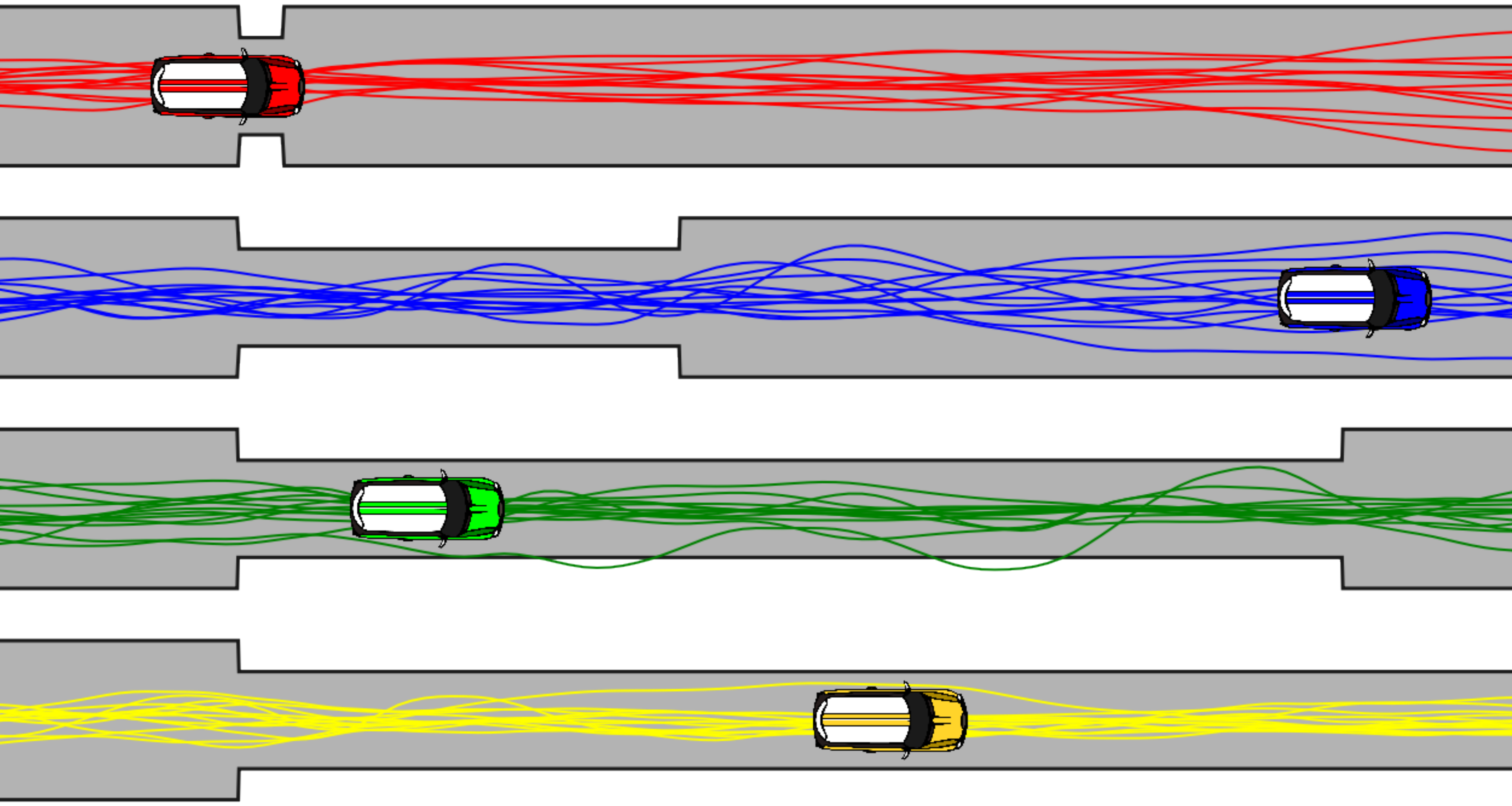
Driver adaptation to road narrowing: reducing speed or increasing neuromuscular stiffness?

E.W.M. Hogerwerf

MSc. Thesis



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Driver adaptation to road narrowing: reducing speed or increasing neuromuscular stiffness?

by

E.W.M. Hogerwerf

to obtain the degree of Master of Science
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Preface

This thesis is the result of my research into driver adaptations to a temporary road narrowing. Here I aimed to find the trade-off that drivers can make between driving speed and neuromuscular adaptation.
I would like to thank my supervisors during this project. David Abbink for his enthusiastic guidance and motivating feedback. Sarvesh Kolekar for being always patient and willing to help, especially during the many hours and evenings in the HMI lab while setting up the experiment. Timo Melman for giving clear advices, helping with statistics and having even time for a meeting in Amsterdam next to the Bosbaan. And all three for giving me the freedom to combine my master thesis research with rowing while still feeling always welcome in the lab to work, to ask questions and of course to have coffee breaks. In addition I would like to thank Anne Pronker for her help with the set up of the grip force sensors and all other Haptics Lab members and fellow master students for the nice atmosphere in the lab.
Finally I would like to thank my parents for supporting throughout all my years of study and keeping believing I would finish it once. And above all Wouter for helping me throughout all ups and downs, hopefully we will now have more free time to spend together.

Ellen Hogerwerf
Delft, November 2018

Contents

Paper

Driver adaptation to road narrowing: reducing speed or increasing neuromuscular stiffness?

Ellen W.M. Hogerwerf, Sarvesh B. Kolekar, Timo Melman and David A. Abbink

Abstract – Drivers continuously adapt to the different needs and constraints in the driving scene. Literature has provided evidence for two adaptation strategies in response to an increased risk (decreasing the road width or increasing the driving speed) while lane keeping: decreasing driving speed and increasing endpoint arm stiffness. However, so far these studies did not investigate the interaction between the two adaptation strategies. The aim of this study is to find the interaction between drivers' speed and neuromuscular adaptation for different risk durations. We hypothesize that the speed reduction is larger when the narrow road is longer which allows for a lesser increase in arm stiffness. Additionally, when the narrow road is shorter the increase in neuromuscular stiffness is larger and allows for a higher speed.

Twenty-six participants drove in a driving simulator experiment in a 1.8m wide car on a 35 km long road. Different levels of risk durations were imposed to the drivers on straight road sections by a road narrowing (from 3.6m to 2.2m) with a varying length (10m, 100m, 250m, and 500m). During the experiment speed reduction was measured and neuromuscular adaptation was quantified by measuring the grip force. Additionally participants subjectively rated their experienced effort from 1-10.

The results show that participants adapted to the road narrowing both by speed reduction as well as increased grip force, without significant impact of the length of the road narrowing. Only on the 10m narrow the speed reduction and increase in grip force was smaller compared to the other three cases. Interestingly, although drivers increased their subjective effort, no differences in speed and grip force adaptation were found between the three longest narrow roads. These results suggest that for narrow road lengths up to 500m drivers adapt their driving style to road width rather than road length. Future studies should identify if the identified speed and grip force adaptations also hold for longer and different durations of risk.

Keywords - Adaptation, Driving simulator, Road width, Driving speed, Grip force

1. INTRODUCTION

The driving environment requires drivers constantly to adapt to all kind of different situations. The ability of humans to adapt allows them to deal with a myriad of situations. Nevertheless human drivers make errors and are reported to be the main cause of traffic accidents [1]. By taking over the driving task from humans, autonomous vehicles have the potential to reduce errors and thereby increase the safety of the driver. Currently these autonomous vehicles are not safe enough on the road [2] and ironically, when autonomous cars would be safe enough, trust in automation seems to be a major roadblock for humans to accept autonomous cars [3],[4]. Until these problems are solved and cars become fully autonomous, advanced driver assistance systems (ADAS) are needed. For these systems it has been shown that systems that interact with humans are better accepted [5],[6].

The current lack of trust could arise from situations where the behaviour of the driver assistance system does not match the expectations of the human. A possible cause for these mismatches could be due to the fact that humans adapt and the ADAS does not take these adaptations into account. Hence to improve the interaction between ADAS and the humans we need to understand human drivers' adaptations. If we truly understand these adaptations, we can use this knowledge to design driver assistance systems that cooperate with humans and are better accepted. The wide range of different situations to which drivers have to adapt are, for example, when approaching a curve [7] or a one-lane bridge [8], when driving on different lane widths [9], [10], when driving in fog [11],[12] or when perturbed by lateral wind gusts [13]. All these different driving situations can trigger adaptations by the driver. Several different theories exist about what a driver takes into account, for example Gibson [14] stated that drivers keep a safe field in front of the car with all possible paths they can drive unimpeded. Fuller [15] suggested that drivers adapt their speed to maintain a certain level of task difficulty and Wilde's risk homeostasis theory [16] says that drivers adapt to different situations to equalize the experienced risk.

This study focuses on driver adaptation strategies to a temporarily decreased lane width, for example in a road work zone [17]. The first important adaptation mechanism for driving on narrow roads is the driving speed [8],[10],[18],[19]. Speed is also an important measure in road safety, since there exists a strong relation between speed and road safety [20]. Charlton [8] showed that drivers drove on narrow roads in both the simulator and on the roads at significantly lower speeds and their

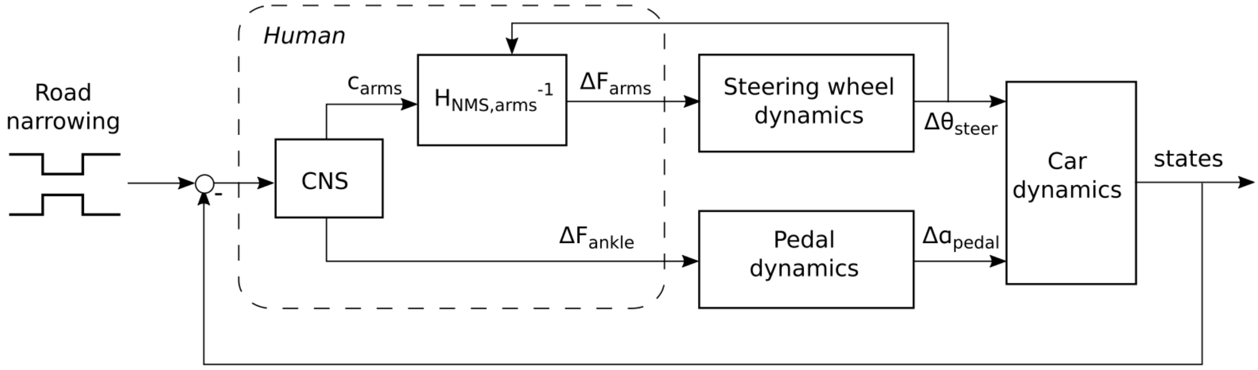

Figure 1 Conceptual model to describe two adaptation mechanisms to deal with a temporary road narrowing: increasing neuromuscular stiffness at the steering wheel and reducing driving speed. Based on the road narrowing and the states of the car, the driver (CNS) gives a command (c_{arms}) to his neuromuscular system ($H_{NMS,arms}$) to interact with the steering wheel or to apply a force to the pedal. The states of the car are influenced by the steering wheel angle ($\Delta\theta_{steer}$) for the change in heading and the pedal displacement ($\Delta\alpha_{pedal}$) for the change in speed.

risk ratings increased. As well as Melman [10] who showed that drivers significantly reduced speed on narrow roads and effort rating increased. McLean [9] showed that driving at a high speed at narrow roads is associated with higher frequency control actions. However these studies all investigated steady state driving behaviour and did not take the duration of a road narrowing into account.

The second important and fast adaptation mechanism to narrow roads is neuromuscular control adaptation. Two types of neuromuscular control are present to increase the endpoint stiffness of the arms: performing co-contraction and changing the reflexive feedback gains [21],[22]. The latter is an energy efficient strategy but suffers from time delays. This study focuses on increasing the endpoint stiffness of the arm by performing co-contraction, which is an energy-consuming but effective control strategy [22]. Another process is present when the dynamics of the environment are known, then an internal model of the dynamics of the environment is made and fast and accurate feedforward control movements can be performed with low endpoint stiffness of the arms [21].

Two studies that measured neuromuscular adaptation on narrow roads are the study of Pronker [23] and Van der Wiel [24]. Pronker investigated driving at a fixed speed of 120 km/h on a 2.5m and 3.6m wide road. In the study of Van der Wiel participants drove at two different speeds (70 and 120 km/h) and on two road widths (2.5m and 4.5m). For both studies drivers increased the endpoint stiffness of the arms on a narrow road at high-speed. However, in these two studies drivers drove at a constant speed, which required a lot of effort on the narrow roads. Van der Wiel already suggested that in real-life it would be likely that drivers would prefer to reduce speed and thereby increase safety margins and reduce the need for the energy-consuming increase in neuromuscular stiffness.

In real-life drivers continuously can make the trade-off between adapting their speed and adapting their neuromuscular system. In Figure 1 a conceptual model is shown to describe this interaction between speed adaptation and neuromuscular adaptation when approaching a road narrowing. The driver observes the road ahead and determines if he has to adapt the current state of the car to the road narrowing, which serves as an input to the central nervous system (CNS). From the CNS a motor command goes either to the muscles of the arms (H_{NMS}) to adapt steering or to the gas or brake pedal to adapt speed. The driver's forces that interact with the steering wheel (ΔF_{arms}) result in a steering angle ($\Delta\theta_{steer}$) and the forces that interact with the pedal (ΔF_{ankle}) result in a pedal angle ($\Delta\alpha_{pedal}$). These two angles serve as an input for the car and adapt the current state of the car in terms of heading and speed.

Neuromuscular control of the driver can be measured using admittance estimation by adding a perturbation on the steering wheel [24],[25],[26], EMG measurements [24][27] and grip force measurements of the hands on the steering wheel [28],[29]. Admittance estimation can be performed to estimate directly the endpoint stiffness of the arms can be determined using a multisine force perturbation. The disadvantage of using this force perturbation is that in order to achieve a good signal-to-noise ratio, high signal amplitudes on the steering wheel are needed. These high amplitudes are disruptive and annoying and can influence driving behaviour. Using EMG the muscle activity can be measured directly, however in order to measure the admittance several electrodes have to be placed and an EMG signal has in general a low signal-to-noise ratio. Recently in a new study, Pronker [28] showed a strong correlation between neuromuscular admittance and grip force, while performing a driving task. This finding motivated us to use grip force measurements as a non-intrusive alternative to EMG or admittance measurements.

Literature shows that drivers adapt their speed when a road narrows [10],[8] and also their neuromuscular system when a road narrows [23],[24]. However since most studies investigated steady state driving behaviour the moment a driver decides to decrease speed is not known from these studies. Transitions in roads can affect the choices a driver makes about the driving strategy and these choices might also be influenced by the duration of the risk. Based on the neuromuscular control studies we hypothesize that for a short duration of the risk, neuromuscular adaptation is more convenient since it does not cost too much energy. And vice versa, for a long narrow road drivers will mainly adapt their speed, which allows them to lower the endpoint stiffness.

The aim of this study is to quantify to what extent the length of a road narrowing (duration of increased risk) influences the two adaptation strategies by the driver: reducing speed and increasing end point stiffness (measured by grip force). In Figure 2 the hypothesized interaction between speed and grip force is visualized. It is hypothesized that with increasing narrow road length:

- Speed reduction (Δ speed) increases.
- Grip force increase (Δ grip force) will decrease.

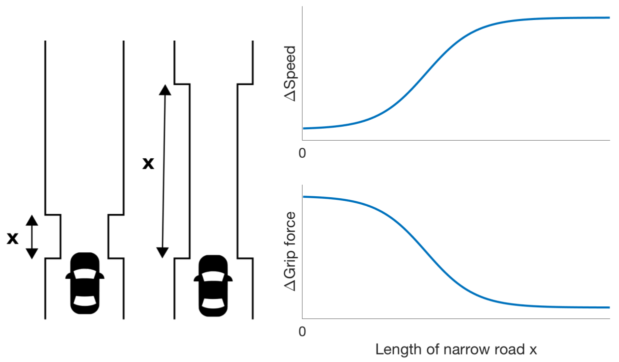

Figure 2 Illustration of the hypothesized impact of the length of the narrow road section (x) on the adaptation mechanisms: speed (upper right graph) and delta grip force (bottom right graph).

2. Method

2.1 Participants

Twenty-six participants (17 male, 9 female) between 20 and 32 years old (M = 25.9 years old, SD = 3.2) volunteered to participate in this study. All participants had normal or corrected to normal eyesight and were in possession of a valid driver's license for at least one year (M = 6.5 years, SD = 3.4).

2.2 Apparatus

The experiment was conducted in a fixed-based driving simulator located at the Control and Simulation Department at the faculty of Aerospace Engineering at the Delft University of Technology. The simulated vehicle had an automatic gearbox and was 1.80 meter wide. The driver's chair was placed in the left side of the vehicle, like a normal Dutch car. During the complete experiment participants drove at a free speed, where speed feedback was given on the display in the dashboard of the vehicle. During the driving task, participants were instructed to keep their hands on a 10-to-2 position. To give participants a better perception of the positions of the car with respect to the road, the bonnet of the vehicle was

Figure 3. left: Tekscan pressure sensors attached on thin gloves, right: output of the pressure sensor visualized

visualized. The data of the simulator was recorded at 100 Hz.

The grip force was measured using Tekscan 4256E pressure sensors attached on gloves; see Figure 3. The grip data was logged at 20 Hz and synchronized with the simulator data. The sensor consists of 349 individual pressure-sensing locations or sensils with a spatial resolution of 7.1 sensors/cm^2. Each sensil can be seen as an individual square and the output for the load on the sensil has an 8-bit resolution. During this study, only the total raw sum of all sensils for the left and right hand were recorded.

2.3 Road conditions and environment

During the experiment participants encountered four different lengths of the narrowed road: 10m, 100m, 250m and 500m. Cones were placed along the road every 10m, which made the shortest road narrowing only one cone long and for the 500m narrow road drivers could not see the end of the narrow road when they approached the narrowing, see Figure 4.

Each of the four conditions were repeated 8 times, which led to 32 narrow sections in total for each participant. In order to prevent learning effects and other order effects the narrow road segments were presented in a counterbalanced order. All possible permutations of the four conditions were generated and random eight different permutations of the four conditions were selected. Three different roads were generated that in total comprised all of 24 possible permutations of the different roads.

The road environment consisted of a single-lane rural road of 35 kilometres. Straight sections were separated with curves and on every straight section 200m after a curve the road narrowed down, which was the entry section, see Figure 5. This ensured a constant preview time for all conditions and no influence by the amount of anticipation. In the same way after each narrow section the road widened again for 200m before the next curve.

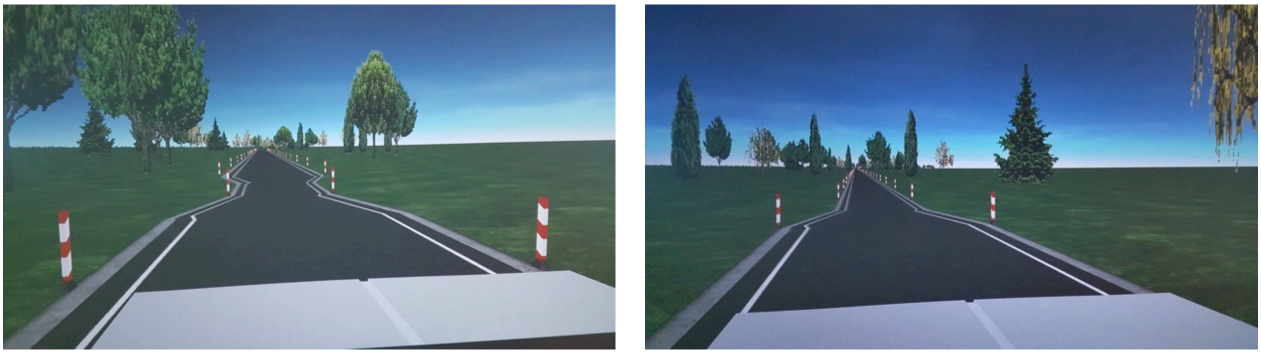

Figure 4 Driving simulator road environment with cones at the lane boundaries. Left the 10 m narrow road is shown and right the 500 m narrow road.

The lane width was 3.6m at the wide road and 2.2m at the narrow road sections. This allowed a lateral deviation from the lane centre of respectively 0.9m and 0.2m on each side of the vehicle. A speed dependent vibration that mimics shoulder rumble strips was implemented on the steering wheel to give feedback when the car was outside the lane boundary.

In order to make the driving task more challenging, a perturbation was applied to the steering wheel. The perturbation was a multisine signal with a period of four seconds and consisting of 6 different frequencies in the range between 0.25 and 18 Hz. The reduced power method [30] was used to generate the perturbation where full power was applied to the lowest three frequencies and reduced power to the three highest frequencies. The final multi-sine is scaled in order to ensure that the driver was not disrupted during driving (M = 0, SD = 0.13 Nm) due to the perturbation.

2.4 *Grip force calibration*

Both grip force sensors (right and left) were calibrated prior to each experiment. The calibration procedure consisted of a grip task with a bulb shaped hand dynamometer (see Figure 3). The bulb shaped dynamometer ensured a good pressure distribution over all sensils of the Tekscan pressure sensors.
In order to perform the calibration, participants were instructed to hold the hand dynamometer in their left hand and subsequently apply a force of 10 kg, 5 kg, 15 kg and a maximum force to the hand dynamometer. The sum of the sensil outputs was recorded and a video was recorded from the display of the hand dynamometer to measure the applied force. Hereafter the procedure was repeated with the right hand.

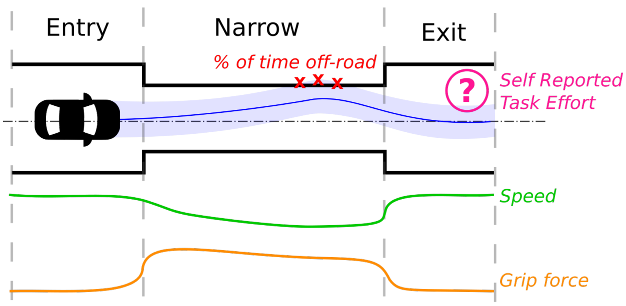

Figure 5 The road narrowing with the four main measures schematically: speed, grip force, percentage of time off-road and SRTE.

