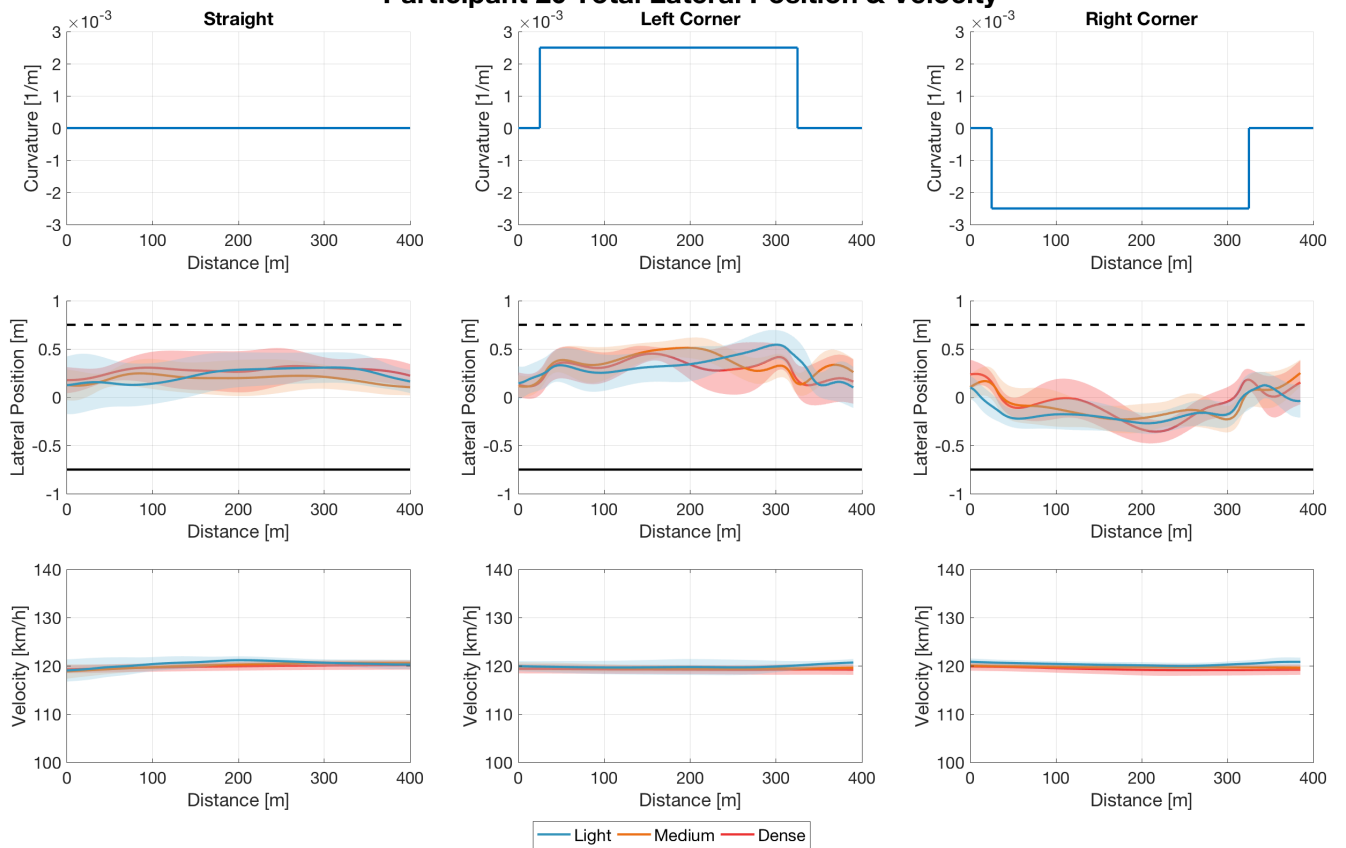
Participant 18 Total Lateral Position & Velocity



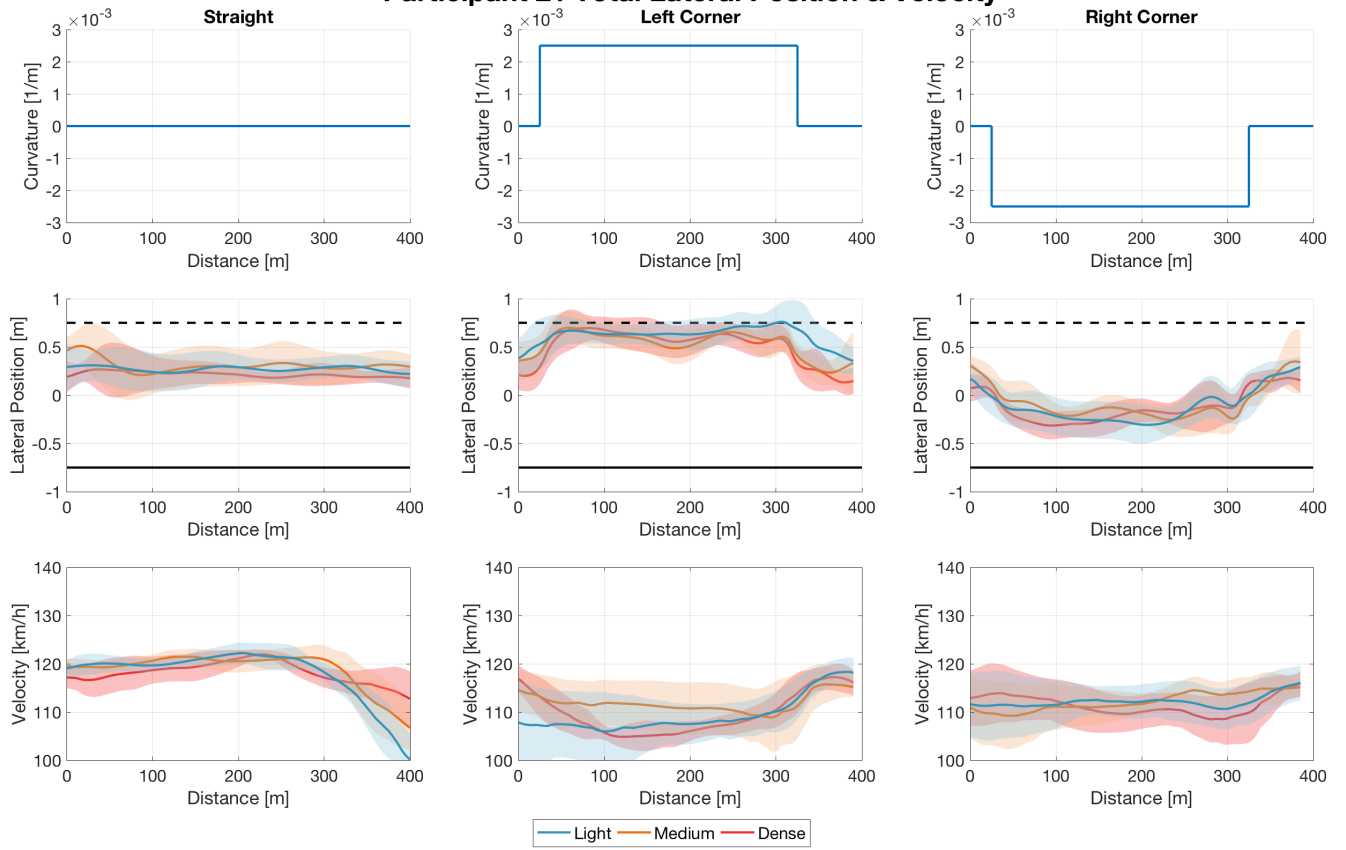
Participant 19 Total Lateral Position & Velocity



