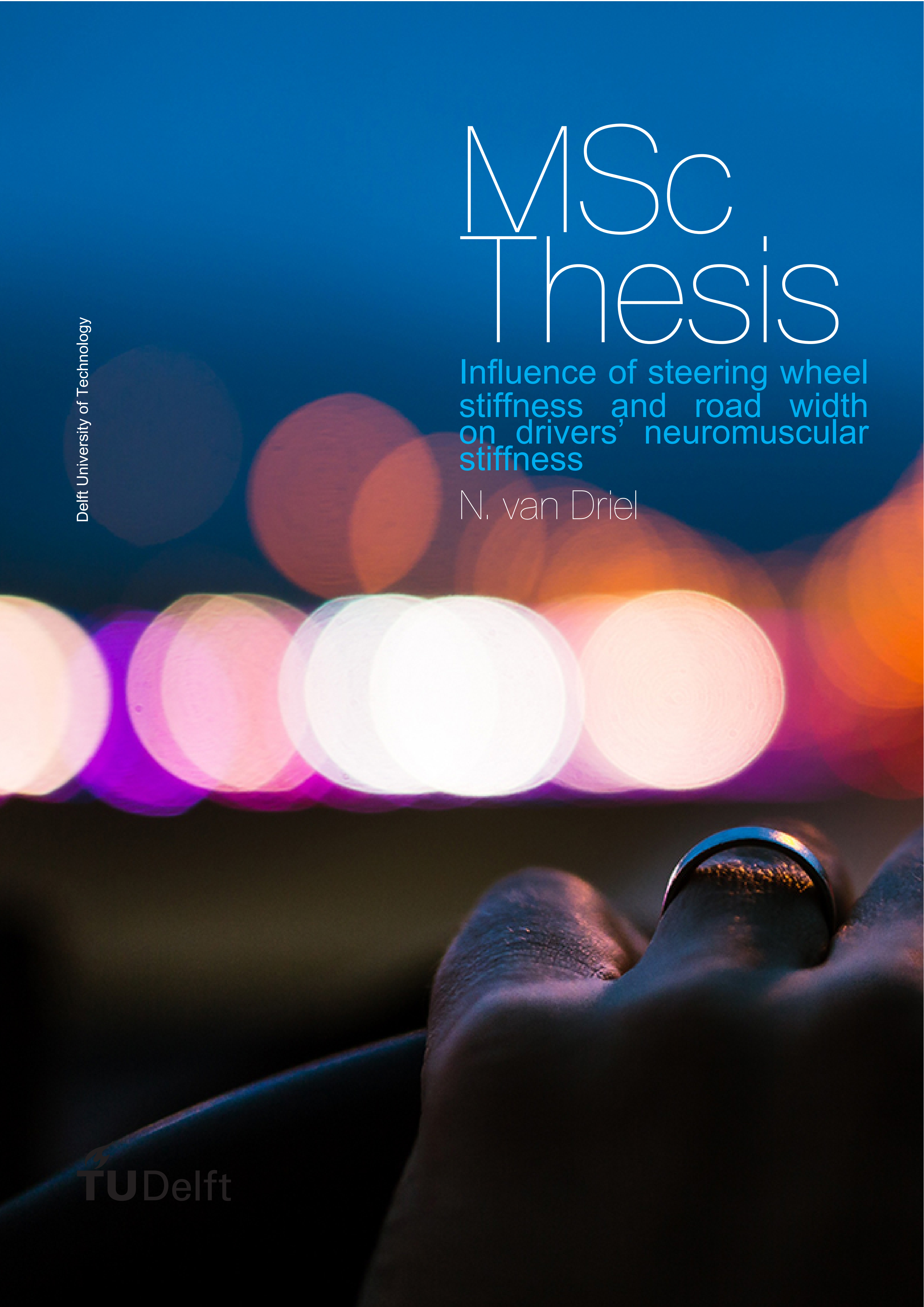

# MSc Thesis

## Influence of steering wheel stiffness and road width on drivers' neuromuscular stiffness

N. van Driel

Delft University of Technology

# MSc Thesis

## Influence of steering wheel stiffness and road width on drivers' neuromuscular stiffness

by

N. van Driel

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| Thesis committee: | Dr. ir. D. A. Abbink, | TU Delft, supervisor |
| | Dr. ir. D. M. Pool, | TU Delft |
| | Dr. ir. T. L. Gibo, | TU Delft, supervisor |
| | Ir. J. G. W. Wildenbeest, | TU Delft, supervisor |



TU Delft

# Preface

During a 6-month MSc thesis project I investigated the physical interaction between driver and steering wheel. Specifically, I focused on the driver's neuromuscular response to steering wheel stiffness.
The first part of this report consists of a journal paper, summarizing the final experiment. The second part consists of appendices, included to provide more background information about and insight into my graduation project as a whole.
The modified driving simulator code, measurement data (including completed forms), MATLAB code for analyses, metric data and figures, and literature have been submitted to the BioMechanical Engineering depository on a USB stick, which is available on request.

I want to thank everyone who contributed to this project, in particular my supervisors David Abbink, Tricia Gibo and Jeroen Wildenbeest for their enthusiastic guidance. Also, I would like to thank Mark Mulder for getting me started with the driving simulator code, Erwin Boer for sharing his view on "the magic of metrics", and Alistair Vardy for the nice discussion on statistics.

*N. van Driel*
*Delft, November 20*

# Contents

# Paper

# Influence of steering wheel stiffness and road width on drivers' neuromuscular arm stiffness

N. van Driel, J.G.W. Wildenbeest, T.L. Gibo, D.A. Abbink
BioMechanical Engineering Dept., Faculty of 3mE, Delft University of Technology

***Abstract*—New technologies like electric power steering and steer-by-wire have made it possible to freely shape the steering wheel dynamics. As the driver is part of the closed-loop vehicle steering system, his neuromuscular response should be taken into account when shaping steering wheel dynamics. It is known that drivers adapt the dynamics of their arm to different traffic situations (e.g., increased neuromuscular stiffness for narrow roads) and to the steering wheel dynamics itself. Based on that knowledge, this research study investigates whether steering wheel stiffness can be used to assist driving behaviour for different road widths. It was hypothesised that with higher steering wheel stiffness ($K_{SW}$), drivers would keep the combined dynamics constant by decreasing their neuromuscular stiffness ($K_{NMS}$). In a critical traffic situation like when a road narrows, high $K_{SW}$ could then allow drivers to relax more, as they would no longer need to increase their own $K_{NMS}$. Eleven subjects took part in a driving simulator experiment where driving criticality was manipulated by alternating wide and narrow straight segments. Three steering wheel settings were tested: baseline, high and 'adaptive' stiffness, which changed gradually from baseline $K_{SW}$ on wide roads to high $K_{SW}$ on narrow roads, and vice versa. Against expectation, no decrease in $K_{NMS}$ was found for higher $K_{SW}$. Adapting $K_{SW}$ to road width, similar to how drivers adapt, did thus not yield the expected benefits in terms of $K_{NMS}$. In addition, even with high $K_{SW}$, performance remained worse on narrow compared to wide roads. However, effort was lower with high $K_{SW}$, while performance was maintained or even increased. Also, subjective ratings were highest for adaptive $K_{SW}$, which enabled drivers to keep effort constant between road widths. While no effects on $K_{NMS}$ were found, adapting $K_{SW}$ can thus be a useful tool in assisting driving behaviour in different road conditions.**

***Index Terms*—Steering wheel stiffness, steering feel, driving criticality, neuromuscular admittance, driver arm stiffness, driving behaviour**

## I. Introduction

TRADITIONALLY, when drivers rotate the steering wheel, the applied torque is transmitted via the steering column to the wheels. Hence, the relationship between steering input and output is determined purely mechanically.
Most new vehicles are equipped with power steering, where a hydraulic or electric actuator amplifies the exerted torque. Going one step further, steer-by-wire systems no longer have mechanical linkages such as the steering column. The direction of the car's wheels is controlled electronically, and an actuator at the steering wheel generates torque feedback, such that drivers can sense the state of the road and tire dynamics. Steer-by-wire systems thus allow the perceived steering wheel dynamics, or 'steering feel', to be tuned to any desired shape. Despite the widely acknowledged importance of torque feedback (e.g., [1], [2], [3]), research has mainly focused on restoring the original steering feel [4]. This has left the question of what would be the ideal steering wheel dynamics in what situation unanswered.

As the interaction between driver and steering wheel affects the overall closed-loop performance of the vehicle, taking drivers' neuromuscular system (NMS) dynamics into account when shaping steering wheel dynamics may be beneficial [5], [6], [7]. Still, little research has been done regarding this topic. What is known, is that the dynamics of the NMS can vary substantially while driving. By means of co-contraction and reflexes, humans are able to adapt the end-point admittance (i.e. the dynamic relation between input force and output displacement) of their arms by a factor 10 [8], [9]. The main reason for adapting NMS admittance is to pursue an acceptable level of task performance. In critical traffic situations, like when driving on narrow lanes and at high speed, NMS admittance is lower [10]. Drivers then apply more co-contraction and/or reflexes to reject perturbations (over a larger control bandwidth or at a relatively low metabolic cost, respectively) [8], [11].
Interestingly, NMS dynamics are also dependent on steering wheel characteristics. Torque feedback itself can lead to higher admittance (as long as it is not conflicting with the driver's intentions) [6], [12]. In other words, not only is the overall steering behaviour affected by the NMS dynamics; the NMS dynamics are influenced by the steering wheel as well. This underlines why an understanding of the physical interaction between driver and steering wheel is important.

Moreover, the fact that humans adapt their arm admittance to the steering wheel could be used to assist them. The dynamics of the steer can be tuned to different driving situations, based on knowledge of how humans adapt to those situations and to changes in steering wheel dynamics.
However, limited literature is currently available about drivers' neuromuscular response to specific steering wheel dynamics. In [13], a human-centred approach was applied to design three steering wheel systems for different driving situations. It was found that steering wheel dynamics should be slow and sluggish on straight roads, and light in curves. Nevertheless, the NMS dynamics of the driver were not considered in evaluating either of the three systems. Also, steering wheel stiffness and damping were changed simultaneously. For a better understanding of the mechanisms involved, the effects of different steering wheel parameters on driving behaviour

should be tested separately. Steering wheel stiffness is expected to have a more beneficial effect on co-contraction than damping when driving straight, as it acts in the same (lower) frequency region as co-contraction. Besides, humans show larger adaptations in the stiffness than in the damping parameter of their arm, and it is mainly stiffness that changes with muscle activation [11]. Therefore, this research study investigates drivers' NMS stiffness response to the stiffness parameter of the steering wheel, and whether it can be adapted to assist them in changing road conditions.

Higher steering wheel stiffness ($K_{SW}$) is expected to make driving straight easier, as it requires more force to steer away from the center of the lane. This way it might compensate for increased driving criticality, like when a road is narrowed [14]. That is, increased $K_{SW}$ is expected to lead to higher performance and/or lower effort when driving straight, while decreased road width is believed to yield lower performance and/or higher effort. With increased $K_{SW}$, drivers would thus not need to increase their neuromuscular stiffness ($K_{NMS}$) to achieve higher task performance, because the steering wheel already takes care of that. In essence, by adapting $K_{SW}$ to road width similar to how drivers would normally adapt their $K_{NMS}$, it is expected that people could drive more relaxed, because $K_{NMS}$ can be kept constant.

Because it is still largely unknown whether these hypotheses are correct, an experiment was designed to gain insight into how $K_{NMS}$ is affected by $K_{SW}$ at different road widths. The main hypothesis of the study was that when $K_{SW}$ is higher, humans will lower their $K_{NMS}$, keeping the combined dynamics of the system constant. This was tested in a driving simulator experiment with three different settings for steering wheel stiffness. Two traffic situations with a different level of criticality, in the form of wide and narrow roads, were investigated to verify the underlying assumptions regarding effort and performance. An additional steering wheel setting was tested in which stiffness is adapted based on road width, to explore if adapting stiffness while driving would lead to different behaviour (e.g., when eventually applied in an interactive steering support system).

## II. Methods

### A. Participants

Eleven subjects took part in the experiment. Seven of them were female, four male, and their average age was 24.5 years (± 1.9 years). All were in the possession of a driver's license, and had been for 5.5 years (± 2.0 years). This research was approved by the Human Research Ethics Committee of Delft University of Technology. Prior to the experiment, informed consent was obtained from all subjects. Participation was voluntary; no financial compensation was given.

### B. Experimental design

*1) Apparatus:* The experiment was performed using the fixed-base driving simulator of the Control and Simulation department at the faculty of Aerospace Engineering, Delft University of Technology. The simulator consisted of an electronically actuated steering wheel (MOOG FCS ECol-8000 S Actuator), which was updated locally at 2500 Hz. Three projectors displayed the simulated environment, covering almost 180 degrees field of view. The refresh rate of the visuals was 50 Hz; the simulation was updated at 100 Hz. Before starting the experiment, the driver seat was adjusted such that each participant's wrists could touch the top of the steering wheel when sitting up straight. They were then asked to hold the steering wheel with the hands at the "10-to-2" positions, and keep them there while driving.

*2) Steering wheel settings:* Three different steering wheel settings were implemented:

1) Baseline $K_{SW}$: 0.13 Nm/deg
   This setting corresponds to regular steering wheel stiffness, and has been used as a baseline setting in previous research [13].
2) High $K_{SW}$: 0.26 Nm/deg
   This setting corresponds to twice the baseline stiffness. The value lies within the lower part of the range of drivers' neuromuscular stiffness [8], whereas normally the driver is dominant over the combined dynamics (i.e. about four times as stiff as the steering wheel). As a result, the driver's response was expected to be affected more than when a lower stiffness setting had been chosen.
3) Adaptive $K_{SW}$: 0.13 $\vee$ 0.26 Nm/deg
   Within this setting, the steering wheel stiffness varies. When a narrowing of the road is encountered, stiffness is gradually increased from baseline to high $K_{SW}$ over a period of 3 seconds. The other way around, when the road starts to widen, stiffness is decreased from 0.26 to 0.13 Nm/deg.

For a more elaborate discussion on how these settings were chosen is referred to the reports of the preliminary and pilot study, in Appendix B and C, respectively.

*3) Simulated environment:* A virtual environment containing a road of varying width was simulated. Cones were placed on either side of the road to indicate its width. 'Wide' segments are 3.6 meters in width, which corresponds to the width of a normal highway [15]. 'Narrow' segments have a width of 2.5 meters, allowing 0.2 meters on both sides of the virtual car before it would cross the lane. These parameters are motivated in Appendix C.

One road contains two narrow and two wide straight segments that each take 20 seconds. They are alternated with slight-medium curves (22.5 degrees at a 500 meter radius). These curves serve not only as a break from driving straight, but more importantly, they ensure that drivers are aware of the dynamics of the steering wheel. Before entering a curve, the transition to a wide or narrow segment is made, see also Fig. 1.

At the start of each lap, the vehicle accelerated from 0 to 120 km/h, such that participants would be aware of the driving speed. Trees around the road (in addition to the cones) and engine sounds enlarged perception of speed. Throughout the rest of each lap, driving speed was fixed at 120 km/h. At

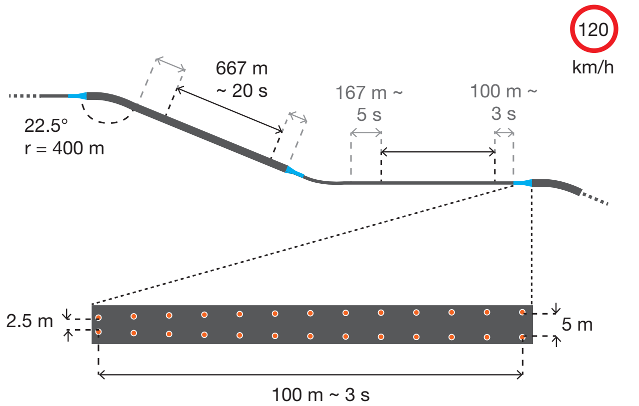



Fig. 1: One wide and one narrow segment (in total, there are two of each per road). Transitions are indicated in blue. Over a length of 100 meter (taking 3 seconds), cones are gradually placed closer to or further away from the middle of the road. After leaving a curve, the driver is allowed 5 seconds to recover, and measurements are stopped 3 seconds before a widening or narrowing of the road to exclude effects of preview. The measured parts of the straight segments are 666.67 meters long segments, taking 20 seconds at 120 km/h.

Fig. 2: Visual warning when a cone is hit: a red light appears on the side of the steer where the car left the road (indicated here by white arrow).

narrow roads, this high speed makes for a highly critical situation.

## C. Tasks

Participants' tasks while driving were to stay in (the center of) the lane and, above all, to avoid hitting any cones. The interior of the car was partly projected onto the screens such that subjects could estimate their position on the road. Moreover, a visual warning sign would appear on the screen when a cone was hit, see Fig. 2. Also, for every tenth hit cone, the total number of hits was briefly displayed above the middle of the road. As a motivational tool, a prize was promised to whoever would hit the least cones.

## D. Procedure

Prior to the experiment, informed consent and relevant personal details were obtained from each participant. Then they were given written instructions. All forms are included in Appendix D. Because of the within-subject design, each participant had to drive with all three steering wheel settings. The order in which the steering wheel settings were tested was randomised over subjects. Also, half the subjects drove on a road that started with a narrow segment, whereas the other half started with a wide segment.

Before testing each setting, a training session of 6.5 minutes was conducted. The wide and narrow segments, 16 in total, were shorter (15 seconds), as were the curves (12.25 degrees at the same radius). By practising repeatedly, subjects had the opportunity to optimise their strategy. Besides, they would be familiarised with the dynamics of the steering wheel. After each training session, the steering wheel condition was tested by performing measurements on the road described in Section II-B3. Questionnaires (see Section II-E4) were filled in before continuing with the next setting. The experimental procedure is summarised schematically in Appendix E.

## E. Metrics

*1) Neuromuscular compliance:* The metric of primary interest is neuromuscular compliance (i.e. the inverse of stiffness) of the drivers' arms. Linear time-invariant system identification techniques were used to estimate the neuromuscular dynamics. A schematic representation is given in Fig. 3.

Drivers' arm admittance $\hat{Y}_{NMS}$ can be estimated by the following relationship [16]:

$$\hat{Y}_{NMS}(f) = \frac{\hat{S}_{DA}(f)}{\hat{S}_{DF}(f)} \quad (1)$$

Where $\hat{S}_{DA}(f)$ is the estimated cross-spectral density between disturbance $d(t)$ and steering wheel angle $a(t)$, and $\hat{S}_{DF}(f)$ between disturbance $d(t)$ and reaction torque $f(t)$.

To get an indication of the amount of linearity and noise present in the system, the coherence function $\hat{\Gamma}_{DA}(f)$ can be estimated:

$$\hat{\Gamma}_{DA}(f) = \sqrt{\frac{|\hat{S}_{DA}(f)|^2}{\hat{S}_{DD}(f)\hat{S}_{AA}(f)}} \quad (2)$$

The Reduced Power Method [17] was applied to design the disturbance force signal, which is shown in Fig. 4. Full power was used up to 1.2 Hz, and reduced power up to 20 Hz, to enable estimation of full bandwidth dynamics without inhibiting reflexive activity. It should be noted that with high steering wheel stiffness, the same perturbation signal results in smaller rotations than with baseline stiffness. To make sure that the task remained the same in both stiffness settings, amplitudes were tuned such that the perturbation alone would never result in a lane departure. The disturbance signal took 5 seconds, meaning that the measurements from one straight road segment (see Fig. 1) can be Welch averaged over four

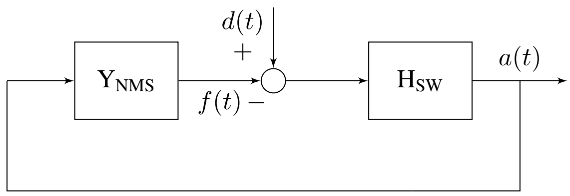



Fig. 3: While subjects were driving, a force disturbance $d(t)$ was applied to the steering wheel. The rotation $a(t)$ of the steering wheel and the reaction torques $f(t)$ were recorded.

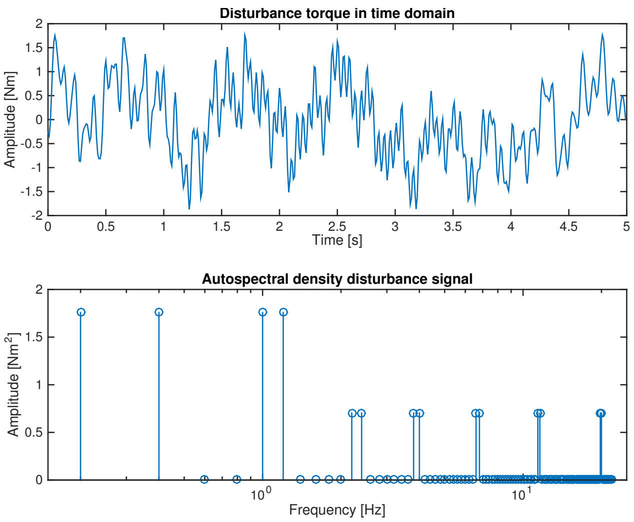



Fig. 4: Disturbance signal

repetitions [18]. Besides, frequencies were clustered in groups of 2, to allow frequency averaging. This resulted in one admittance estimate per segment, starting at a frequency of 0.3 Hz, as is schematically shown in Appendix E. The admittance value at this lowest frequency point is taken as an indication of neuromuscular compliance, which is the inverse of $K_{NMS}$:

$$K_{NMS}^{-1} = \hat{Y}_{NMS}\,(0.3) \tag{3}$$

In the end, the mean of the two repetitions (i.e. the two segments) will be considered, averaging out intra-subject variability.

To get perspective on the findings for the neuromuscular response, metrics of effort and performance must also be analysed. After all, in a task like driving, people always make trade-off's between the two.

*2) Effort:*

std(T) The standard deviation of the measured torque on the steering wheel (std(T)) is used as a metric of physical control effort.

SRR The steering wheel reversal rate (SRR) was determined by counting the number of times that the steering wheel was reversed at a rate of at least 15 deg/s.

*3) Performance:*

$TLC^{-1}$ Time-to-lane crossing (TLC) reveals drivers' lane-keeping performance by indicating how long it takes before the car would leave the road. Here, TLC is calculated from the sides of the car, using lateral position $\epsilon_y$ and speed $v_y$. Since TLC is measured on straight roads, additional information from accelerations is not needed [19]. At each point in time, only the most critical of both sides of the road is considered by taking the minimum of the absolute left and right TLC. Finally, because TLC can go to infinity when the car goes through the middle of the lane, we look at its inverse ($TLC^{-1}$), which is cut off at 0.025 $s^{-1}$:

$$TLC^{-1} = \left( \min \left| \frac{\frac{RW}{2} \pm \left(\epsilon_y + \frac{CW}{2}\right)}{v_y} \right| \right)^{-1} \tag{4}$$

Where $RW$ is road width and $CW$ is car width. Per segment, the mean $TLC^{-1}$ is calculated.

#HIT The number of hit cones (#HIT) is recorded, because this is what is fed back to subjects as an indicator of the performance on their primary task.

std($\epsilon$) Mean lateral error indicates whether participants had a bias towards either side of the road. Standard deviation of lateral error shows how much variance exists around this bias, i.e. how large the corrections were.

*4) Acceptance:* Finally, the Van der Laan questionnaire [20] was used as a tool to assess the subjectively rated acceptance (consisting of satisfaction and usefulness) of the different steering wheel systems. The complete questionnaire is attached in appendix F.