The results of the calibration procedure were used later on to express the grip force during driving as a relative force with respect to participants' maximum grip force. The fixed load calibration task was used to check whether the output of the sensors was linear and the maximum grip task to express the grip force as the relative effort during driving.

2.5 *Experimental procedure*

Before the experiment participants read and signed informed consent and filled out a questionnaire about their driver experience and the driving behaviour questionnaire (DBQ) [31]. The DBQ results give information about speed behaviour during driving since they have been found to have a moderately strong relationship with recorded measures of speed and speeding [32]. After filling out the questionnaires, participants sat down in the chair of the driving simulator and put on the gloves with grip force sensors for the calibration procedure.

Prior to the experiment, participants performed a training trial of 7 minutes on a 3.6 m wide road in order to familiarize with the driving simulator environment. During the training trial participants experienced the off-road vibration when crossing the lane boundary, which allowed them to practice to position the car correctly within the lane boundaries. During the experiment participants were instructed to drive like they normally would do and to not hit any cones. No speed advice was given and questions regarding the speed choice were not answered. The experimenter was standing next to the participants during the experiment and after each narrow section, the participants answered the question: '*How much effort did it cost you to successfully drive this section?'* Participants responded a number between 1 for no effort and 10 for a lot of effort. Note that the same wording was used as Melman [10] did, based on Fuller's task difficulty and risk determination [33].

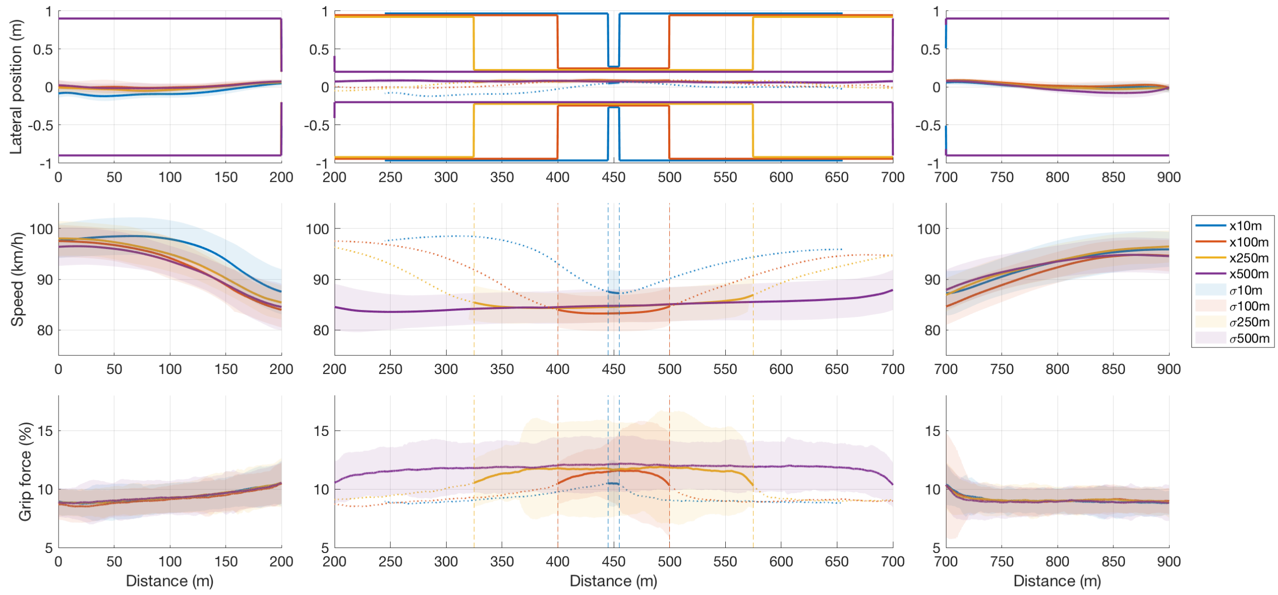

Figure 6 Mean results for all participants for all four conditions as a function of the travelled distance. The top panels show the lateral position along with the lane width, the middle panels the speed and the bottom panels the grip force. The left panels show the entry section, the middel panels the narrow road section centered in the middle of each road narrowing and right panels the exit section.

2.6 Dependent measures

Only the straight sections of the road were used for analysis. The following measures were calculated for these sections:

2.6.1 Speed

- Δ Speed (km/h). This is defined as the mean driving speed over the narrow section minus the mean driving speed over the first 50m of the wide entry section. The speed is averaged over only the first
- 50m of the entry section to exclude anticipation effects in the speed, which might be present when participants are approaching the narrow section.
- Mean and minimum speed (km/h). The mean speed is defined as the mean speed over the complete narrow section and the minimum speed as the minimum speed within the narrow section.

2.6.2 Grip force

- Δ Grip force (%). Grip force is used as a measure for neuromuscular adaptation and the mean grip force over the left and right hand is used. Δ Grip force is defined as the mean grip force over the narrow road section minus the mean grip force at the first 50m of the entry section.
- Mean and maximum grip force (%). Grip force is expressed as the relative grip applied by a participant with respect to the participants' maximum grip during the maximum grip task. The relative grip force is calculated by:

$$F(\%) = \frac{F_{raw}(-) - S_0}{S_{max} - S_0} \cdot 100\% \qquad \text{Equation 1}$$

Where $F_{raw}(-)$ is the raw grip sensor output during the experiment, S_0 is the sum of the raw sensor output with no load, and S_{max} is the maximum sensor output

2.6.3 Effort

- Self reported task effort (SRTE) (-). Participants reported after every narrow section how much effort it cost them to drive the narrow section.
- Standard deviation lateral position (SDLP) (m). The standard deviation lateral position is the standard deviation of the mean lateral position and is a measure of 'weaving' during driving [34].

2.6.4 Performance

Performance measures were taken in order to verify whether participants maintained a same level of performance between the four conditions.

- Percentage of time off-road (%). The percentage of time for a narrow section that the car was outside the lane boundaries.
- Mean and maximum absolute lateral position (m). The absolute lateral error was defined as the distance between the centre of the car and the centre of the lane.

Table 1 Means (M), standard deviations (SD), effect sizes (d_z), and results of the repeated measures ANOVA (F, p) per dependent measure.

	10m	100m	250m	500m		Pairwise comparisons					
	M (SD)	M (SD)	M (SD)	M (SD)	p value, F(3,75)	1-2 p (d_z)	1-3 p (d_z)	1-4 p (d_z)	2-3 p (d_z)	2-4 p (d_z)	3-4 p (d_z)
Mean speed (km/h)	87.36 (29.61)	83.46 (29.17)	84.68 (28.58)	84.57 (28.14)	p=0.074 F=2.40	(0.50)	(0.37)	(0.23)	(0.04)	(0.18)	(0.18)
Minimum speed (km/h)	87.02 (29.77)	81.26 (30.13)	80.54 (30.35)	78.93 (29.95)	p=1.18e-7 F=14.78	xx (0.78)	xx (0.86)	xxx (0.91)	(0.34)	(0.46)	(0.21)
Δ Speed (km/h)	-10.71 (12.32)	-13.79 (11.25)	-13.14 (10.59)	-11.81 (10.87)	p=0.0016 F=5.58	xx (0.73)	x (0.57)	(0.30)	(0.02)	(0.34)	(0.49)
Mean grip force (%)	10.47 (4.50)	11.26 (4.86)	11.58 (5.07)	11.81 (5.44)	p=1.58e-5 F=9.79	x (0.67)	xx (0.73)	xx (0.82)	(0.22)	(0.25)	(0.005)
Maximum grip force (%)	10.91 (4.70)	12.82 (5.47)	13.60 (5.87)	14.13 (6.42)	p=5.08e-11 F=24.09	xx (0.80)	xxx (1.04)	xxx (1.46)	(0.41)	xx (0.77)	(0.22)
Δ Grip force (%)	1.63 (1.38)	2.64 (2.23)	2.73 (2.17)	2.92 (2.18)	p=1.81e-5 F=9.66	x (0.60)	x (0.64)	xx (0.86)	(0.10)	(0.29)	(0.23)
Mean absolute lateral error (m)	0.086 (0.028)	0.096 (0.024)	0.088 (0.023)	0.086 (0.027)	p=0.15 F=1.83	(0.32)	(0.05)	(0.04)	(0.42)	(0.55)	(0.14)
Maximum absolute lateral error (m)	0.10 (0.028)	0.16 (0.024)	0.17 (0.027)	0.19 (0.032)	p=2.19e-19 F=57.41	xxx (1.80)	xxx (2.24)	xxx (2.37)	(0.36)	xx (0.75)	(0.51)
SDLP (m)	0.01 (0.01)	0.04 (0.01)	0.04 (0.01)	0.04 (0.01)	p=1.51e-23 F=81.53	xxx (2.39)	xxx (2.46)	xxx (2.81)	(0.14)	(0.09)	(0.05)
Time off-road (%)	5.25 (6.59)	5.12 (4.56)	3.19 (3.00)	2.75 (2.73)	p=0.32 F=1.19	(0.21)	(0.015)	(0.088)	(0.32)	(0.42)	(0.095)
SRTE (-)	2.66 (0.94)	4.48 (0.91)	5.34 (1.08)	6.34 (1.36)	p=4.74e-28 F=115.60	xxx (1.86)	xxx (2.09)	xxx (2.90)	xxx (1.09)	xxx (1.80)	xxx (1.28)

x: p<0.05; xx: p<0.01; xxx: p<0.001

2.7 Statistical analysis

For each dependent measure, the mean over all eight repetitions was computed. These means values were collected in a 26x4 matrix (26 participants and 4 conditions). First the matrix was rank-transformed according to Conover and Iman [35] to account for possible violations of the assumption of normality. This rank-transformed matrix with ranks from 1 to 104 was submitted to a repeated measure ANOVA with the four narrow lengths as a within-subject factor. Bonferroni corrections were applied to the six pairwise comparisons between the narrow road lengths. The effect sizes d_z for pairwise comparisons were calculated according Faul [36]:

$$d_z = \frac{|\mu_{x-y}|}{\sigma_{x-y}} \qquad \text{Equation 2}$$

Where μ_{x-y} is the mean and σ_{x-y} the standard deviation of the difference between two conditions.

3. Results

3.1 Effects of narrow road length

To illustrate the average driver behaviour in response to the four road narrowing sections, Figure 6 shows the lateral position along with the lane width (top panels), speed (middle panels) and grip force (bottom panels) averaged over all participants, for entry (left panels), steady state (middle panels) and exit part (right panels). The results for each condition were averaged over all 8 repetitions per participant and then over all 26 participants.

As can be seen in Figure 6, the entry strategy shows different results for the 10m long narrow section. Drivers decreased speed later for the 10m road narrowing than for the other three conditions. Also in the narrow section, the speed reduction was less for the 10m than for the other three conditions where the speed was maintained at the same level until just before the road widens again, when the driver accelerated again. The entry strategy of the grip force shows a similar pattern for all four conditions. Driver slightly increased their grip force for all narrow road conditions when approaching the road narrowing.

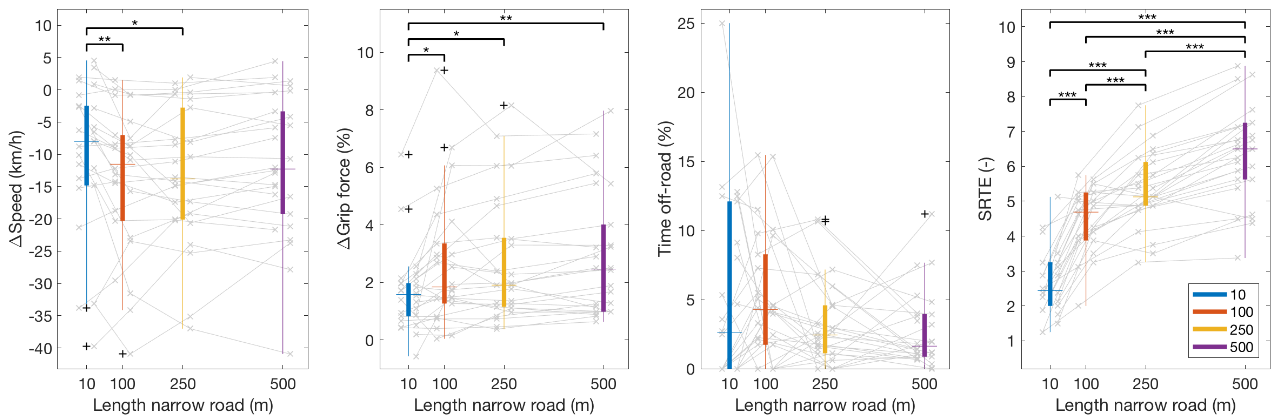

Figure 7 Boxplots with the mean results. From left to right: Δspeed, Δgrip force, percentage of time off-road and Self Reported Task Effort (SRTE). Brackets indicate significant differences, *: p<0.05; **: p<0.01; ***: p<0.001

The steady state strategy results are also shown in Table 1, which shows the complete results of the statistical analysis for all four conditions. It can be seen that both speed and grip force were sensitive to the narrow road since the speed decreased for each condition and the grip force increased. The boxplot in Figure 7 visualizes the results for the four main measures, including the individual results for each participant averaged over eight repetitions. ΔSpeed is significantly smaller for the 10m road narrowing than the 100m and 250m road narrowing. ΔGrip force is significantly smaller for the 10m narrow road than the three other conditions. The only measure that significantly increased with narrow road length, was the SRTE. Higher responses were given for longer narrow roads. The performance was similar for all four conditions as can be seen by the percentage of time off-road.

The exit strategy in Figure 6 shows a similar result as the entry strategy. Within the exit section, the drivers increased speed again to approximately the speed at which they drove before they entered the entry section. Also the grip force reduced again in the exit section to the level of the beginning of the entry section.

Table 2 Mean results for all succesful repetitions without cone hits

	10m M (SD)	100m M (SD)	250m M (SD)	500m M (SD)
Successful repetitions	190	160	149	120
Δ Speed (km/h)	-10.84 (12.74)	-13.32 (11.09)	-13.70 (11.84)	-12.83 (13.10)
Δ Grip force (%)	1.62 (1.36)	2.21 (2.07)	2.29 (1.97)	2.71 (2.16)
SDLP (m)	0.01 (0.004)	0.035 (0.012)	0.039 (0.011)	0.044 (0.011)
Mean SRTE (-)	2.61 (0.90)	4.10 (0.92)	4.95 (1.12)	6.06 (1.53)

3.2 *Effect of cone hits*

The main metrics were also calculated for only the successful repetitions, which are the narrow road sections that were driven without cone hits. A total number of 190, 160, 149 and 120 narrow road sections without cone hits were recorded for each condition (10m, 100m, 250m and 500m) respectively out of 208 in total for each condition. The mean results for only the successful trials are shown in Table *2*. The speed reduction, grip force increase and SDLP values only slightly differed from the results over all repetitions. The SRTE response was still significantly higher for longer narrow roads.

3.3 *Learning effect*

The effect of the repetition order of the experiment is shown in Figure 8. This figure shows the lateral position, speed and the relative grip force as a function of the travelled distance averaged over all participants for each repetition. The speed and grip force along the travelled distance show a similar pattern for all repetitions. A clear order effect is visible for both measures for all four conditions since the grip force decreased for each consecutive repetition. The mean speed is the highest during the first and last repetition.

In Table 3 the other objective measures and the SRTE values are shown for each repetition for the 500m long narrow road condition. It can be seen that the percentage of time off-road decreased during the experiment. The SRTE slightly dropped at the end of the experiment though it remained relatively constant.

4. Discussion

4.1 *Main results*

This driving simulator study aimed to investigate the interaction between two adaptation mechanisms that can be employed by drivers to maintain lane-keeping performance during a road-narrowing: decreasing speed

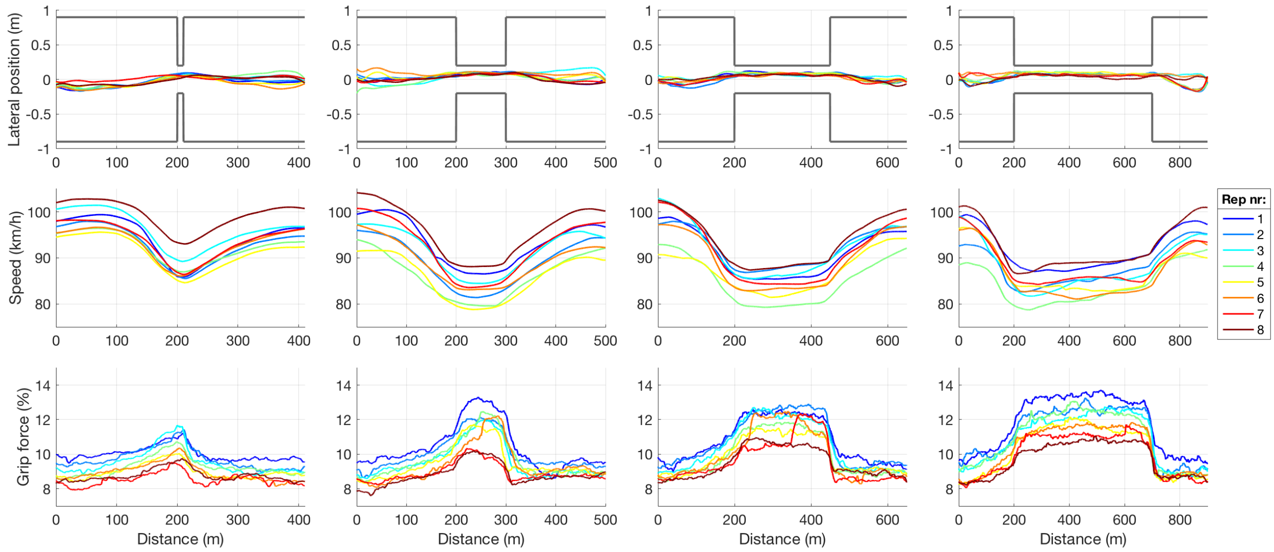

Figure 8. Speed and grip force for each repetition averaged over all participants for the four narrow road length conditions. A clear order effect is visible for speed and grip force over trails

Table 3. Mean (M) and standard deviations (SD) averaged per repetition over all subjects for the 500m long narrow road section.

	Repetition number							
	1	2	3	4	5	6	7	8
	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)
Speed (km/h)	88.05 (29.63)	85.02 (32.15)	84.03 (29.04)	80.97 (27.58)	83.08 (27.81)	82.06 (27.86)	84.81 (28.69)	88.57 (29.33)
Grip force (%)	13.16 (7.23)	12.47 (6.43)	12.12 (5.60)	12.22 (5.69)	11.42 (5.70)	11.47 (5.55)	11.00 (4.87)	10.57 (4.74)
Time off-road (%)	3.24 (5.57)	3.36 (5.13)	1.98 (3.44)	4.33 (7.97)	5.44 (16.43)	2.00 (2.90)	1.11 (1.93)	0.51 (1.63)
Mean absolute lateral position (m)	0.09 (0.04)	0.09 (0.04)	0.08 (0.04)	0.10 (0.03)	0.10 (0.04)	0.08 (0.03)	0.07 (0.04)	0.07 (0.03)
SDLP (m)	0.05 (0.02)	0.05 (0.02)	0.05 (0.02)	0.06 (0.02)	0.05 (0.02)	0.05 (0.02)	0.05 (0.02)	0.05 (0.02)
SRTE (-)	5.85 (1.80)	6.50 (1.61)	6.46 (1.50)	7.00 (1.23)	6.46 (1.75)	6.42 (1.98)	6.23 (1.95)	5.77 (1.84)

and increasing endpoint arm stiffness. Specifically we hypothesized that the duration of the risk (in our case, the length of the road narrowing) would influence driver's choices in employing either of the adaptation mechanisms. Narrowing the road from 3.6m to 2.2m successfully triggered substantial driver adaptation for most drivers. The road width reduction showed a strong effect on both speed (lower) and grip force (higher) as was also found in previous research ([10], [23], [24]). Interestingly, as opposed to what we hypothesized, there was no effect of the length of a narrow road on the decrease in speed and increase in grip force. Only the subjective effort was sensitive to the different road narrowing lengths, which suggests that while not changing their driving style for longer narrow road lengths, participants were putting more effort in the driving task.

4.2 Interaction between Δ speed and Δ grip force

The lengths of the narrow sections were chosen to investigate whether a trend exists for the interaction between speed and grip force dependent as a function of the duration of risk. The 500m road narrowing was supposed to be long enough to force drivers into a steady state driving style and is also comparable to the 400m used by Pronker [23]. For this longest narrow road section (x=500m), we hypothesized that, on average, drivers would opt to adapt more by decreasing speed than by increasing grip compared to a shorter narrow road section (x=10m). However, contrary to our hypotheses, on average drivers chose to increase grip force for all narrow road lengths.

The 500m road narrowing might not have been long enough to reduce speed more, which would have allowed them to lower grip force. The mean driving speed on 500m narrow sections was 84.6 km/h, which means an average driving time of 21.2s. It might be that this length was still short enough for participants to decide to drive with a high endpoint stiffness and that drivers will decrease their driving speed more when the narrow road would be much longer when also fatigue can be a factor that influences their decisions tot adapt.

An essential part of the experiment was the identical trajectory before and after each narrow road, which was the 200m preview in the entry section and the 200m exit section. The entry section provided a preview of the upcoming narrow section and especially the results for the driving speed showed that a lot of adaptation happens during this time.

The width of the narrow road was chosen in order to design a critical driving task that drivers should be able to drive without crossing the lane boundaries. Melman et al. [10] showed that a 2.0m wide road was too narrow given the very high number of cone this. Since the percentages of time off-road from this study were low, it can be concluded that the width of 2.2m for the narrow roads was well chosen in order to be able to drive without cone hits.