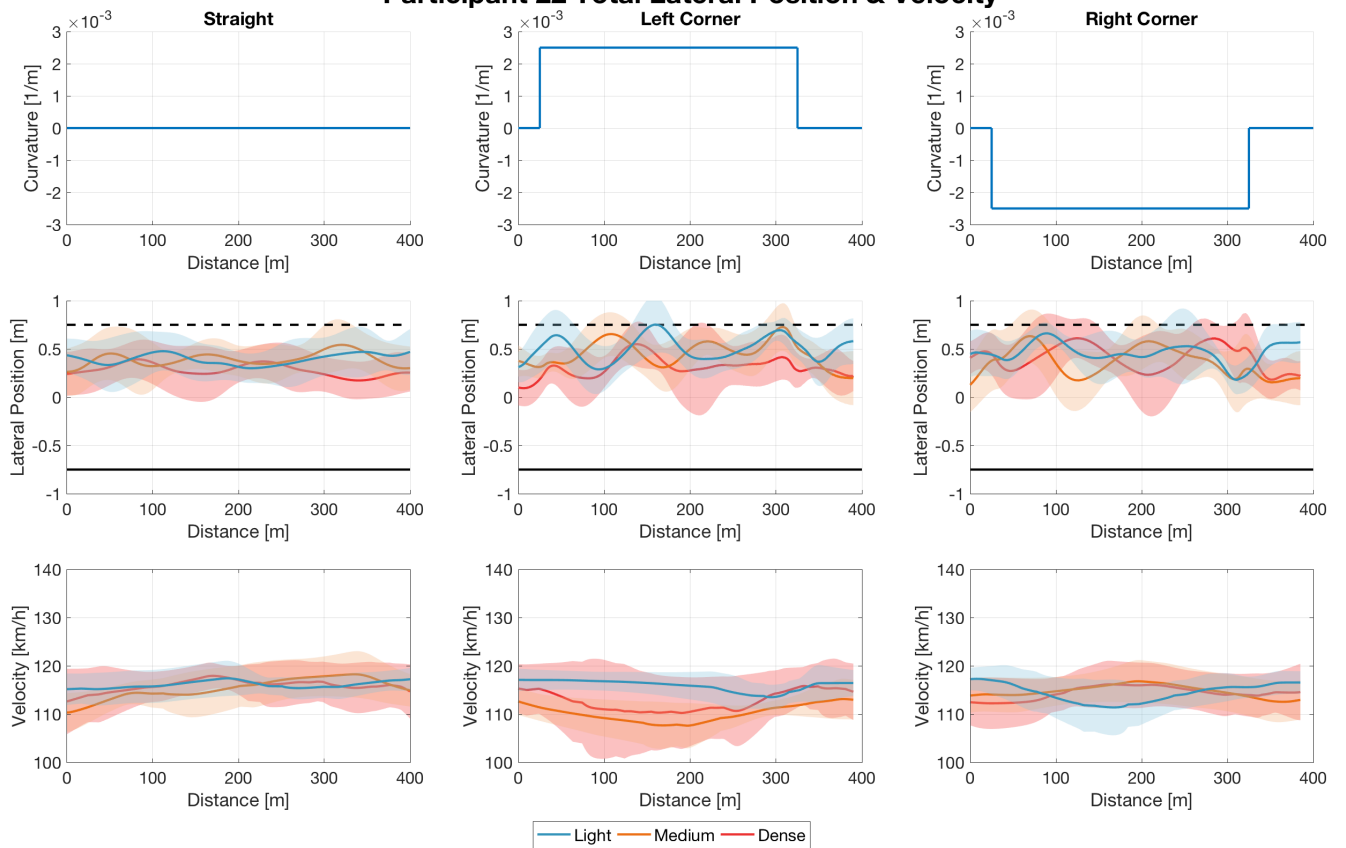
Participant 20 Total Lateral Position & Velocity