### *F. Statistical analysis*

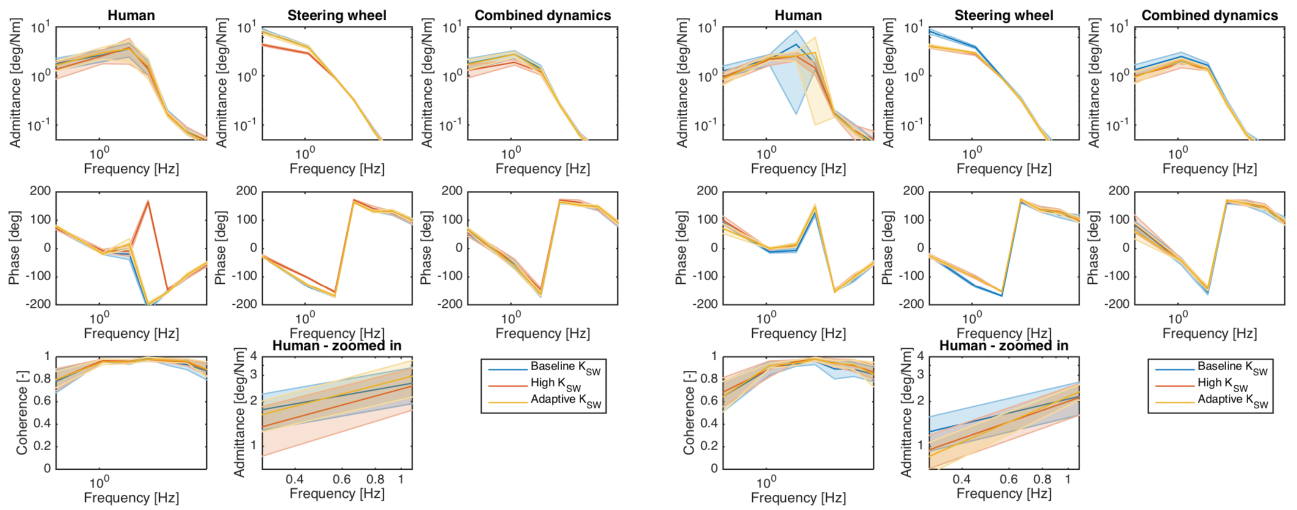
All data were statistically analysed using SPSS software. The three steering wheel systems were compared with repeated-measures ANOVA. Bonferroni corrections were applied to pairwise comparisons. To assess the effects of road width, paired-sample T-tests were done per steering wheel system. Questionnaire outcomes were analysed with the Friedman test, and Wilcoxon's signed rank test was used as post hoc.

## III. Results

### *A. Neuromuscular compliance*

The results from system identification of the human, steering wheel, and combined dynamics are shown on the full frequency range in Fig. 5. Human neuromuscular responses to the different steer settings are largely overlapping (first column in Fig. 5a and 5b). Furthermore, admittance of the combined system appears to be higher with low $K_{SW}$ - including adaptive $K_{SW}$ on wide roads - than with high $K_{SW}$ (third column in Fig. 5a and 5b).

The focus of this research is on the low-frequency response, where stiffness is dominant over the dynamics. Note that, in reporting these and following results, 'higher' or 'lower' steering wheel stiffness will be used as generalised terms that include adaptive $K_{SW}$, except when trends are deviating. The results for estimated neuromuscular admittance on the lowest frequency point (f = 0.3 Hz), hereafter referred to as compliance, are shown in Fig. 6a. Contrary to the hypothesis, neuromuscular compliance is not increased for high compared to low $K_{SW}$, either on narrow or wide roads. Furthermore, neuromuscular compliance was higher on wide than on narrow roads, but only significantly so with adaptive stiffness ($t(10) = 3.980$, $p < 0.01$).




(a) Wide road (b) Narrow road

Fig. 5: Estimated admittance and phase ranges per steering wheel system: mean ± 95% confidence interval of all subjects. Coherence of the estimation is shown in the bottom left sub-plot. In the bottom center sub-plot is zoomed in on the low frequency region of human admittance, to show the difference between wide roads (left) and narrow roads (right) more clearly. There, the estimated admittance on f = 0.3 Hz represents human compliance. A larger version of these figures can be found in Appendix G.

TABLE I: Summary of statistical results of repeated-measures ANOVA and paired-sample T-tests.'B' = baseline $K_{SW}$; 'H' = high $K_{SW}$; 'A' = adaptive $K_{SW}$. Since A = B on wide roads, and A = H on narrow roads, these pairwise comparisons are not included. × means $p \geq 0.05$; • means $p < 0.05$; •• means $p < 0.01$; ••• means $p < 0.001$.

| | | Wide | | | | | Narrow | | | | | Wide vs. narrow | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Per steering wheel | | | Pairwise | | Per steering wheel | | | Pairwise | | Per steering wheel | | |
| | | B | H | A | B - H | H - A | B | H | A | B - H | B - A | B | H | A |
| $K_{NMS}^{-1}$ | Mean | 1.78 | 1.39 | 1.68 | | | 1.3 | 0.99 | 0.99 | | | 0.48 | 0.41 | 0.7 |
| | Std. | 0.82 | 0.83 | 0.66 | | | 0.56 | 0.38 | 0.46 | | | 0.85 | 0.83 | 0.58 |
| | Effect size | F(2,20) = 1.505 | | | | | F(2,20) = 2.092 | | | | | t(10) = 1.874 | t(10) = 1.625 | t(10) = 3.980 |
| | p | × | | | - | - | × | | | - | - | × | × | •• |
| $\#HIT$ | Mean | 0 | 0.09 | 0 | | | 4.18 | 4.09 | 3.91 | | | -4.18 | -4 | -3.91 |
| | Std. | 0 | 0.3 | 0 | | | 3.4 | 2.86 | 3.73 | | | 3.4 | 2.81 | 3.73 |
| | Effect size | F(2,20) = 1.000 | | | | | F(2,20) = 0.025 | | | | | t(10) =-4.079 | t(10) =-4.72 | t(10) =-3.472 |
| | p | × | | | - | - | × | | | - | - | •• | •• | •• |
| $std(\epsilon)$ | Mean | 0.11 | 0.09 | 0.1 | | | 0.08 | 0.08 | 0.08 | | | 0.03 | 0.01 | 0.03 |
| | Std. | 0.03 | 0.02 | 0.02 | | | 0.02 | 0.01 | 0.03 | | | 0.03 | 0.02 | 0.02 |
| | Effect size | F(2,20) = 0.953 | | | | | F(2,20) = 0.242 | | | | | t(10) = 3.396 | t(10) = 1.547 | t(10) = 4.330 |
| | p | × | | | - | - | × | | | - | - | •• | × | •• |
| $SRR$ | Mean | 2.03 | 1.58 | 1.91 | | | 2.29 | 1.88 | 1.76 | | | -0.25 | -0.3 | 0.15 |
| | Std. | 0.31 | 0.33 | 0.36 | | | 0.23 | 0.33 | 0.4 | | | 0.19 | 0.15 | 0.21 |
| | Effect size | F(2,20) = 21.425 | | | | | F(2,20) = 16.589* | | | | | t(10) =-4.443 | t(10) = -6.868 | t(10) = 2.344 |
| | p | ••• | | | •• | •• | ••* | | | •• | •• | •• | ••• | • |
| $std(T)$ | Mean | 0.72 | 0.65 | 0.71 | | | 0.83 | 0.76 | 0.75 | | | -0.11 | -0.12 | -0.04 |
| | Std. | 0.1 | 0.08 | 0.11 | | | 0.11 | 0.07 | 0.09 | | | 0.08 | 0.07 | 0.07 |
| | Effect size | F(2,20) = 11.621 | | | | | F(2,20) = 4.846 | | | | | t(10) =-4.388 | t(10) = -5.355 | t(10) = -2.123 |
| | p | ••• | | | •• | • | • | | | × | • | •• | ••• | × |
| $TLC^{-1}$ | Mean | 0.05 | 0.04 | 0.05 | | | 0.13 | 0.12 | 0.12 | | | -0.08 | -0.08 | -0.07 |
| | Std. | 0.01 | 0 | 0.01 | | | 0.04 | 0.02 | 0.02 | | | 0.04 | 0.02 | 0.02 |
| | Effect size | F(2,20) = 7.786 | | | | | F(2,20) = 1.337 | | | | | t(10) =-7.491 | t(10) =-12.874 | t(10) =-13.287 |
| | p | •• | | | • | • | × | | | - | - | ••• | ••• | ••• |

* Mauchly's sphericity test was violated, Greenhouse-Geisser assumed.

TABLE II: Results of Friedman's test and post hoc Wilcoxon signed rank test for questionnaire data. 'B' = baseline $K_{SW}$; 'H' = high $K_{SW}$; 'A' = adaptive $K_{SW}$. × means $p \geq 0.05$; • means $p < 0.05$; •• means $p < 0.01$.

| | | Wide and narrow | | | | | |
|---|---|---|---|---|---|---|---|
| | | Per steering wheel | | | Pairwise | | |
| | | B | H | A | B - H | H - A | B - A |
| Satisfaction | Mean | -0.55 | -0.09 | 0.57 | | | |
| | Std. | 0.75 | 0.73 | 0.82 | | | |
| | Effect size | $\chi^2(2) = 9.333$ | | | | | |
| | p | •• | | | × | × | •• |
| Usefulness | Mean | 0.09 | 0.4 | 0.56 | | | |
| | Std. | 0.48 | 0.54 | 0.54 | | | |
| | Effect size | $\chi^2(2) = 3.297$ | | | | | |
| | p | × | | | - | - | - |

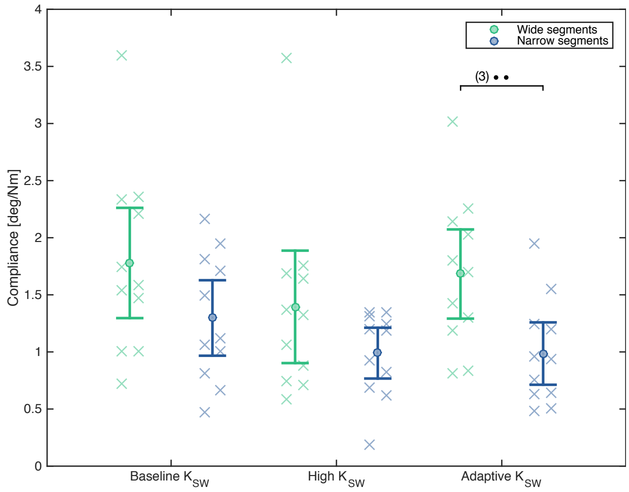
### B. Effort

It was found that with higher $K_{SW}$, SRR is significantly lower than with lower stiffness, both on narrow and on wide roads. These results are visualised in Fig. 6b, and statistics are reported in Table I. Furthermore, SRR is significantly higher on narrow than on wide roads, for baseline and high $K_{SW}$ (see Table I). Interestingly, with adaptive stiffness, SRR is significantly *lower* on narrow than on wide roads.

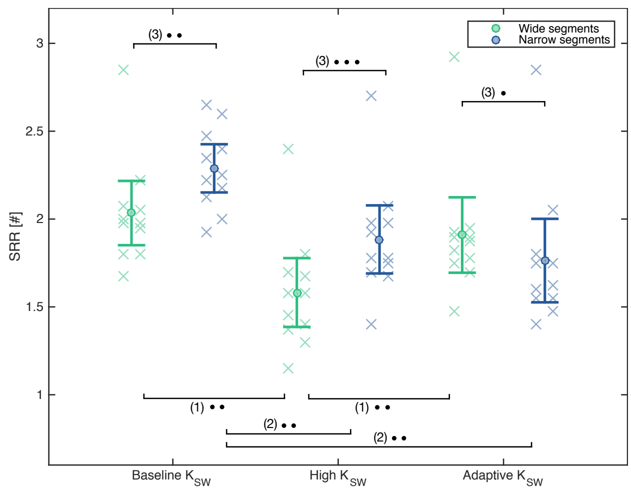
Effort was also significantly lower for higher $K_{SW}$ with respect to std(T), as can be seen in Fig. 6c and Table I. In addition, std(T) is larger on narrow than on wide roads, but only with baseline and high $K_{SW}$. The effect of road width on std(T) was thus counteracted by adaptive $K_{SW}$.

### C. Performance

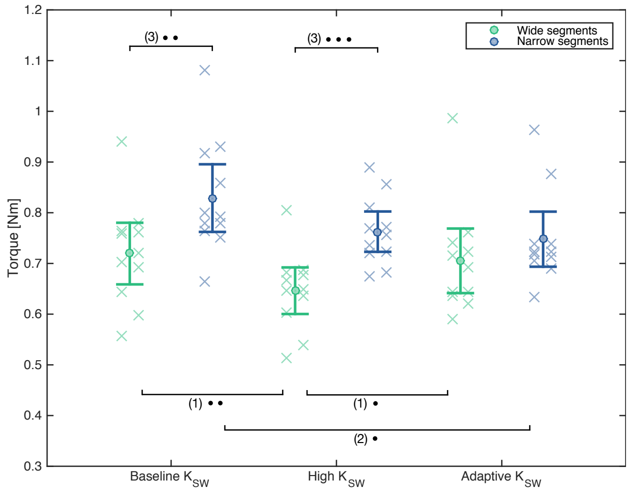
With higher $K_{SW}$, mean $TLC^{-1}$ is lower compared to lower $K_{SW}$, as can be seen in Fig. 6d. This effect is only significant



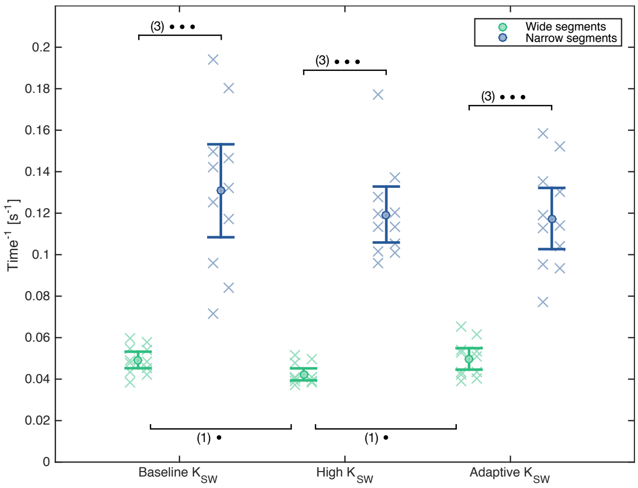

(a) Human NMS compliance (admittance on f = 0.3 Hz). NMS compliance is lower on narrow than on wide roads, but only (significantly) with adaptive $K_{SW}$. No significant effects of steering wheel stiffness were found.




(b) Steering reversal rate (SRR). SRR is lower when roads are wider or when $K_{SW}$ is higher. With adaptive $K_{SW}$, SRR is lower on narrow compared to wide roads.




(c) Standard deviation of torques (std(T)). With high and baseline $K_{SW}$, std(T) is higher on narrow than on wide roads. Adaptive $K_{SW}$ cancels this effect. After all, with higher steering wheel stiffness, std(T) is lower.




(d) Mean inverse time-to-lane crossing ($TLC^{-1}$). On narrow roads, $TLC^{-1}$ is substantially higher than on wide roads. With high $K_{SW}$, $TLC^{-1}$ is lower than with baseline $K_{SW}$, but only (significantly) on wide roads.

Fig. 6: For all metrics, the mean ± 95% confidence interval of the results are shown. An '×' indicates a data point from a single subject. This value represents the average of two repetitions (i.e. of two road segments with the same width), such that there is one data point per subject per road width per steering wheel setting. In total, eleven subjects took part, so eleven points are plotted for each combination of conditions. Per steering wheel setting, the wide road results are plotted in green (on the left) and the narrow in blue (on the right). The following comparisons are made: (1) among all steer settings on a wide road, so all green data; (2) among all steer settings on a narrow road, so all blue data; (3) between narrow and wide per steer setting, so each blue-green combination. Significant effects are indicated: • means $p < 0.05$, •• means $p < 0.01$, and • • • means $p < 0.001$. Note that the results for adaptive $K_{SW}$ should correspond to those with low $K_{SW}$ on wide roads and to high $K_{SW}$ on narrow roads.

on wide roads ($F(2,20) = 7.786$, $p < 0.01$). No significant effects of $K_{SW}$ were found on the standard deviation of the lateral error (std($\epsilon$)) or the number of hit cones (#HIT). Furthermore, mean $TLC^{-1}$ is higher with decreased road width, see Table I. Std($\epsilon$) is smaller on narrow than on wide roads, whereas the number of hit cones is larger, see Table I. Overall, performance on the metrics deemed most relevant to the driving tasks, i.e. $TLC^{-1}$ and #HIT, was worse on narrow than on wide roads. For additional plots, the reader is referred to Appendix G.

### *D. Acceptance*

The results from the Van der Laan questionnaire indicate that subjects were significantly more satisfied with the adaptive steering wheel system than with baseline stiffness ($\chi^2(2) = 9.333$, $p < 0.05$). For satisfaction as well as usefulness, mean subjective ratings were lowest for baseline $K_{SW}$ and highest for adaptive $K_{SW}$, see Table II. The metric plots can be found in Appendix G.

## IV. Discussion

Findings suggest that, against expectations, when steering wheel stiffness $K_{SW}$ is higher, humans do not decrease their neuromuscular stiffness $K_{NMS}$ to keep the combined dynamics constant. This implies that adapting $K_{SW}$ to road width, similar to how drivers adapt, would not yield the expected benefits in terms of $K_{NMS}$. Indeed, adaptive $K_{SW}$ (which is higher on narrow roads) actually enlarged the effect

of road width on $K_{NMS}$, rather than eliminating it.
In explaining the findings, first, the applied experimental methods are discussed in order to verify if the obtained results are valid. Then, explanations from a more theoretical perspective are considered. Finally, the results regarding effort and performance metrics will be considered.

First of all, as inter-subject variability is known to be large for human NMS properties, this could explain why no significant effects of $K_{SW}$ on $K_{NMS}$ were found. However, the increase in $K_{NMS}$ for decreased road width is not significant with baseline $K_{SW}$, while a significant effect was found in [10]. This implies that normal inter-subject differences may not be enough to account for all of the variability encountered in the results. On the other hand, in [10], wide roads were 4.5 instead of 3.6 meters. Perhaps if the current study had applied a larger difference in road width as well, a significant effect on $K_{NMS}$ would have been found. Other explanations for the variability in the results will be considered below, such as unreliable estimation of $K_{NMS}$, or the possibility that subjects applied different strategies in performing the task.
The reliability of the estimation of $K_{NMS}$ was optimised by applying a perturbation signal with a short time period to reduce time-variance, and by averaging over multiple repetitions in the time-domain as well as in the frequency domain. Resulting coherence on the lowest frequency is around 0.8 on wide roads, and 0.7 on narrow roads. Some time-variant behaviour might still have occurred, but further shortening of the perturbation signal would increase its lowest frequency. For the same reason, time-variant system identification as applied in [21] can not capture the relevant (low frequency) information. Another downside of a short time period is predictability. Already, a phase lead is visible in the human response, indicating that to some extent, subjects anticipated the disturbance. As a result, anticipatory muscle activation may have influenced the stiffness of their arms by acting as an additional force input [16]. However, the effect disappears after 1 Hz, and coherence on lower frequencies is still high, indicating that the effect of noise was small. Anticipation has thus probably not affected the results considerably.
Another explanation for the variability in $K_{NMS}$ could be that the driving tasks allowed subjects to perform different strategies. By looking at the results from all the subjects together, individual trade-off's may have been averaged out. For instance, it would not be detected if some chose to increase $K_{NMS}$ at the benefit of performance, while others decreased $K_{NMS}$ and kept performance constant. To that end, an analysis of individual trends was done, which is described in Appendix H. However, no subgroups applying distinct strategies were identified, decreasing the likeliness of this explanation.
Summarising, the variability in the results might explain why the hypothesis was not verified, and is most likely due to inter-subject differences in NMS parameters. Since a careful trade-off between the mentioned limitations was made in the design of the perturbation signal, it is uncertain whether reliability of the estimates can further be improved with available system identification techniques. Rather than redesigning the signal, more participants could be measured to reduce the influence of inter-subject variability. This idea is supported by the fact that observed power was low (0.282 on wide and 0.378 on narrow roads). At the same time, this indicates that even if the hypothesised relationship between $K_{SW}$ and $K_{NMS}$ would exist, it would not be strong.

Therefore, next to the explanations from an experimental point of view, the possibility should be considered that the relationship between $K_{NMS}$ and $K_{SW}$ is simply not as expected. Part of the underlying assumption was that drivers would increase their $K_{NMS}$ on narrow roads, to improve performance. However, performance was still worse on narrow than on wide roads, also with high $K_{SW}$. Perhaps drivers did not merely adapt their $K_{NMS}$ to maintain performance, but other mechanisms influenced their NMS adaptation as well. It is also possible that $K_{SW}$ was not as beneficial for performance as expected, or that subjects did not notice the improvements. These explanations will be discussed below.
First of all, people might want to maintain a certain level of dominance over the steering wheel, regardless of their performance. Higher $K_{SW}$ would then lead to a higher $K_{NMS}$, such that the relative contribution to the combined dynamics stays the same. Although not significantly, a trend like this could be recognised in Fig. 6a, so the results do not rule out the alternative hypothesis ($p = 0.246$ on wide roads; $p = 0.150$ on narrow roads). Clues for this theory could not be found in literature though; impedance control is regarded mainly as a strategy for increasing stability [22]. To verify such a hypothesis, follow-up research would be needed.
Also, instead of co-contracting more, people might have employed a higher level of reflexive activity with baseline $K_{SW}$ to compensate for the increased task difficulty. This is indicated by the peaks in human admittance around 3-4 Hz, shown in the upper left graphs in Fig. 5a and 5b, which appear to be larger for baseline $K_{SW}$. After all, stability of the system is not affected by steering wheel stiffness, meaning that subjects can safely apply reflexes (also) with low $K_{SW}$. The participants may have been satisfied with the increased end-point admittance resulting from the reflexive activity, and even applied less co-contraction. A similar explanation was given in [8] for the decreased levels of muscle activity for perturbation signals with lower reduced power. However, to be able to draw any conclusions on the relative contribution of reflexes and co-contraction, EMG recordings need to be made in a future experiment.
Next to impedance control and reflexes, humans make use of internal models of the inverse dynamics to determine the torques needed to achieve a desired movement. Creating an internal model requires learning of the system dynamics, so in unfamiliar tasks the contribution of impedance control is larger than for well-known dynamics [23]. While subjects were allowed to update their internal model of the system dynamics during training, they remained more accustomed to baseline than to high $K_{SW}$. This means that they might still not (as) fully comprehend the effects of higher steering wheel stiffness. However, as strong effects of steering wheel

stiffness were found on the other metrics, it is not believed that this was of major influence.

Moreover, part of the underlying assumption could not be verified either: higher $K_{SW}$ - in combination with higher effort - was not enough to compensate for the decreased performance on narrow roads with respect to TLC and number of hit cones. In other words, with high $K_{SW}$ the task was still harder at narrow roads. Also, no effect of steering wheel stiffness was found on the number of hit cones, while this metric most directly relates to the subjects' task and also was what they received feedback on. As a result, the positive effects of high $K_{SW}$ might not have been completely clear to the subjects. If performance improvements had been more apparent, they may have been encouraged to relax more when driving with high $K_{SW}$ [24].