The SRTE responses showed to be highly sensitive to road narrowing length. These results are contrary to Fuller's theory [33] where drivers will modify their speed to maintain a certain task difficulty level. However, our results correspond the results of Melman et al. [10] where drivers also did not adapt their driving style to regulate their subjective effort. Our results suggest that either risk duration is an extra factor that should be taken into account in Fuller's task difficulty theory to give the complete picture of human adaptations or the threshold for humans was not reached due to the short sections of the narrow road. However the latter is not likely due to the high SRTE ratings in this study. In addition, the results suggest that the SRTE index correlates with the total grip force over a complete narrow section.

4.3 Learning effect

Before the experiment, participants performed a training trial on the wide road. During this trial they became familiar with the driving simulator environment but did not experience the road narrowing before the experiment. During the experiment they encountered the four narrow road conditions every time in one of the 24 possible permutation orders. The results from Figure 8 and Table 3 show that the grip force decreases with each repetition, while at the same time the driving performance increases in terms of a lower percentage of time off-road. Since the grip force did not decrease for longer narrow road lengths, this suggests that the order effect was stronger for grip force than for narrow road length.

The learning effect for motor control tasks is demonstrated by Osu et al. [37] where the endpoint stiffness decreased with a decreasing performance error. The decreasing grip force for all repetitions in this study suggests that learning was not completed at the end of the experiment and that more repetitions were needed. The learning effect is also suggested during driving in the study of Pick and Cole [38]. In this study a learning effect was observed when measuring EMG during lane-change manoeuvres in three different cars with different steering torque feedback. It was found that the level of co-contraction reduced with driver experience for each car while path following error also decreased, which suggested the existence of a learning process. Since there was also a decrease in grip force found for this study, the results suggest that in addition to the EMG measurements from Pick, grip force is also sensitive to learning.

The calibration results emphasize the importance of having the calibration task when measuring grip force with the Tekscan sensors. Two main problems raised: Tekscan sensors experienced signal degradation over time [39] and the individual differences that exist between participants. The measured signal degradation of the sensors can be seen in the results from the calibration task, see Appendix C. Using a hand dynamometer that provided a uniform distribution has shown to be a successful tool to take the individual differences and degradation into account. Since there was no post-calibration performed after the driving task, it is unknown whether the degradation of the Tekscan sensors has influenced the grip force during the experiment.
Another factor that might have influenced the grip force results is the use of gloves. With the gloves there is no direct connection to the steering wheel with the hands. This might already lead to some co-contraction. Another way to measure grip could be to implement grip sensors in the rim of the steering wheel.

4.4 Limitations

4.4.1 Individual differences

Although the experiment was designed with fixed trajectories and participants performed the task well, still large individual differences can be seen in the results, see the individual means in Figure 7. Here the largest amount of participants chose the strategy of adaptation both speed and grip force at the same time within the narrow sections, see Appendix A for detailed results of the individual differences. Contrary to the between subject differences, the within subject differences were small during the experiment. Participants showed to be consistent in their own driving style for all the four conditions and seemed to make the trade-off between speed reduction and increasing grip force based on their individual preferences.

A relatively small amount of participants participated in this study, which might have influenced the generalizability of the results. The participants that participated in this study were all between 20 and 32 years old and either university students or rowers from the Dutch national team. The participants were highly motivated to perform well in the experiment and to stay inside the lane boundaries, which might explain that they did not slow down on the longest narrow road condition, while maintaining a high endpoint stiffness.

4.4.2 Perturbation

A low amplitude multisine perturbation was applied to the steering wheel to simulate natural drift (as was also performed in Melman et al. [10]. Without this perturbation participants would be able to position the car at the beginning of a straight section (wide road) with a correct heading and successfully traverse the narrow section with no additional steering action required. However it might be that participants increased their endpoint stiffness to some extent due to the force perturbation on the steering wheel during driving, which could have influenced the grip force results. This effect was limited since the standard deviation of the perturbation signal was very low (0.13 Nm) in this study, where Pronker [23] performed the admittance estimation used a signal with a SD of 0.85 Nm (road widths Pronker 3.6m and 2.5m).

The vibration on the steering wheel when drivers hit a cone has shown to be an effective way to inform drivers when they were outside the lane boundaries. The vibration also did not influence the results when comparing the results over all sections with the results over the sections without cone hits; see the results in Table *2*.

4.4.3 Driving simulator

The experiment in this study is performed in a fixed-base driving simulator, which has the advantage of the ability to perform a lot of repetitions in a consistent environment. Also participants could drive at the speed they preferred without being impeded. However the disadvantage of the driving simulator is the lack of physical risks. Because of this the participants might not have experienced the risk when driving on the shortest narrow road sufficiently. However the task was still well executed given the low percentage of time off-road and the off-road vibration was effective to inform drivers when they were outside the lane boundaries. Also the clear results for speed and grip force adaptation show that drivers experienced the road narrowing trigger effectively.

4.5 Future work

The results of our driving simulator experiment showed that participants did have time in the entry section to adapt their speed and grip force to drive successful in the narrow road section. However, contrary to the hypothesis, participants did not reduce speed more for a longer road narrowing. This might be because participants did not have the time to lower speed within the narrow section since they were highly focussed on performing well. Future studies should identify if a road narrowing that is longer than 500m would trigger drivers to reduce speed more and thereby decrease their grip force. In addition, real car tests can provide information whether the risk experienced during the 10m road narrowing in the simulator can be translated to real driving.

In addition, the results of this experiment showed that measuring grip force is a promising, non-invasive and sensitive method to measure driver adaptation. However for future experiments a more robust measurement system is recommended.

5. Conclusion

The main goal of this study was to find the interaction between speed and neuromuscular adaptation during driving dependent of the length of a risk. Four different lengths of a narrow road were tested: 10m, 100m, 250m and 500m. It was shown that the road narrowing did evoke speed and grip force adaptation. From the results can be concluded that:

- The different lengths of the narrow road did not significantly influence the amount of speed reduction and the increase in grip force. Only on the 10m road narrowing the speed reduction and increase in grip force was significantly smaller compared to the other three cases.
- Contrary to the hypothesis, the increase in grip force did not decrease for longer narrow roads, but the grip force was significantly lower on the 10m road narrowing.
- The subjective effort increased significantly with longer narrow road lengths.

The results suggest that the road narrowing was a successful trigger for adaptations, but not the length of the narrow road sections itself.

References

[1] S. Singh, "Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey," *Natl. Highw. Traffic Saf. Adm.*, no. February, pp. 1–2, 2015.

[2] D. J. Fagnant and K. Kockelman, "Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations," *Transp. Res. Part A Policy Pract.*, vol. 77, pp. 167–181, 2015.

[3] J. Vitale and C. A. Giffie, "What's ahead for fully autonomous driving," Deloitte Global Automotive Consumer Study, 2017.

[4] M. Konig and L. Neumayr, "Users' resistance towards radical innovations: The case of the self-driving car," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 44, pp. 42–52, 2017.

[5] D. A. Norman, "The 'problem' with automation: inappropriate feedback and interaction, not 'over-automation'.," *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, vol. 327, no. 1241, pp. 585–93, 1990.

[6] D. A. Abbink *et al.*, "A Topology of Shared Control Systems—Finding Common Ground in Diversity," *IEEE Trans. Human-Machine Syst.*, vol. 48, no. 5, pp. 1–17, 2018.

[7] W. van Winsum and H. Godthelp, "Speed Choice and Steering Behavior in Curve Driving," *Hum. Factors J. Hum. Factors Ergon. Soc.*, vol. 38, no. 3, pp. 434–441, 1996.

[8] S. G. Charlton and N. J. Starkey, "Risk in our midst: Centrelines, perceived risk, and speed choice," *Accid. Anal. Prev.*, vol. 95, pp. 192–201, 2016.

[9] J. R. McLean and E. R. Hoffmann, "The effects of lane width on driver steering control and performance," *Proc. Sixth Aust. Road Res. Board Conf.*, pp. 418–440, 1972.

[10] T. Melman, D. A. Abbink, M. M. van Paassen, E. R. Boer, and J. C. F. de Winter, "What determines drivers' speed? A replication of three behavioural adaptation experiments in a single driving simulator study," *Ergonomics*, vol. 0139, pp. 1–22, 2018.

[11] M. Saffarian, R. Happee, and J. C. F. De Winter, “Why do drivers maintain short headways in fog? A driving-simulator study evaluating feeling of risk and lateral control during automated and manual car following,” *Ergonomics*, vol. 55, no. 9, pp. 971–985, 2012.

[12] J. O. Brooks *et al.*, “Speed choice and driving performance in simulated foggy conditions,” *Accid. Anal. Prev.*, vol. 43, no. 3, pp. 698–705, 2011.

[13] W. W. Wierwille, J. G. Casali, and B. S. Repa, “Driver steering reaction time to abrupt-onset crosswinds, as measured in a moving-base driving simulator.,” *Hum. Factors*, vol. 25, no. 1, pp. 103–116, 1983.

[14] J. J. Gibson and L. E. Crooks, “A Theoretical Field-Analysis of Automobile-Driving,” *Am. J. Psychol.*, vol. 51, no. 3, pp. 453–471, 1938.

[15] R. Fuller, “Towards a general theory of driver behaviour,” *Accid. Anal. Prev.*, vol. 37, no. 3, pp. 461–472, 2005.

[16] G. J. Wilde, “Risk homeostasis theory: an overview.,” *Inj. Prev.*, vol. 4, no. 2, pp. 89–91, 1998.

[17] L. Domenichini, F. La Torre, V. Branzi, and A. Nocentini, “Speed behaviour in work zone crossovers. A driving simulator study,” *Accid. Anal. Prev.*, vol. 98, pp. 10–24, 2017.

[18] B. Lewis-Evans and S. G. Charlton, “Explicit and implicit processes in behavioural adaptation to road width,” *Accid. Anal. Prev.*, vol. 38, no. 3, pp. 610–617, 2006.

[19] S. Liu, J. Wang, and T. Fu, “Effects of lane width, lane position and edge shoulder width on driving behavior in underground urban expressways: A driving simulator study,” *Int. J. Environ. Res. Public Health*, vol. 13, no. 10, pp. 1–14, 2016.

[20] R. Elvik, P. Christensen, and A. Amundsen, *Speed and road accidents: An evaluation of the Power Model*, vol. 740, no. December. 2004.

[21] R. Osu *et al.*, “Short- and Long-Term Changes in Joint Co-Contraction Associated With Motor Learning as Revealed From Surface EMG,” *J. Neurophysiol.*, vol. 88, no. 2, pp. 991–1004, 2002.

[22] D. W. Franklin, “Impedance control: Learning stability in human sensorimotor control,” *2015 37th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, no. August 2015, pp. 1421–1424, 2015.

[23] A. Pronker, “Estimating an LPV model of neuromuscular admittance with grip force as scheduling parameter,” Delft University of Technology, 2016.

[24] D. W. J. Van Der Wiel, M. M. Van Paassen, M. Mulder, M. Mulder, and D. A. Abbink, “Driver Adaptation to Driving Speed and Road Width: Exploring Parameters for Designing Adaptive Haptic Shared Control,” *Proc. - 2015 IEEE Int. Conf. Syst. Man, Cybern. SMC 2015*, pp. 3060–3065, 2016.

[25] D. A. Abbink and M. Mulder, “Measurements of Muscle Use during Steering Wheel Manipulation,” in *IEEE SMC Conference Proceedings*, 2011, pp. 4–9.

[26] J. Antonin, Z. Rencheng, and N. Kimihiko, “A Scaling Method for Real-Time Monitoring of Mechanical Arm Admittance,” pp. 1551–1556, 2015.

[27] A. J. Pick and D. J. Cole, “Measurement of Driver Steering Torque Using Electromyography,” *J. Dyn. Syst. Meas. Control*, vol. 128, no. 4, p. 960, 2006.

[28] A. J. Pronker, D. A. Abbink, M. M. Van Paassen, and M. Mulder, “Estimating driver time-varying neuromuscular admittance through LPV model and grip force,” vol. 1, pp. 15481–15486, 2017.

[29] H. Nakamura, D. A. Abbink, and M. Mulder, “Is grip strength related to neuromuscular admittance during steering wheel control?,” *Conf. Proc. - IEEE Int. Conf. Syst. Man Cybern.*, pp. 1658–1663, 2011.

[30] W. Mugge, D. A. Abbink, and F. C. T. Van Der Helm, “Reduced power method: How to evoke low-bandwidth behaviour while estimating full-bandwidth dynamics,” *2007 IEEE 10th Int. Conf. Rehabil. Robot. ICORR’07*, vol. 00, no. c, pp. 575–581, 2007.

[31] J. C. F. De Winter and D. Dodou, “National correlates of self-reported traffic violations across 41 countries,” *PAID*, vol. 98, pp. 145–152, 2016.

[32] J. C. F. De Winter and D. Dodou, “The Driver Behaviour Questionnaire as a predictor of accidents: A meta-analysis,” *J. Safety Res.*, vol. 43, no. 1, pp. 85–90, 2012.

[33] R. Fuller, C. McHugh, and S. Pender, “Task difficulty and risk in the determination of driver behaviour,” *Rev. Eur. Psychol. Appl.*, vol. 58, no. 1, pp. 13–21, 2008.

[34] J. C. Verster and T. Roth, “Standard operation procedures for conducting the on-the-road driving test, and measurement of the standard deviation of lateral position (SDLP),” *Int. J. Gen. Med.*, vol. 4, pp. 359–371, 2011.

[35] W. J. Conover and R. L. Iman, “Conoer & Iman 1981 Rank transformation as a bridge between parametric and non parametric statistics.pdf.” American Statistical Association, pp. 124–129, 1981.

[36] F. Faul, E. Erdfelder, A. Lang, and A. Buchner, “G * Power 3 : A flexible statistical power analysis program for the social , behavioral , and biomedical sciences,” *Behav. Res. Methods*, vol. 39, no. 2, pp. 175–191, 2007.

[37] R. Osu *et al.*, “Short- and long-term changes in joint co-contraction associated with motor learning as revealed from surface EMG.,” *J. Neurophysiol.*, vol. 88, no. 2, pp. 991–1004, 2002.

[38] A. J. Pick and D. J. Cole, “Driver steering and muscle activity during a lane-change manoeuvre,” *Veh. Syst. Dyn.*, vol. 45, no. 9, pp. 781–805, 2007.

[39] J. M. Brimacombe, D. R. Wilson, A. J. Hodgson, K. C. T. Ho, and C. Anglin, “Effect of Calibration Method on Tekscan Sensor Accuracy,” *J. Biomech. Eng.*, vol. 131, no. 3, p. 034503, 2009.

A
Individual results

The results from the experiment showed large individual differences in adaptation strategies. For example some participants chose to keep speed constant and only adapt grip force. Also for the absolute speed choices and grip force results, the results show a large between subjects variability. Based on the Δ speed and Δ grip force results, four different individual adaptation strategies can be defined qualitatively:

1) Both speed and grip force adaptation (Δ speed > 5 km/h and Δ grip force > 1.6%)
2) Mainly grip force adaptation (Δ speed < 5 km/h and Δ grip force > 1.6%)
3) Mainly speed adaptation (Δ speed > 5 km/h and Δ grip force < 1.6%)
4) Negligible adaptation (Δ speed < 5 km/h and Δ grip force < 1.6%)

In Figure A-1 the Δ grip versus Δ speed for all participants averaged over all conditions is shown. Based on these mean results the participants are allocated to one of the four categories.

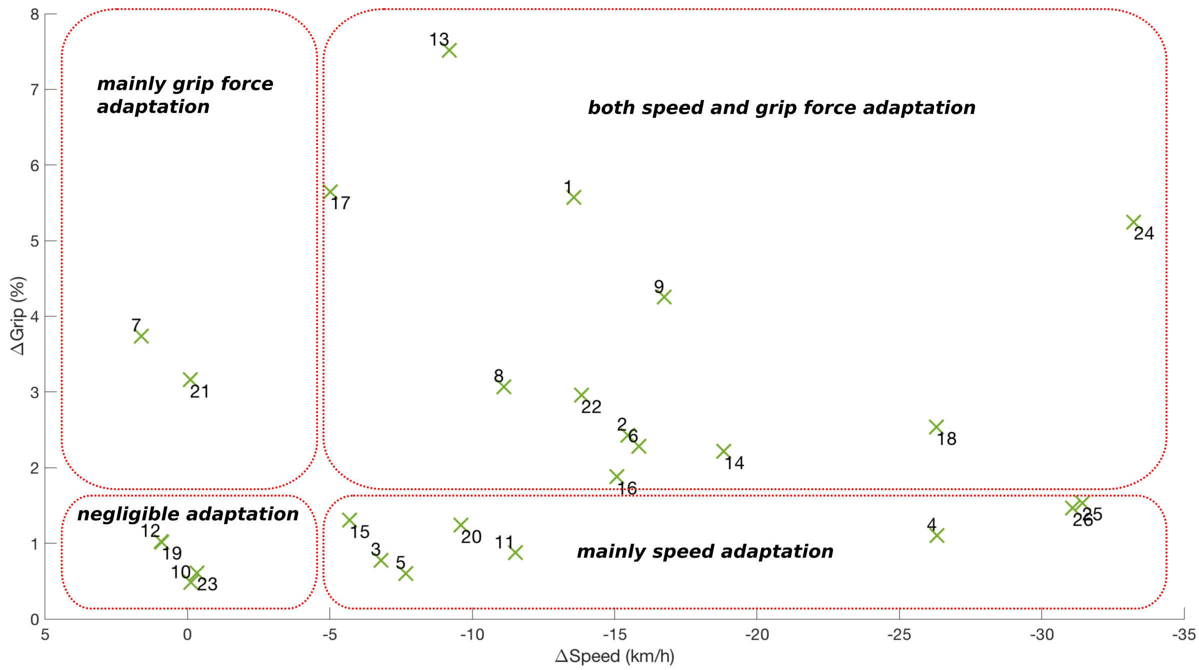

Figure A-1 Qualitatively defined individual adaptation strategies

The following four figures show the results of a single participant from each of the four categories.

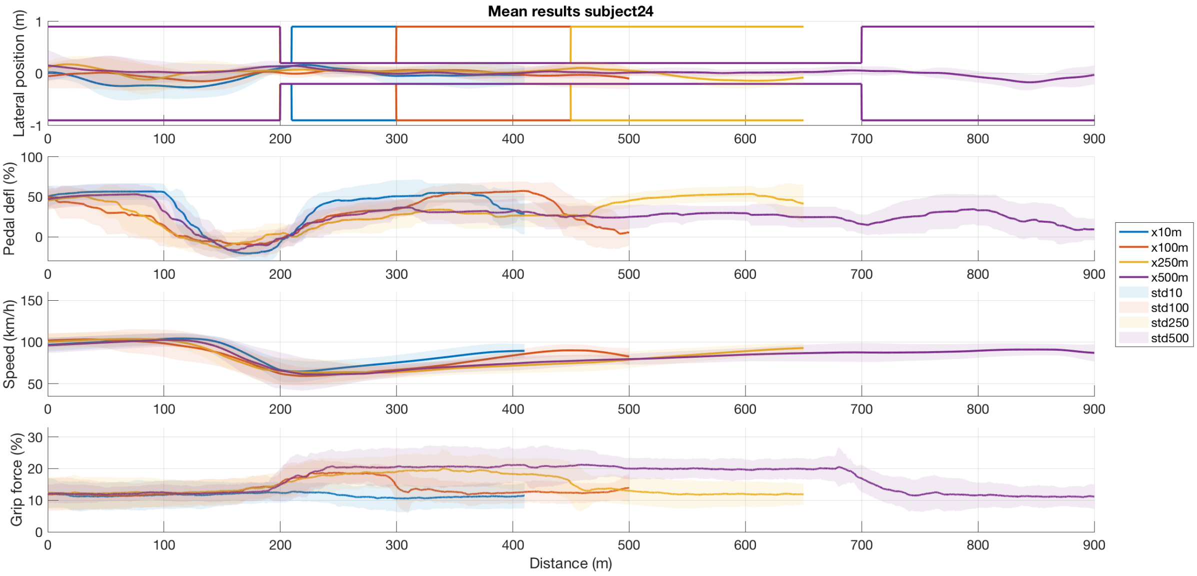

Figure A-2 Mean results over 8 repetitions for subject 24 with adaptation of both speed and grip force in narrow roads sections

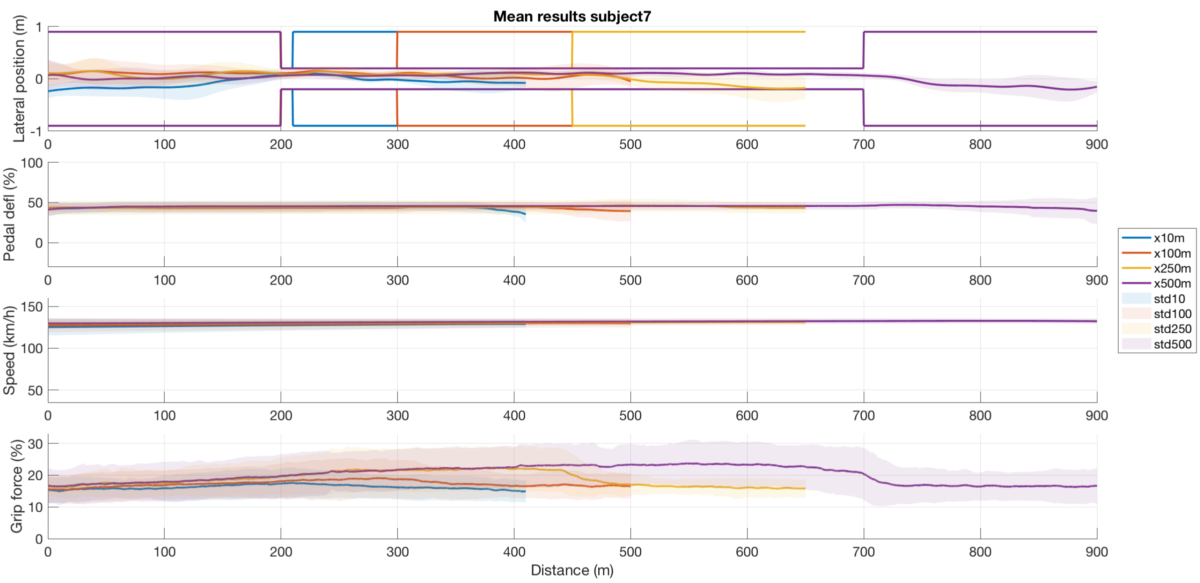

Figure A-3 Mean results over 8 repetitions for subject 7 with mainly adaptation of grip force in narrow section