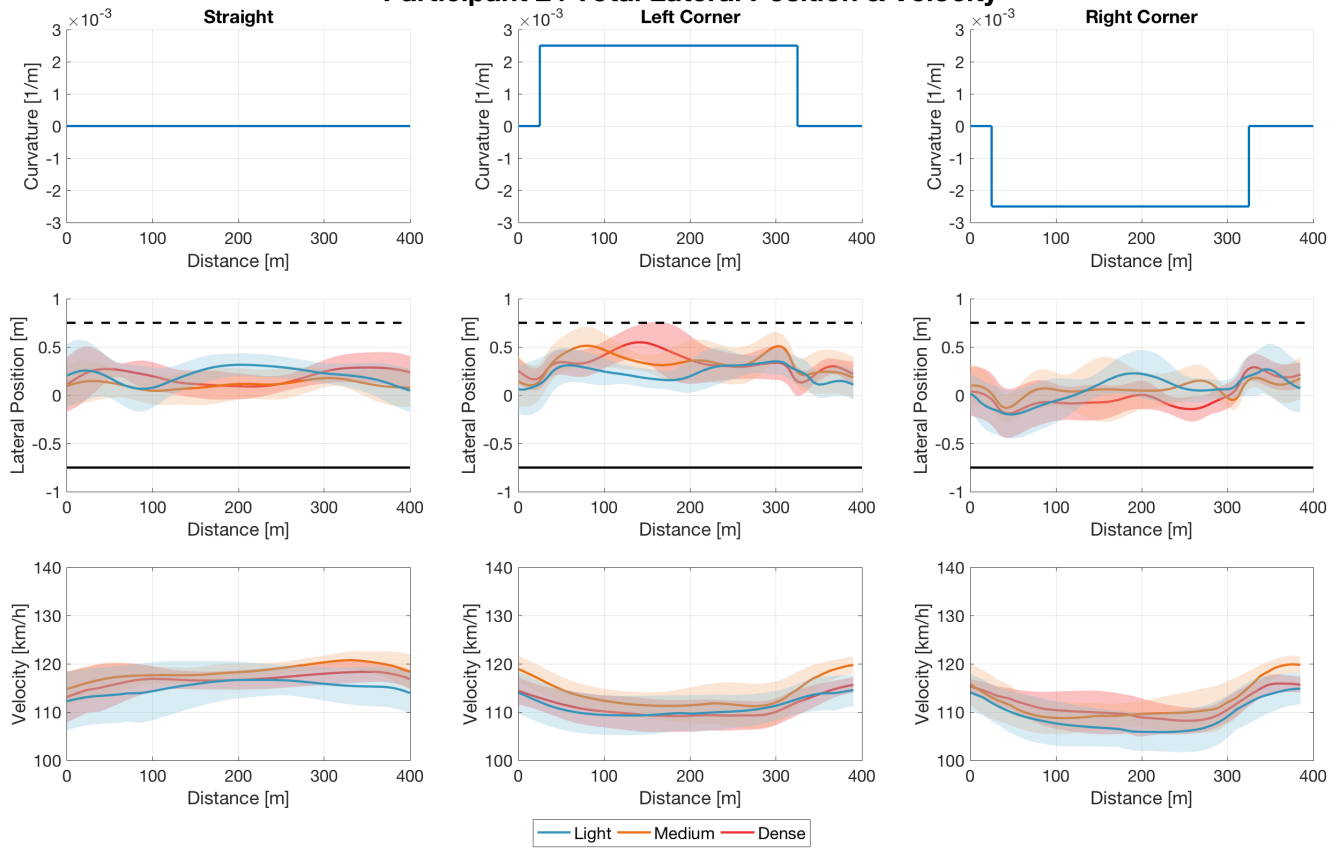
Participant 21 Total Lateral Position & Velocity



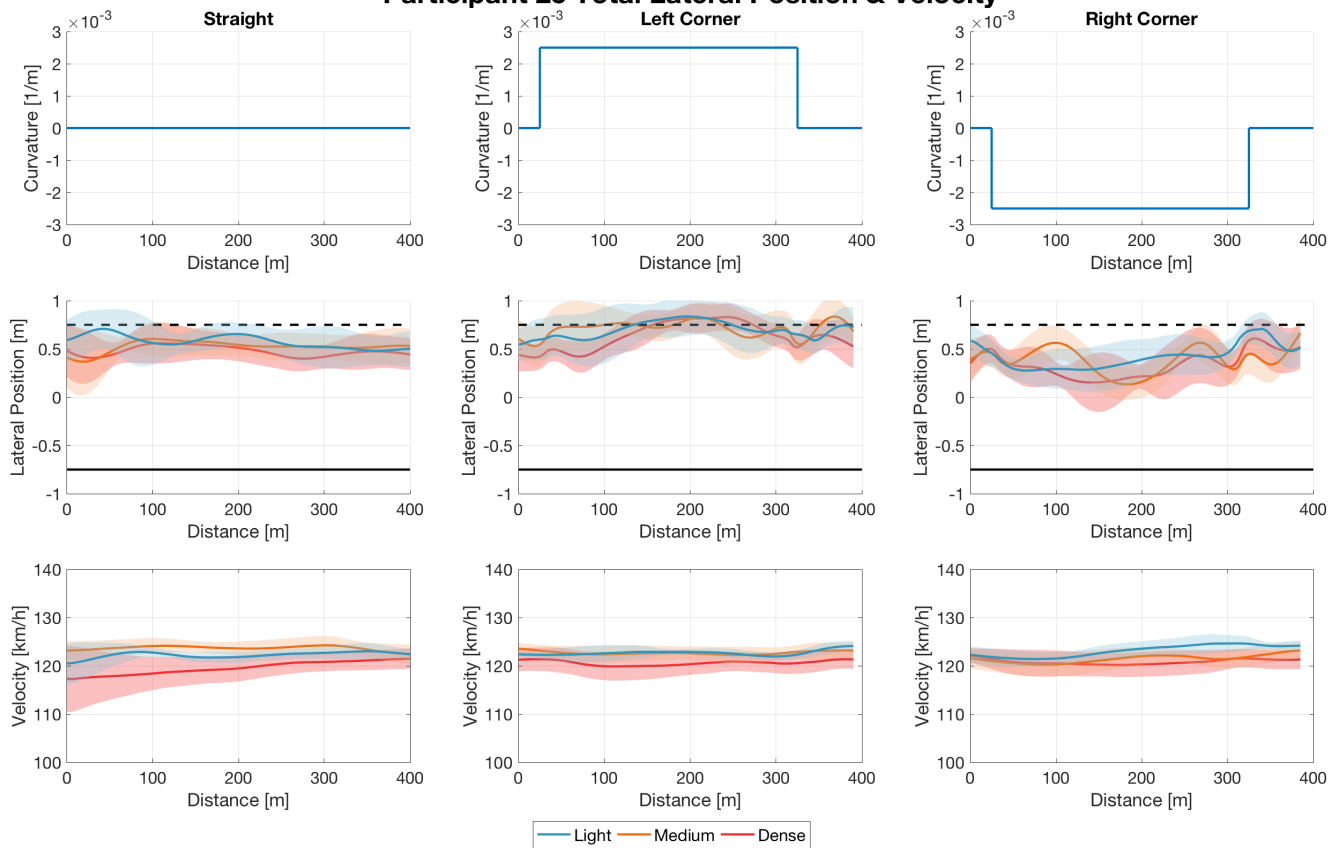
Participant 22 Total Lateral Position & Velocity