Finally, it should be acknowledged that higher inherent steering wheel stiffness is in fact not always beneficial. When the car is aligned correctly, it takes more force to deviate from the straight path. However, when the car is directed away from the center of the lane, it is also harder to steer back. The increased effort when taking curves might have influenced the participants' driving behaviour. More importantly, the perturbation signal, although its mean is zero, does result in small misalignments. These are thus particularly undesirable with high steering wheel stiffness. As applying higher levels of co-contraction is a well-known strategy to reduce the effect of perturbations, this could even lead to higher $K_{NMS}$ with higher $K_{SW}$. On the other hand, the perceived amplitude of the perturbation (i.e., the steering wheel rotations resulting from the force signal) is larger with lower steering wheel stiffness, possibly averaging out these effects. However, as shown in [8], the effect of task instruction on NMS admittance can be ten times larger than the effect of perturbation amplitude. It is therefore deemed most important how subjects perceived the driving task, i.e. whether or not they felt the need to actively resist perturbations to keep the steering wheel angle constant. Also, by tuning the amplitudes of the disturbance signal such that it would never (even with low $K_{SW}$ on narrow roads) by itself result in a lane departure, it was attempted to prevent a difference in task between the steering wheel systems. However, since steering back to the center of the lane is harder with high $K_{SW}$, as explained before, the perturbations might have had a different effect after all. Therefore, for future research on this topic, it would be recommended to apply a method without perturbations to estimate $K_{NMS}$, for example using EMG measurements, to ensure that the task is not affected differently with the steering wheel systems.

Despite the lack of significant results regarding $K_{NMS}$, clear effects of steering wheel stiffness have been found on other metrics. Effort is lower with higher $K_{SW}$ (including adaptive $K_{SW}$ on narrow roads) with respect to both steering reversal rate (SRR) and standard deviation of torques (std(T)). At the same time, with higher $K_{SW}$, mean inverse time-to-lane crossing ($TLC^{-1}$) is similar or lower. So while effort clearly decreased, performance was maintained or even improved. As expected, higher steering wheel stiffness thus seems to make it easier to drive straight. These positive effects were generally stronger on wide than on narrow roads, as is shown in Table I. For example, the decrease in $TLC^{-1}$ is only significant on wide roads. A possible explanation could be that people have higher $K_{NMS}$ on narrow roads, also when $K_{SW}$ is high. The impact of high $K_{SW}$ on the combined dynamics is then smaller, which could lead to less clear effects.

Also, as expected, effort is higher on narrow than on wide roads. With adaptive $K_{SW}$, effort is kept constant between road widths, or even reduced on narrow roads (std(T) or SRR, respectively). The underlying assumption that increased $K_{SW}$ can compensate for increases in effort when road width is decreased, is thus verified. In contrast, as stated before, increased $K_{SW}$ is not enough to compensate for the difference in performance between narrow and wide roads.

Nevertheless, subjective ratings of both usefulness and satisfaction were highest for adaptive $K_{SW}$, and significantly higher than baseline $K_{SW}$ for satisfaction. As opposed to the other metrics, the Van der Laan questionnaire concerned the entire (straight) road, so the steering systems were evaluated on narrow and wide segments together. Interestingly, when looking at the other results over the whole road, the 'total' effort and performance are worse with adaptive than with high $K_{SW}$. The only exception is $K_{NMS}$, which is lower with adaptive $K_{SW}$ on wide roads. This might have outweighed the other results, emphasising the importance of understanding drivers' NMS response. Another explanation for the fact that subjects favoured adaptive $K_{SW}$ could be that they preferred to keep effort more or less constant across road widths. Either way, while no direct positive effects on $K_{NMS}$ could be found, the concept of adapting stiffness shows clear potential: not only could stiffness be applied to reduce effort while maintaining or improving performance, subjects showed a clear preference for adaptive stiffness.

## V. Conclusions

A driving simulator experiment was conducted to investigate drivers' neuromuscular stiffness ($K_{NMS}$) in response to steering wheel stiffness ($K_{SW}$) on wide and narrow roads. It was hypothesised that by adapting $K_{SW}$ to road width, drivers would be allowed to keep their $K_{NMS}$ constant.

- Against expectations, drivers did not decrease their $K_{NMS}$ with higher $K_{SW}$. In fact, adaptive $K_{SW}$, which - like drivers - is stiffer on narrow roads, showed a stronger increase in $K_{NMS}$ for reduced road width compared to constant $K_{SW}$.
- In general, increased $K_{SW}$ did have a positive effect on effort, while maintaining or even improving performance. However, even with high $K_{SW}$, performance was worse on narrow than on wide roads, possibly explaining why $K_{NMS}$ still increased.
- Nonetheless, adaptive $K_{SW}$ did allow subjects to keep effort constant between road widths, and was well-liked.

It can thus be concluded that although adapting $K_{SW}$ to road width did not reveal beneficial effects on $K_{NMS}$, the concept has the potential to assist drivers in other aspects.

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# Appendices

# A

# Background: human steering and adaptivity

To understand how a human can be assisted in steering, it is important to understand how a human steers in the first place. Therefore, this appendix will briefly explain how humans control their movements. A distinction is made between visual and neuromuscular control.

According to Michon's hierarchy, driver control behaviour can be divided into three levels: strategical, tactical, and operational [1]. The first has to do with general planning (e.g. trip route) and determines the reference $r_H$. On the tactical level, choices are made within a shorter period of time (seconds), and include manoeuvres such as obstacle avoidance, turning, and overtaking. Finally, on the operational level, the tactical plans are realised by creating actual steering inputs. The time constant on this level is in the order of milliseconds.
Visual control thus occurs on a tactical level, where the central nervous system (CNS) determines the desired steering angle $\alpha_H$, based on visual feedback and other environmental cues $\epsilon_H$. Neuromuscular control takes place on the operational level, by creating actual steering inputs $u_H$ to realise the desired angle. Also, the neuromuscular system (NMS) sends sensory feedback $FB_{NMS}$ to the CNS. The interaction is visualised in Fig. A.1.

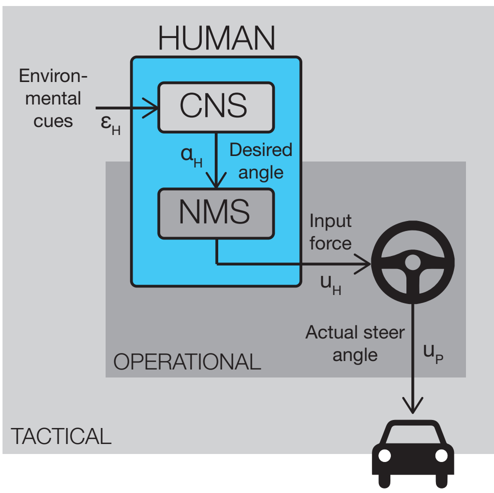


Figure A.1: Interaction between visual and NMS control, on a tactical and operational level, respectively.

Here, the mechanisms underlying this interaction will be elaborated. The section on visual control will explain the (tactical) mapping from visual cues $\epsilon_H$ to desired angle $\alpha_H$. Then, it will be explained how this desired angle $\alpha_H$ is translated to an actual input $u_H$ by NMS control on an operational level. Furthermore, attention will be paid to the different factors influencing the human's control characteristics to show when and how humans adapt.

## A.1. Visual control

Many aspects influence the driver's behaviour, ranging from general driver skills such as planning capabilities to features like stress and tiredness. Neural Network and fuzzy logic models do exist to describe behavioural and cognitive processes (see [2] for an overview). However, in this study, the focus is on (biomechanical) control. For that, according to [3], vision the is most important sense in driving. More specifically, the focus is on tasks that involve lateral control: lane keeping, lane changing, curve negotiation and obstacle avoidance. By modelling a driver performing these tasks, insight into how we steer is gained.

In [4, 5] it was proposed that a driver uses preview to perform steering tasks: by looking ahead on the road, we are able to perform not only compensatory control, but also anticipatory control. How this achieved at a neuromuscular level, will be explained in A.2. In [6] a two-point visual control model is introduced. The 'near point' represents the car's current position, and is used for compensatory control. The 'far point' on the other hand is an indication of the road curvature and is used for anticipatory control. Both points are illustrated in Fig. A.2. In curve negotiation tasks, the far point is equal to the 'tangent point' (instead of the center of the lane) [7, 8], which accounts for curve-cutting behaviour. In a car-following task, the far point is on the lead vehicle. Both situations are shown in Fig. A.2.

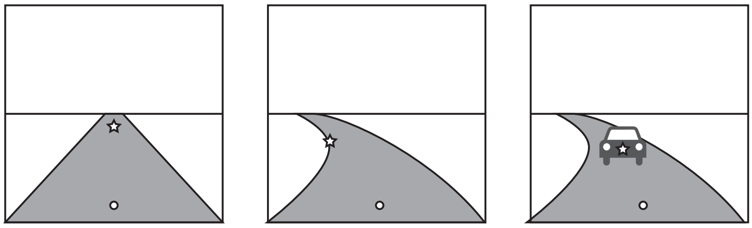

Figure A.2: Two-point visual control, adapted from [6]. The star represents the far point, the circle is the near point. The far point can be in the middle of the lane for a straight road (left), on the tangent point of a curve (middle) or on the lead vehicle (right).

It is assumed that the driver adjusts the steering angle $\varphi$ such that the angle of the desired target $\theta$ is minimised. This way, the car is aligned in the direction of the target. The target angle corresponds to $\theta_n$ for the near point and to $\theta_f$ for the far point. Using a standard proportional integral (PI) control law, the steering task can be described as follows:

$$\varphi = k_f\theta_f + k_n\theta_n + k_I \int \theta_n \mathrm{d}t \tag{A.1}$$

Modeling the visual controller as above, it is assumed that the human has an optimising control strategy. However, in practice, humans 'satisfice' rather than optimise: there is a certain threshold for error below which no corrective action is taken [9]. This means that humans do not necessarily try to stay in the center of their lane when driving, they accept some deviation from the 'optimal' path.

## A.2. Neuromuscular control

Once the desired steering angle is determined by visual control, the central nervous system (CNS) can activate muscles via motor neurons ($\alpha$-neurons). There are two control strategies that operate in parallel [10]:

- Impedance control [11]
  An antagonistic pair of muscles can be contracted at the same time, called co-contraction. This

strategy increases impedance and stability, but it goes at a higher metabolic cost. In many tasks, a trade-off between stability and energy is therefore made [12]. The stiffness, viscosity and inertia parameters can be controlled separately [13].

- Internal model control [14]
  An internal model is made of the inverse dynamics, allowing the human to determine the torques needed to achieve a desired movement. Creating an internal model requires learning of the system dynamics, so in unfamiliar tasks the contribution of impedance control is larger than for well-known dynamics.

Finally, another mechanism contributes to NMS control:

- Reflexes
  Some kinesthetic sensors do not only send information to the CNS, but also directly to the $\alpha$-motorneuron, creating spinal reflexes.

The different mechanisms are illustrated in Fig. A.3. Based on the internal model, the CNS can send a neural command to the muscles to achieve a desired angle. Activation dynamics $H_{act}$ represent the process from neural excitation to muscle force build-up. The Golgi Tendon Organ (GTO) and muscle spindles (SPI) result in direct feedback by creating spinal reflexes that bypass the CNS. The intrinsic dynamics $H_{int}$ represent the intrinsic viscoelastic properties of the arm muscles. By co-contraction the parameters of $H_{int}$ can be adapted voluntarily. In fact, $H_{int}$ changes with any muscle activity, and not only when impedance control is used. $H_{arm}$ represents the arm's inertia, which can not be adapted without changing the arm configuration. Finally, the grip dynamics $H_{grip}$ of the hand depend on the way the driver chooses to hold the steering wheel. Moreover, grip force was shown to be related to NMS admittance (i.e. the dynamic relation between input force and output displacement) [15], also during a steering task [16].

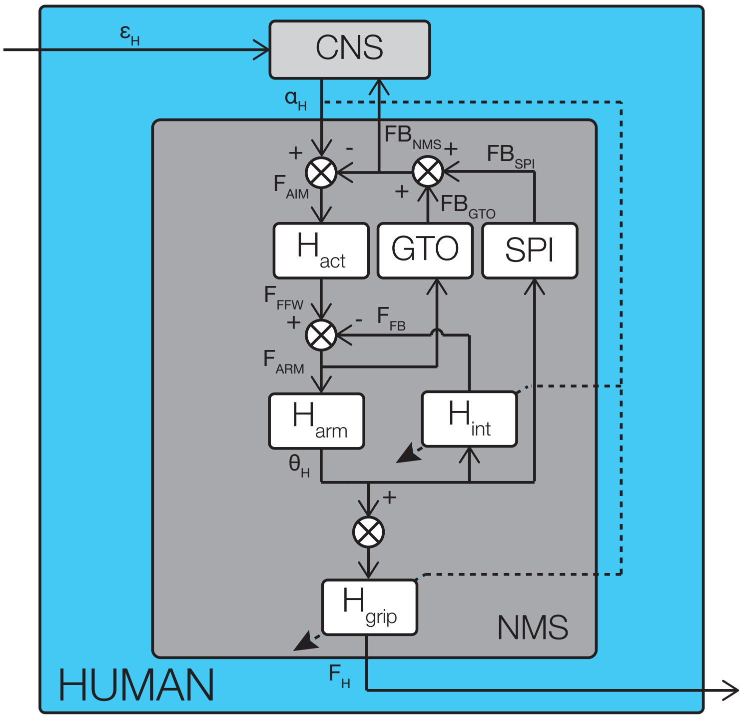


Figure A.3: Human NMS model, adapted from [17]. The intrinsic dynamics $H_{int}$ and grip dynamics $H_{grip}$ can be adapted voluntarily. $CNS$ = central nervous system; $GTO$ = Golgi Tendon Organ; $SPI$ = muscle spindles; $H_{act}$ = activation dynamics; $H_{arm}$ = arm inertia; $F_{AIM}$ = desired force; $F_{FFW}$ = feed-forward force; $F_{FB}$ = feedback force; $FB_{NMS}$ = sensory feedback; $\theta_H$ = arm angle; $F_H$ = human force.

As a result of the nonlinear behaviour of muscle spindles, differing activation rates, and the force-length and force-velocity relationship in muscles, the neuromuscular system is non-linear [18]. However, to be able to estimate NMS properties, the assumption of linearity is often made.

# A.3. Adaptivity

Besides the complex interaction between the control mechanisms described above, human movement control also has a highly adaptable nature. This section will provide an overview of the different factors influencing both visual and NMS control.

## A.3.1. Visual control

Naturally, the extent to which visual control contributes in a driving task, is dependent on environmental visibility conditions such as fog. This can affect the desired degree of HSC: stronger haptic feedback can compensate for the lack of visual information [19]. Moreover, the addition of HSC to driving can change it from a mainly visual to a visual and haptic task. This is shown in [20], where the haptic gas pedal decreased visual control gains. Similarly, in [21] haptic guidance for a car steering task resulted in lower visual demand. The weighing of visual versus haptic control is dependent on the gain of the HSC.

## A.3.2. NMS control

As is shown in Fig. A.3, the intrinsic dynamics and grip dynamics (together determining NMS admittance) can be adapted voluntarily by the CNS, based on the control strategy. However, many other factors are known to have an impact on neuromuscular admittance. Here, a brief overview will be given.

- Task difficulty
  First of all, learning influences NMS admittance. The more familiar a person is with a task, the less co-contraction he will use and the higher his admittance is (i.e. less stiff) [10, 14, 22]. Furthermore, the higher the desired level of accuracy, the stiffer the NMS, as humans make a trade-off between metabolic cost and task achievement [23]. Also, stiffness is increased in unstable directions. Summarising, it can be derived that human stiffness increases with task difficulty.
  Some research has focused specifically on arm admittance while driving. It was shown that, for a larger lane width and/or a higher speed, admittance decreases [24]. Also, curves have been shown to increase neuromuscular stiffness [25]. Again, these factors can be related to task difficulty.

- Haptic feedback
  In [26] it is shown that haptic guidance leads to a higher admittance in the ankle, indicating that the subjects give way to the guidance forces. However, when there is a conflict between the goals of the driver and the controller, humans will increase their stiffness to resist the controller. The stronger the guidance, the more the humans will need to resist to overcome a conflict. Depending on the situation, HSC can thus decrease or increase admittance.

- Arm geometry
  Limb geometry affects hand stiffness and viscosity [13, 27]. This means that the configuration of the driver's arm while holding the steering wheel, as well as the radius of the steering wheel itself, affect NMS admittance. The relationship between these conditions and admittance is not known exactly. Therefore they are best kept constant in an experiment. Note that when the steer is rotated while driving, the configuration of the arm changes as well.

- Experimental conditions
  Finally, task instruction has a large effect in experiments. Three classical motion control tasks are: the 'relax' task (RT), the 'maintain position' task (PT) and the 'maintain force' task (FT) [26]. A low admittance is found for PT (because of high levels of co-contraction) and high admittance for a FT (and RT) [28]. The effect of these different conditions on neuromuscular stiffness might be as large as a factor 40 [28]. So task instruction greatly affects NMS admittance, because it inherently changes the control strategy.

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# B

# Prelimary study report

# Drivers' Arm Stiffness for Varying Steering Wheel Parameters and Perturbation Bandwidths

## B.1. Introduction

When driving a car, humans are known to vary the neuromuscular admittance of their arms by means of co-contraction and reflexes [1, 2]. Changes in admittance occur based on numerous internal and external factors, such as the traffic situation, the way of holding the steering wheel, and the steering wheel itself. This enables drivers to adapt the way they control a vehicle to what is suitable for the specific situation.

Previous research has shown variations in neuromuscular responses to different road widths and vehicle speeds [3]. On narrow roads and at high velocities, drivers showed increased arm stiffness. This can be attributed to the increased criticality with respect to the lane-keeping task, which required the driver to use higher levels of co-contraction.

### B.1.1. Project goal

The fact that drivers also adapt their neuromuscular settings to the characteristics of the steering wheel can be used to assist them. For example, for a lane-keeping task at high speed, the stiffness of the steering wheel could be increased. Through physical interaction with the steer, the driver would sense the change, and the need to add his own neuromuscular stiffness would be eliminated. In this project it is investigated if indeed, when the steering wheel stiffness changes, drivers keep the combined dynamics constant by adapting their own admittance. Eventually, the aim is to understand if such adaptive steering wheel stiffness would work and how it should be implemented.

### B.1.2. Nissan data analysis

The neuromuscular response to different steering wheel parameters has not yet thoroughly been researched while driving. In [4], three different steering wheel dynamics were tested in different driving situations. It was found that on straight roads, and especially at higher speeds, the steering wheel dynamics should be 'slow and sluggish', but 'slack and light' in curves and for evasive manoeuvres.

A further investigation of the data available from the aforementioned experiment was done to compare the neuromuscular responses to the four steering wheel settings (see Table 2.1), for fast and slow driving. In contrast to the original theory that the combined dynamics of the physical interaction would be kept constant when the steering wheel dynamics changed, it was found that drivers actually increase their arm stiffness with increasing steering wheel stiffness, see Fig. 2.1 and 2.2. Furthermore, humans did not increase their neuromuscular stiffness as much as expected, see Fig. 2.3.

Table 2.1: Settings used in the Nisssan experiment

| Steering wheel settings | $K_{SW}$ [Nm/rad] | $B_{SW}$ [Nms/rad] | $I_{SW}$ [Nms$^2$/rad] |
|---|---|---|---|
| S1 | 16.8 | $B+++$ | $I++$ |
| S2 | 8.4 | $B++$ | $I+$ |
| S3 | 4.2 | $B+$ | 0.3 |
| S4 | 2.1 | 2 | 0.3 |

An explanation for these findings could be that before, only stiffness was discussed, while in the experiment the damping and inertia parameter were increased simultaneously with stiffness. More damping in the steer-

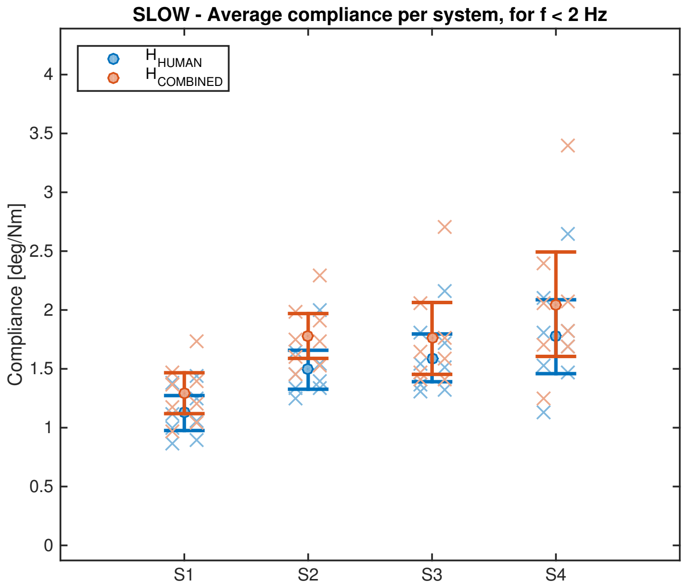


Figure 2.1: Average compliance for $f < 2$ Hz at a speed of 80 km/h.

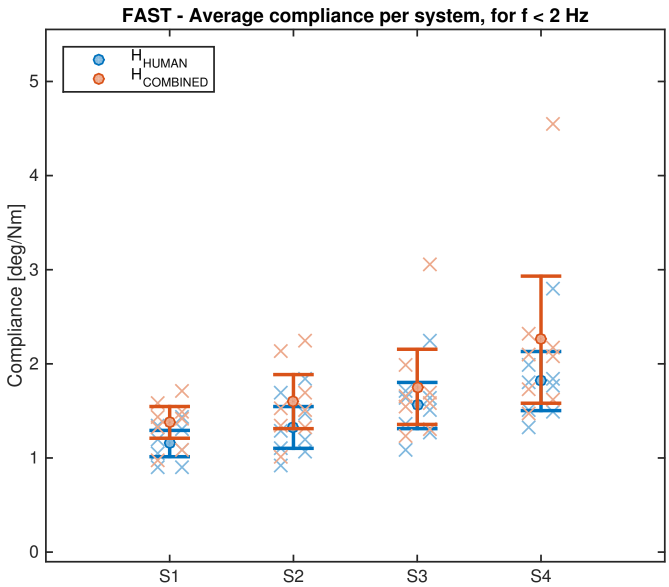


Figure 2.2: Average compliance for $f < 2$ Hz at a speed of 140 km/h.

ing wheel has a stabilising effect on the total dynamics, which allows the driver to safely increase reflexive activity. Since co-contraction comes at a higher metabolic cost, drivers might then prefer to use reflexes instead. The neuromuscular stiffness is larger resulting from co-contraction is larger than that of reflexes, so higher steering wheel damping leads to lower human stiffness. This theory does not help explain the findings from the data analysis; possibly because it is based on the idea that reflexes can replace that co-contraction. However, if they are used already, and additional damping leads to (even) higher reflexive activity, admittance might actually increase.