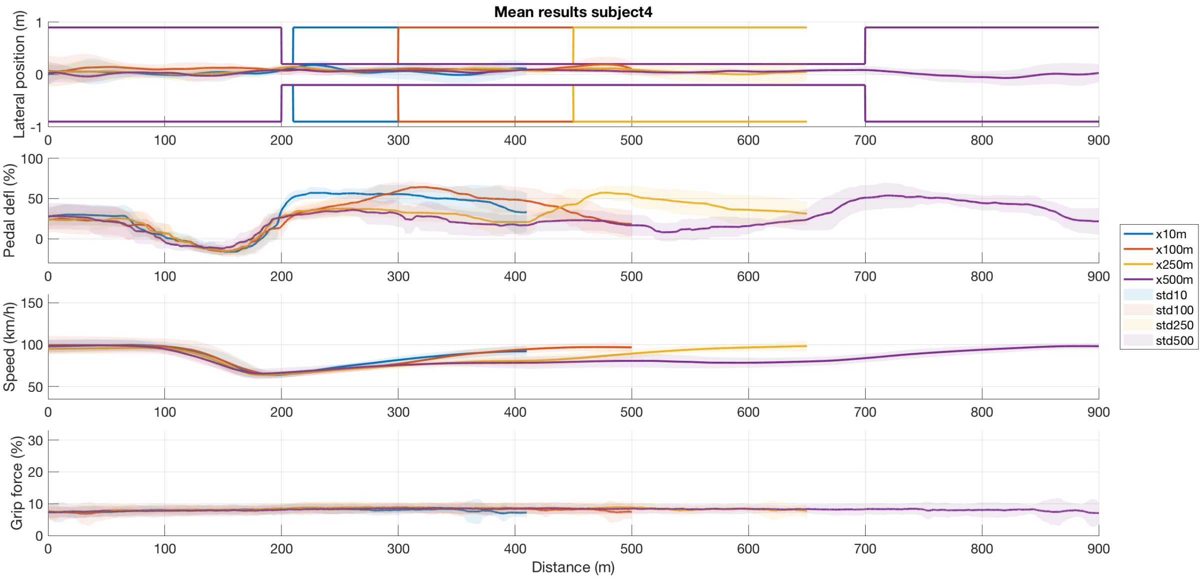

Figure A-4 Mean results over 8 repetitions for subject 4 with mainly adaptation of driving speed in narrow section

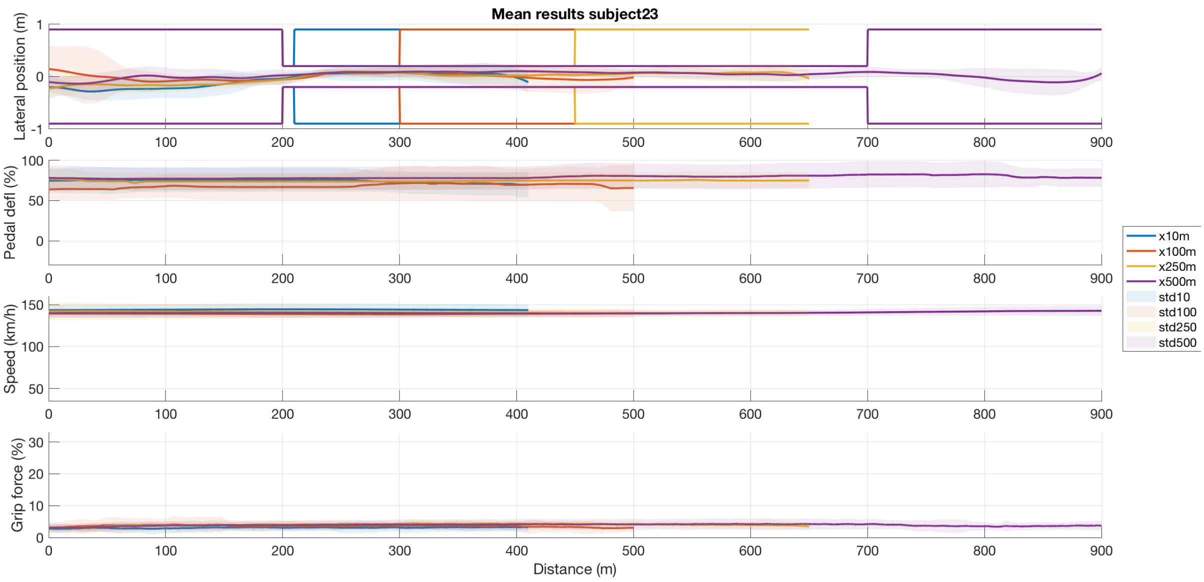

Figure A-5 Mean results over 8 repetitions for subject 23 with negligible speed and grip force adaptation

B
Correlations

B.1. Correlation matrices

Table B-1 Spearman rank-order correlation matrix for the 10m long narrow road

	1	2	3	4	5	6	7	8	9	10	11
1) Mean speed	1										
2) Δ Speed	0.78	1									
3) Mean grip	-0.37	-0.32	1								
4) Δ Grip	-0.07	-0.19	0.60	1							
5) Mean absolute lateral error	-0.23	-0.03	0.28	0.21	1						
6) SDLP	0.14	-0.05	-0.27	-0.19	-0.10	1					
7) Percentage of time off-road	-0.16	-0.03	0.13	-0.04	0.42	0.16	1				
8) SRTE	0.01	-0.06	0.11	0.17	0.21	-0.16	0.03	1			
9) DBQ	0.08	-0.10	-0.23	-0.15	-0.36	-0.08	-0.20	0.002	1		
10) Years license	0.10	-0.06	0.10	0.27	-0.55	0.14	-0.38	-0.47	0.25	1	
11) Mileage	0.10	0.09	0.13	0.15	-0.17	-0.19	-0.14	-0.07	0.47	0.34	1

Table B-2 Spearman rank-order correlation matrix for the 100m long narrow road

	1	2	3	4	5	6	7	8	9	10	11
1) Mean speed	1										
2) Δ Speed	0.65	1									
3) Mean grip	-0.26	-0.15	1								
4) Δ Grip	-0.04	-0.14	0.75	1							
5) Mean absolute lateral error	0.03	0.29	-0.06	0.15	1						
6) SDLP	0.52	0.31	0.01	0.09	-0.06	1					
7) Percentage of time off-road	0.25	0.44	0.01	0.20	0.61	0.52	1				
8) SRTE	0.28	0.07	0.19	0.30	-0.07	0.28	0.15	1			
9) DBQ	0.02	-0.27	-0.19	-0.18	-0.04	-0.05	-0.17	-0.14	1		
10) Years license	0.03	-0.13	0.07	0.08	-0.09	0.01	-0.20	-0.21	0.25	1	
11) Mileage	0.06	0.12	0.13	-0.01	-0.05	-0.18	-0.06	0.01	0.47	0.34	1

Table B-3 Spearman rank-order correlation matrix for the 250m long narrow road

	1	2	3	4	5	6	7	8	9	10	11
1) Mean speed	1										
2) Δ Speed	0.57	1									
3) Mean grip	-0.29	-0.15	1								
4) Δ Grip	-0.06	-0.14	0.76	1							
5) Mean absolute lateral error	-0.24	0.06	0.27	0.20	1						
6) SDLP	0.38	0.26	0.22	0.13	-0.03	1					
7) Percentage of time off-road	0.41	0.39	0.23	0.27	0.47	0.68	1				
8) SRTE	0.22	0.05	0.22	0.30	-0.07	0.30	0.30	1			
9) DBQ	0.02	-0.31	-0.14	-0.01	0.0003	-0.03	-0.10	-0.05	1		
10) Years license	0.02	-0.25	0.04	-0.01	0.06	0.07	-0.07	-0.11	0.25	1	
11) Mileage	0.03	0.03	0.20	0.15	0.11	0.02	-0.02	0.18	0.47	0.34	1

Table B-4 Spearman rank-order correlation matrix for the 500m long narrow road

	1	2	3	4	5	6	7	8	9	10	11
1) Mean speed	1										
2) Δ Speed	0.51	1									
3) Mean grip	-0.27	-0.09	1								
4) Δ Grip	-0.08	-0.20	0.75	1							
5) Mean absolute lateral error	-0.25	0.14	-0.02	0.11	1						
6) SDLP	-0.14	0.02	0.10	0.06	-0.14	1					
7) Percentage of time off-road	0.08	0.15	0.03	0.13	0.38	0.42	1				
8) SRTE	-0.14	-0.19	0.46	0.59	-0.16	0.09	-0.08	1			
9) DBQ	0.07	-0.29	-0.19	0.05	0.22	0.19	0.21	0.02	1		
10) Years license	0.08	-0.26	0.01	0.08	0.01	0.11	0.04	-0.07	0.25	1	
11) Mileage	0.02	-0.002	0.12	0.19	0.08	-0.07	-0.03	0.24	0.47	0.34	1

B.2. Correlations between conditions

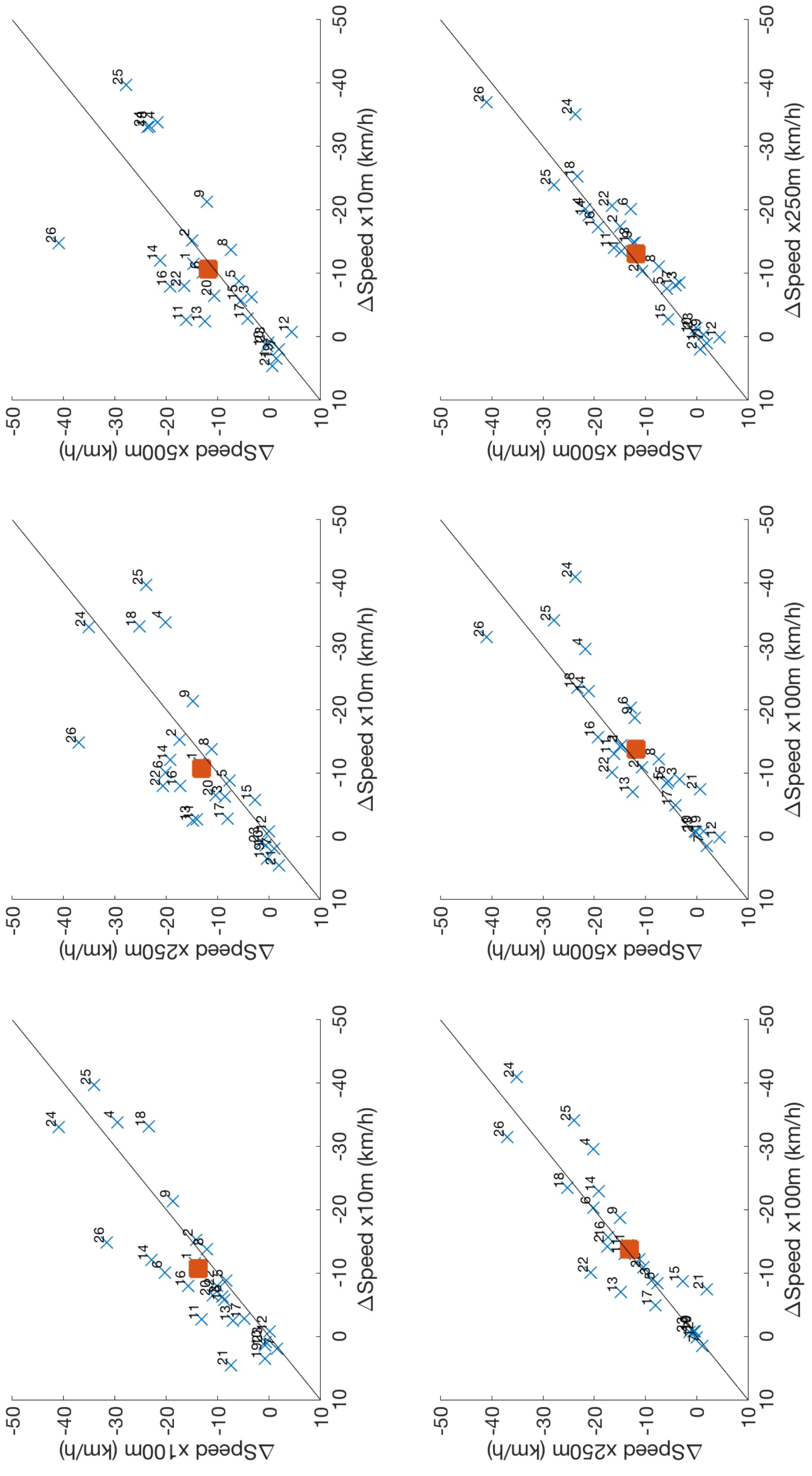

Figure B-1 Δ Speed for each condition compared to each of the three other conditions

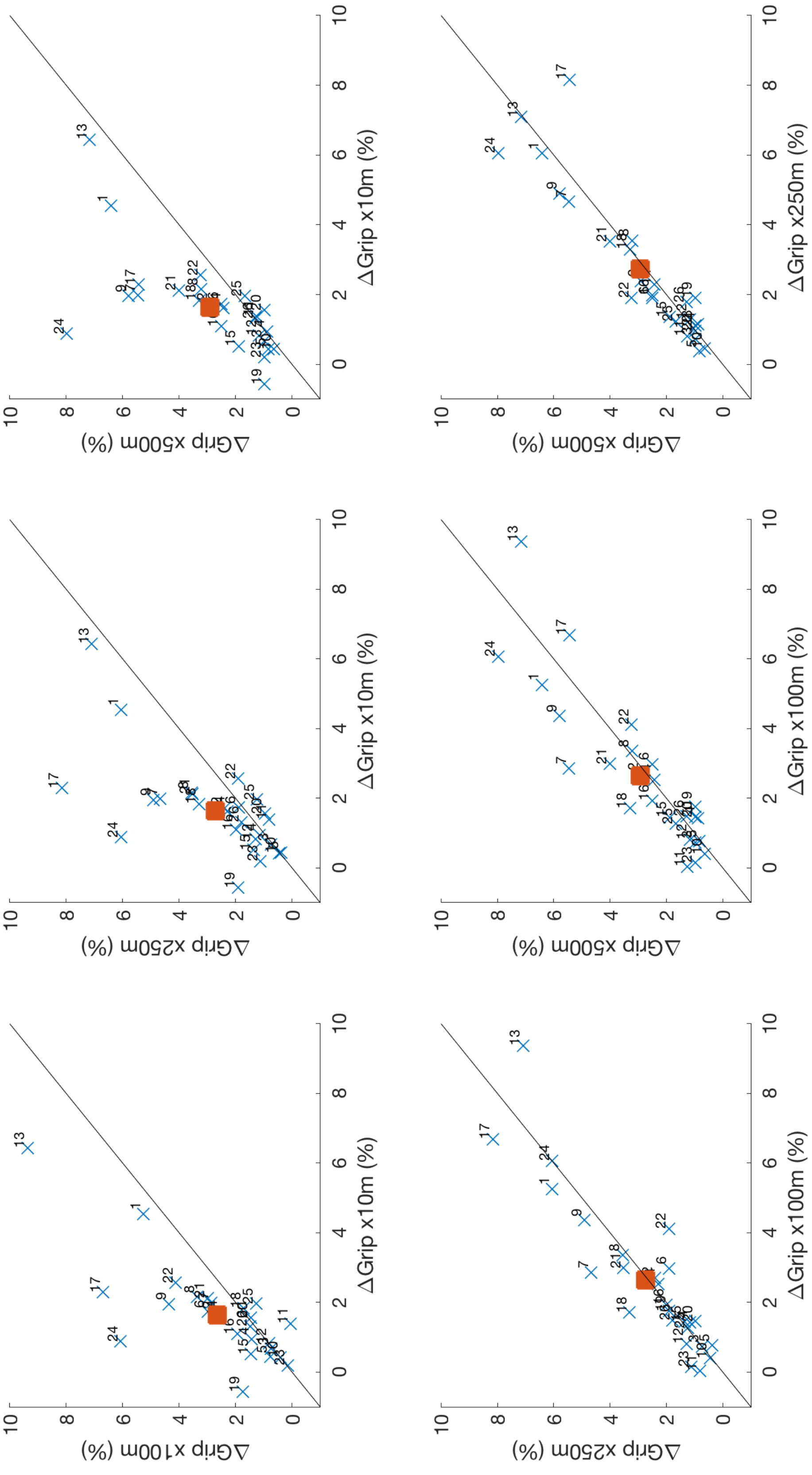

Figure B-2 Δ Grip force for each condition compared to each of the three other conditions

B.3. Correlations between measures

Six correlation figures are made for the four main measures: Δ Speed, Δ Grip force, percentage of time off-road and the Self Reported Task Effort (SRTE).
1) Δ Speed vs. Δ Grip, 2) Δ Speed vs. off-road, 3) Δ Speed vs. SRTE, 4) Δ Grip vs. off-road, 5) Δ Grip vs. SRTE and 6) SRTE vs. off-road

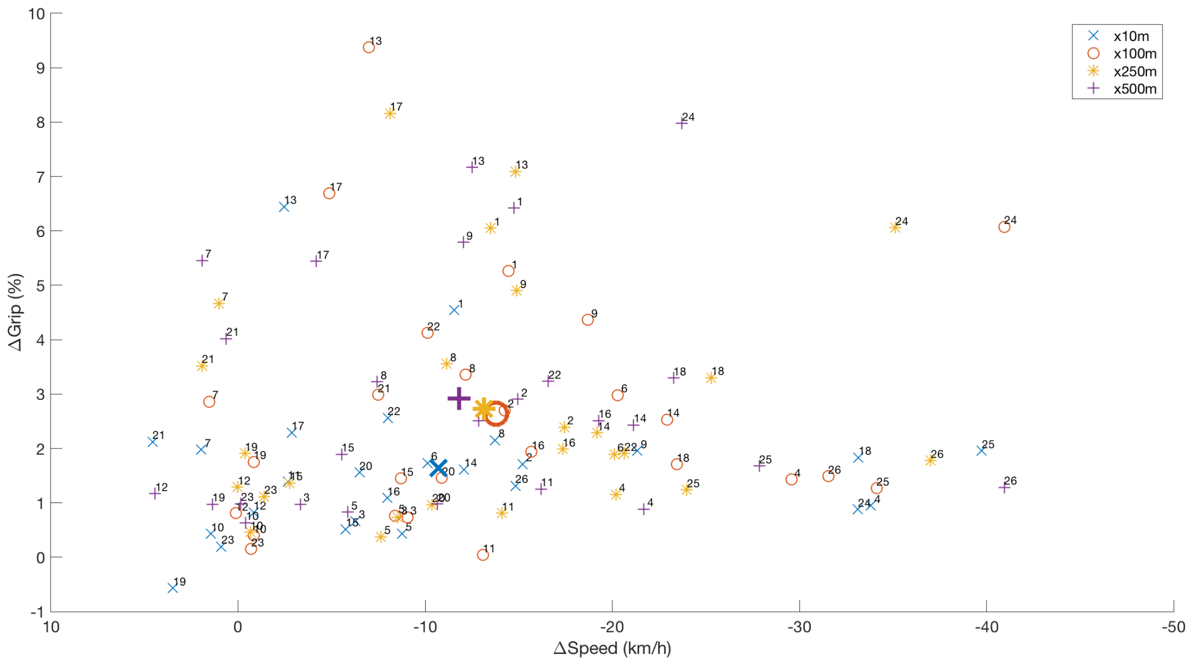

Figure B-3 Δ Speed vs. Δ Grip force

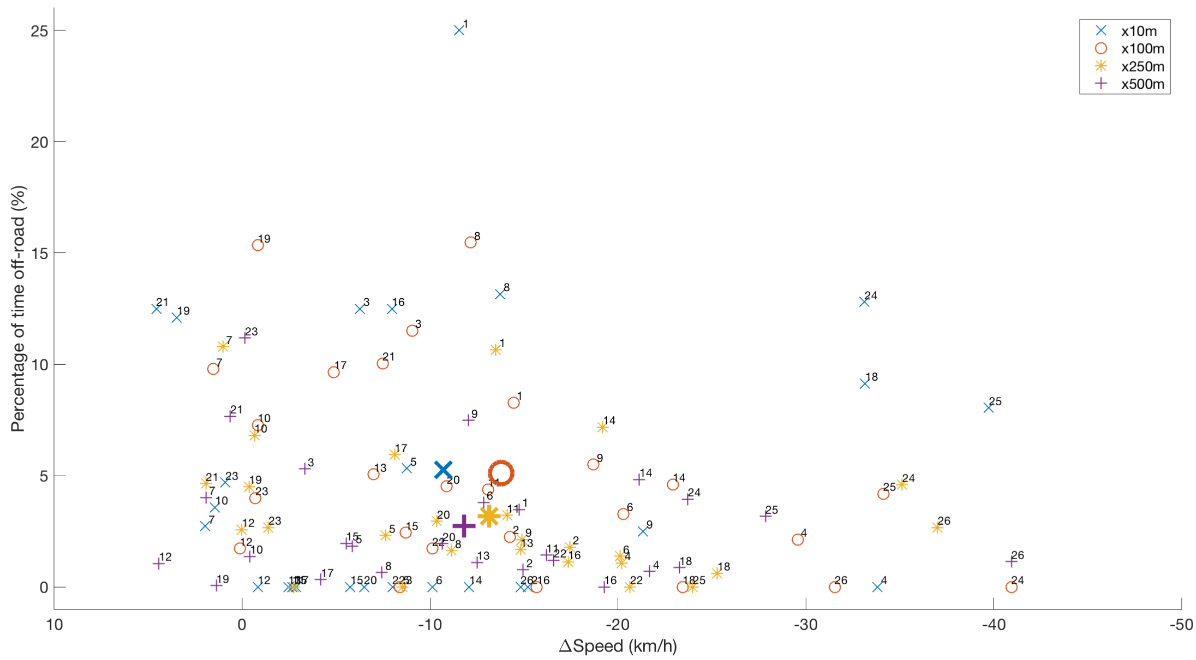

Figure B-4 Δ Speed vs. Percentage of time off-road

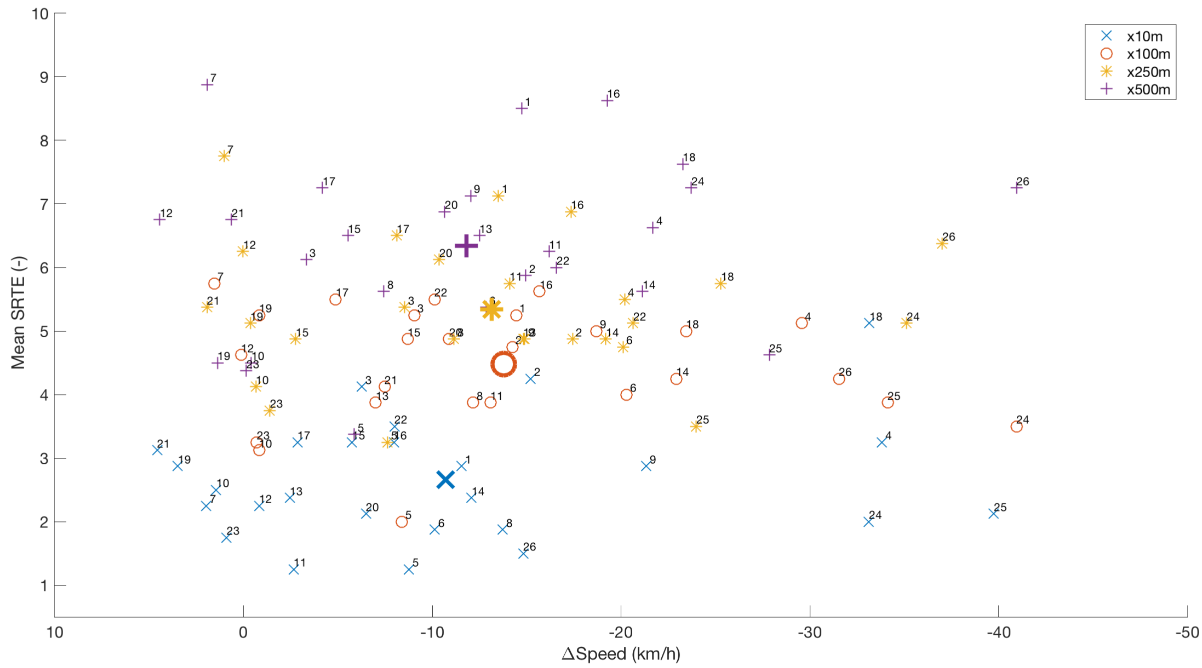

Figure B-5 Δ Speed vs. Self Reported Task Effort (SRTE)