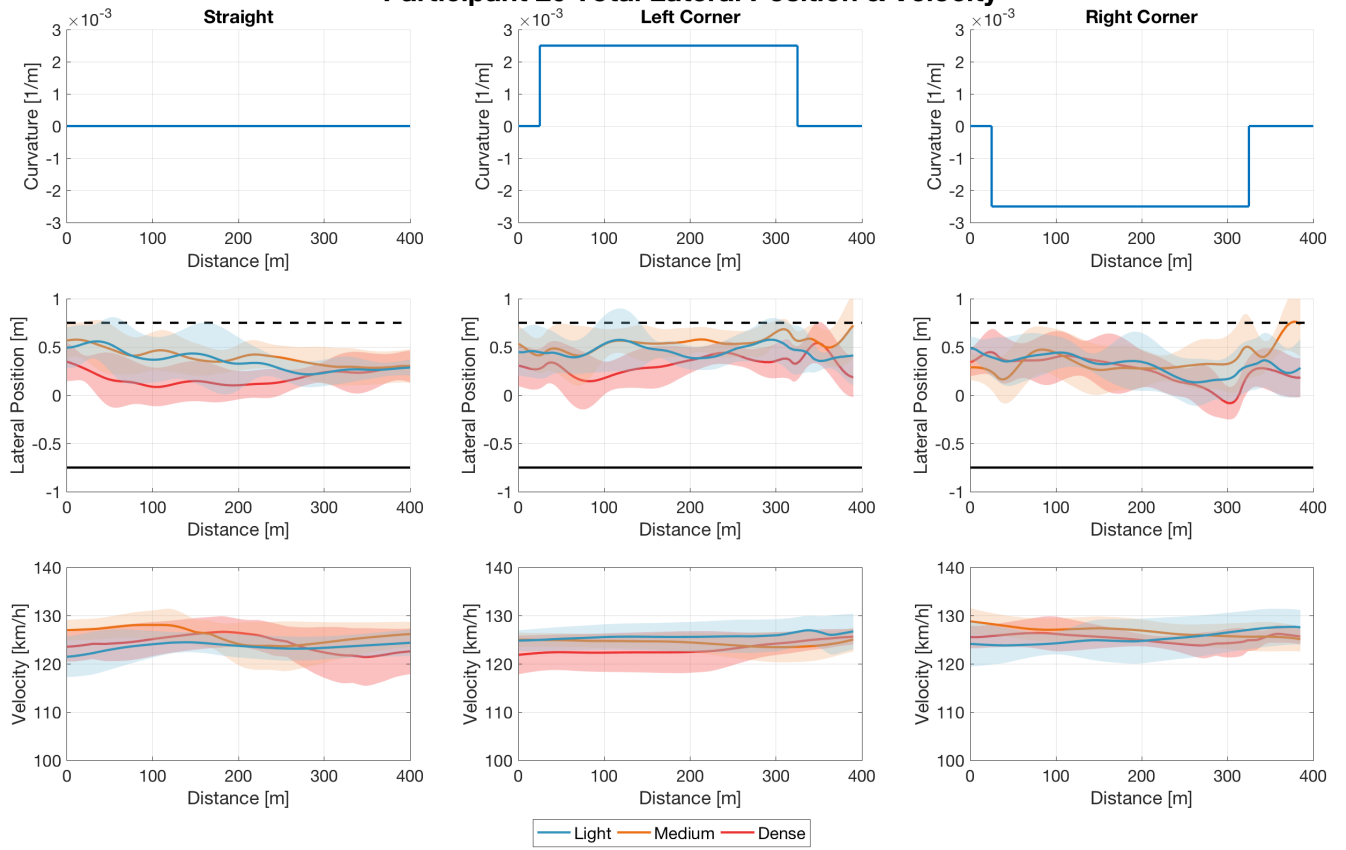
Participant 24 Total Lateral Position & Velocity