Furthermore, the perturbation signal used to measure the neuromuscular admittance might have had an effect on the results. It is known that disturbances with full power at a higher bandwidth inhibit reflexive

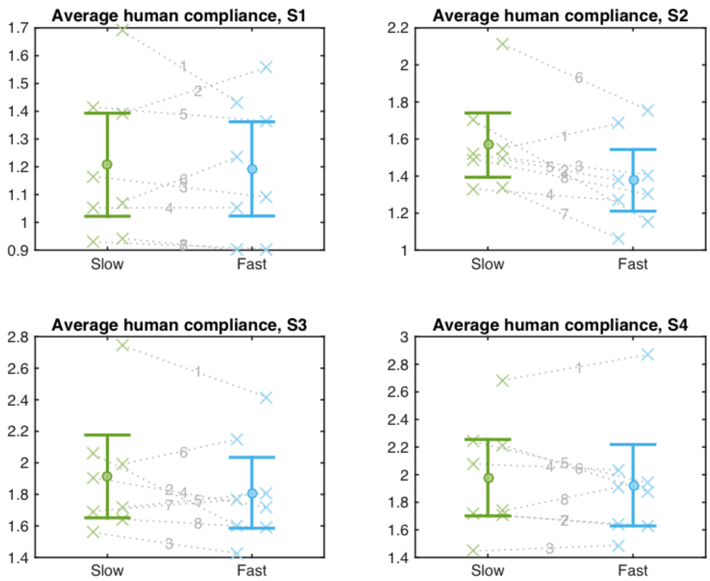


Figure 2.3: Average human compliance for $f < 2$ Hz at low versus high speeds.

activity, so a reduced power method was used in the experiment. This might have led to an increased use of reflexes (and thus a relatively low stiffness) compared to real-life driving.

### B.1.3. PRELIMINARY EXPERIMENT

Because literature does not provide evidence for any of the explanations for the difference between the original hypothesis and the findings from the data analysis, a preliminary experiment was conducted. The goal was to gain a better understanding of how humans adapt to different steering wheel parameters. For that, the following hypotheses with respect to compliance will be tested:

- When steering wheel stiffness $K_{SW}$ increases, humans lower their neuromuscular stiffness $K_{NMS}$, keeping the combined stiffness $K_{TOT}$ constant
  Note that this is the original hypothesis, but only on low frequencies (such that $Y_{NMS} \approx \frac{1}{K_{NMS}}$). For verification, the effects of changing only the stiffness parameter of the steering wheel are analysed. Also, the effect of different bandwidths of perturbation signals is taken into account.

- Increasing steering wheel damping $B_{SW}$ leads to higher human admittance on low frequencies ($\approx K_{NMS}$) by allowing reflexive activity.

Note that these hypotheses are based on the assumption that performance stays equal.

## B.2. METHODS

### B.2.1. INDEPENDENT VARIABLES

To test the first hypothesis, considering the effects of steering wheel stiffness and perturbation bandwidth, four conditions are needed:

C1 Baseline stiffness, baseline perturbation bandwidth
C2 Baseline stiffness, high perturbation bandwidth
C3 High stiffness, baseline perturbation bandwidth
C4 High stiffness, high perturbation bandwidth

For the second hypothesis, a full power perturbation is not effective because it inhibits reflexive activity. This leads to one extra condition:

C5 High damping (rest baseline)

All independent variables and their respective baseline and high settings are listed in Table 2.2. Finally, relating to the original project goal of adaptive stiffness, different levels of criticality were taken into account by implementing a narrowing of the road.

Table 2.2: Settings of independent variables; $f_{FP}$ = frequency up to which full power is used.

| Variable | Baseline setting | High setting |
|---|---|---|
| Perturbation signal bandwidth | $f_{FP} = 1$ Hz | $f_{FP} = 5$ Hz |
| Steering wheel stiffness | $K_{SW} = 0.113$ Nm/deg | $K_{SW} = 0.213$ Nm/deg |
| Steering wheel damping | $B_{SW} = 0.037$ Nms/deg | $B_{SW} = 0.065$ Nms/deg |

### B.2.2. Experimental set-up
Five subjects took part in the preliminary experiment, three female and two male, aged around 25 years old, all with a driving license. They were asked to drive two laps in the fixed-base driving simulator at the faculty of Aerospace Engineering, TU Delft.

The simulated road consisted of three straight segments and a left and right curve (in random order). The curves separated the straight segments, and were preceded and followed by a transition segment of 100 m. In the first segment of 400 m, the vehicle speed increased from 0 to 70 km/h. Measurements were only performed on the other two 632 m long segments, one of which was wide and the other narrow. The width of the entire road was 5.5 m, and at the narrow segment, cones were placed on both sides such that the width was reduced to 2.5 m.

### B.2.3. Disturbance
The length of the straight segments used for measuring was chosen such that they would take subjects 32.5 seconds at 70 km/h. From this, the first three and last two seconds would be extracted to account for transitions between the narrow and wide road. To be able to perform system identification, a 27.5 second force perturbation signal was designed. It was optimised to make the time domain differences between the high and low bandwidth condition as small as possible, while having high resolution on low frequencies. To that end, the signal contained 9 frequency points with power between 0.1 and 1 Hz and only 6 between 1 and 5 Hz. Both can be seen in Fig. 2.4.

### B.2.4. Metrics
With the perturbation signal, the dynamics of the different systems (i.e. the human, the steering wheel and their physical interaction) can be estimated. To get an estimate of the compliance, the average admittance on low frequencies (e.g. <1 Hz) can be analysed. Another option is to perform parameter estimation by means of a least-squares optimisation algorithm. Both methods will be compared.

However, compliance alone does not give enough insight. For a more complete understanding, metrics of performance and effort are analysed as well. Standard deviation of the lateral error shows how well subjects perform with respect to staying in the middle of the lane. Time to lane crossing (TLC) says something about lane-keeping performance and is more sensitive to speed and velocity:

$$\mathrm{TLC} = \frac{y}{\dot{y} + \ddot{y}}$$

Effort can be indicated by the mean steering wheel reversal rate (SRR) and the standard deviation of the exerted torques.

## B.3. Results
All figures showing the results from the preliminary study can be found in Chapter B.6. Below, the results of adapting the different steering wheel parameters and perturbation bandwidths will be discussed. Also, the effects of narrow versus wide roads are analysed. Note that no statistical analyses were performed, as only five subjects took part in the experiment. The results described here can thus not be used to drawn any legit conclusions, and merely serve to gain more insight into the mechanisms at hand.

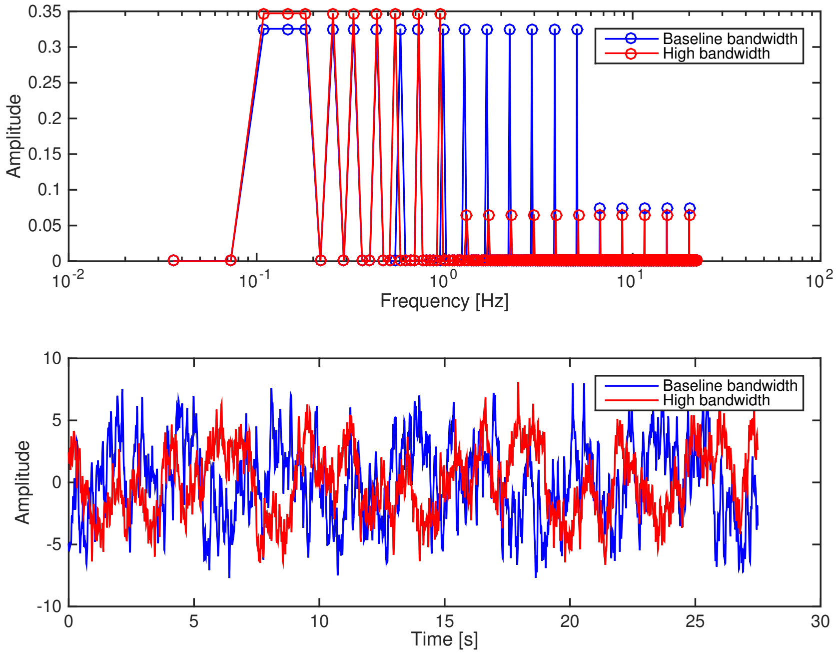


Figure 2.4: Autospectral density disturbance signals

### B.3.1. BASELINE VS. HIGH STIFFNESS

First, high stiffness of the steering wheel will be compared to the baseline condition. This means comparing C1 to C3 and C2 to C4 (see also Chapter B.2). In most of the figures in Chapter B.6, this comparison is made in the upper two plots. The effects on different metrics are discussed below:

- Human compliance
  Average admittance on $f < 1$ Hz did not change for different steering wheel stiffness settings on wide or narrow roads, see Fig. 2.6 and Fig. 2.7. Similar results were obtained by analysis of the mean estimated parameter, see Fig. 2.9 and Fig. 2.10. With low bandwidth perturbations, two out of five subjects showed lower admittance and three showed higher or constant admittance for higher steer stiffness. With high bandwidth perturbations, individual admittance was almost constant between baseline and high steer stiffness. Also, it was expected that humans would keep the combined admittance of the system constant across conditions. However, no such trend could be found (Fig. 2.6 - 2.10): it looks like combined compliance decreased with increased $K_{SW}$.

- Performance
  On wide road segments, higher stiffness of the steering wheel did not lead to better performance with respect to lateral errors, see Fig. 2.12. On narrow segments however, the standard deviation of the lateral error was lower for higher steer stiffness, see Fig. 2.13. Also, minimum time to lane crossing (TLC) was generally larger for high stiffness. This effect was visible on both wide and narrow roads, and especially with a higher perturbation bandwidth, see Fig. 2.15 and 2.16. It should be noted that the subjects that had lower admittance with high steer stiffness, showed a decrease in TLC on narrow segments. Their performance with respect to lateral error did not improve either.

- Effort
  The average reversal rate was lower for a stiffer steering wheel, although the effect was not clear on narrow segments with low perturbation bandwidths, see Fig. 2.18 and 2.19. Torques only decreased when a high bandwidth perturbation was used, and slightly increased with low bandwidth perturbations, see Fig. 2.21 and 2.22.

### B.3.2. Baseline vs. high perturbation bandwidth

To analyse the effect of perturbation bandwidth, C1 is compared to C2 and C3 to C4 (see also Chapter B.2). In most of the figures in Chapter B.6, this comparison is made in the middle two plots.

- Human compliance
  On narrow roads with low steer stiffness, a decrease in compliance with increased bandwidth was found, see Fig. 2.7 and 2.10. However, on wide roads, compliance either increased with bandwidth or stayed the same, as can be seen in Fig. 2.6 and 2.9.
- Performance
  No effects of perturbation bandwidth were visible for the standard deviation of lateral error, see 2.13 and 2.12. The minimum TLC was lower for higher bandwidths on wide road segments, as is shown in Fig. 2.15.
- Effort
  In general, effort was higher for higher perturbation bandwidths. An increase in SRR can be seen in Fig. 2.18 and 2.19. Torques only increased for high bandwidth perturbations at low steering wheel stiffness.

### B.3.3. Baseline vs. high damping

Comparing baseline to high steering wheel damping is done by examining the differences between C1 and C5 (see also Chapter B.2). In most of the figures in Chapter B.6, this comparison is made in the bottom plot.

- Human compliance
  On narrow and wide segments, compliance (both as averaged admittance and as an estimated parameter) was lower for higher steering wheel damping. This effect can be seen in Fig. 2.6,2.7, 2.9, and 2.10.
- Performance
  On wide segments, larger lateral errors were found for high damping, see Fig. 2.12. On narrow segments, lower errors were found, as shown in Fig. 2.13. On average, performance with respect to TLC improved slightly, but the individual trends varied a lot, as can be seen in Fig. 2.15 and 2.16.
- Effort
  Mean SRR was slightly lower for high damping, see Fig. 2.18 and 2.19. Torques on the other hand increased, see Fig. 2.21 and 2.21.

### B.3.4. Narrow vs. wide roads

Finally, for analysing the effects of road width, a separate figure is created (see Chapter B.6), with a sub-plot for each condition. The most important results are:

- Human compliance
  Although individual trends show a slight increase in admittance on wide roads across conditions, the effect is most clear with a high bandwidth perturbation, especially with baseline steering wheel stiffness, see Fig. 2.8 and 2.11. It can be seen that in the first condition (baseline steer stiffness and low bandwidth perturbation), one of the subjects showed lower admittance instead.
- Performance
  Larger lateral errors were found on wide roads, as is shown in Fig. 2.14. The only subject that made smaller errors on wide roads, was the one that decreased admittance. The minimum time to lane crossing was much larger on wide road segments, see Fig. 2.17.
- Effort
  With respect to the average steering wheel reversal rate, no changes in effort were found between narrow and wide roads, see Fig. 2.20. The standard deviation of exerted torques was lower on wide roads, see Fig. 2.23.

## B.4. Conclusions & Discussion

The main hypotheses of the experiment with respect to compliance were:

- On low frequencies, $K_{NMS}$ decreases when $K_{SW}$ increases.

- Increasing steering wheel damping $B_{SW}$ leads to higher $K_{NMS}$ by allowing reflexive activity.

Furthermore, it was tested whether:

- Increasing perturbation bandwidth leads to lower $K_{NMS}$ by inhibiting reflexive activity.
- $K_{NMS}$ is lower on wide than on narrow segments.

The results did not provide proof for any of the hypotheses, but do give insight into whether or not the involved mechanisms worked as expected. The findings are elaborated below, taking into account the other metrics as well.

### B.4.1. STEERING WHEEL STIFFNESS

It was expected that with higher steering wheel stiffness, humans would be more compliant. This hypothesis was not verified. Similarly, when performance is kept equal between a baseline and high stiffness condition, effort was expected to be lower for high steering wheel stiffness. This was however not the case for all conditions. At the same effort, higher stiffness of the steering wheel was expected to lead to higher performance. Regarding lateral errors, this was verified for narrow roads. The minimum TLC was generally larger for high stiffness. It can be concluded that on average, subjects kept effort and compliance constant, while performance improved. Looking at individual results also demonstrates a relationship between compliance and performance: subjects who increased compliance seemed to have performed worse.

### B.4.2. PERTURBATION BANDWIDTH

On narrow roads with low steer stiffness, the expected decrease in compliance with increased bandwidth was found, but not on wide roads. This indicates that co-contraction was only applied instead of reflexes when it was considered to be necessary. SRR increased for high versus low bandwidths. Still, TLC is generally lower for higher bandwidth perturbations. The standard deviations of lateral error and torque were not clearly affected.

### B.4.3. STEERING WHEEL DAMPING

Against expectation, human compliance was found to be smaller for higher steering wheel damping, while no general increase in performance was found. Since with high damping, initiating a change in steering angle requires more force, it makes sense that SRR decreased while torques increased.

### B.4.4. ROAD WIDTH

Compliance was not as much increased on wide segments as expected, but the standard deviation of lateral errors was larger. Besides, when a subject decreased admittance on a wide road, this resulted in smaller errors. So again, performance might have improved at the cost of effort. Indeed, no changes were found in SRR, but torques were lower on wide roads.

Overall, the effects of steering wheel stiffness and perturbation bandwidth were more or less as expected. However, when comparing the baseline stiffness of the steering wheel to a higher setting, largest differences were found in the performance metrics. A possible explanation is that subjects did not get a lot of feedback on their performance. It is hard to tell when the car is exactly in the middle of the lane. Also, as the minimum TLC values are all rather high, lane keeping was no challenge. Moreover, time to lane crossing was much larger on wide than on narrow segments. This is due to TLC being calculated using the road width: both are directly and positively related. In fact, TLC is one of the mechanisms through which humans can identify changes in criticality. It is therefore not as much a dependent variable of the experiment as it is an independent one.

The effects of damping were not as predicted. In [1], a neuromuscular model of a driver was created and its response to different steering wheel dynamics was evaluated for a double lane-change manoeuvre. The more oscillatory the steering wheel, the higher the level of co-contraction predicted by the model. However, this trend could not be found in their measured data. This was attributed to the internal model drivers have of the car dynamics, which reduces co-contraction as it more closely matches the system dynamics. Since the baseline settings are more familiar, subjects had a more accurate reference model, possibly reducing co-contraction. Another explanation is that in the baseline damping condition, subjects already applied reflexes. When damping increased, so did their reflexive activity, resulting in higher admittance rather than lower. Besides, as more reflexive activity leads to lower end-point admittance, this may have influence the low-frequency results as well. The effects of co-contraction and reflexes may thus not be so easily separated.

Finally, the two ways of estimating compliance yielded similar results. Both were unable to show significant differences for most conditions. However, effects on metrics other than compliance were visible. Also, the variance was large, which implies that results may have been unreliable, although coherence on low frequencies was around 0.7. Individual trends varied too: sometimes subjects chose to pursue a higher performance, which would come at decreased compliance.

## B.5. Recommendations for final experiment

From the results of this preliminary study, the following recommendations can be drawn for the final experiment.

### B.5.1. Feedback

First of all, differences between high and low steering wheel stiffness and damping are mainly found in the performance metrics. Therefore experiment needs to give clearer feedback to the subjects on how they are doing, such that the effects migrate towards other metrics. This could be achieved by implementing sounds, vibrations or visual warnings for hitting a cone or the leaving road. Also, projecting the inside of the car in the simulated scene would give more information on the driver's position on the road. Finally, constant monitoring of performance could be allowed by displaying relevant data (e.g., distance to lane border), although this is less natural.

### B.5.2. Steering wheel parameters

Next, the effectiveness of higher steering wheel stiffness versus increasing the damping parameter is compared. With similar results on effort and compliance, higher damping and higher stiffness both increased TLC, but only higher stiffness decreased the standard deviation of the lateral error. Also, difference in lateral errors, effort and compliance between wide and narrow road are the larger between baseline and high damping. This means that it might lead to clearer effects than steering wheel stiffness, but also that the mechanisms are already better understood. Perhaps, the perceived increase in damping was larger, so a higher stiffness value should be tested in a future experiment. Besides, it is hard to draw conclusions on the effect of increased damping, because the baseline setting was equal to the inherent damping in the driving simulator, and might already allow enough reflexive activity for the task. For the final experiment, the focus is therefore on the stiffness parameter.

### B.5.3. Stiffness settings

Originally, it was hoped that the settings for steering wheel stiffness could be derived from the average values for human stiffness on a wide road (low stiffness setting) and on a narrow road (high stiffness setting). This way, the steering wheel would adjust as much as humans would naturally do. However, the preliminary experiment has not resulted in distinct values. The only available data is from [3], where human compliance increased from approximately 2.6 to 3.6 deg/Nm as road width increased from 2.5 to 4.5 meter, at 120 km/h, and from approximately 3.1 to 4.3 deg/Nm at 70 km/h. In the preliminary experiment, baseline stiffness means that the the steering wheel is twice as compliant as the human, and four times as compliant with high stiffness. The contribution of the human to the combined dynamics is thus larger, and especially dominant in the baseline stiffness condition. This can also be seen in Fig. 2.8 and 2.11. Using the values from [3] would mean increasing the steering wheel stiffness, which might have greater impact on human compliance. The different options are shown in Table 2.3.

Table 2.3: Optional stiffness settings

| Steering wheel stiffness | Baseline setting | High setting |
|---|---|---|
| $K_{SW,PRELIMINARY}$ | $K_{SW} = 0.113$ Nm/deg | $K_{SW} = 0.213$ Nm/deg |
| $K_{SW,HUMAN}$ | $K_{SW} = 0.278$ Nm/deg | $K_{SW} = 0.385$ Nm/deg |

More extreme settings were applied in [4]. The stiffest value was twice as stiff as the high stiffness condition of the preliminary experiment, the most compliant twice as compliant as the baseline stiffness. Variance in

the results was large for the most compliant setting. The stiffest setting did affect human admittance, but not in the desired direction: it decreased, as can be seen in Fig. 2.1 and 2.2. Also, the effects of speed were most clear for S2 and S3, which correspond to the settings used in the preliminary study, see Fig. 2.3.
Summarising, applying the values from [3] or the settings used in the preliminary both seem to have pros an cons, and as the effects are yet unclear, it is advised that both options are tested in a pilot before the final experiment. To create only one new condition, the high setting from the preliminary experiment then becomes the medium setting (which is also close to the low stiffness from [3]) and the new highest stiffness is equal to the largest $K_{SW,HUMAN}$.

Table 2.4: Steering wheel stiffness in final pilot

| Variable | Baseline setting | Medium setting | High setting |
|---|---|---|---|
| $K_{SW,FINAL-PILOT}$ | $K_{SW}$ = 0.113 Nm/deg | $K_{SW}$ = 0.213 Nm/deg | $K_{SW}$ = 0.385 Nm/deg |

### B.5.4. INTERNAL MODEL

It should be kept in mind that the baseline steering wheel stiffness is better incorporated in the driver's internal model and might thereby lead to a lower level of co-contraction (see also [1]). For a more fair comparison, it could be chosen to use for example 1.5 times versus three times the baseline stiffness. However, it is unknown what specific steering wheel settings the drivers are used to, and therefore impossible to make a truly fair comparison.
Another solution could be to apply a between-subjects design for the experiment, such that they can be trained for one specific condition and are not able to compare the settings. However, a within-subject design is preferred because the variance between subjects was found to be larger than the effect of conditions.
For the final experiment, subjects need more training such that they better understand the effects of the increased stiffness and have more time to update the internal model. Also, because subjects need to fight high stiffness on curved segments, they might not appreciate it on straight segments either. The curves should therefore be made less demanding, by using a larger radius (e.g. 400 m) and smaller angle (e.g. 22.5 degrees), especially when driving at higher speed.

### B.5.5. ADAPTIVE STIFFNESS

The higher goal of this project was to investigate whether adapting the steering wheel stiffness to different levels of criticality could be beneficial and how it should be implemented. A first step in this direction can be made by adding an 'adaptive stiffness' setting to the experiment. This can be implemented by using high stiffness in more critical circumstances (i.e. on the narrow segment) and low stiffness in less critical situations (wide road). Attention needs to be paid as to how the transitions between stiffness levels should be made. For example, a binary switch or a linear transition might not feel as natural as an S-curve, which is thought to lead to more accepting reactions. On the other hand, subjects should be able to notice the difference, so the transition should not take too long.

### B.5.6. PERTURBATION SIGNAL

To get insight in the use of reflexes versus co-contraction without testing different steer damping settings, a low and a high bandwidth perturbation could be applied again in the final experiment. For now, this was the only comparison that clearly showed differences in effort and compliance rather than in performance metrics. However, the results from the preliminary experiment met the expectations, meaning that the effects of bandwidth are already understood. To limit the number of conditions, the final experiment will therefore only use one perturbation signal. Using a low perturbation bandwidth revealed more change in compliance between low and high steer stiffness, but the effects of road width were clearer with a high perturbation bandwidth. Because of the enhanced feedback in the final experiment, and the fact that road width did lead to differences in admittance in [3] where a low bandwidth signal was used, it is assumed that a low bandwidth signal will suffice. Besides, using a high perturbation bandwidth is thought to be less 'valid', because reflexes are inhibited, which is not the case in normal driving.
To get higher coherence and lower variance, the perturbation signal must be designed such that it allows averaging. This can be done by clustering the frequencies, or by using more repetitions of the signal in the time domain. Also, amplitudes are increased on higher frequencies to improve the signal-to-noise ratio. The signal can be designed differently when there is no need for a high and a low bandwidth signal that are similar in

time domain, and if log-spacing is not necessary. For an example, see 2.5.