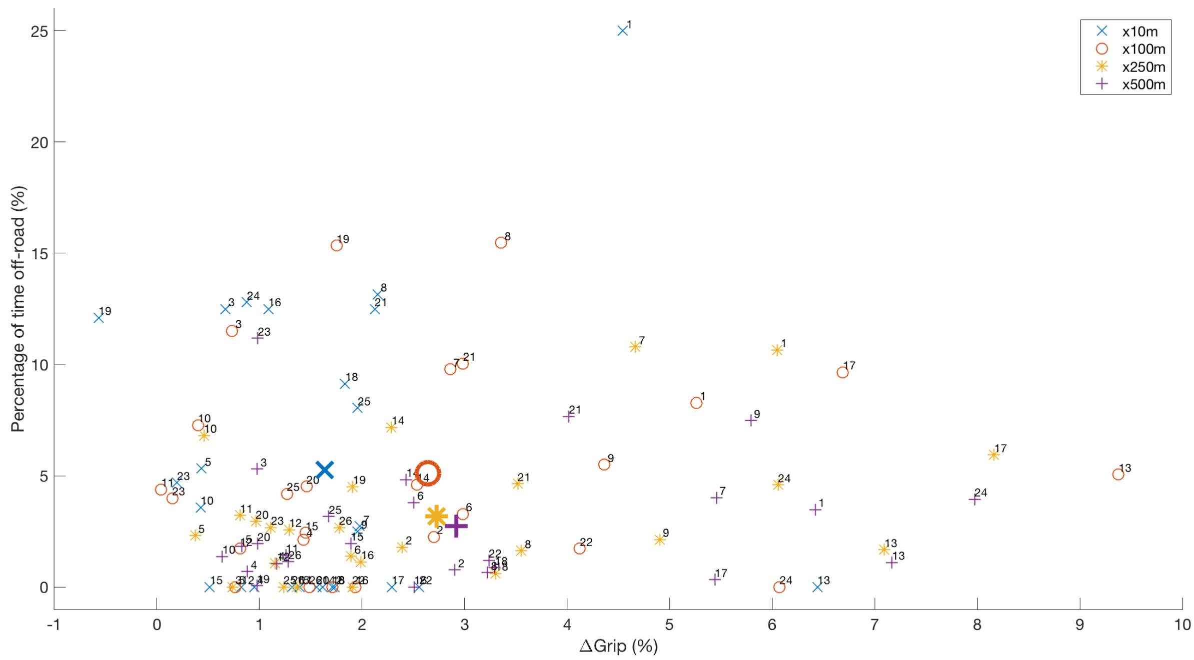

Figure B-6 Δ Grip force vs. Percentage of time off-road

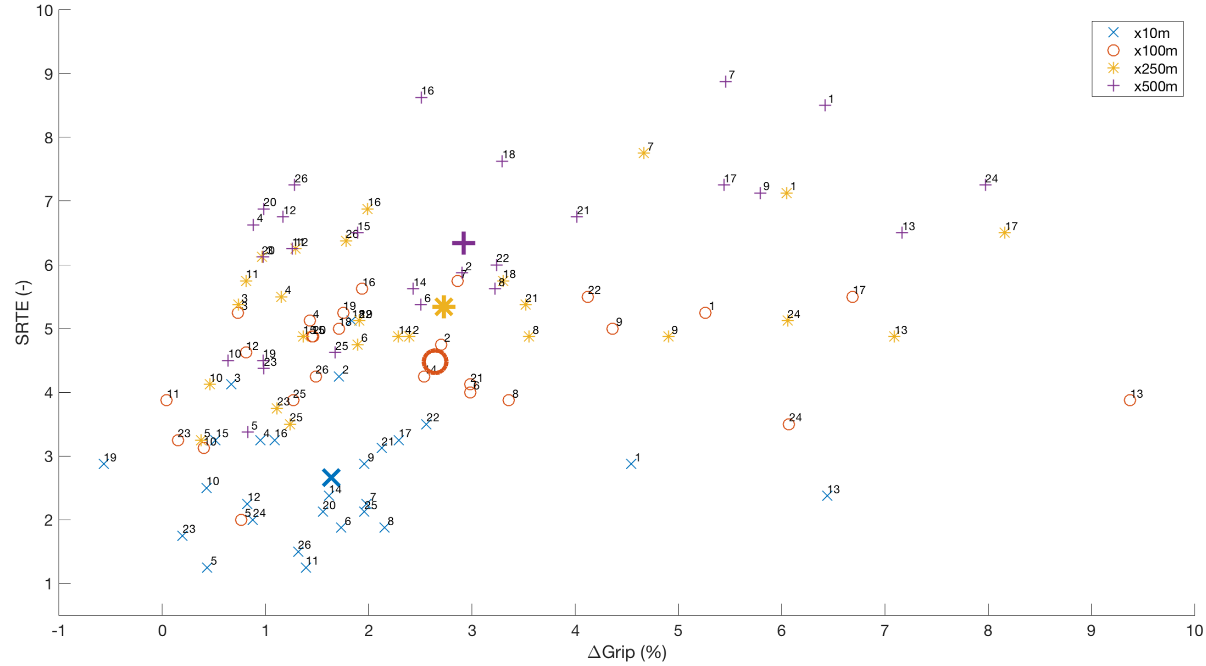

Figure B-7 Δ Grip vs. Self Reported Task Effort (SRTE)

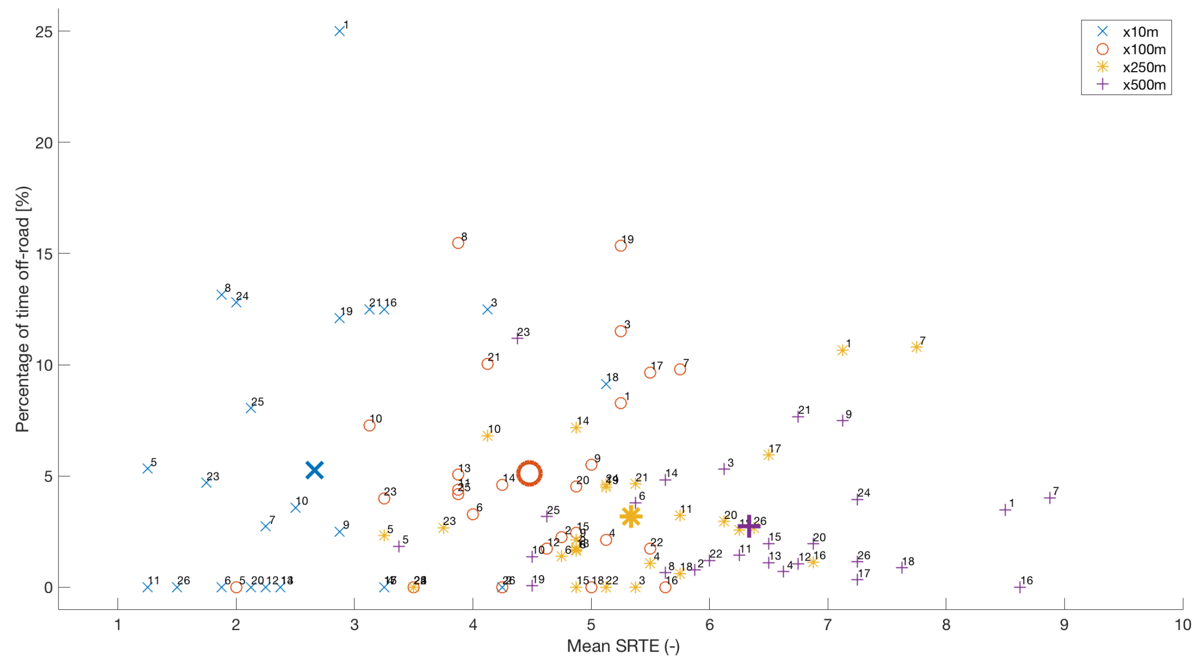

Figure B-8 Self Reported Task Effort (SRTE) vs. Percentage of time off-road

In order to see how the performance decreases with an absolute higher speed or increases with an absolute higher grip, correlation figures are created for these mean measures.
1) Mean speed vs. off-road, 2) Mean grip vs. off-road and 3) Mean speed vs. mean grip

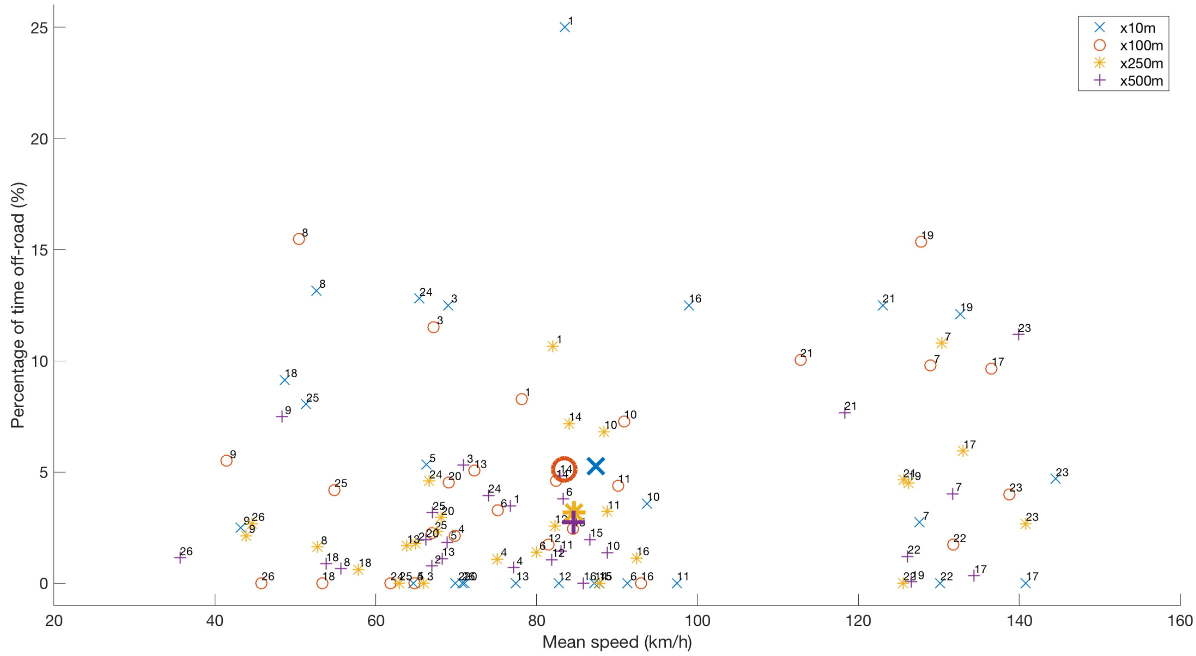

Figure B-9 Mean speed vs. Percentage of time off-road

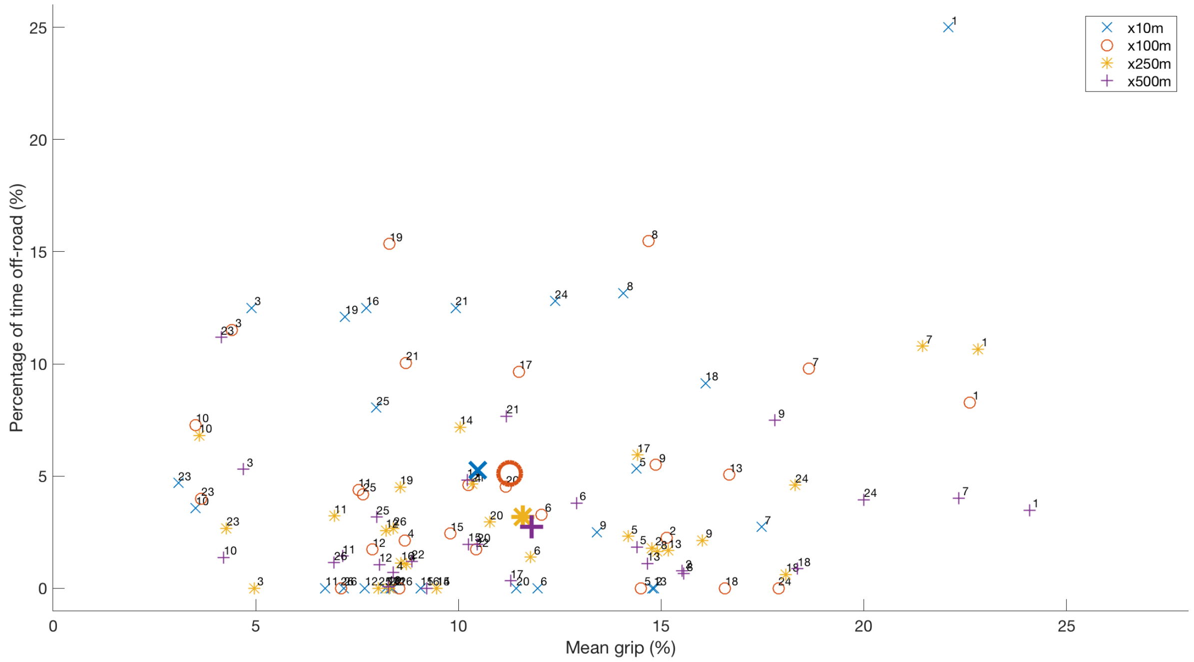

Figure B-10 Mean grip vs. Percentage of time off-road

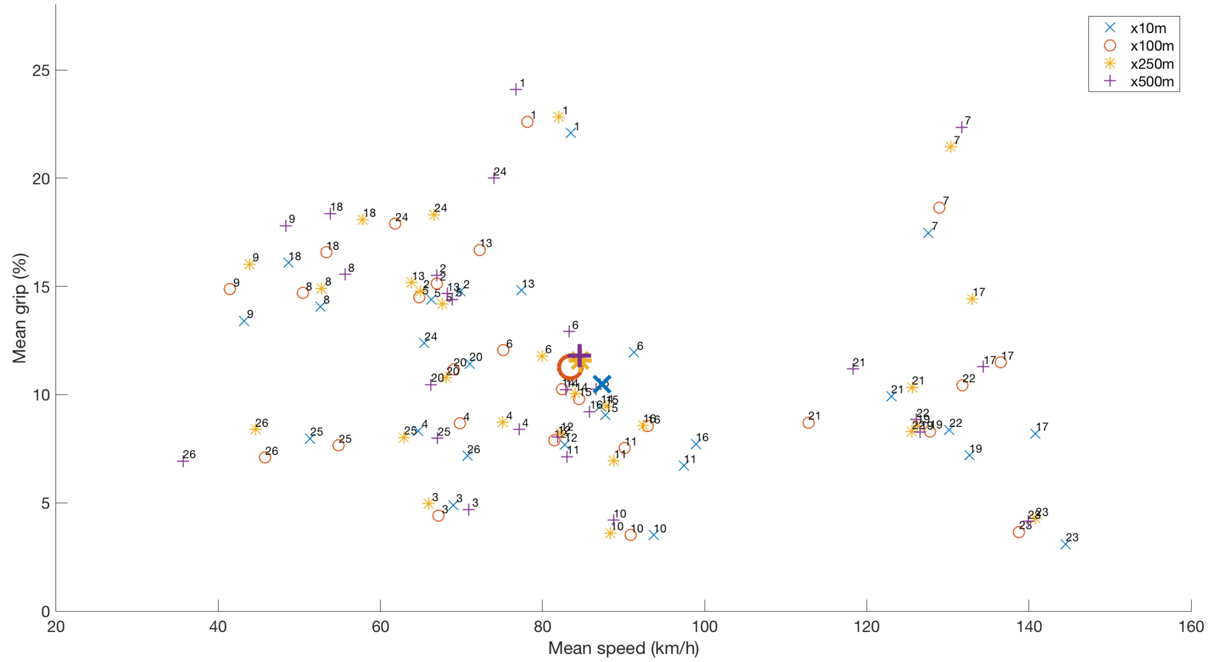

Figure B-11 Mean speed vs. Mean grip force

C
Calibration grip force sensors

C.1. Calibration method

The Tekscan grip sensor 4256E is used during the entire experiment to measure grip force applied on the steering wheel by the drivers. The Tekscan sensor consists of a thin, high-resolution sensor that can be attached to a glove. Each sensor has eighteen sensing regions and each sensing region has multiple sensing elements, or sensils, to measure pressure points on the hand [1]. For the experiment the grip data is measured and synchronized with the data measured in the simulator, the Tekscan output is logged at 20 Hz.
Two main problems arise when using the Tekscan sensors, first the individual differences that are present and second it is known that the Tekscan sensors can experience signal degradation, which is for example a loss of sensitivity over time [2]. Pronker [3] assumed a linear relation between grip force sensor output and grip force applied on the steering wheel and converted the raw output of the sensors according the specifications of the Tekscan sensors.

The individual differences comprise the differences in the size of the hands of participants and differences in strength of the hands. Not the entire hand area will be fully covered for all participants when wearing the gloves. Also when wearing the gloves, no direct connection between hands and steering wheel, might have caused inaccuracies due to slipping of hands for example. A calibration is needed in order to take the individual differences into account. To account for the differences in strength, the grip force was expressed in relative grip force for each participant. The scaling based on the maximum grip force was chosen to express the grip force in percentages for each participant. This was an intuitive method to compare participants, also used by Eksioglu [4]. On the narrow sections individual participants applied on average did not apply more than 40% of their max grip force on the steering wheel This percentage coincides with the results of Eksioglu, who measured on average around 30% of the maximum force.
A calibration procedure that provides a uniform distribution of a known force to the sensils is needed before the experiment. Tekscan itself provides equilibration devices, however these are not usable anymore when the sensors are attached to gloves. The Tekscan sensors were brand new before the start of the experiment and glued with flexible glue on thin gloves. In order to investigate other different possible calibration procedures, first small weights were used to apply a known force to the sensil area, however these did not provide the desired uniform distribution on the sensils. Hereafter it was found that a balloon shaped object would provide the uniform distribution and that a calibrated hand dynamometer would be a successful tool to calibrate the grip sensors before each experiment.

Figure C-1 Left: hand dynamometer, middle: gloves with Tekscan sensors, right: raw sensil output while applying a force to the hand dynamometer

C.2. Analysis

During the calibration procedure videos were recorded of the display of the hand dynamometer. These videos were used to measure the actual loads that participants were applying during all load conditions. In Table C-2 the recorded hand dynamometer outputs are shown for each load condition. Since often participants had an overshoot when applying the force, the peak value is listed next to the mean hold value.

In order to calculate the mean raw output of the Tekscan sensors for each load condition, first the area in the figure is selected where participants applied the prescribed force. Then the mean raw output of this selected area is computed. In order to exclude effects of the selected area, the indices were determined where the output is less than 95% of the mean value of the first selected area. The first and last indices where the output is larger than 95% of the mean value are used as the start and endpoint for calculating the mean value. Over this region the mean and maximum value were computed. The calculated mean value for each load condition is shown in the left figure of Figure C-2, Figure C-3 and Figure C-4.

C.3. Results

The mean results and dynamometer output results for each load condition is shown in Table C-1. The raw output of the Tekscan decreases with the participants that participated. Especially the fixed load output of the calibration task showed a decrease in signal output, for the last participant the raw output was only around 50% of the output for the first participant. Nevertheless the raw output was also for the last participants still large enough to see differences in grip force between the wide and narrow road during driving.