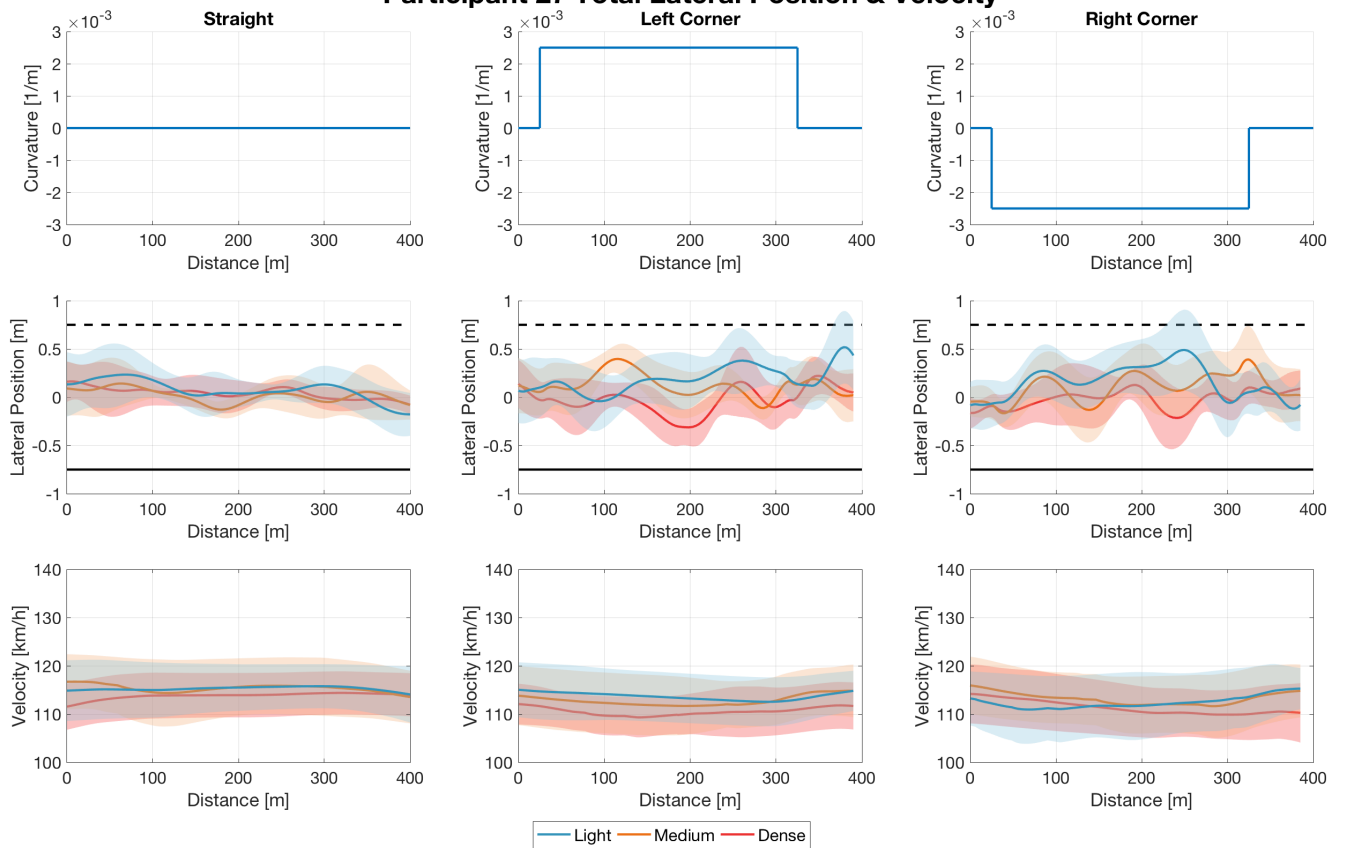
Participant 25 Total Lateral Position & Velocity



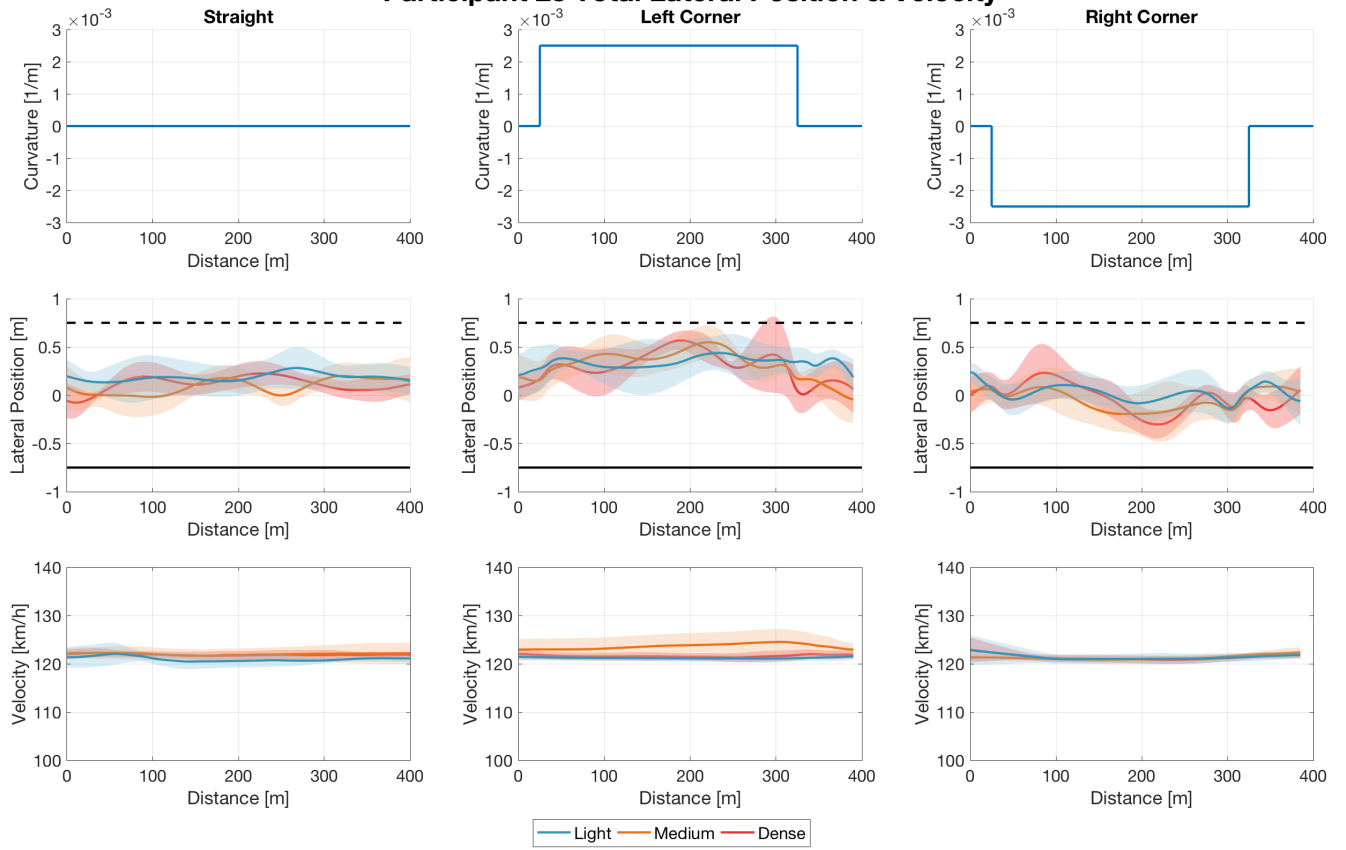
Participant 26 Total Lateral Position & Velocity