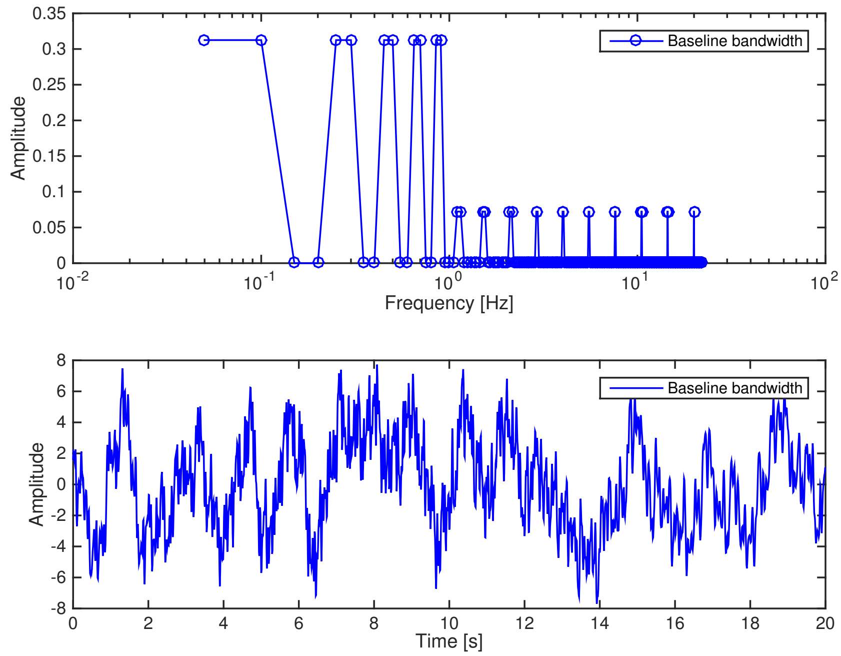


Figure 2.5: New design of perturbation signal, optimised for one bandwidth

### B.5.7. Experimental setup

Since TLC values were generally high in the current setup, the speed in the future experiments should be increased to 120 km/h, to make the lane-keeping task more critical. Also, the car width needs to be taken into account in the calculation of TLC. Furthermore, the efficiency of the simulated roads should be optimised such that the starting segment, transitions, and curves take up less time. The length of the segments for measuring can be slightly increased. Also, cones are now only placed to indicate the narrow segments. For better consistency, they should also be on both edges of the wide road.

In a final pilot, new perturbations and enhanced feedback on performance should be applied. It is hypothesised that because coherence is improved and performance is kept more constant, so differences in (effort and) compliance between should become clearer. The conditions are:

- C1 Baseline stiffness, baseline perturbation bandwidth
- C2 Medium stiffness, baseline perturbation bandwidth
- C3 High stiffness, baseline perturbation bandwidth
- C4 Adaptive stiffness, low perturbation bandwidth

## B.6. Results: Plots

In each of the box plots on the following pages, × represents an average, minimum or standard deviation of a single subject. Results from the same subject are connected and the subject number is assigned to each line, in order to visualize individual trends. In the figure titles and captions, ‘$K_{SW}$’ means steering wheel stiffness, ‘BW’ indicates bandwidth and ‘$B_{SW}$’ stands for steering wheel damping.

### B.6.1. Compliance

The compliances are plotted for the human, steering wheel and their combined dynamics. For easier visualization, only the individual trends for human compliance are shown.

### Average low-frequency admittance

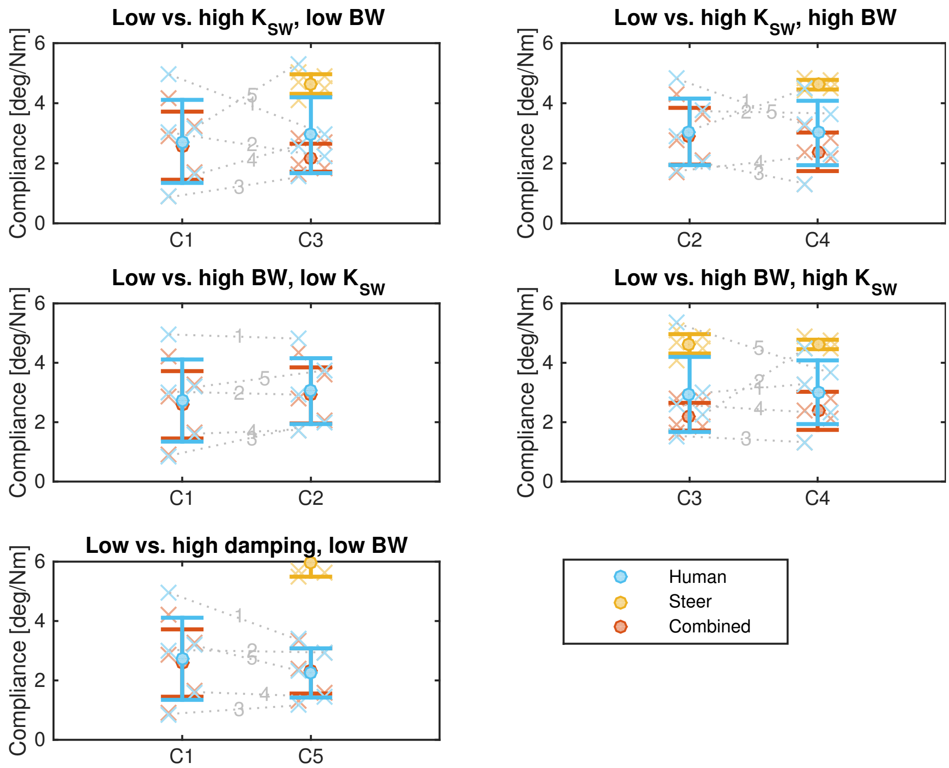


Figure 2.6: Average compliance for $f < 1$ Hz on a wide road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

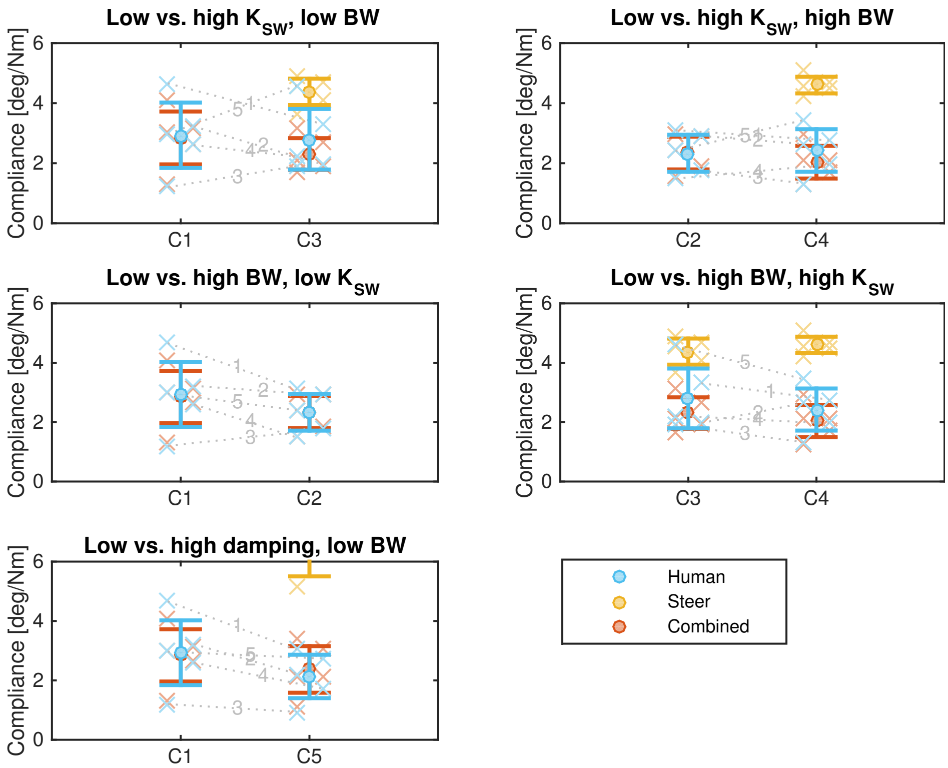


Figure 2.7: Average compliance for $f < 1$ Hz on a narrow road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

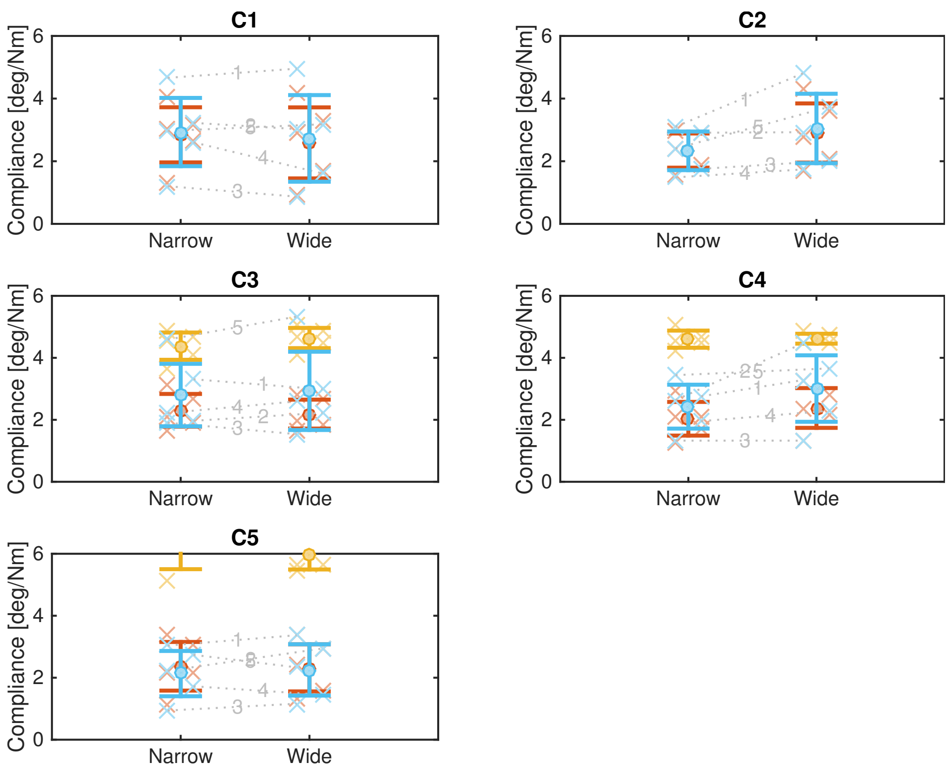


Figure 2.8: Average compliance for $f < 1$ Hz on a narrow vs. a wide road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

## ESTIMATED COMPLIANCE PARAMETER

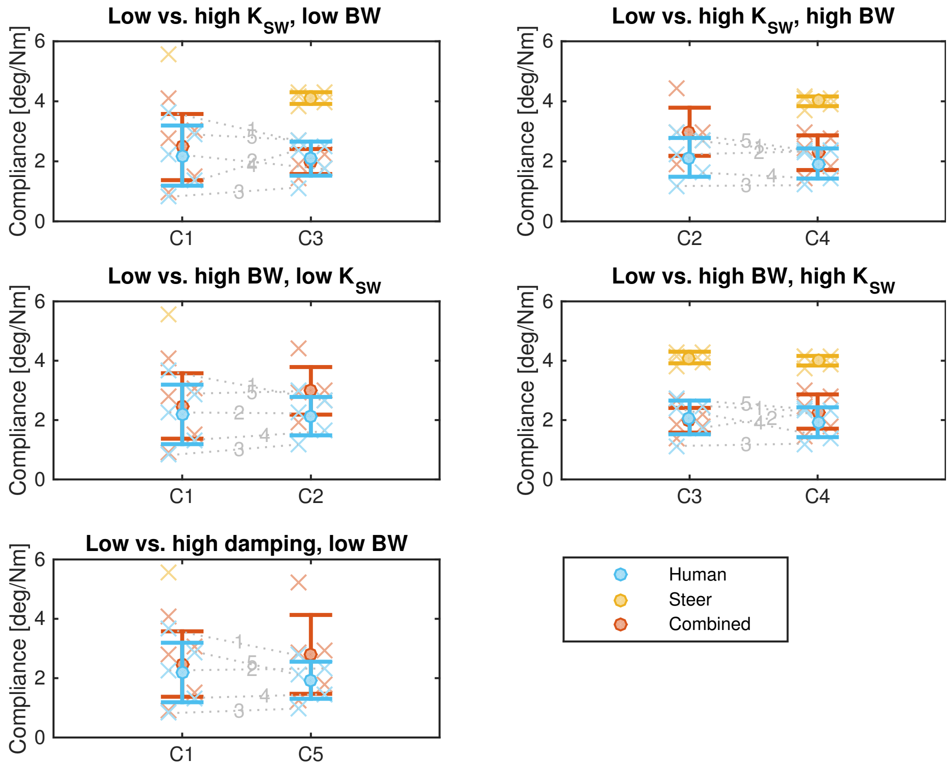


Figure 2.9: Estimated compliance on a wide road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

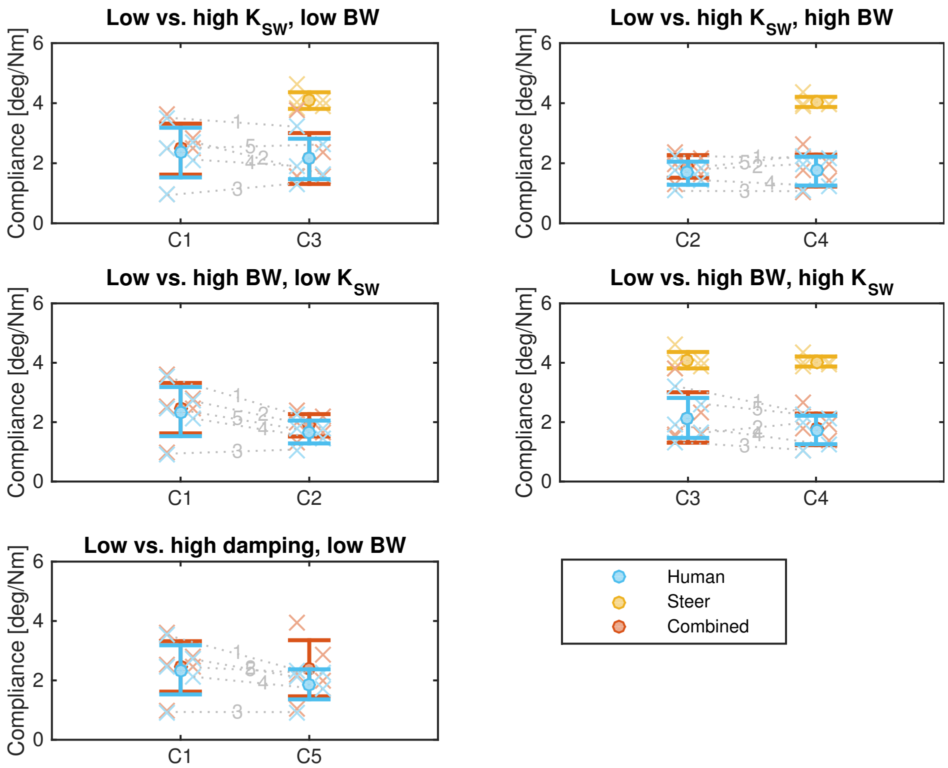


Figure 2.10: Estimated compliance on a narrow road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

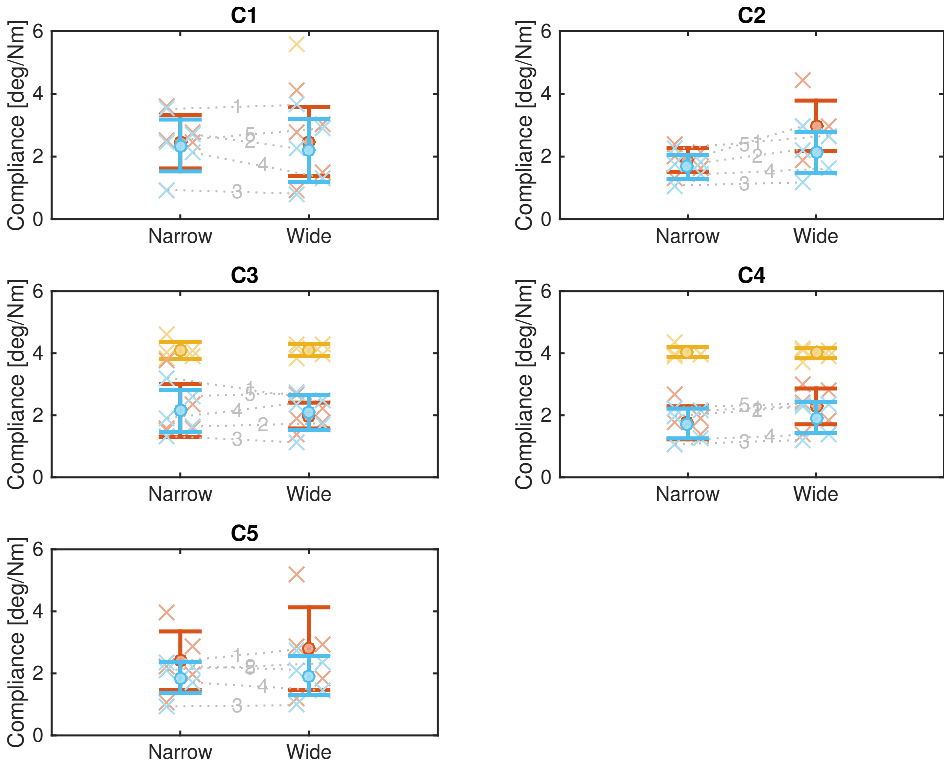


Figure 2.11: Estimated compliance on a narrow vs. a wide road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

## B.6.2. PERFORMANCE METRICS

### LATERAL ERROR

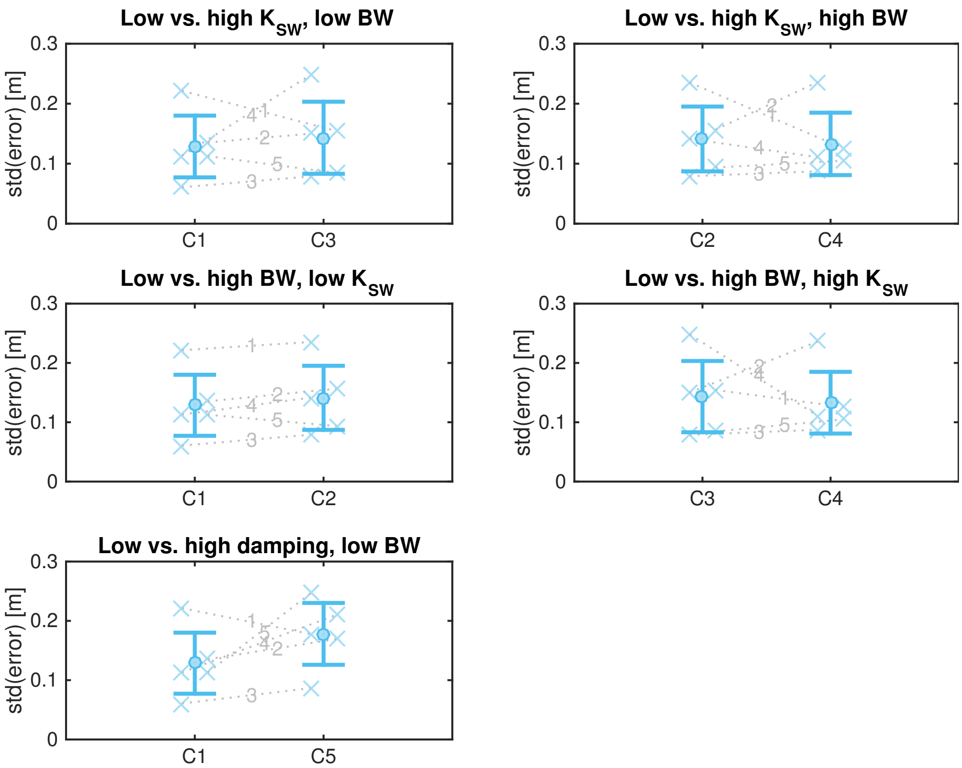


Figure 2.12: Standard deviation of lateral error on a wide road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

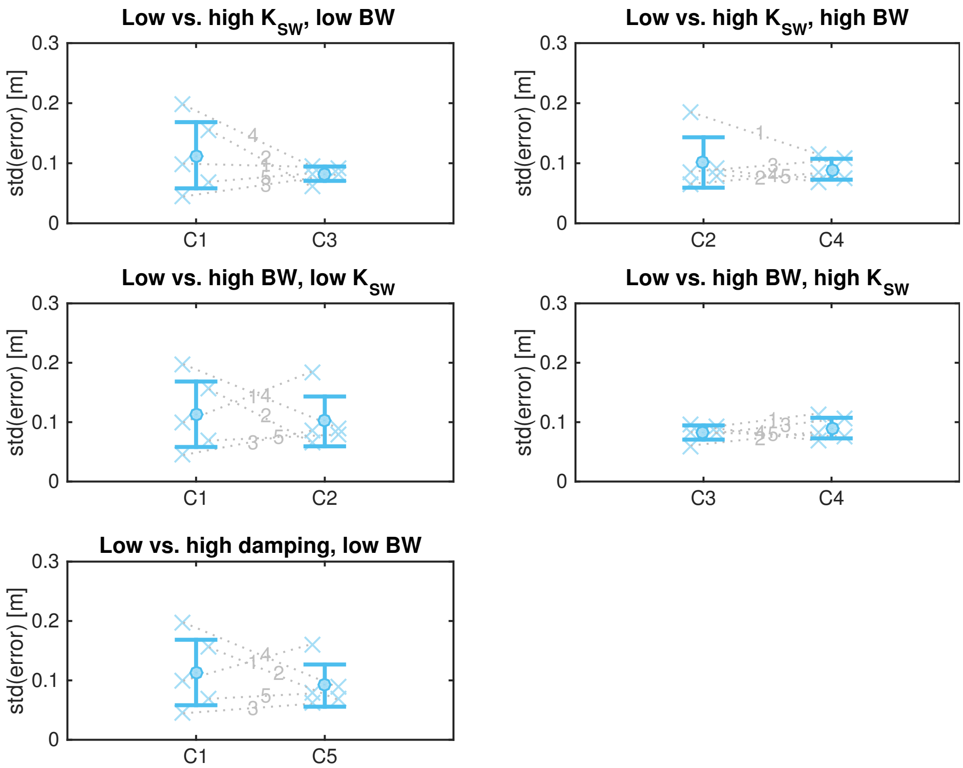


Figure 2.13: Standard deviation of lateral error on a narrow road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

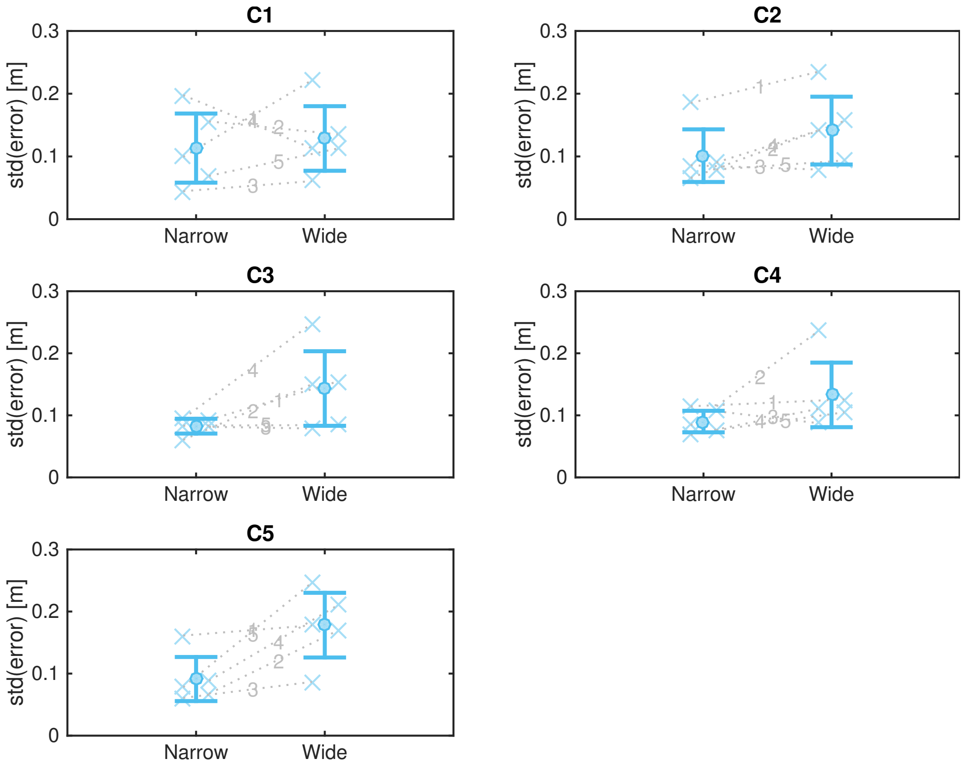


Figure 2.14: Standard deviation of lateral error on a narrow vs. a wide road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