However it can be seen that the raw output mainly decreases with the first ten participants that participated. Whether this decrease is caused by pre-tension between the gloves and the glued sensors or by degeneration of the sensors is unknown. Nevertheless since there is a clear decrease visible in the total output during the experiment, the results emphasize the importance of performing a calibration task before the experiment. It might also be that during the experiment the raw output of the sensors decreased. A post calibration at the end of the experiment would have been needed to investigate whether the grip force output was also influenced by signal degradation during the experiment. Despite this, the decrease in grip force within the experiment due to the learning effect was on average still larger than the decrease in grip force between two consecutive calibration tasks of two individual participants.

For all subjects the linear fit is based on all measurements. Note that this is different from the relation that is used during the experiment where only the no load and the maximum load condition are used to determine the relative grip force. In Figure C-2, Figure C-3 and Figure C-4 three examples are shown of the calibration results. It can be seen that the no load output for subject 1 in Figure C-2 is higher than the other two subjects and therefore the linear fit is less good for this subject.

In Figure C-3 the calibration results of subject 20 is shown as an example of a good linear fit and also the raw output for the left and right hand is the same for all load conditions. For some subjects a difference between the raw output of the sensors for the left and right hand can be seen, for example subject 20, see Figure C-4. The linear fit is still good, however probably due to the difference in fit of the gloves on the left and right hand, a different output for the left and right hand is recorded.

Table C-1 Raw Tekscan output for each hand for the mean values of the different load conditions

	Left					Right				
	0	5	10	15	Max	0	5	10	15	Max
	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)
Subject	$\cdot10^3$	$\cdot10^3$	$\cdot10^3$	$\cdot10^3$	$\cdot10^3$	$\cdot10^3$	$\cdot10^3$	$\cdot10^3$	$\cdot10^3$	$\cdot10^3$
1	1.93	18.54	32.34	25.76	35.29	2.82	20.01	32.36	26.22	41.16
2	1.57	15.84	27.22	21.14	36.55	2.27	20.10	32.20	26.25	44.25
3	1.63	15.03	23.89	17.29	32.93	1.98	17.76	30.58	24.39	34.59
4	0.47	12.56	24.88	15.83	37.20	1.76	16.43	29.53	23.05	42.23
5	0.11	8.87	19.49	15.30	18.92	0.79	12.60	24.41	18.58	23.97
6	0.37	8.18	19.26	10.03	32.60	0.63	13.27	28.71	18.51	36.34
7	0.26	9.48	21.70	14.06	25.33	0.87	11.39	25.29	16.30	27.04
8	0.34	9.07	20.49	11.87	21.71	0.52	10.41	23.01	15.96	26.13
9	0.13	8.20	20.27	11.44	17.35	0.41	8.13	18.99	12.80	21.00
10	0.56	11.44	23.44	15.71	43.42	0.74	15.85	24.02	18.88	41.83
11	0.086	7.58	19.99	12.59	25.23	0.38	11.15	22.48	16.76	23.20
12	0.35	9.75	18.19	12.95	26.15	0.24	7.96	19.28	13.40	25.74
13	0.41	7.55	20.90	15.33	22.10	0.14	8.27	21.80	13.50	22.66
14	0.24	7.77	20.36	12.96	21.70	0.20	8.66	16.76	12.90	27.50
15	0.20	8.69	20.97	12.49	26.27	0.52	9.26	20.96	14.07	31.80
16	0.066	8.86	19.92	14.26	31.29	0.49	11.79	24.09	17.02	39.99
17	0.25	7.69	20.79	13.35	22.70	0.40	9.31	19.75	14.47	26.52
18	0.021	6.38	17.26	12.00	21.05	0.22	6.64	18.12	12.29	19.99
19	0.0053	6.76	18.15	12.03	20.40	0.23	9.17	20.23	13.72	27.42
20	0.030	4.84	13.73	8.16	18.24	0.049	7.10	16.98	12.04	23.30
21	0.11	4.66	13.57	7.29	19.92	0.022	5.32	12.74	8.49	23.59
22	0.010	5.59	16.55	10.26	22.53	0.21	6.20	16.47	9.63	25.59
23	0.062	6.49	16.69	10.36	26.41	0.12	7.68	18.01	12.21	32.57
24	0.061	6.92	16.57	8.18	13.55	0.017	5.49	13.92	14.09	15.65
25	0.051	5.96	14.61	9.53	13.92	0.026	5.62	15.39	9.82	14.84
26	0.044	6.71	16.36	8.77	16.52	0.084	5.25	14.61	8.95	23.85
M	0.36	8.82	19.91	13.034	24.97	0.63	10.42	21.57	15.55	28.57

Table C-2 Hand dynamometer outputs for each load condition

Subject	Left hand 10 kg Hold	Left hand 10 kg Peak	Left hand 15kg Hold	Left hand 15kg Peak	Left hand 5 kg Hold	Left hand 5 kg Peak	Left hand max kg Hold	Left hand max kg Peak	Right hand 10 kg Hold	Right hand 10 kg Peak	Right hand 15kg Hold	Right hand 15kg Peak	Right hand 5 kg Hold	Right hand 5 kg Peak	Right hand max kg Hold	Right hand max kg Peak	Notes
1	10	10	15.5	16	5	5.5	18	19	10	10	15	16.5	5	5	21	22	
2	10	11	15.5	15.5	5	5	32	34	10.5	10.5	14.5	15	5	5	29	29	
3	10	10	15	15.5	4	4.5	23	23	10	10	14	15	5	5	19	21	
4	10	11	15	15	5	5.5	29	29	10	10	15	16.5	5	5	29	30	Left 5kg: two efforts, value from 2nd
5	9	10	13.5	14.5	5	5	13	13	9	10	15.5	14	5	5	15	15	Left 5 kg: two efforts, value from 1st, right 5 kg: first high peak (11.5 kg), then 5 kg
6	10	10.5	15.5	15.5	5.5	5.5	25	25	10	12	14.5	14.5	5	6	22	22	Right 10 kg: first hold low on 5 kg
7	10	10.5	16	16	5	6	19	19	10	10.5	15	16	5	6	17	17	
8	10	11	15	15	5	6	15	15	9.5	9.5	15	15	5	6	20	20	
9	10	10	15	15.5	5	6	14	14	10	10	15	15	5	5	17.5	17.5	
10	10	10	15	16.5	5	5	38	38	9.5	10	15	15.5	7.5	7.5	42	42	Left 10 kg: first hold at 5 kg, then 10 kg --> remove first part
11	10	11.5	15.5	15.5	5	5	19.5	19.5	10	10.5	14.5	15	5	6.5	16.5	16.75	Right 10 kg: two efforts (first one to 15), value from 2nd
12	10	11	15	16.5	5	5	22	22	10	10	15	15	5.25	5.2	19.5	19.5	
13	9.75	9.75	15	15	5	5.5	17.5	17.5	10	11.75	15	15	5	5	18	19	
14	10	12.5	15	16.5	4	4.5	17	17	9.5	11	14.5	15	5	5	20	20	
15	10.5	12	15	15	5	6	25	25	10	11	14.5	15.5	5	6	26	27.5	
16	10.5	11	15.5	15.5	5	5	28	28	10	12	15	15	5	5	34	34	
17	10	10	15	15	5	6.25	17	18	10	11	14.5	15	6.75	6.75	20	21	Left 10 kg: after 10 kg, peak to 15, should be removed, right 10 kg: 3rd effort is correct
18	10	10	15	15.25	5	6	18	18	10	12	15	16.5	6.75	6.75	17	18	Left 10 kg: first hold at 5 kg, then 10 kg --> remove first part
19	10.5	11.5	15.5	17.5	5	5	18.25	18.25	9.75	12	14.5	15	5	5.25	23	23	Right: 15 and 5 kg are exchanged first 5 and than 15
20	10.5	11.25	15	15	5	5	20	21.5	10	10	14	15	5	5	19.5	19.5	
21	10	11	16	16	5	7	25	25	9.75	12.5	14	16.5	5	5	27	27	
22	10	10	15	17.5	5	5	21	23	10	11	14.5	17	5.25	5.25	24.25	24.25	Left 10 kg: first hold at 5 kg, then 10 kg --> remove first part
23	10	11	15	16	5	5.75	25	28	10	11	14.5	15	5	6	32	32.5	
24	9.75	11	14.5	15	6	6	13	13	9.5	10	14.5	14.5	5	5	14.5	14.5	Left 10 kg: first hold at 5 kg, then 10 kg --> remove first part
25	10	11	15	15.5	5	5.5	15.5	15.5	9.25	11	14.5	15	5.5	5.5	14	14	Left 10 kg: first hold at 5 kg, then 10 kg --> remove first part
26	9	9.75	15	16	5	6	16	16.5	9.5	10	14	16.5	6	6	22	23	Right 10 kg: first hold at 5 kg, then 10 k, first part removed

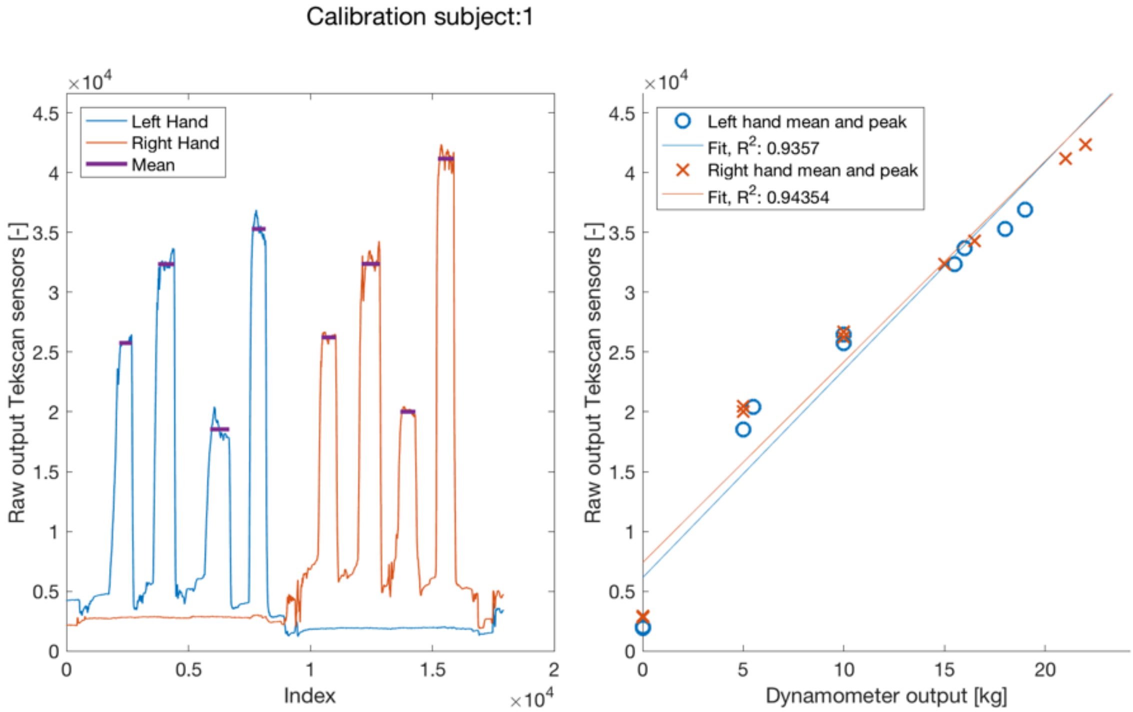

Figure C-2 Calibration results subject 1, left: raw output for each load condition (10 kg, 15 kg, 5 kg and max) for the left (blue) and right (red) hand.

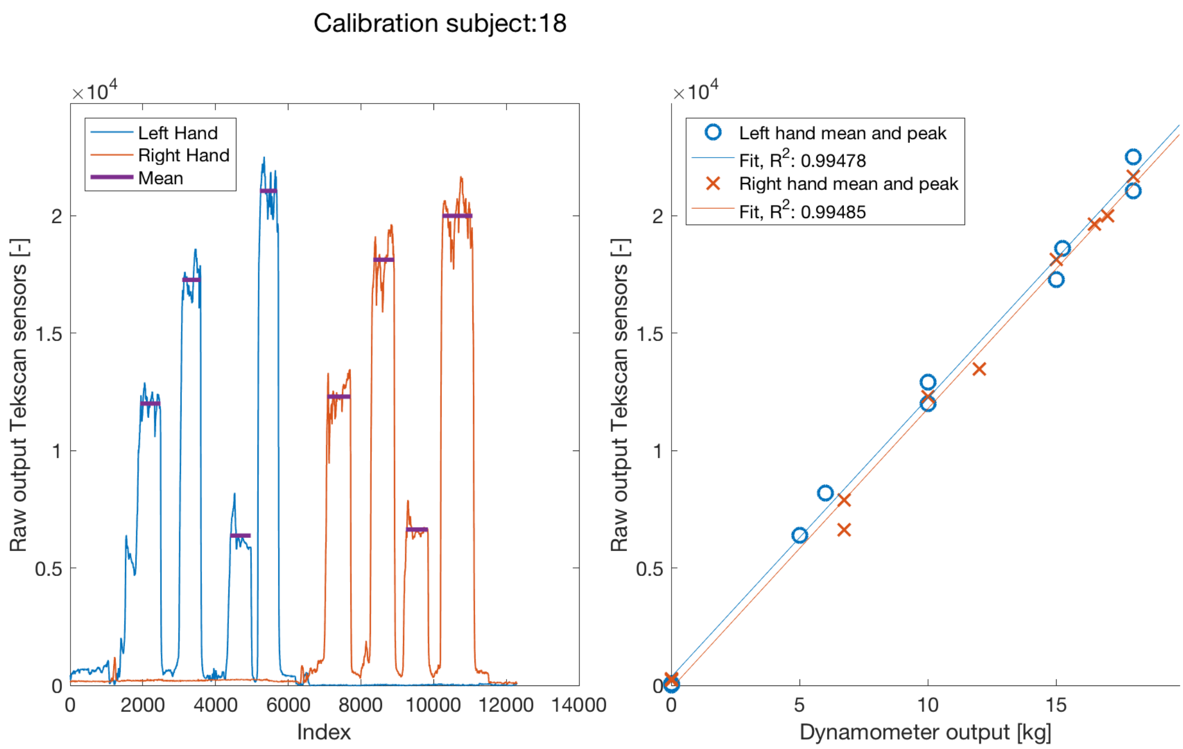

Figure C-3 Calibration results subject 18, left: raw output for each load condition (10 kg, 15 kg, 5 kg and max) for the left (blue) and right (red) hand.

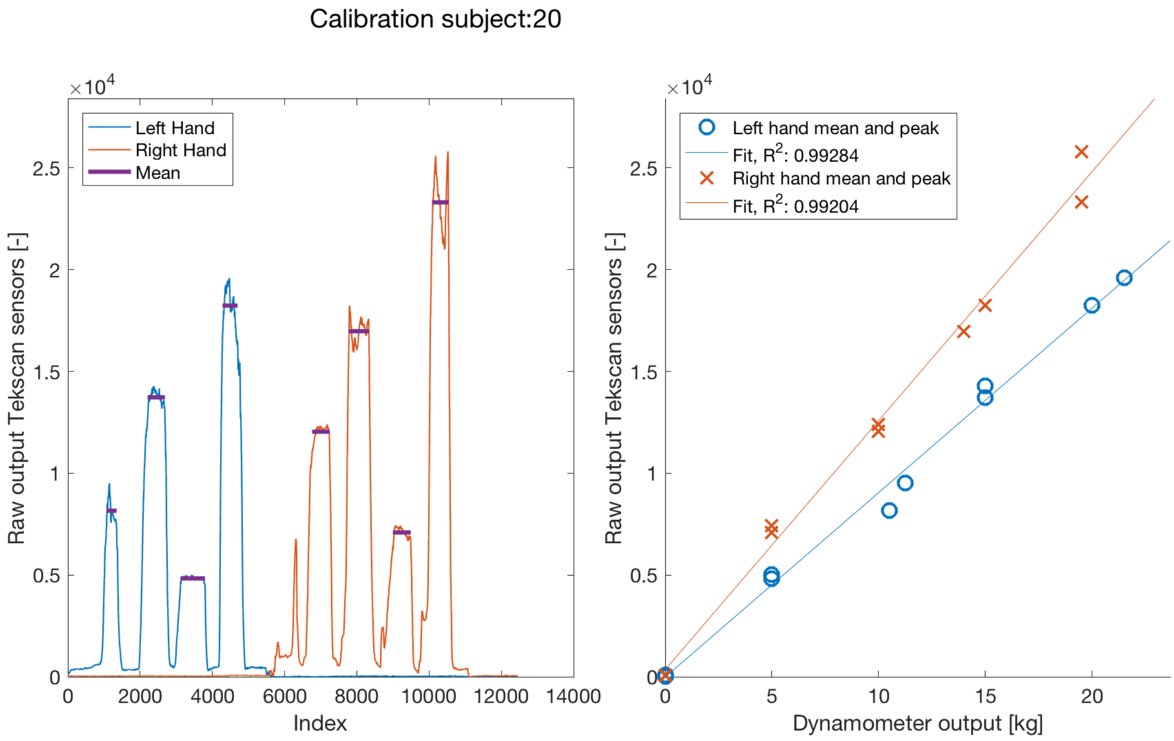

Figure C-4 Calibration results subject 20, left: raw output for each load condition (10 kg, 15 kg, 5 kg and max) for the left (blue) and right (red) hand.

D
Road design

For final experiment 10m, 100m, 250m and 500m narrow road lengths were used. The straight sections are separated with randomly generated left and right curves. The same amount left and right curves were generated. The curves are placed in the same order for all three roads; only the order of the narrow sections is different for the three roads. The three different roads that are designed consists all 8 out of the 24 possible permutations of the four conditions. In Table D-1 the randomly assigned permutations for each road are shown.

Table D-1 The 24 possible permutation orders distributed over the three roads

Road	Rep nr	Permutation order			
Road 1	1	10m	100m	250m	500m
	2	500m	250m	10m	100m
	3	250m	500m	100m	10m
	4	100m	250m	10m	500m
	5	500m	100m	250m	10m
	6	250m	100m	500m	10m
	7	500m	10m	100m	250m
	8	100m	10m	250m	500m
Road 2	1	250m	10m	100m	500m
	2	100m	250m	500m	10m
	3	10m	250m	500m	100m
	4	10m	500m	250m	100m
	5	500m	100m	10m	250m
	6	10m	100m	500m	250m
	7	100m	500m	250m	10m
	8	100m	10m	500m	250m
Road 3	1	500m	250m	100m	10m
	2	250m	10m	500m	100m
	3	500m	10m	250m	100m
	4	100m	500m	10m	250m
	5	10m	250m	100m	500m
	6	10m	500m	100m	250m
	7	250m	500m	10m	100m
	8	250m	100m	10m	500m

The frequency content of the perturbation is shown in **Table D-2**. For the final experiment the perturbation signal was scaled to a SD of 0.13 Nm.

Table D-2 Frequency, amplitude and phase shift of the sinusoids in the multisine perturbation signal

N	Frequency [Hz]	Amp [-]	Phase [rad]
1	0.25	1	2.91
2	1	1	2.87
3	2	1	3.78
4	4.25	0.65	4.20
5	8.75	0.65	4.94
6	18	0.65	3.30

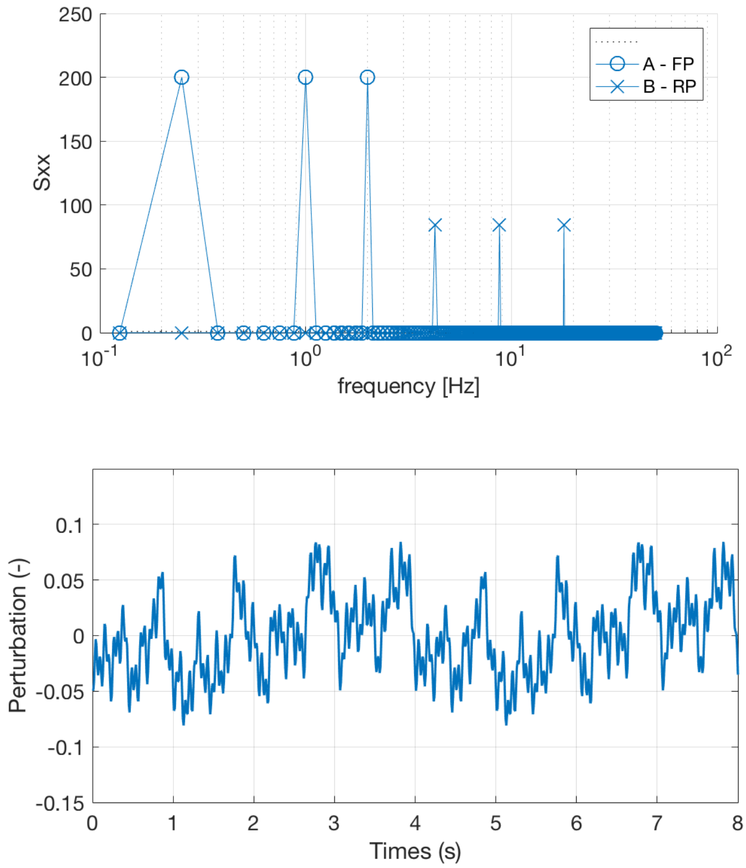

Figure D-1 Perturbation signal that was applied to the steering wheel during the experiment

E
Informed Consent form and questionnaire

E.1. Informed consent

Informed consent for human subject research

Driver adaptation study – Ellen Hogerwerf

Before agreeing to participate in this study it is important that the information in this document is carefully read and understood. This document will describe the purpose, procedures, risks and possible discomforts of this experiment.

You are invited to take part in a research study in the fixed-based driving simulator located at the faculty of Aerospace Engineering of the Delft University of Technology. The goal of this study is to investigate adaptation by the human driver to changes in the environment. The outcome of this study will be statistically analysed and published in a Master thesis, and potentially be used in a scientific publication as well.