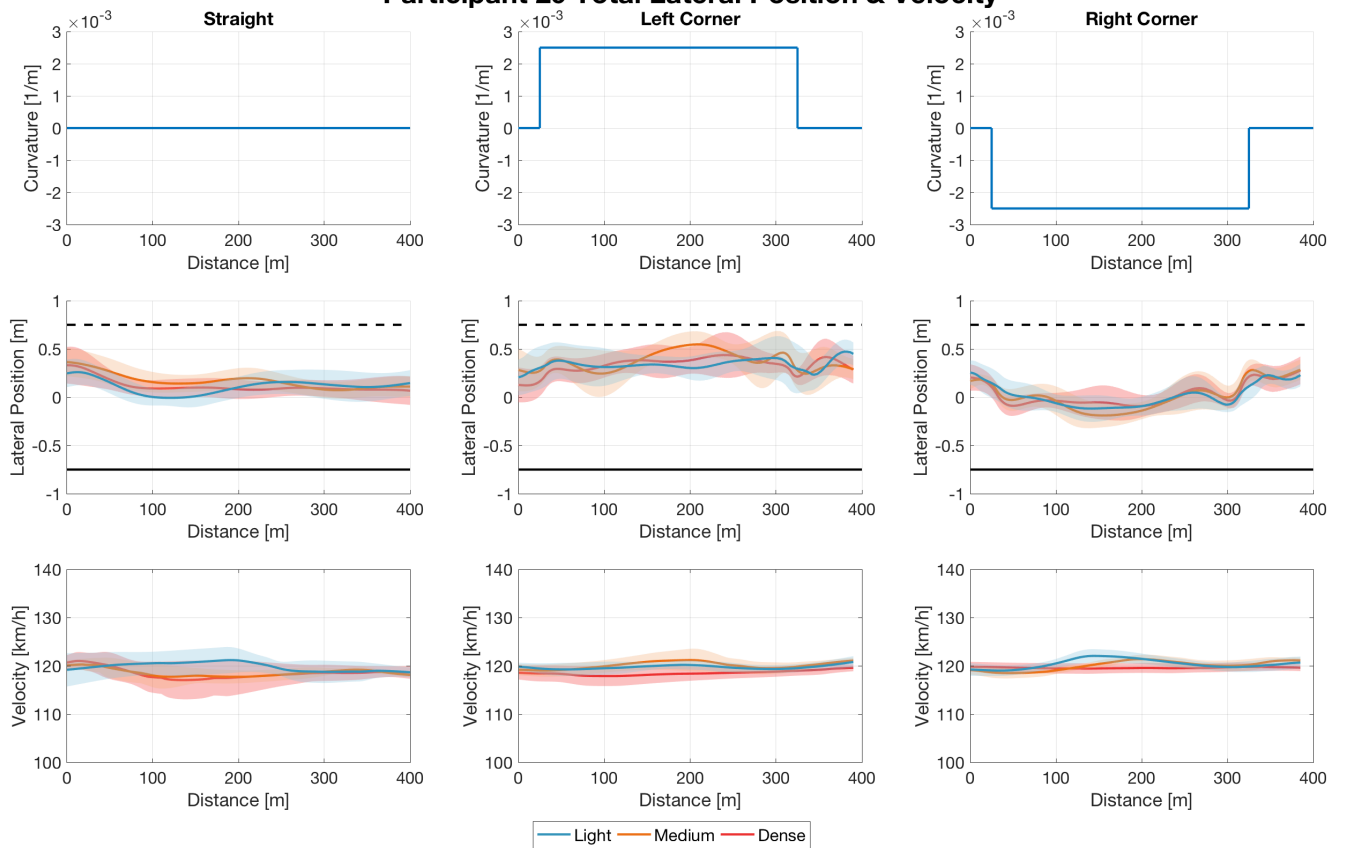
Participant 27 Total Lateral Position & Velocity

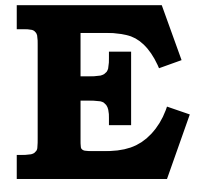


Participant 28 Total Lateral Position & Velocity



Participant 29 Total Lateral Position & Velocity





Forms

E.1. [Experimental Information](#)

Human driving behaviour in a head mounted display based virtual reality driving simulator.