## TIME TO LANE-CROSSING (TLC)

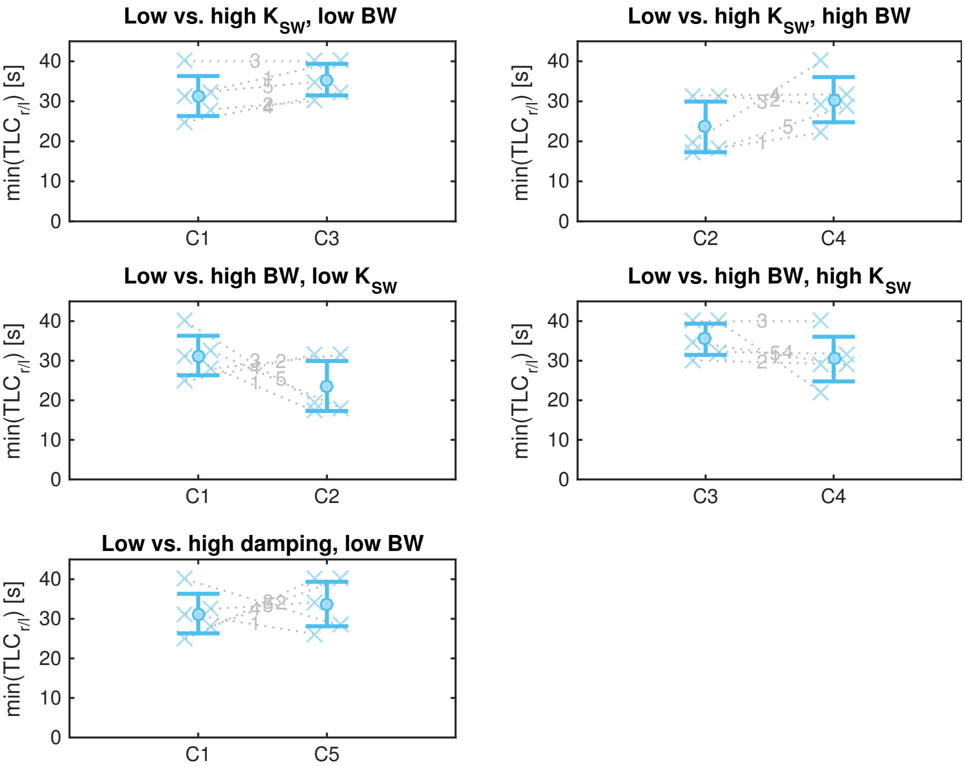


Figure 2.15: Minimum TLC on a wide road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

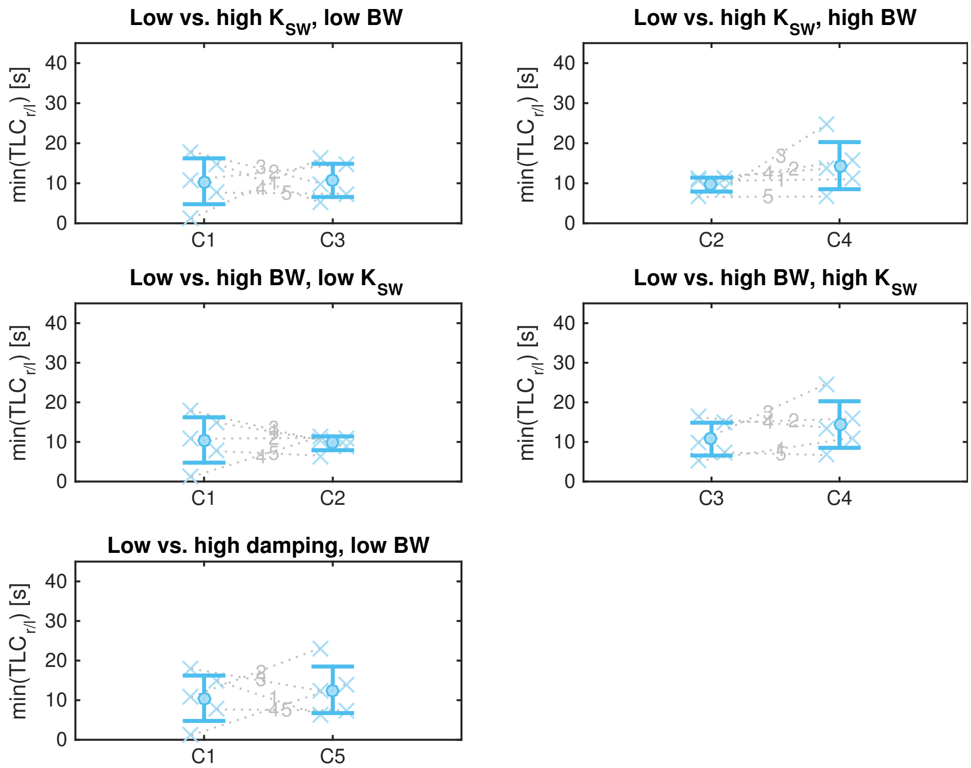


Figure 2.16: Minimum TLC on a narrow road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

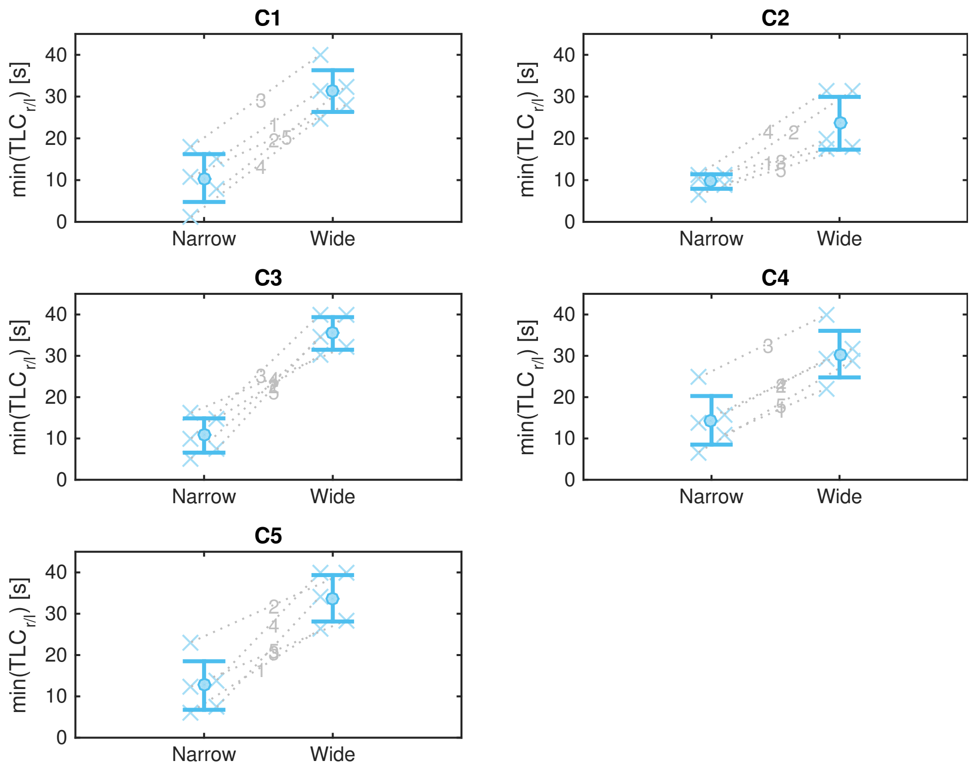


Figure 2.17: Minimum TLC on a narrow vs. a wide road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

### B.6.3. EFFORT METRICS

#### STEERING REVERSAL RATE (SRR)

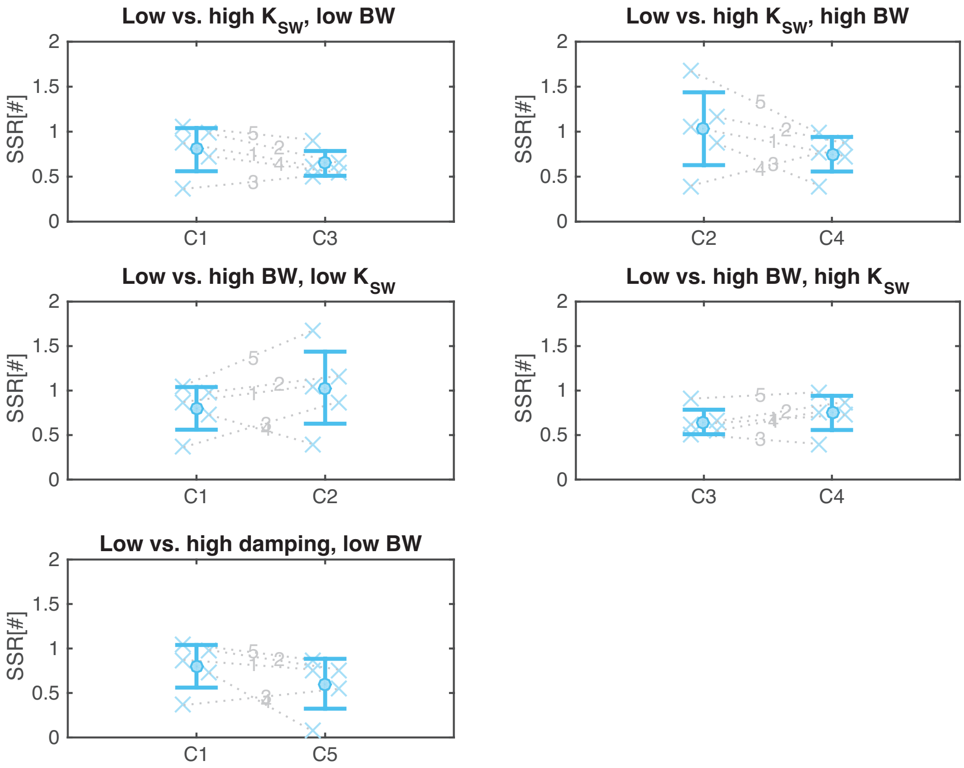


Figure 2.18: Mean SRR on a wide road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

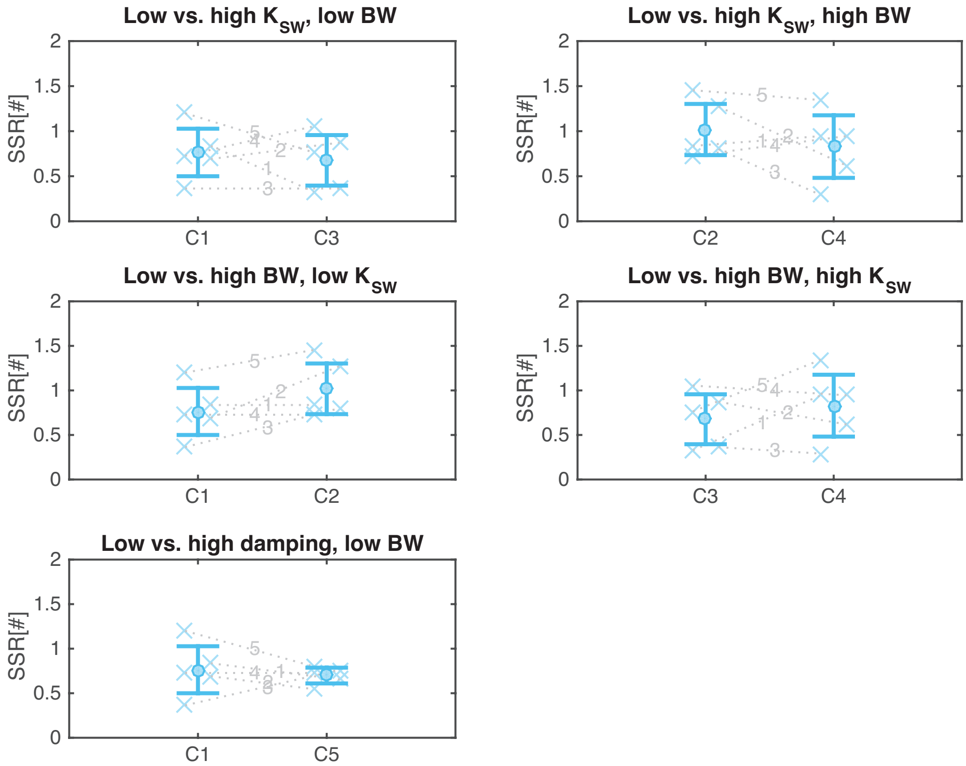


Figure 2.19: Mean SRR on a narrow road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

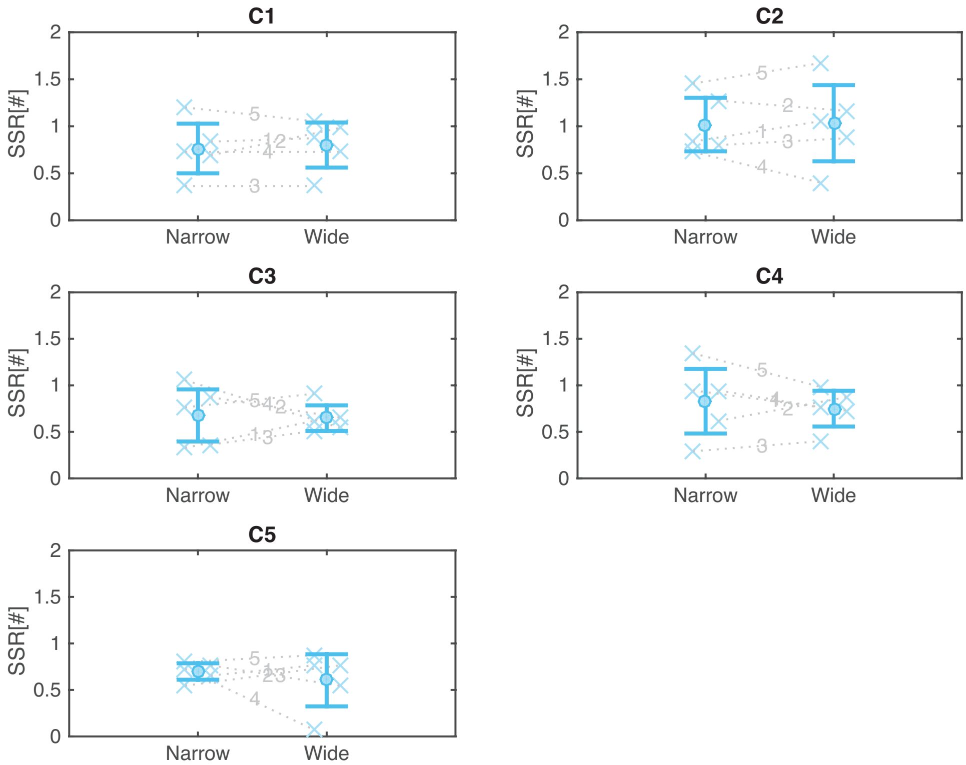


Figure 2.20: SRR on a narrow vs. a wide road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

## EXERTED TORQUE

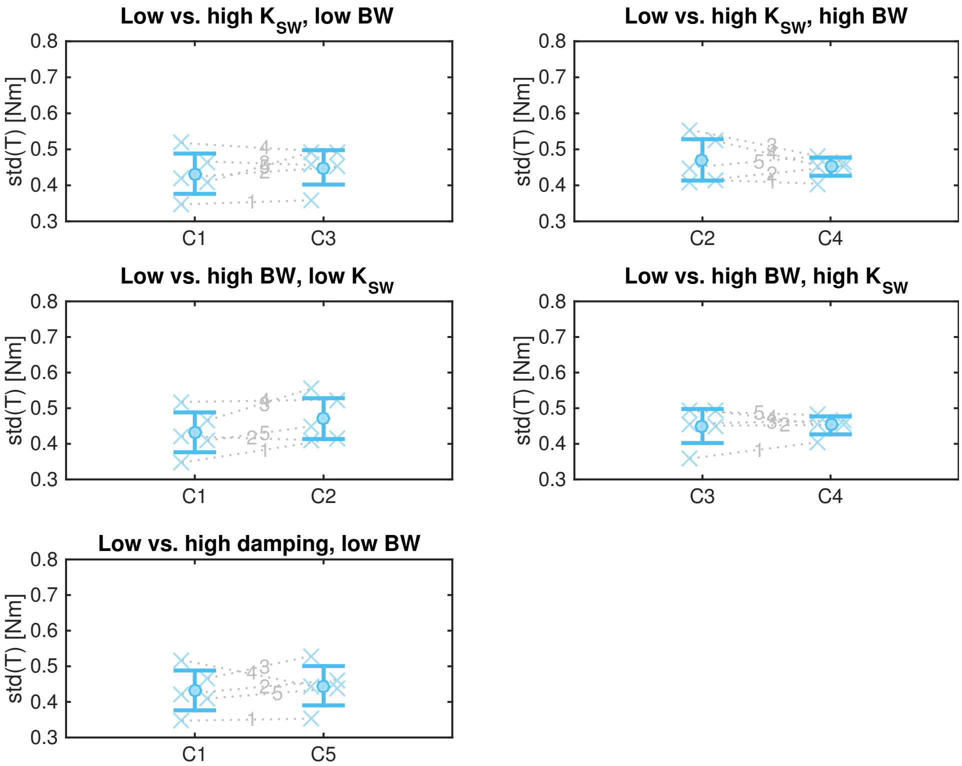


Figure 2.21: Standard deviation of torque on a wide road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

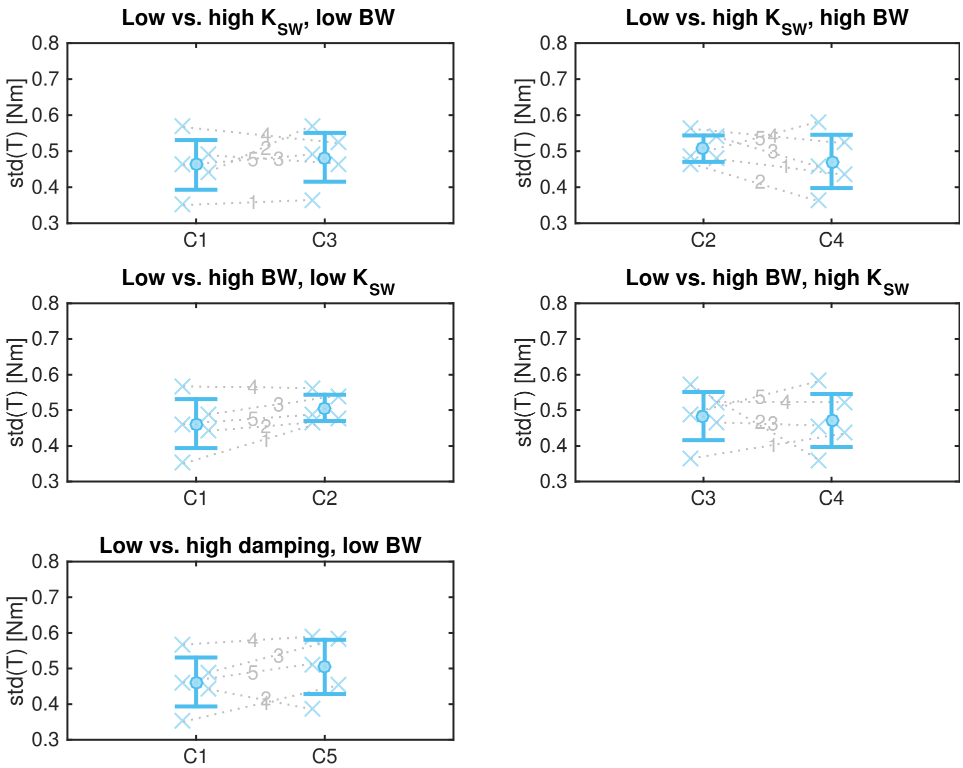


Figure 2.22: Standard deviation of torque on a narrow road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

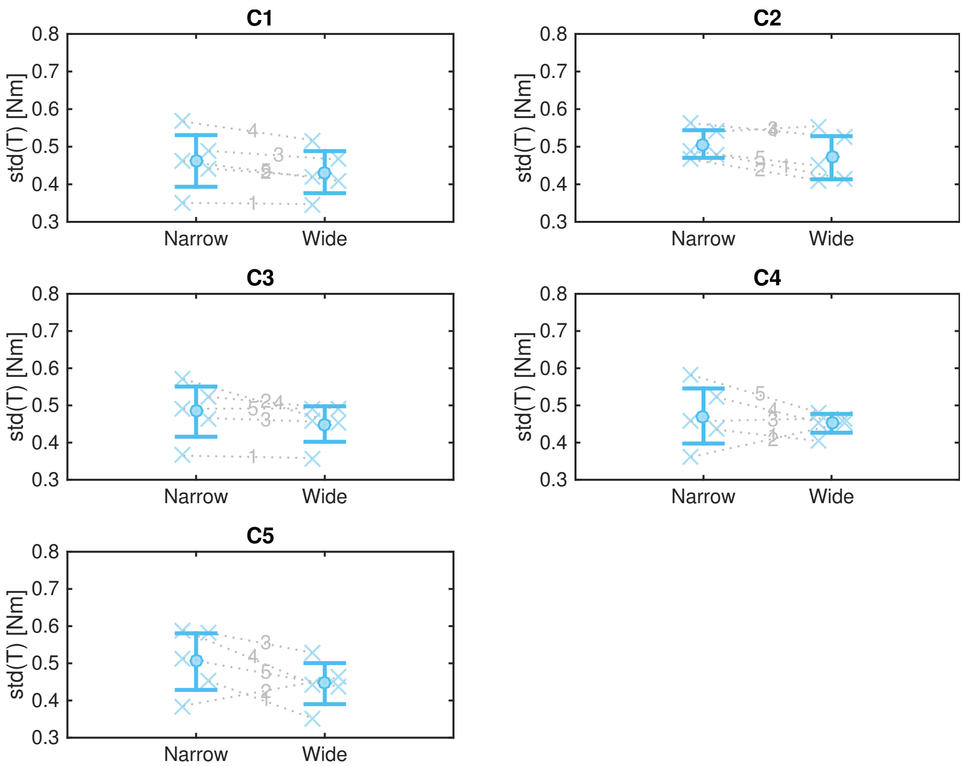


Figure 2.23: Standard deviation of torque on a narrow vs. a wide road segment.
C1 = low $K_{SW}$, low BW; C2 = low $K_{SW}$, high BW; C3 = high $K_{SW}$, low BW; C4 = high $K_{SW}$, high BW; C5 = high $B_{SW}$, low BW.