Procedure
Before you start you will be asked to carefully read and sign this consent form, to read the instructions and to fill out some personal details. The total length of the experiment will be approximately 45 minutes.
You will wear gloves with grip force sensors during the entire experiment. First you are asked to put these gloves on and to perform a calibration task with a hand dynamometer. Please hold the bulb of the hand dynamometer in your left hand and squeeze for 5 seconds at respectively 10 kg, 15 kg, 5 kg and maximum force. Repeat this procedure with your right hand.
The driving task will start with a 7-minute practice session in order to familiarize with driving simulator environment. Once the training is completed, you will be asked to drive a rural road track in the simulator for about 20 minutes. The driving task consists of completely manual driving, which means that you are free to control the speed of the vehicle yourself and you also have to steer. Imagine you are driving a normal Dutch car in the simulator, which means that you're sitting on the left chair in the vehicle. The front of the car is visualized on the screen during driving.

Please drive the entire track as you normally would drive.

You will experience small perturbations on the steering wheel during the experiment, which can be considered as wind gusts or bumps on the road. On the side of the road cones are positioned at the lane boundaries between which you will have to stay. Please try to **not hit any cone during driving!** When a cone is hit, you will experience an uncomfortable vibration on the steering wheel, which you should avoid.
Please hold the steering wheel with your hands at a "10-to-2" position, and do not reposition them during the experiment. Your seat position can be adjusted, please inform the investigator if you are seated comfortably.

During the experiment parts of the road will be narrowed. In these parts the lane narrows together with the cones that are placed at the lane boundaries. After each narrowed road section the investigator will ask you the following question:

How much effort did it cost you to successfully drive this section?
Please answer this question with a number between 1 and 10.

No effort				*Some effort*				*A lot of effort*	
1	2	3	4	5	6	7	8	9	10

Risks
Potential risk to you during driving consists of slight motion sickness (slight car sickness or slight light-headedness) due to the conflicting cues of visual movement without actual body movement. Please inform the investigator if you experience motion sickness, are tired, or feel uncomfortable in any way. The experiment can be stopped at any time.

Confidentiality
All data recorded in the experiment will be kept confidential and will only be used for research purposes. Data will be stored anonymously and securely and will be made available only to persons conducting the study.

Participation
Your participation in this study is voluntary; you may decline to participate without any consequences. Furthermore, if you decide to participate, you may withdraw from the study at anytime without consequences.

Contact information
If you have questions at any time about the study or the procedures, you may contact the principal researcher:
Ellen Hogerwerf
T: +31616799082
E: E.W.M.Hogerwerf@student.tudelft.nl

I have read and understand the information provided above and I hereby agree to participate voluntarily in this study and know my rights to withdraw.

Participant’s Name: ____

Participant's Signature: ______________________________ Date: ___________________

E.2. Questionnaire

Participant nr.: ………..

Personal details

Age: ____________________________ ◻ Male ◻ Female

Driving license since: ________________

1. On average, how often did you drive a vehicle in the last 12 months?
   - ☐ Never
   - ☐ Less than once a month
   - ☐ Once a month to once a week
   - ☐ 1 to 3 days a week
   - ☐ 4 to 6 days a week
   - ☐ Every day

2. About how many kilometres did you drive in the last 12 months?
   - ☐ 0
   - ☐ 1 - 1000
   - ☐ 1.001 - 5.000
   - ☐ 5.001 - 10.000
   - ☐ 10.001 - 20.000
   - ☐ 20.001 – 25.000
   - ☐ 25.001 – 35.000
   - ☐ 35.001 – 50.000
   - ☐ 50.001 – 100.000
   - ☐ More than 100.000

3. How many accidents were you involved in when driving a car in the last 3 years? (please include all accidents, regardless of how they were caused, how slight they were, or where they happened)
   - ☐ 0
   - ☐ 1
   - ☐ 2
   - ☐ 3
   - ☐ 4
   - ☐ 5
   - ☐ More than 5

4. How often do you play videogames?
   - ☐ Never
   - ☐ Less than once a month
   - ☐ Once a month to once a week
   - ☐ 1 to 3 days a week
   - ☐ 4 to 6 days a week
   - ☐ Every day

5. How often do you do the following? Becoming angered by a particular type of driver, and indicate your hostility by whatever means you can.

Never	Hardly ever	Occasionally	Quite often	Frequently	Nearly all the time
1	2	3	4	5	6

6. How often do you do the following? Disregarding the speed limit on a motorway.

Never	Hardly ever	Occasionally	Quite often	Frequently	Nearly all the time
1	2	3	4	5	6

7. How often do you do the following? Disregarding the speed limit on a residential road.

Never	Hardly ever	Occasionally	Quite often	Frequently	Nearly all the time
1	2	3	4	5	6

8. How often do you do the following? Driving so close to the car in front that it would be difficult to stop in an emergency

Never	Hardly ever	Occasionally	Quite often	Frequently	Nearly all the time
1	2	3	4	5	6

9. How often do you do the following? Racing away from traffic lights with the intention of beating the driver next to you.

Never	Hardly ever	Occasionally	Quite often	Frequently	Nearly all the time
1	2	3	4	5	6

10. How often do you do the following? Sounding your horn to indicate your annoyance with another road user.

Never	Hardly ever	Occasionally	Quite often	Frequently	Nearly all the time
1	2	3	4	5	6

E.3. Questionnaire results

							Items Driving behaviour questionnaire (DBQ)						
Subject	Age	Male/ female	Years license	DriveFreq	KmYear	NrAcc	Vangered	Vmotorway	Vresident	Vfollowing	Vrace	Vhorn	Videogames
1	22	Female	2	3	4	1	3	1	1	1	2	1	1
2	25	Male	1	3	3	1	3	2	3	2	2	2	3
3	24	Male	2	3	3	1	1	4	4	1	3	2	1
4	26	Male	8	4	4	1	1	4	2	2	2	2	1
5	28	Female	10	3	4	1	1	1	1	1	2	1	1
6	32	Female	14	3	3	1	3	3	4	1	4	2	1
7	29	Female	11	3	5	1	3	3	2	2	2	1	1
8	25	Female	7	3	3	1	2	3	2	1	1	1	1
9	20	Male	3	3	3	1	3	1	1	2	2	2	4
10	24	Male	3	2	2	1	2	3	2	2	2	1	6
11	27	Female	9	3	6	1	4	6	3	2	2	2	1
12	20	Male	3	3	2	1	2	1	1	1	1	2	3
13	30	Male	10	5	7	1	2	3	2	2	3	1	1
14	29	Female	8	3	2	2	3	3	3	2	3	1	1
15	25	Male	7	4	5	1	3	4	3	2	1	3	1
16	26	Male	4	3	3	1	2	2	3	2	2	1	3
17	28	Male	8	4	6	1	3	4	2	2	2	1	3
18	26	Male	5	6	6	2	4	6	5	3	5	1	1
19	24	Male	3	2	2	1	3	2	1	1	2	3	4
20	21	Female	4	2	2	1	2	2	3	1	1	1	2
21	24	Male	6	3	3	1	2	3	2	1	4	1	5
22	27	Male	9	2	2	1	2	2	2	1	2	1	1
23	26	Male	5	4	8	2	5	5	3	1	6	2	5
24	25	Male	5	2	2	2	2	3	3	2	3	2	2
25	30	Female	9	3	2	1	3	2	2	2	2	2	1
26	31	Male	12	5	6	2	4	4	3	2	4	1	3
M (SD)	25.9 (3.2)	Female: 9, Male 17	6.5 (3.4)										

Response coding for each item according De Winter and Dodou [8]:

KMYear		Drivefreq/videogames		NrAcc	
Score	KM	Score	Frequency	Score	Frequency
1	0	1	Never	1	0
2	1-1000	2	Less than once a month	2	1
3	1001-5000	3	Once a month to once a week	3	2
4	5001-10000	4	1-3 days a week	4	3
5	10001-20000	5	4-6 days a week	5	4
6	20001-25000	6	Every day	6	5
7	25001-35000			7	>5
8	35001-50000				
9	50001-100000				
10	> 100000				

F
Extensive results

F.1. Learning effect

The figures in this section show the individual results for each repetition and for each condition. The means are the mean results over all participants for each repetition number.

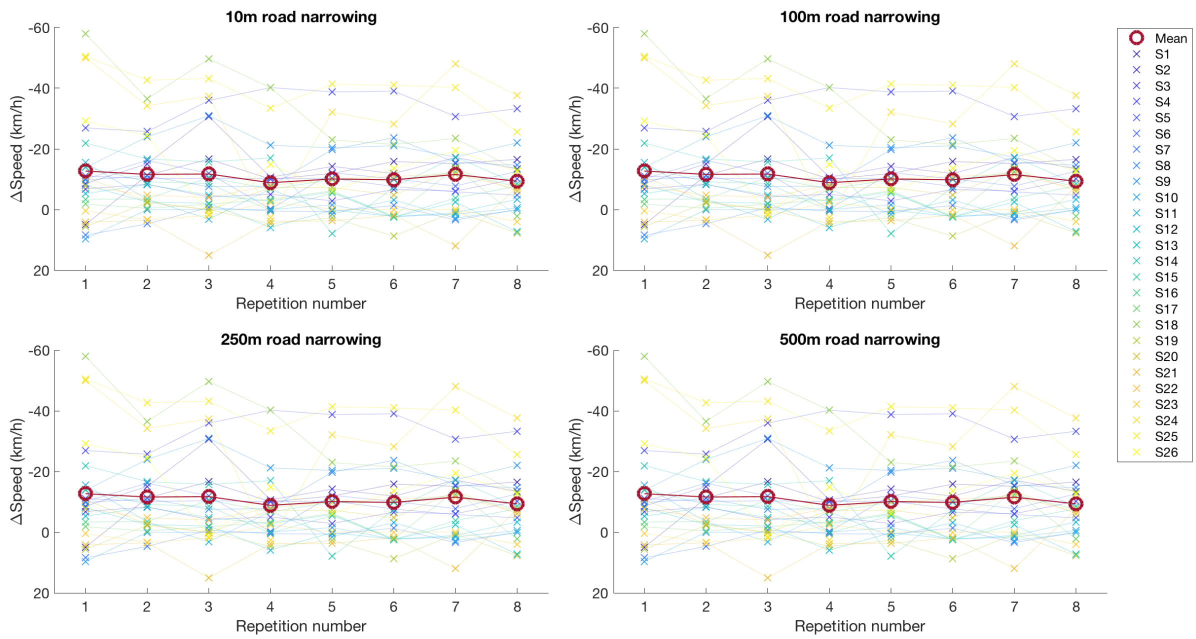

Figure F-1 Δ Speed for all repetitions for all conditions, it can be seen that for all conditions the Δ speed remains relatively constant during the experiment

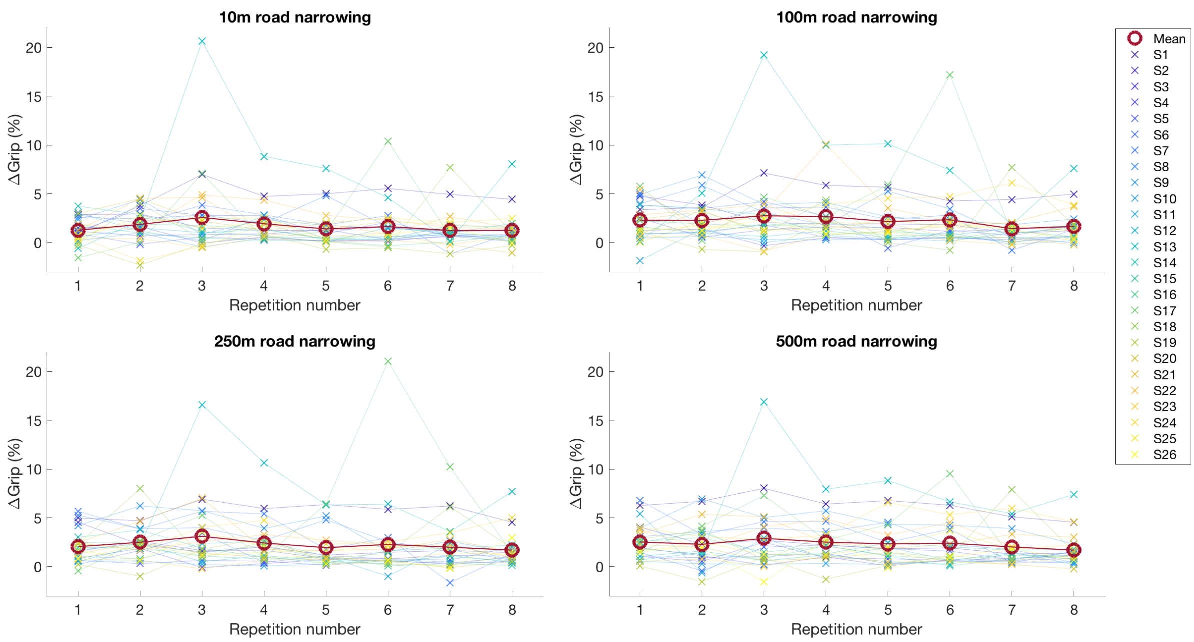

Figure F-2 Δ Grip force for all repetitions for all conditions, it can be seen that the Δ grip force slightly decreases during the experiment

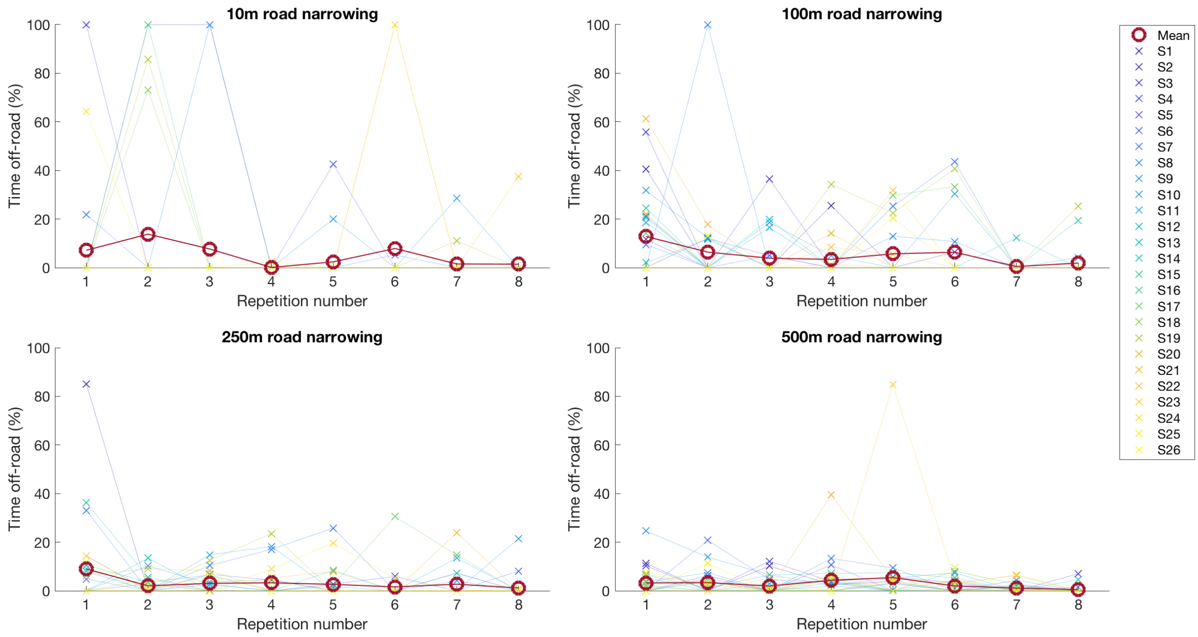

Figure F-3 This figure shows the percentage of time off-road for all repetitions and for all conditions, which decreases for all conditions during the experiment. Note that the percentage of time off-road for the 10m road narrowing is the highest since a small time off-road already results in high percentages.

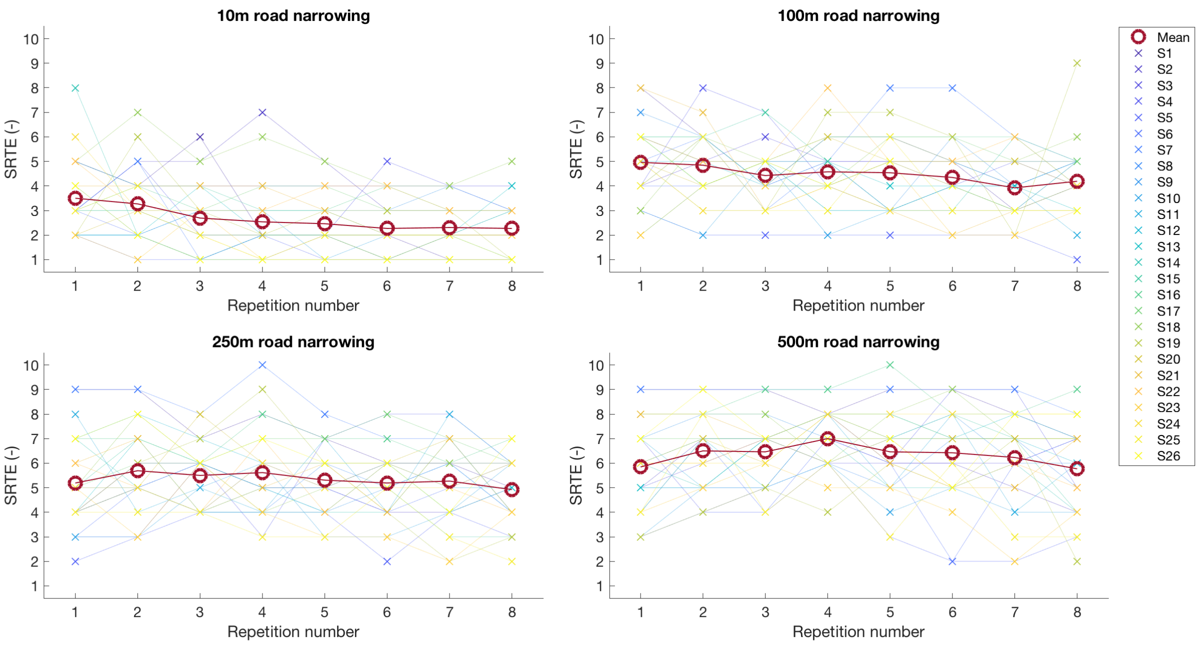

Figure F-4 Self Reported Task Effort (SRTE) for all repetitions for all conditions. Mainly for the 10m road narrowing the SRTE decreased during the experiment, the other conditions show a relatively constant SRTE response.

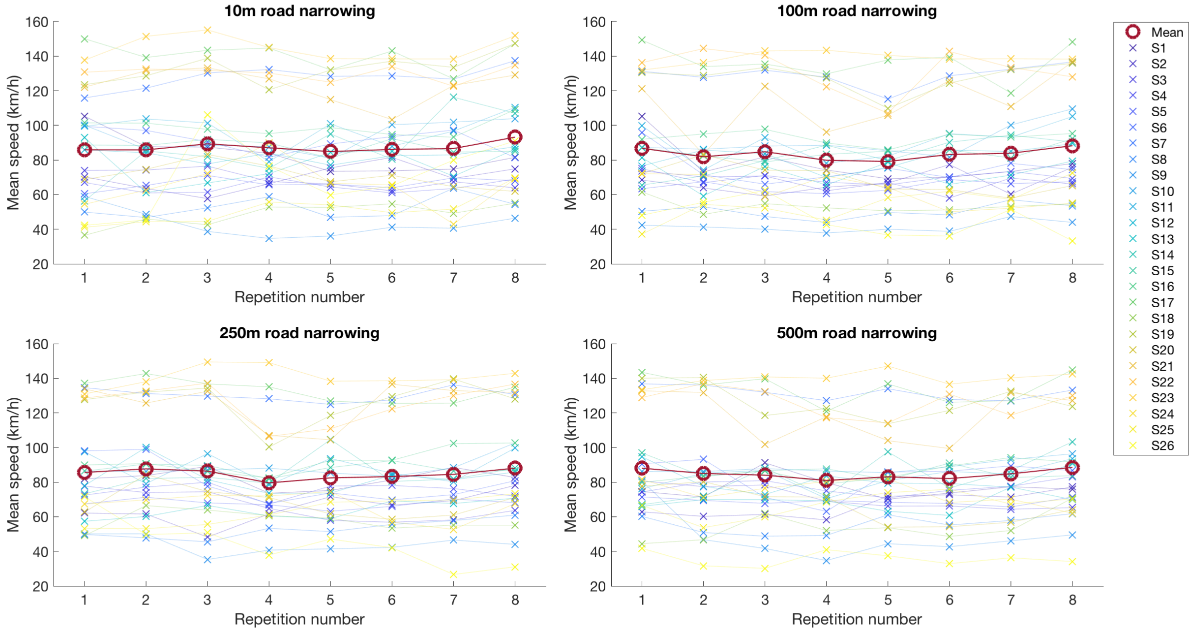

Figure F-5 Mean speed for all repetitions for all conditions. For all conditions the mean speed increases for especially for the last two repetitions.