Experimental Information

Introduction

Thank you for choosing to be a part in my Msc. thesis research. In this document it will be elaborated what this human subject experiment will entail and how it will be executed. This document is divided in the exact steps the experiment will go down, overall the experiment will take around 45 minutes of your time.

Step 1. Consent form

I will need you to sign an official informed consent form before you start the experiment. I will hand this form to you right after you have finished reading this experimental information hand-out.

Step 2. Familiarizing with the setup.

Before I let you use the virtual reality driving simulator I will shortly explain the different parts. You can take place on the seat so that you can easily reach the pedals and steering wheel and so that you are comfortable to start the training.



Step 3. Training.

Before we start the data collection session I would like you to get familiar with the handling of the virtual car. Therefore I will let you drive around on a simple road for some time ($\sim 5\text{min}$) to get a feel for the throttle, brake and steering. Before we can start this session you should do the following things:

1. Sit down on the chair making sure you can reach the pedals & the steering wheel and are in a comfortable position.
2. Putting on the head mounted display (HMD) and make sure it sits comfortably (you can wear them with glasses on). Also put on the headset for the sound.
3. If I ask you to, please look **directly forward over the steering wheel**.
4. I will now place you in the correct position in the car.
5. Once you are in the correct position and I give the sign that you can start driving you **tap the brake pedal first**, after that you can use the throttle, and start driving.

Step 4. Experiment.

After the training is completed we will start the experiment. The start will be the same as the steps described in step 3 (3-5).

Task description:

I want you to drive on the winding road *as you would if you were in a real car*. Try to avoid the roadside objects (trees) at all costs, if you drive through them you will hit them and we will have to restart the session.

Every now and then you will hear a question through the headphones asking you to state how risky you perceive the current situation. The voice will say: 'Please state your perceived risk on a scale of on 1 to 10'. If this is asked please say the number between 1 and 10 that you chose aloud.

We will be doing 3 sessions of driving with a short break in between where you will be asked to fill in a short workload questionnaire. The questions **are regarding the last 4 corners that you have driven**. For example, if the question is: 'how mentally demanding do you rate the task?', 'the task' means the last 4 corners that you drove.

E.2. [Informed Consent Form](#)

Informed Consent Form for the Human Subjects Experiment

This Informed Consent Form is written for men and women who attend the human subject's experiment. The title of our research project is "The effect of roadside vegetation on driving behaviour in a head-mounted-display based virtual reality driving simulator."

Principal Investigator:	Giltay, J.N.P. (Joris)
Organization:	TU Delft
Sponsor:	-
Version:	V1

This Informed Consent Form has two parts:

- **Information Sheet (to share information about the research with you)**
- **Certificate of Consent (for signatures if you agree to take part)**

You will be given a copy of the full Informed Consent Form

PART 1: Information Sheet

Introduction

My name is Joris Giltay and I am doing my graduation project at the Haptics Lab for my Master of Science (MSc.) for the study Mechanical Engineering – Biomechanical Design track at the Delft University of Technology. I am researching the effects of roadside vegetation on driving behavior by using a head mounted display based virtual reality driving simulator that I implemented. This form will give you information about the research and invites you to be a part of it. Before you decide to do so you can talk to anyone you feel comfortable with about the research. If there are words or parts of this informed consent form that are unclear to you or you do not understand please ask me to stop as we go through the information and I will take the time to explain it to you. If you have any questions later you can always ask them by using my contact information mentioned at the section "Contact Information".

Purpose of the research

The purpose of this research is to evaluate driving behavior in a head mounted display based virtual reality driving simulator. The experiment will entail driving on a 10km winding road for three times and answering several questionnaires during the experiment. The overall time the experiment will take is about 45 minutes.

Benefits and risks of participating

There are no known direct risks of participating in this experiment. Participants might feel mildly nauseating sensations during the experiment due to simulator sickness. Simulator sickness is a phenomenon that can occur due to the fact that the things you are seeing in the virtual environment do not match your other senses (such as your vestibular sense) this mismatch can cause mild nausea. The experimental sessions are relatively short (about 8 minutes) and there is a break between them. However, whenever you feel like you cannot

handle the simulator you should give the experimenter a heads-up and we will quit immediately.

If you participate in this research there are no direct benefits for you other than a minor treat as a thank you for participating, and hands on experience in a human subjects experiment.

Confidentiality

The information that we collect from this research project will be kept confidential. Information about you that will be collected during the research will be put away and no-one but the researchers will be able to access it. Any information about you will be anonymized and will have a number instead of your name and no personal data will be recorded. Only information related and obtained via this experiment will be used. The obtained data will be processed by the researchers only. At the end of the research, a copy of all data will be provided to the TU Delft. There is a possibility for the collected data to be published in a paper or/and thesis. This will be done respecting your anonymity.

Right to Refuse or Withdrawal

You do not have to take part in this research if you do not wish to do so. You may stop participating in the research at any time that you wish without any consequences. It is your choice and that choice will be respected.

Contact Information

As mentioned in the introduction, if you have questions you may ask them now, later or after the study has started. If you wish to ask questions later you can contact Joris Giltay using the information given below. For any other question related to the TU Delft or to file a complaint against the experimenter, you can contact dr.ir. S.M.Petermeijer(TU Delft) or prof. dr. ir. David Abbink (TU Delft).

Name:	J.N.P. Giltay (Joris)	dr. Ir. S.M. Petermeijer	prof. dr. ir. David Abbink
Address:	Graswinckelstraat 10	Mekelweg2	Mekelweg 2
Postcode:	2613 PW Delft	2628 CD Delft	2628 CD Delft
Tel:	0615335333	-	-
Email:	jorisgiltay@gmail.com	s.m.petermeijer@tudelft.nl	d.a.abbink@tudelft.nl

PART 2: Certificate of Consent

Please mark the appropriate boxes

Yes No

Taking part in the study

I have read and understood the study information dated [/ /], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.