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[1] A. Pick and D. Cole, *A Mathematical Model of Driver Steering Control Including Neuromuscular Dynamics,* Journal of Dynamic Systems, Measurement, and Control **130**, 031004 (2008).

[2] D. Abbink, M. Mulder, and M. van Paassen, *Measurements of Muscle Use during Steering Wheel manipulation,* Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics , 1652 (2011).

[3] D. van der Wiel, *Driver's neuromuscular stiffness response to road width and vehicle speed,* Tech. Rep. (Technical University of Delft, 2014).

[4] M. Mulder, D. Abbink, E. Boer, and M. van Paassen, *Human-centered Steer-by-Wire design: Steering wheel dynamics should be task dependent,* 2012 IEEE International Conference on Systems, Man, and Cybernetics (SMC) , 3015 (2012).

# C
# Pilot study

## C.1. Introduction

Before conducting the final experiment, a final pilot study was carried out with two subjects. Goals were to check the effects of implementing the changes from the preliminary pilot, and to explore if any final improvements for the final experiment are needed. Besides, it is expected that increased feedback on performance will mitigate effects of steering wheel stiffness $K_{SW}$ towards neuromuscular stiffness $K_{NMS}$ (and other effort metrics). That way, the hypothesis that $K_{NMS}$ decreases with increasing $K_{SW}$ could be tested more effectively.

## C.2. Methods

Two 25-year old female students, each with a drivers license, took part in the pilot experiment. From the preliminary study, the following settings for steering wheel stiffness were determined (see Appendix B):

1. Baseline stiffness 0.11 Nm/deg
2. High stiffness 0.22 Nm/deg
3. Extra high stiffness 0.44 Nm/deg
4. Adaptive stiffness 0.11-0.22 Nm/deg

Several changes were made in the experimental set-up with respect to the preliminary study. Feedback on performance was enhanced with respect to the preliminary experiment by the addition of a car frame, such that subjects could better estimate their position on the road, and visual warning signs when cones were hit. Driving speed was increased from 70 to 120 km/h, to increase criticality. The roads were made longer and more time-efficient to capture more data: curves were made less sharp and shorter (22.5 degrees, r = 500 m), and transition times were reduced. Besides, for both narrow and wide roads, two measurement segments of 20 seconds were created. Also, different roads were made for training, consisting of 8 wide and 8 narrow segments of 15 seconds, with slight curves (12.25 degrees, r = 500 m) in between. This allowed participants not only to update their internal model of the system dynamics, but also to repeatedly optimise their strategy. In total, one training session lasts for 6.5 minutes.

In the recommendations from the preliminary pilot (see Appendix B) it was suggested to use a disturbance force with two bands, that lasted for 20 seconds. Instead, it was chosen to reduce the time length of the signal to 10 seconds, such that one segment would allow two repetitions and Welch averaging. The resulting signal is shown in Fig C.1.

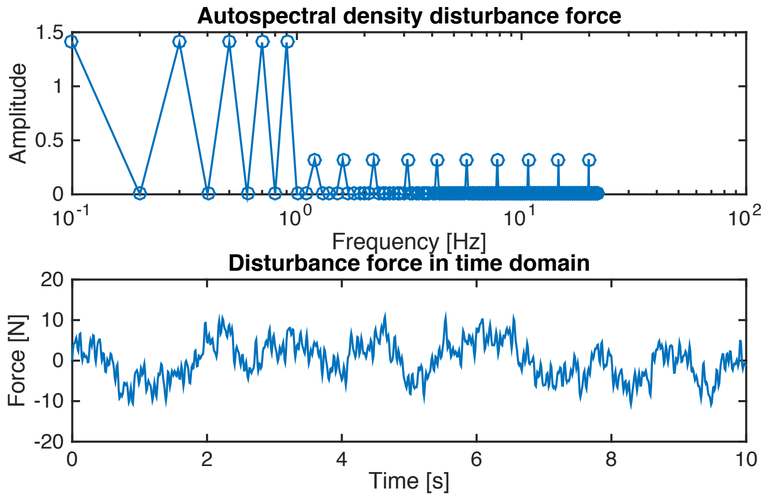


Figure C.1: Design of the force perturbation signal

The primary metric is neuromuscular compliance, which is calculated by estimating the admittance of the arm and averaging the results below 1 Hz. Other metrics of effort are:

- Mean steering reversal rate (SRR)
- Standard deviation of torque

For performance, the following metrics are analysed:

- Standard deviation of lateral error
- Number of hit cones
- Minimum time to lane crossing (TLC)

## **C.3.** Pilot results

Some of the pilot results are shown and briefly described below. Note that, as only two subjects took part in the pilot experiment, no real conclusions can be drawn from these results. First, the resulting average compliance values for the human, steer and combined dynamics are shown. In Fig. C.2, the results from the wide segments are shown. There clearly is a lot of variance. This was the same for the other metrics. Therefore, no further attention will be paid to the wide road results.
As can be seen in Fig. C.3, it does seem like neuromuscular compliance is higher for high than for baseline steering wheel stiffness, and combined compliance is more or less constant. However, human and combined compliance are both lowest with extra high steering wheel stiffness. Besides, there is a lot of variance in the estimation of the adaptive steering wheel stiffness, while both values should be the same, and equal to the high stiffness setting. Furthermore, it can be seen in Fig. C.4 that SRR decreases with increasing steering wheel stiffness. The other metrics do not show a clear effect either, as can be seen in Fig. C.5 - C.8.

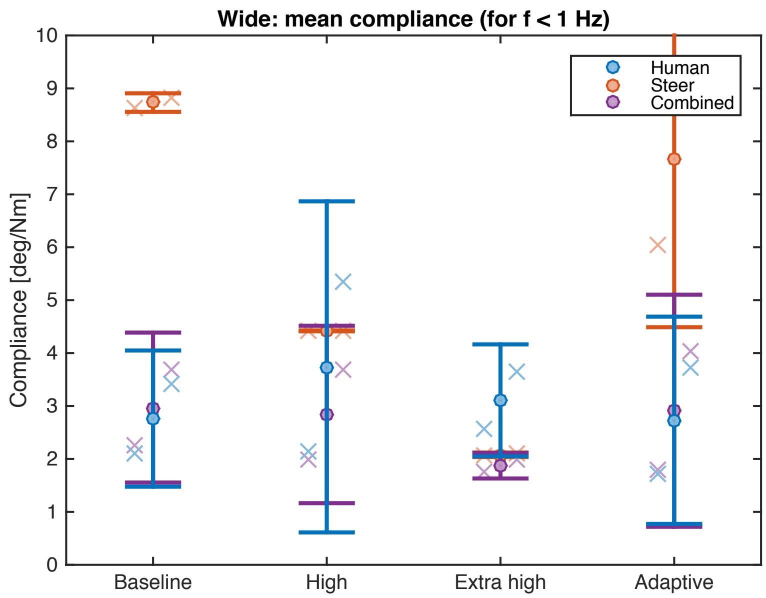


Figure C.2: Wide road: human NMS compliance (average admittance for f < 1 Hz)

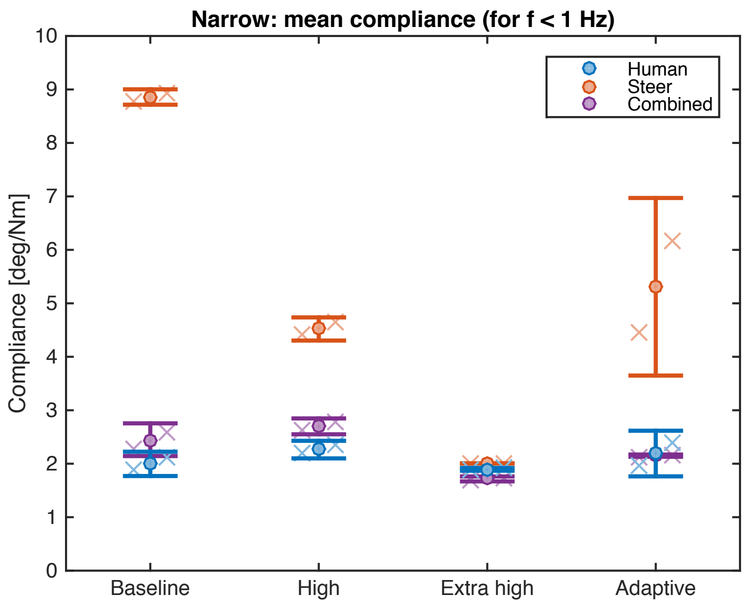


Figure C.3: Narrow road: human NMS compliance (average admittance for f < 1 Hz)

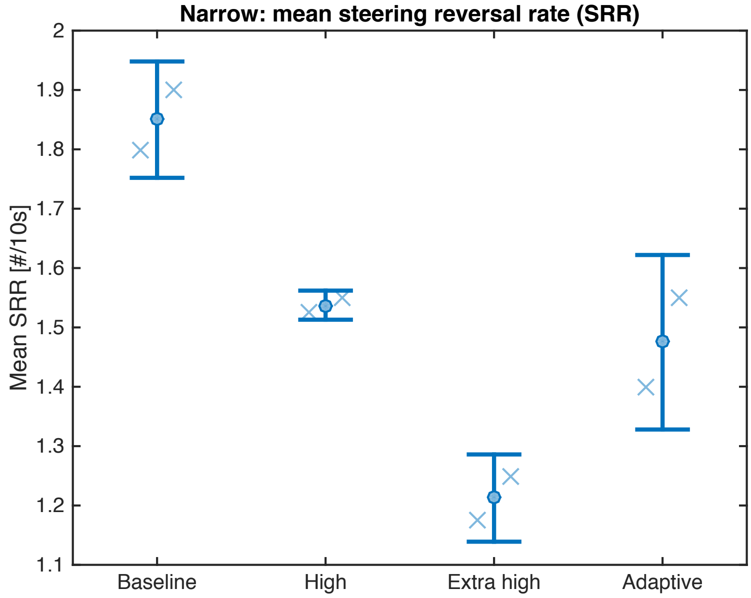


Figure C.4: Narrow road: steering reversal rate (SRR)

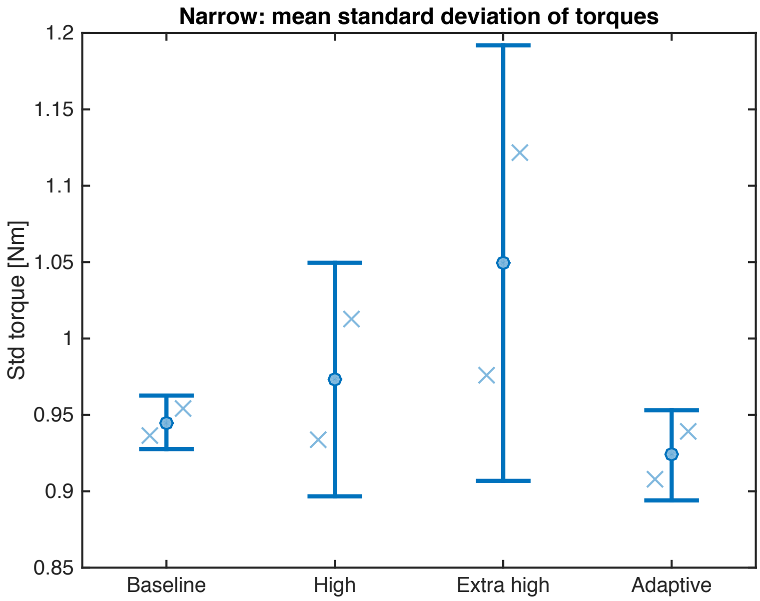


Figure C.5: Narrow road: standard deviation of applied torque

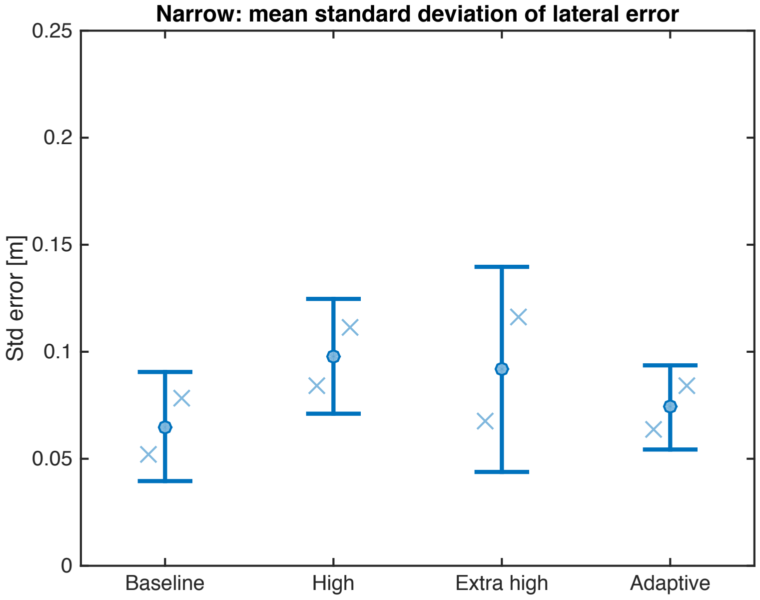


Figure C.6: Narrow road: standard deviation of lateral error

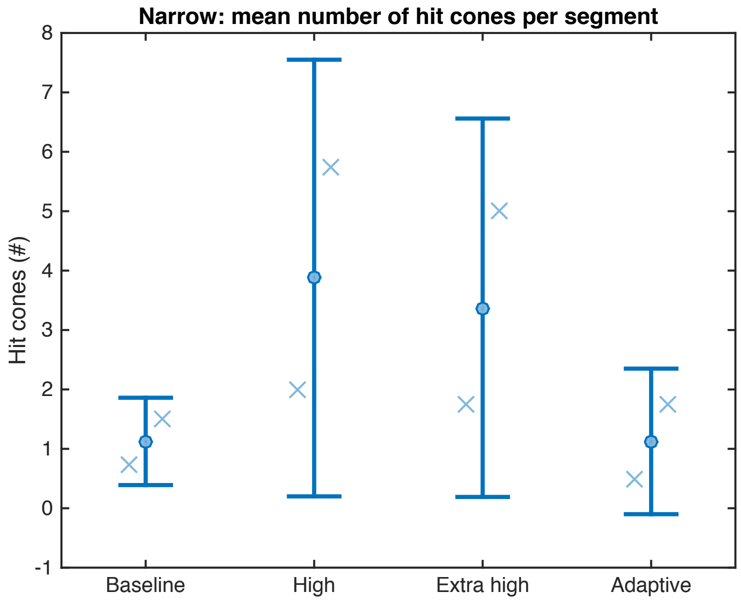


Figure C.7: Narrow road: number of hit cones

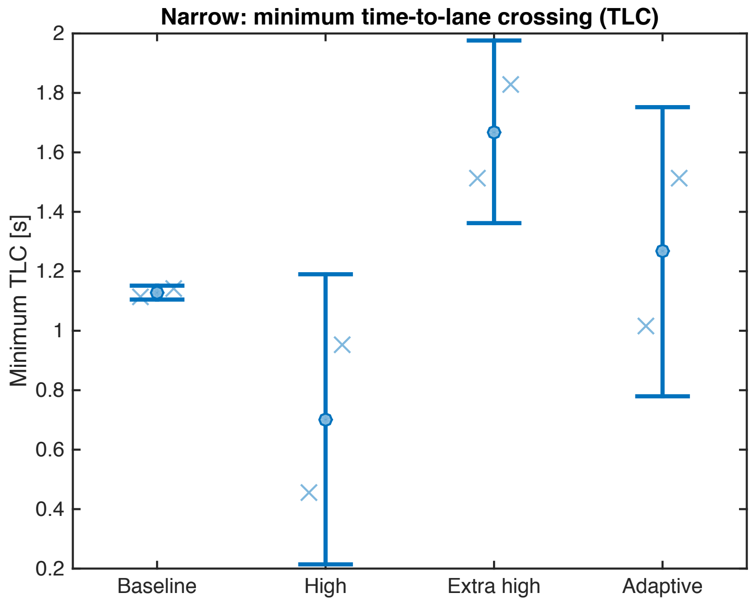


Figure C.8: Narrow road: minimum time-to-lane-crossing (TLC)

## C.4. Conclusions and discussion

First of all, no proof for the original hypothesis was found: neuromuscular stiffness does not clearly decrease when steering wheel stiffness increases. However, this might have to do with the way human admittance is estimated. The variance in the estimation of the adaptive steering wheel stiffness indicates that results are not reliable. Either way, the relationship between $K_{NMS}$ and $K_{SW}$ might not be as clear as expected.
Furthermore, it is shown that with higher steering wheel stiffness, effort in terms of SRR decreases, while no clear trends are found on the other metrics. This indicates that performance is kept more constant with respect to the preliminary study, which can be attributed to the implemented feedback. Especially with regards to TLC (Fig. C.8), the results seem unrelated to steering wheel stiffness. If anything, in Fig. C.5-C.7 it looks like performance and effort are worst with high or extra high $K_{SW}$. Somehow, the results for adaptive $K_{SW}$ are similar to those with baseline $K_{SW}$, while on a narrow road adaptive $K_{SW}$ is equal to high $K_{SW}$.

## C.5. Recommendations for final experiment

To improve the reliability of the admittance estimates, it is recommended to redesign the perturbation signal once more. Instead of 10 seconds, the force disturbance should repeat itself every 5 seconds. This allows for 4 repetitions on one segment, and is expected to reduce the time-variance within each estimate. Furthermore, to get an indication of the reliability of the results, the data should be averaged in the frequency domain as well, such that coherence can be estimated. Frequency points with power (both full and reduced) are therefore clustered in groups of two. Note that these changes will also result in a reduced frequency resolution and an increased lowest frequency. However, reliability and having an estimate of reliability are prioritised. The main interest of the experiment is in the low frequency behaviour. Even though the lowest frequency is now increased, it is still considered low enough to be acceptable for an estimation of stiffness. The new signal is shown in Fig. C.9.

Furthermore, there was too much variance on wide segments. It is believed that this is due to the fact that subjects literally had a lot of room for variant behaviour. Therefore, the wide road segments should be narrowed. It is suggested that they are replaced by segments of 3.6 meters wide, which is the normal width on a highway in the Netherlands. Moreover, the time-domain results of the lateral errors made by the subjects show that they already stayed more or less within the 3.6 meters, see Fig. C.10. The reduction in width will thus not increase the difficulty of the task.

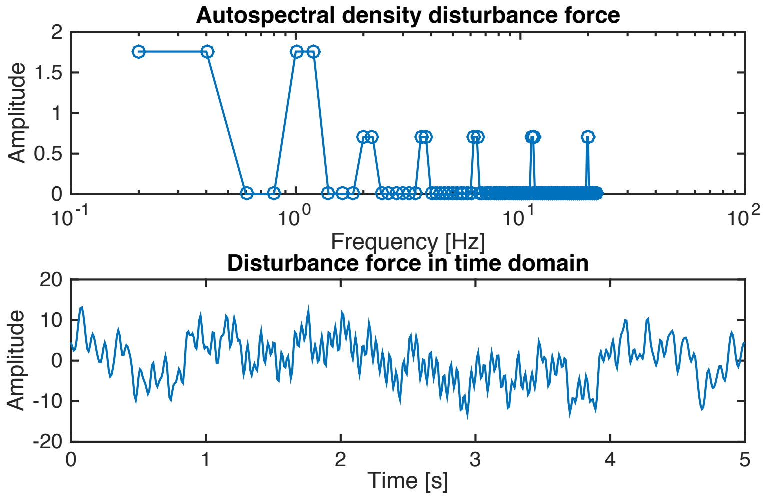


Figure C.9: New design of the force perturbation signal

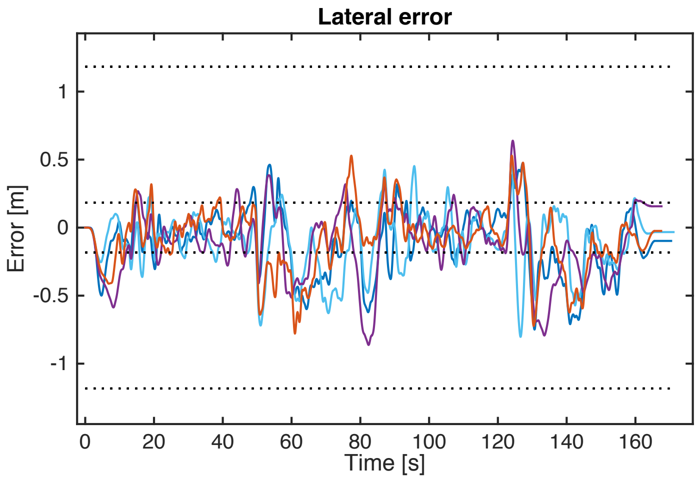


Figure C.10: Time-domain results for lateral errors show that subjects already stay within ± 1.3 m from the center. Note that ± half the car width (1.067 m) of is subtracted from the lateral errors of the middle of the car, such that this corresponds to ± 0.7 m from the sides of the car. The inner dotted line corresponds to the narrow road width of 2.5 m; the outer dotted lines indicate a wide road of 5.0 m.

Finally, it is believed to be better to eliminate the extra high stiffness setting. In this condition, the steering wheel stiffness is (as explained in the preliminary report, see Appendix B) in the range of stiff humans. It was expected that this would lead to clearer effects, but that is not the case. Besides, for safety reasons, a setting where the steer can be dominant over the driver is not likely to be used in a real car. Therefore the condition is not realistic, and keeping it in would interfere with the other results. Also, reducing the number of conditions will allow a better comparison of the results. For these reasons, in the final experiment, only the following steering wheel systems will be tested:

- Baseline stiffness
- High stiffness
- Adaptive stiffness

# D

# Consent form and written instructions

# Dear participant,

You are invited to take part in a research study utilizing the fixed-based driving simulator located at the faculty of Aerospace Engineering of the Technical University of Delft. The simulator has been employed by the Haptics Lab research group of the faculty of 3mE to study the physical interaction between human and machine. In this experiment, it is investigated if and how drivers adapt their behavior, when steering wheel stiffness and/or road width changes. Insights arising from this research might contribute to the development of an adaptive steering wheel, designed to assist drivers in different traffic situations.

**Procedure**

You will be asked to carefully read and sign this consent form before you begin. You will then be asked to fill out some personal details in a form, after which you will be provided with instructions for the driving task. Three different steering wheel settings will be tested. For each condition, you will start with a 6-minute practice session in order to familiarize yourself with the simulated driving environment and with the steering wheel settings. Once your training is completed, you will be asked to drive a virtual course for about 2.5 minutes. After a short break, you will be asked to fill out a short questionnaire before continuing with the next training session. In total, the experiment will take around 40 minutes.

**Risks**

The only potential risk to you during testing consists of slight motion sickness (slight car sickness or slight lightheadedness) 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 information in the study records (mainly force and position measurements) will be kept confidential. Data will be stored anonymously and securely and will be made available only to persons conducting the study. No reference will be made in oral or written reports, which could link participants to the study.

**Contact information**

If you have questions at any time about the study or the procedures, you may contact the principal researcher Nienke van Driel at (+31)6 539 245 11, or at n.vandriel@student.tudelft.nl.

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

**Consent**
I have read and understand the above and I have received a copy of this form. I hereby agree to voluntarily participate in this study.