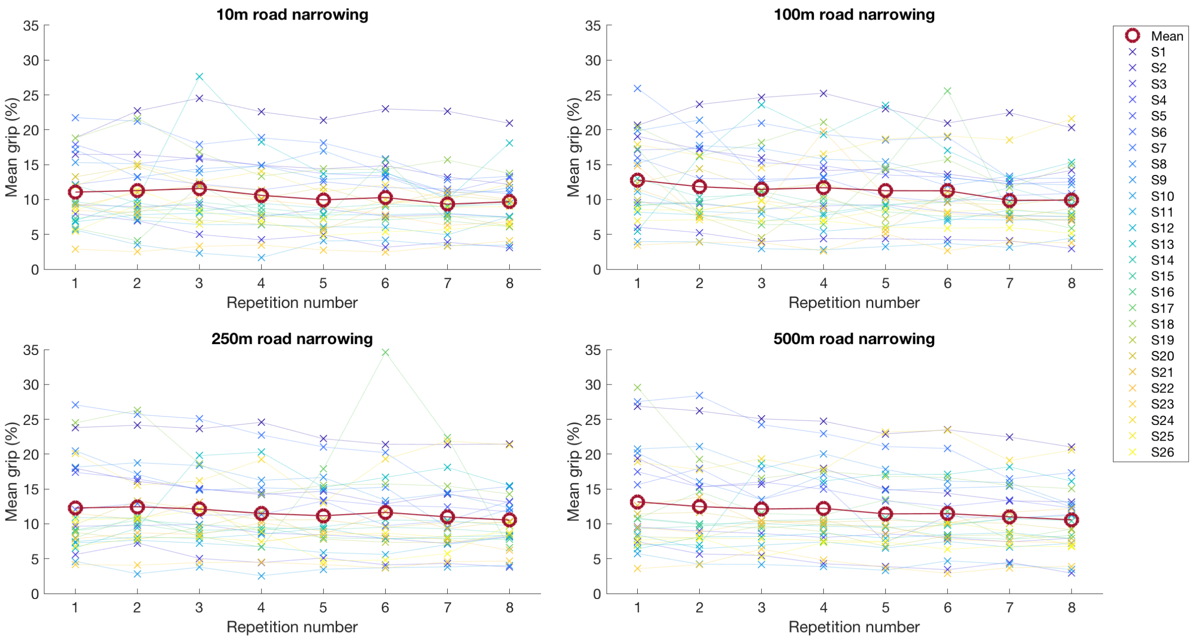

Figure F-6 Mean grip force for all repetitions for all conditions. For all conditions the mean grip force decreases during the experiment.

As can be seen from the calibration results in Table C-1, the raw output for the fixed load conditions mainly decreased for the first half of the participants. To investigate whether the decrease in grip force (the suggested learning effect) is not found due to the degradation of the sensors, the results for each repetition are averaged over participant 14-26 and visualized in Figure F-7.

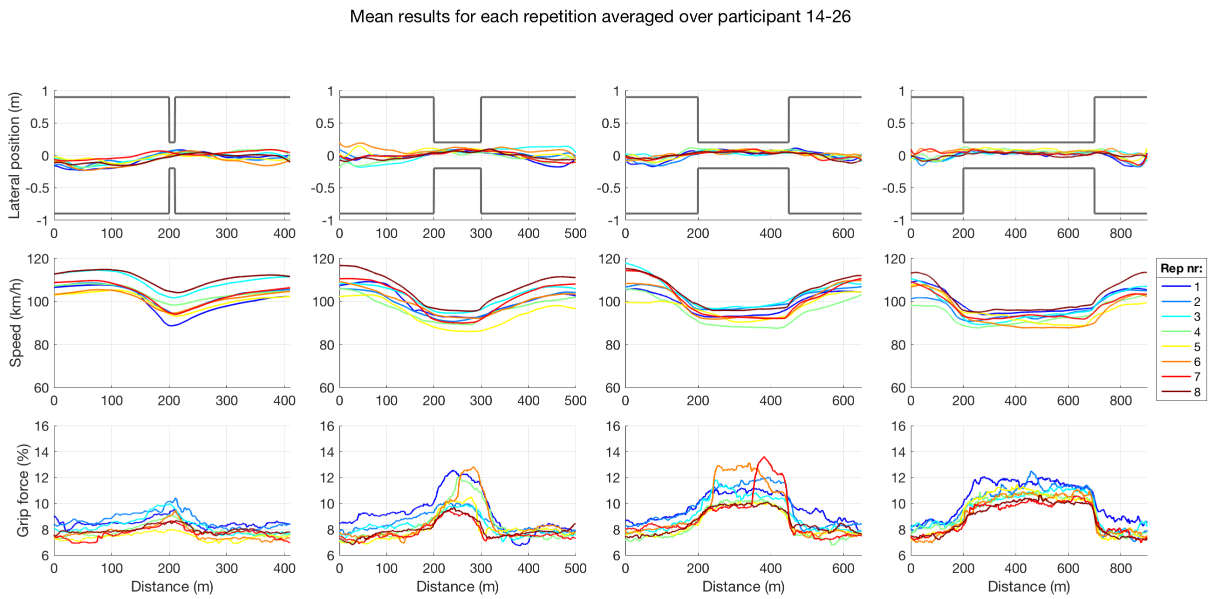

Figure F-7 Results for each repetition averaged over participant 14-26. It can be seen that the grip force still decreases for these participants. However, the differences between the repetitions are slightly smaller than the results averaged over all repetitions.

F.2. Standard Deviation Lateral Position

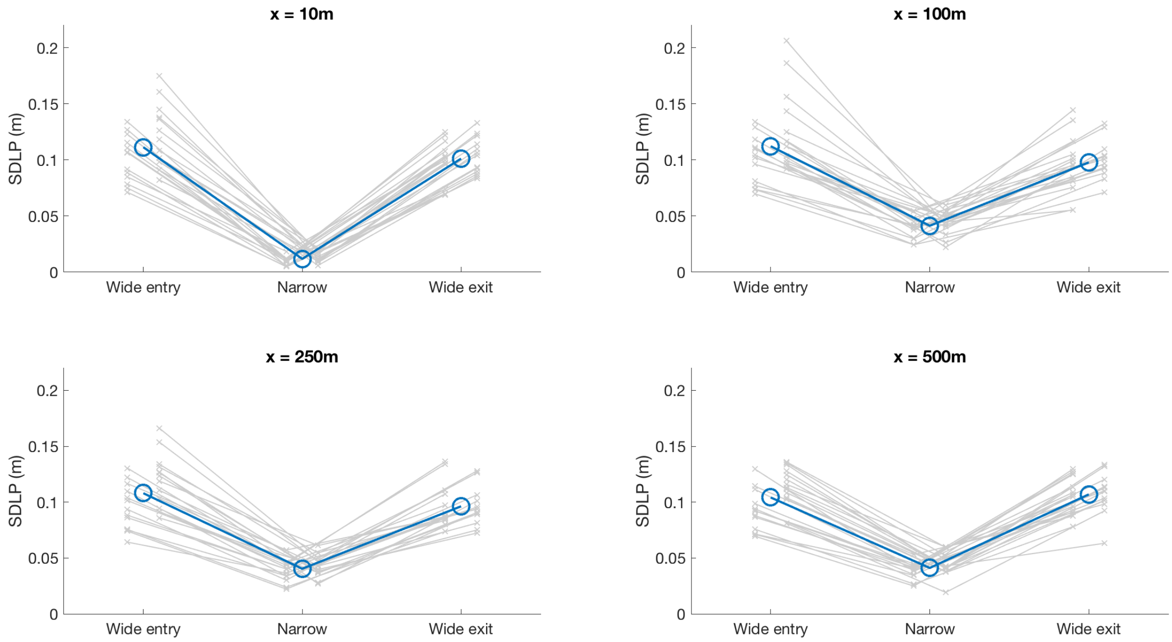

Figure F-8 SDLP values for the wide entry, narrow and wide exit section for all four conditions. The SDLP clearly reduced due to the narrow road section, which can indicate a higher control effort by the subjects.

F.3. Self Reported Task Effort

Table F-1 SRTE scores for each section from each individual subject

Subject	Narrow section number																														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	5	8	9	9	9	9	4	6	7	9	4	6	6	8	2	8	9	6	7	2	6	5	9	2	8	1	3	6	4	1	5	7
2	4	3	4	5	5	6	7	5	5	6	7	5	7	7	5	5	6	5	5	5	3	5	6	4	4	5	4	3	5	3	4	5
3	5	4	6	5	5	4	6	5	7	4	6	6	5	6	4	5	4	5	5	6	4	6	5	6	6	6	4	5	6	5	4	7
4	3	4	3	7	4	3	5	8	6	5	7	2	4	3	2	8	6	5	7	2	8	4	9	5	9	4	5	8	4	3	6	5
5	2	2	3	3	2	3	4	1	1	4	4	2	2	6	4	2	3	2	1	4	1	2	2	2	2	2	4	1	1	1	3	3
6	4	3	4	3	5	2	7	4	4	1	4	4	5	7	2	6	2	5	3	6	1	2	4	4	5	6	2	3	6	5	2	7
7	3	5	9	9	9	9	5	6	8	9	3	1	5	10	1	9	9	8	8	2	7	8	9	2	9	2	6	7	5	2	4	8
8	5	2	4	5	6	5	5	2	1	4	5	4	2	6	4	4	5	3	2	6	2	4	7	5	3	7	6	2	3	2	5	4
9	7	4	7	2	5	2	8	6	8	3	6	4	5	7	3	5	3	4	3	7	3	8	6	5	6	6	4	4	4	5	3	6
10	4	3	3	3	5	3	2	2	5	5	5	3	2	6	3	6	4	3	3	1	3	3	5	2	4	2	3	4	4	3	6	4
11	8	2	6	7	4	4	5	2	1	5	7	5	1	8	4	3	5	3	1	7	1	4	8	4	4	4	8	1	2	1	6	6
12	6	7	5	3	8	3	7	5	5	2	7	4	4	8	2	6	2	6	5	8	2	7	5	6	5	7	2	4	5	5	2	6
13	2	2	4	5	5	7	2	4	4	7	5	4	5	5	2	6	7	4	4	2	6	4	7	1	8	2	4	4	3	4	5	7
14	7	8	6	6	4	5	5	2	1	4	7	5	2	7	4	3	5	3	2	4	1	3	5	4	6	6	7	2	4	1	4	4
15	4	5	6	5	7	4	7	6	7	4	6	7	5	8	3	5	3	5	3	7	2	8	4	5	3	7	2	3	3	5	3	4
16	3	6	7	8	8	7	4	6	6	9	4	3	6	8	3	9	10	6	7	3	7	6	8	4	8	3	6	6	5	3	7	9
17	5	3	6	7	5	6	7	3	3	6	7	5	4	8	7	6	8	6	4	7	3	6	7	8	5	7	7	3	5	3	7	6
18	8	5	3	5	8	7	8	6	8	5	6	5	4	6	6	4	5	5	6	8	4	9	5	6	6	7	4	5	6	6	5	7
19	2	5	4	3	4	6	6	3	7	5	3	3	7	9	2	4	6	7	6	3	4	6	5	3	7	3	2	2	9	1	3	2
20	4	2	5	6	4	5	7	3	2	8	6	5	2	8	6	6	7	5	2	6	2	5	7	6	5	7	7	2	4	2	7	7
21	8	6	8	4	7	4	8	7	7	4	4	3	4	8	4	5	3	6	3	6	2	5	2	4	7	5	2	3	4	3	2	7
22	5	6	6	6	6	5	3	5	4	7	5	3	8	7	3	6	7	5	4	4	6	5	5	4	6	3	6	5	4	3	4	5
23	5	2	2	4	4	3	5	1	3	6	6	4	1	5	4	4	5	5	2	3	1	2	4	3	2	2	2	2	3	2	4	4
24	6	5	5	6	5	3	6	3	6	2	4	3	4	8	1	6	1	5	3	8	1	8	3	5	5	8	1	3	6	4	1	8
25	3	4	4	4	8	4	4	6	4	4	3	2	3	3	1	6	3	6	3	2	5	3	6	2	3	2	3	3	3	1	2	3
26	7	4	6	7	4	8	9	2	1	6	7	5	1	7	7	4	7	5	1	6	1	4	5	6	3	8	4	1	3	1	8	7

F.4. Cone hits

The total amount of straight sections with a road narrowing for each condition was 8*26 = 208. In the statistical results in the paper the results are analysed for all sections, no matter if a cone was hit or not. The amount of sections without hitting the lane boundaries for each subject is shown in the table below. The total amount of sections without cone hits is for 10m: 190, for 100m: 160, for 250m: 149 and for 500m: 120.

Table F-2 Amount of successful repetitions for each participant

Participant	10m	100m	250m	500m	Total
1	6	6	6	4	22
2	8	6	7	7	28
3	7	6	8	2	23
4	8	6	6	6	26
5	7	8	5	6	26
6	8	6	6	4	24
7	7	5	4	4	20
8	6	5	5	6	22
9	7	6	5	2	20
10	7	4	5	6	22
11	8	6	4	3	21
12	8	6	5	5	24
13	8	6	7	5	26
14	8	6	4	1	19
15	8	7	8	5	28
16	7	8	7	8	30
17	8	5	5	6	24
18	7	8	7	4	26
19	6	4	6	7	23
20	8	6	5	5	24
21	7	5	5	2	19
22	8	6	8	6	28
23	7	7	5	6	25
24	6	8	4	1	19
25	7	6	8	5	26
26	8	8	4	4	24
Total	190	160	149	120	619

G
Pilot studies

Pre-pilot studies

Pilot studies were performed to determine the different lengths of the narrow road sections that would be used and to investigate if drivers would adapt to the road narrowing. The road widths that were used are 3.6m for the wide road and 2.2m for the narrow road. For the narrow road 2.2m is chosen to design a critical task, which drivers still should be able to drive successfully.

The first pre-pilot study was performed with one subject with narrow road lengths of 20m, 50m and 250m. The straight sections with the road narrowing were either 500m or 600m long and the road narrowing was place in the middle of that straight section. Also three different laps were generated, within each lap four repetitions of one length of narrow road section.
However, during this pre-pilot no feedback was given when driving outside the lane boundaries and therefore the participant mainly increased speed during the experiment. Also the 500m or 600m long straight section did not provide a constant preview time for all conditions, which was something that was desired when comparing the different narrow road lengths.

The second pre-pilot experiment was designed as one long track of 30 km with straight sections separated by random left and right curves. The order of narrowed sections was randomized and a constant preview time for all conditions was generated. Which means that narrow road always started at 200 meter after the curve and 200 meter after narrowed road before next curve starts. One participant drove this track and the results showed that the vibration on the steering wheel was an effective trigger to ensure driver would stay inside the lane boundaries. However no steady state driving speed was reached after 250m, and therefore a longer 500m narrow road was included in the next pilot study. The 500m narrow road section is also chosen based on the fact that it is commonly used as a steady state length by other studies [6],[7]. Also after this pre-pilot experiment a perturbation was added to make the driving task more challenging and to ensure the car goes off the road after a certain period ('make it a driving task, not a game')

Final pilot experiment

The final pilot experiment was performed with three participants and four different narrow road lengths: 40m, 100m, 250m and 500m, all with eight repetitions. Also in order to investigate subjective effort, participants were asked after every narrow road section how much effort it cost them to drive that narrow road section.
From the results already a large between subject variability could be seen between participants and it could be seen from the results that participants already slowed down on the 40m road narrowing. Therefore it was chosen to replace the 40m road narrowing for the final experiment with the shortest possible narrow road length in the simulator of 10m, which was visualized with one cone.

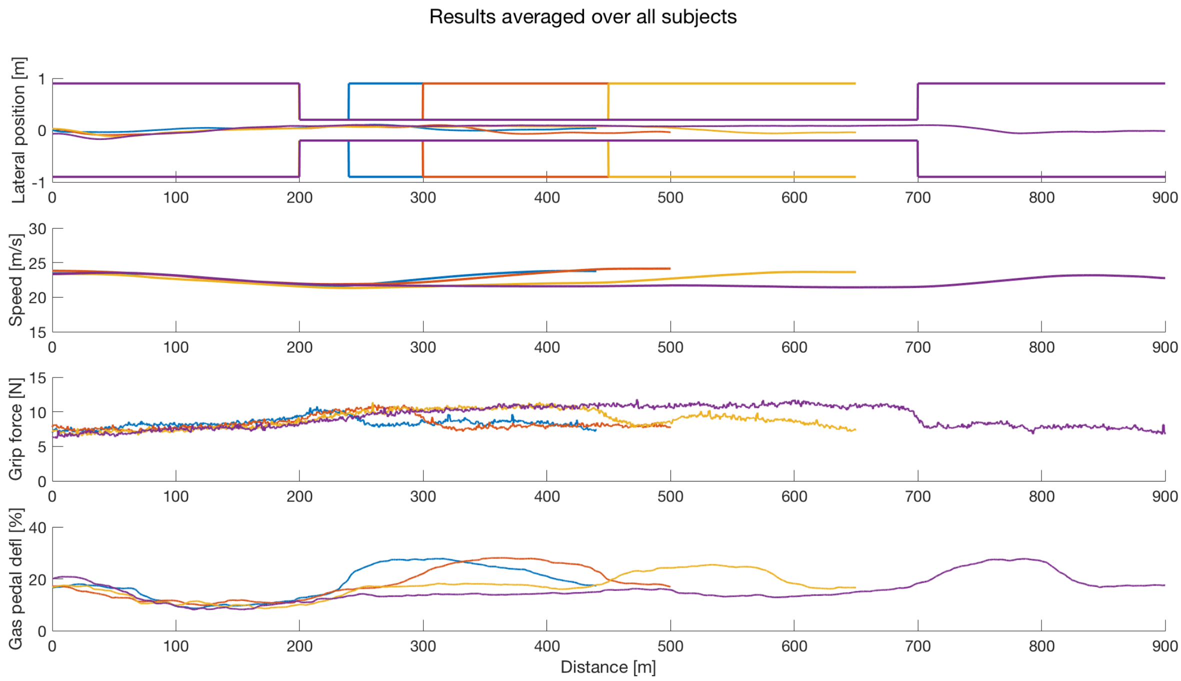

Figure G-1 The results of the final pilot study for mean speed, mean grip force and SRTE as a function of the length of the road narrowing.

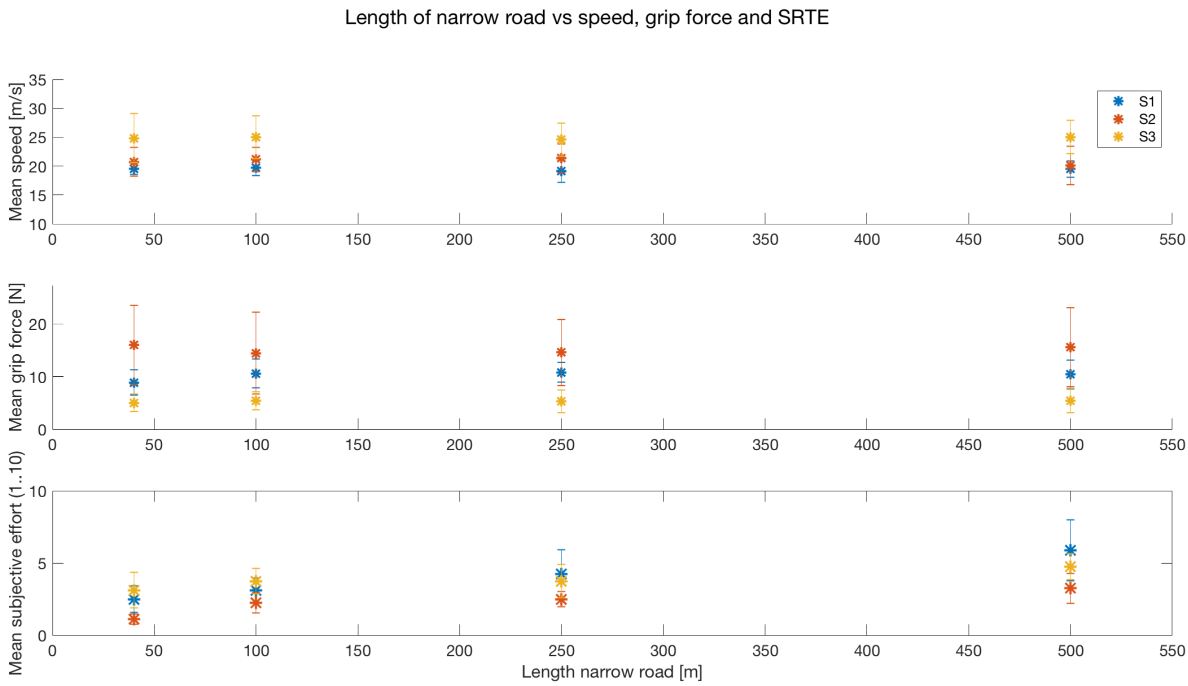

Figure G-2 The results of the last pilot study for mean speed, mean grip force and SRTE as a function of the length of the road narrowing. The grip force is here expressed in Newton using the conversion according the specifications of the Tekscan sensors.

Bibliography

[1] “Tekscan - Pressure Mapping, Force Measurement & Tactile Sensors.” [Online]. Available: https://www.tekscan.com/products-solutions/systems/grip-system. [Accessed: 18-Oct-2018].

[2] J. M. Brimacombe, D. R. Wilson, A. J. Hodgson, K. C. T. Ho, and C. Anglin, “Effect of Calibration Method on Tekscan Sensor Accuracy,” *J. Biomech. Eng.*, vol. 131, no. 3, p. 034503, 2009.

[3] A. J. Pronker, D. A. Abbink, M. M. Van Paassen, and M. Mulder, “Estimating driver time-varying neuromuscular admittance through LPV model and grip force,” vol. 1, pp. 15481–15486, 2017.

[4] M. Eksioglu and K. Kizilaslan, “Steering-wheel grip force characteristics of drivers as a function of gender, speed, and road condition,” *Int. J. Ind. Ergon.*, vol. 38, no. 3–4, pp. 354–361, 2008.

[5] T. Melman, D. A. Abbink, M. M. van Paassen, E. R. Boer, and J. C. F. de Winter, “What determines drivers’ speed? A replication of three behavioural adaptation experiments in a single driving simulator study,” *Ergonomics*, vol. 0139, pp. 1–22, 2018.

[6] A. Pronker, “Estimating an LPV model of neuromuscular admittance with grip force as scheduling parameter,” Delft University of Technology, 2016.

[7] D. W. J. Van Der Wiel, M. M. Van Paassen, M. Mulder, M. Mulder, and D. A. Abbink, “Driver Adaptation to Driving Speed and Road Width: Exploring Parameters for Designing Adaptive Haptic Shared Control,” *Proc. - 2015 IEEE Int. Conf. Syst. Man, Cybern. SMC 2015*, pp. 3060–3065, 2016.

[8] J. C. F. De Winter and D. Dodou, “National correlates of self-reported traffic violations across 41 countries,” *PAID*, vol. 98, pp. 145–152, 2016.