☐ ☐

I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.

☐ ☐

I understand that taking part in the study involves driving down a 10km winding road in a head mounted display based virtual reality driving simulator and filling in some questionnaires.

☐ ☐

Risks associated with participating in the study

I understand that taking part in the study can possibly involve the following risks:
Simulator sickness causing minor nauseating feelings.

☐ ☐

Use of the information in the study

I understand that the information I provide will be used for: *reports, publications, and data processing.*

☐ ☐

I understand that personal information collected about me that can possibly identify me, such as, performance and effort parameters will be anonymized and will not be shared beyond the study team and the TU Delft.

☐ ☐

Signatures

Name of participant

Signature

Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Researcher name

Signature

Date

E.3. Personal Details Driving Simulation Study

Personal Details Driving Simulation Study

Please make sure you enter this form completely before you start the experiment

* Required

1. Participant nr: *

2. Gender *

Mark only one oval.

☐ Female

☐ Male

3. Age *

4. Do you wear glasses (at the moment)? *

Mark only one oval.

☐ Yes

☐ No

5. How many years have you been licensed to drive? *

6. On average, how often did you drive a car in the last 12 months? *

Mark only one oval.

☐ Daily

☐ 4 - 6 times a week

☐ 1 - 3 times a week

☐ Between once a week and once a month

☐ Less than once a month

☐ Never

☐ Prefer not to say

7. How many kilometers did you drive in the last 12 months? **Mark only one oval.*

- ☐ 0
- ☐ 1 - 1,000
- ☐ 1,001 - 5,000
- ☐ 5,001 - 10,000
- ☐ 10,001 - 20,000
- ☐ 20,001 - 50,000
- ☐ 50,001 - 100,000
- ☐ Over a 100,000
- ☐ Prefer not to say

8. How many times do you play (racing) games with a steering wheel? **Mark only one oval.*

- ☐ Daily
- ☐ 4 - 6 times a week
- ☐ 1 - 3 times a week
- ☐ Between once a week & once a month
- ☐ Less than once a month
- ☐ Never
- ☐ Prefer not to say

9. How many accidents were you involved in when driving a car in the last three years? **Mark only one oval.*

- ☐ 0
- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5 or more
- ☐ Prefer not to say

10. How many times have you driven in a driving simulator? **Mark only one oval.*

- ☐ 0
- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5 or more

11. How many times have you used a VR headset like the HTC Vive?*Mark only one oval.*

- ☐ 0
- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5 or more
-

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E.4. NASA Task Load Index (TLX) questionnaire

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date
------	------	------

Mental Demand
How mentally demanding was the task?

Very Low
Very High

Physical Demand
How physically demanding was the task?

Very Low
Very High

Temporal Demand
How hurried or rushed was the pace of the task?

Very Low
Very High

Performance
How successful were you in accomplishing what you were asked to do?

Perfect
Failure

Effort
How hard did you have to work to accomplish your level of performance?

Very Low
Very High

Frustration
How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low
Very High

F

Training Map Layout

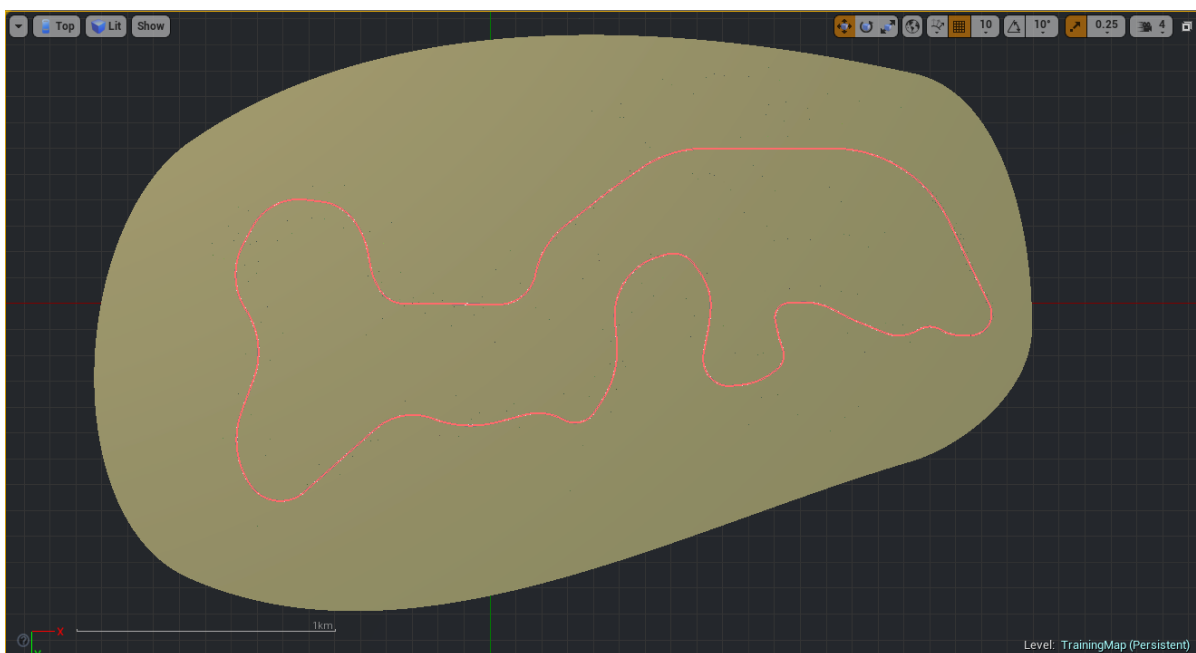


Figure F.1: Topview of the layout of the trainingmap, the actual scale is shown in the bottom left corner. The track included both sharp and shallow corners to get a feel for the vehicle handling. In the map hills and trees were also present which are not shown here.