Participant's Name: ______________________________________________

Participant's Signature: Date: __________________

Investigator's Name: ______________________________________________

Investigator's Signature: Date: __________________

# Personal details

Name: ______________________________

Surname: ______________________________

Email address: ______________________________

Date of birth: ______________________________

Gender: ______________________________

Weight (in kilograms): ______________________________

Height (in meters): ______________________________

You have had a driver's license since: ______________________________

On average, you have been driving:

- ☐ >1x daily
- ☐ >1x weekly
- ☐ >1x monthly
- ☐ >1x yearly

# Instructions

During the experiment, your response to different steering wheel settings will be tested in a driving simulator. For each of the three systems, you will first practice on a virtual training circuit and consequently drive in a similar testing environment.

While driving in the simulator, you will only need to steer. The speed is automatically controlled at 120 km/h. You can compare the simulated environment to a highway that is under maintenance. Parts of the road will be narrowed by cones. While driving, you will also feel some perturbations in the steering wheel. You can think of these as bumps in the road or small wind gusts.

The main tasks while driving are to **stay in the center of the road** and, more importantly, to **avoid hitting any cones**. You should know that the simulated task is a highly critical (and perhaps even impossible) one; the chance that you will hit zero cones is small. However, please do try to keep the number of hit cones as low as possible. You will get feedback when your car strikes a cone by a visual warning sign: a red light will appear on the screen, on the side of the steer where you leave the path. Your total number of hit cones will show on the screen every now and then. This information can be used to improve your strategy during training. Hitting few cones is also in your own advantage: the participant with the best performance will be rewarded with a prize!

When in the simulator, the investigator will make sure you're seated comfortably. Please hold the steering wheel with your hands at the "10-to-2" positions, and do not reposition them during the experiment. It is important that, while driving, you keep a firm grip (not too tight) and **do not let go** of the steering wheel.

The research study focuses on driving on straight roads. The simulated environment will also contain curves, to allow you to notice the change in the steering wheel stiffness. However, your performance in these curves is not important and will not be analyzed. Please focus on achieving high performance on straight road segments only. Also, when filling in the questionnaire, please only consider the effects of the steering wheel settings on the straight segments.

If you have any questions now or during the experiment, do not hesitate to ask the investigator. Thank you very much for your participation.

# E

# Schematics

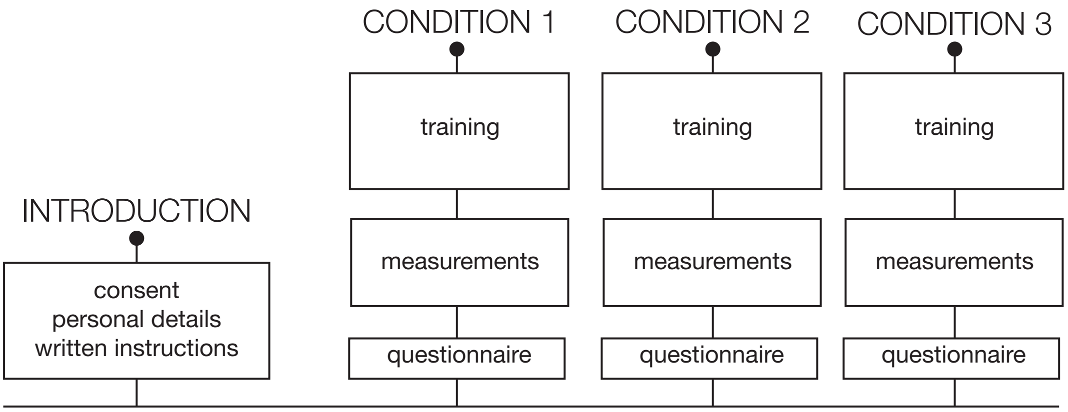


Figure E.1: Experimental procedure per subject. Conditions 1 - 3 represent the different steering wheel settings, which appear in controlled randomized order.

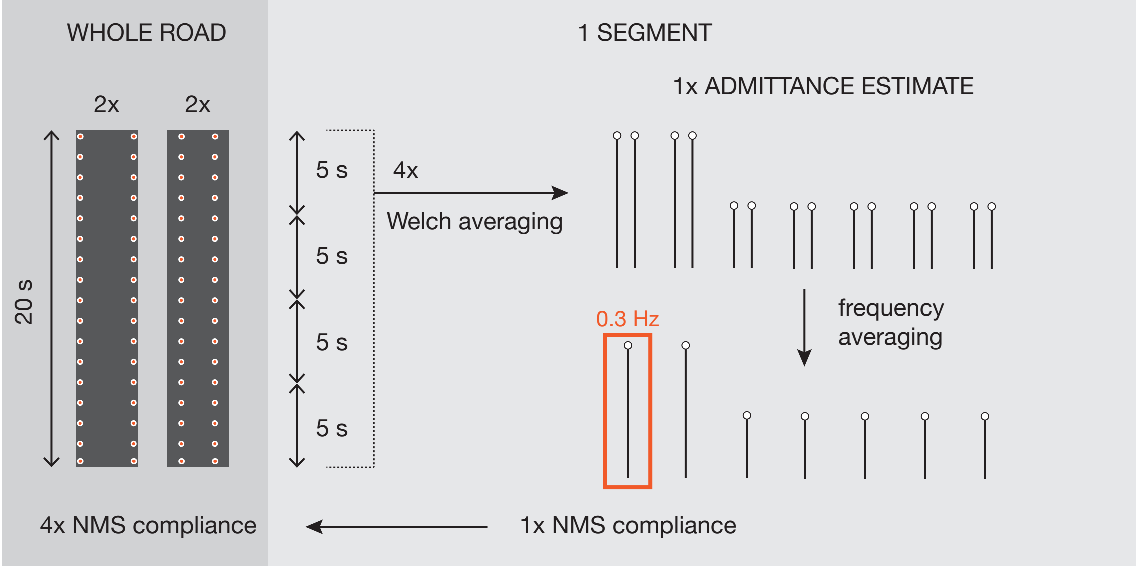


Figure E.2: Data analysis for stiffness estimation. One road (i.e. one trial) contains four segments, of which two are narrow and two are wide. Each segment is 20 s long (after clipping), such that the 5-second disturbance signal allows data to be Welch averaged four times. After frequency averaging over two bands, the final admittance estimate is obtained. The value at the lowest frequency point of 0.3 Hz is used as an estimate of compliance (inverse stiffness).

# F

# Van der Laan questionnaire

# Questionnaire

**System 1** To be filled in by investigator: ☐

For performing the driving tasks at straight road segments, I find this system:

1. Useful |__|__|__|__|__| Useless
2. Pleasant |__|__|__|__|__| Unpleasant
3. Bad |__|__|__|__|__| Good
4. Nice |__|__|__|__|__| Annoying
5. Effective |__|__|__|__|__| Superfluous
6. Irritating |__|__|__|__|__| Likeable
7. Assisting |__|__|__|__|__| Worthless
8. Undesirable |__|__|__|__|__| Desirable
9. Raising Alertness |__|__|__|__|__| Sleep-inducing

**System 2** To be filled in by investigator: ☐

For performing the driving tasks at straight road segments, I find this system:

1. Useful |__|__|__|__|__| Useless
2. Pleasant |__|__|__|__|__| Unpleasant
3. Bad |__|__|__|__|__| Good
4. Nice |__|__|__|__|__| Annoying
5. Effective |__|__|__|__|__| Superfluous
6. Irritating |__|__|__|__|__| Likeable
7. Assisting |__|__|__|__|__| Worthless
8. Undesirable |__|__|__|__|__| Desirable
9. Raising Alertness |__|__|__|__|__| Sleep-inducing

**System 3** To be filled in by investigator: ☐

For performing the driving tasks at straight road segments, I find this system:

| | | | |
|---|---|---|---|
| 1. | Useful | |__|__|__|__|__| | Useless |
| 2. | Pleasant | |__|__|__|__|__| | Unpleasant |
| 3. | Bad | |__|__|__|__|__| | Good |
| 4. | Nice | |__|__|__|__|__| | Annoying |
| 5. | Effective | |__|__|__|__|__| | Superfluous |
| 6. | Irritating | |__|__|__|__|__| | Likeable |
| 7. | Assisting | |__|__|__|__|__| | Worthless |
| 8. | Undesirable | |__|__|__|__|__| | Desirable |
| 9. | Raising Alertness | |__|__|__|__|__| | Sleep-inducing |

# G

# Other results

Here, some results will be considered that have not been discussed in detail in the paper. A larger version of Fig. 5a and 5b from the paper is included. For performance, plots of the metrics that did not yield significant results will be given. In addition, the *minimum* time-to-lane crossing (TLC) will be analysed. With respect to effort, the results of another way of looking at applied torques are presented. Finally, results from the acceptance questionnaire are visualised.

## G.1. Estimated admittance

The results from system identification, included in the paper (Fig. 5a and 5b), are shown here in more detail. The estimated admittance and phase ranges are plotted for each steering wheel system in Fig. G.1 and G.2. The first row shows estimated admittance for the human, steering wheel and combined dynamics; the second row contains their phase plots. For all results, the mean $\pm$ 95% confidence interval is indicated.

It can be seen that the human admittances with the different steering wheel systems are largely overlapping, both on narrow and wide roads. In the estimated steering wheel admittance, the difference in the settings is visible. Also, in the combined dynamics, admittance is lower with higher steering wheel stiffness (including adaptive $K_{SW}$ on narrow roads). This suggests that humans do not attempt to keep the combined dynamics constant. As their low-frequency admittance is lower, they could dominate over the steering wheel, yet the combined dynamics clearly show the effect of steering wheel settings. Furthermore, it can be noted that the human response shows a phase lead on low frequencies. This indicates that subjects could to some extent anticipate the disturbance signal. However, this effect disappears after 1 Hz. Due to wrapping of the angles, phase jumps are visible around $\pm$ 180 degrees. The higher-frequency phase attenuation is a result of the inherent time delay of the driving simulator system.

Coherence of the estimation is shown in the bottom left sub-plot. For all steer settings, it is around 0.8 on wide roads and around 0.7 on narrow roads. This indicates that some noise or non-linearity may be present in the system, but the overall estimation is reliable. As these values represent a mean, less reliable trials may have been included in the results. To check if that might have affected the outcomes, all data were analysed using per subject only the repetition (i.e. one of the two wide or narrow straight road segments) with the highest coherence. The results did not deviate from previous findings.

In the bottom center sub-plot is zoomed in on the low frequency region of human admittance, to capture the difference between wide and narrow roads and between the steering wheel settings more clearly. It can be seen that low-frequency admittance is generally lower on narrow roads (Fig. G.2) than on wide roads (Fig. G.1). Also, when steering wheel stiffness is lower, so with baseline $K_{SW}$ (blue) or adaptive $K_{SW}$ on wide roads (yellow, Fig. G.1), admittance is higher than with high $K_{SW}$ (red) or adaptive $K_{SW}$ on narrow roads (yellow, Fig. G.2).

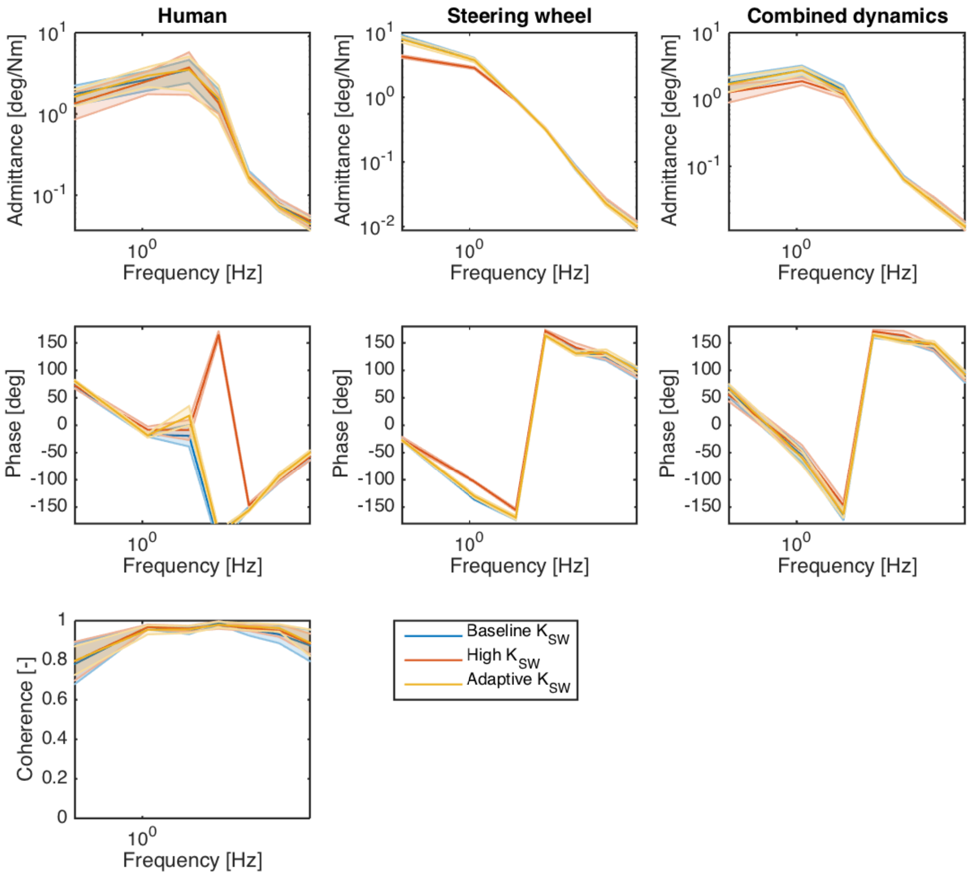


Figure G.1: Wide road results per steering wheel system, where adaptive $K_{SW}$ = baseline $K_{SW}$.

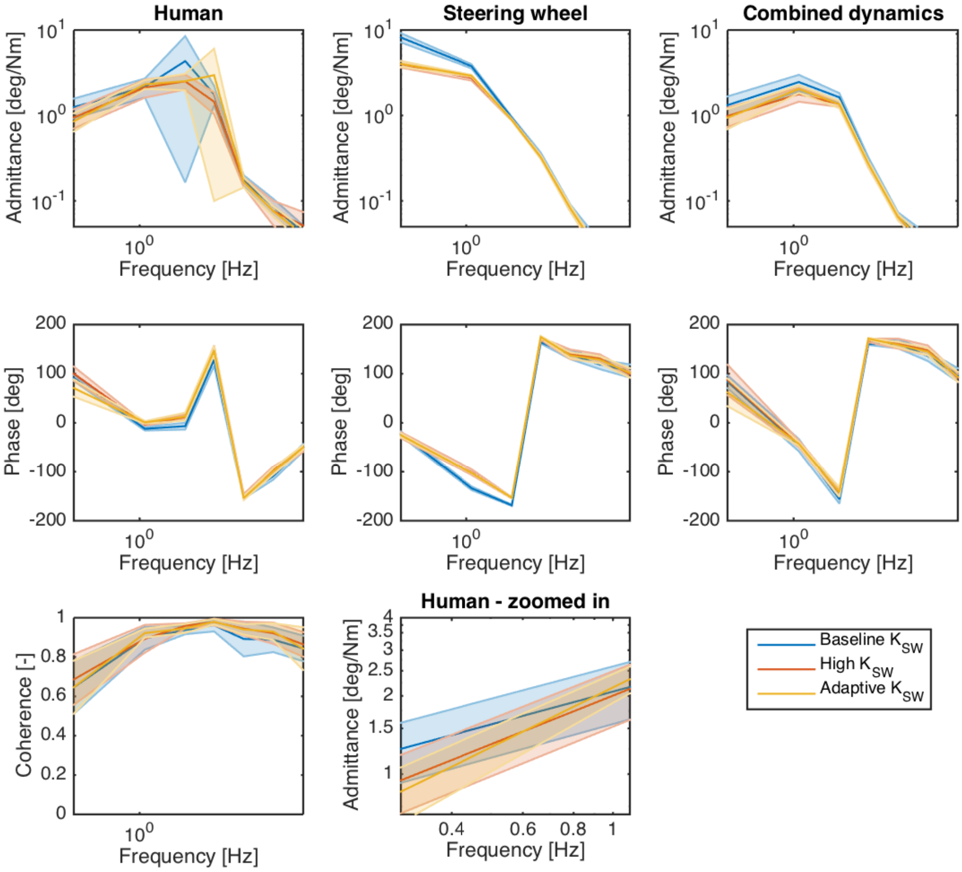


Figure G.2: Narrow road results per steering wheel system, where adaptive $K_{SW}$ = high $K_{SW}$.

## G.2. Performance

First, additional plots will be given for the performance metrics that were not significantly affected by steering wheel stiffness $K_{SW}$ (see paper, Table I). When looking at the number of hit cones (#HIT), plotted in Fig. G.3, a clear difference is visible between wide and narrow roads. During the whole experiment, not more than a single cone was hit on wide segments. Per narrow segment, an average of four cones was hit. However, a lot of variability is present in the results. In Fig. G.4, it can be seen that individual trends diverge too. A further analysis is explained in Appendix H.

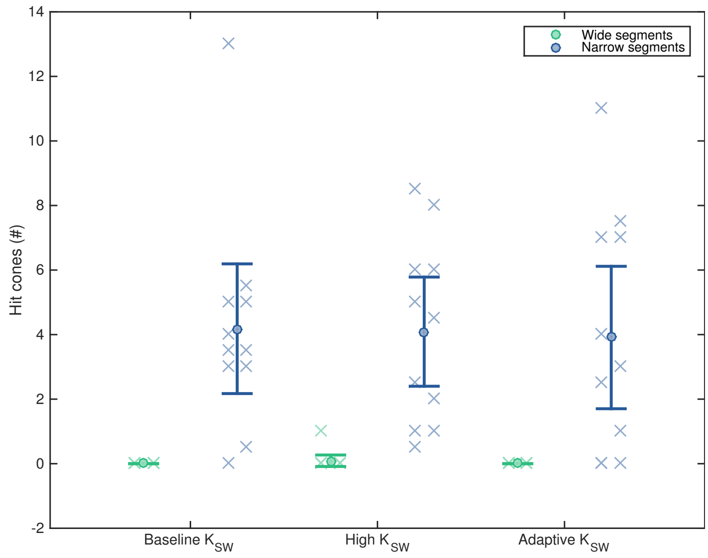


Figure G.3: Average number of hit cones per segment

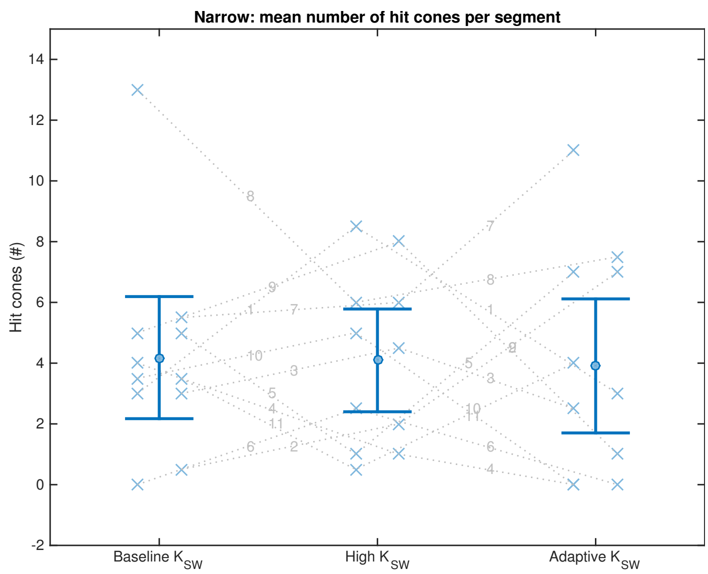


Figure G.4: Average number of hit cones per segment on narrow roads. The data points of each subject are connected and the lines are numbered. It can be seen that some subjects hit fewer cones with high $K_{SW}$, while others hit more than with baseline or adaptive $K_{SW}$.

In Fig. G.5, mean lateral errors are shown. This metric indicates the average distance that subjects kept between the middle of their car and the center of the lane, i.e. their bias towards either side of the road. The absolute bias is larger on wide segments, as the tasks not to hit cones or leave the road allow more deviation. It can also be seen that most subjects show a bias to the left on wide roads (negative mean error). Because the driver seat is on the left of the virtual car, this side is easier to control visually. The biases largely disappear on narrow roads. Because mean lateral error is not seen

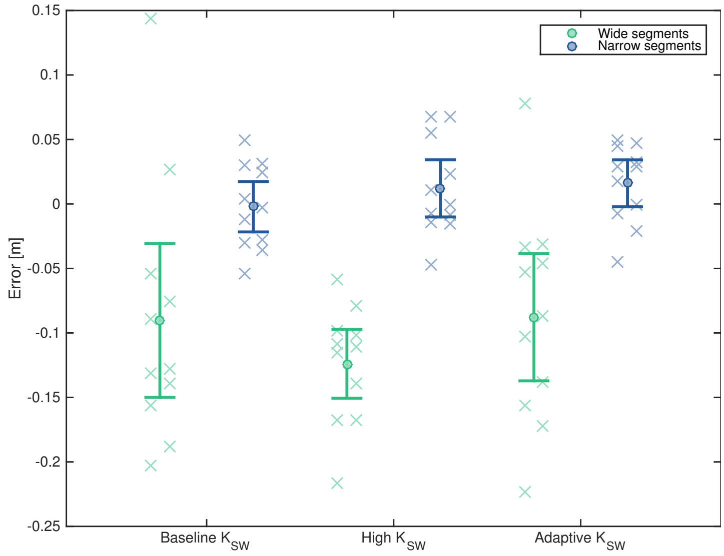


Figure G.5: Mean lateral error

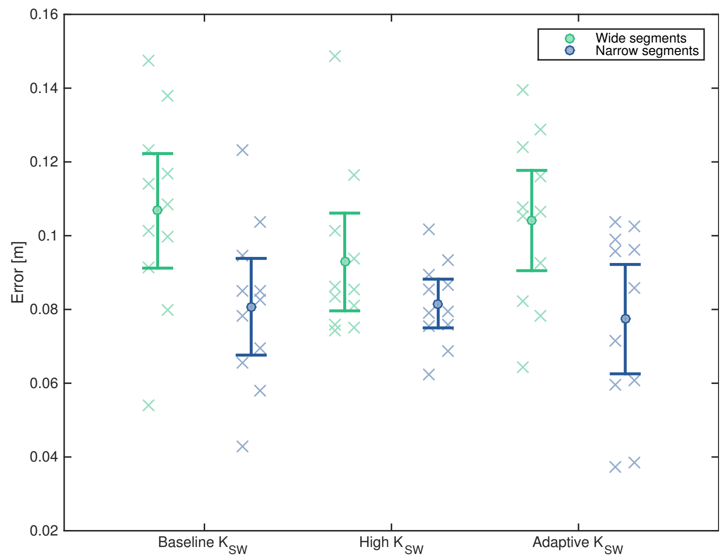


Figure G.6: Standard deviation of lateral error

as a relevant metric for performance with respect to the task requirements, it is not reported in the paper.

The standard deviations of lateral error (std($\epsilon$), which are reported in the paper) provide more insight into the subjects' ability to control the car by showing the variance in its lateral position. The results are visualized in Fig. G.6. On wide roads, high $K_{SW}$ appears to lead to lower std($\epsilon$), although this effect is not significant (see paper, Table I). Also, std($\epsilon$) is larger on wide than on narrow segments. This makes sense since the metric does not directly relate road width to task performance, like #HIT and time-to-lane-crossing (TLC).

Finally, the mean of inverse time-to-lane crossing ($TLC^{-1}$) is reported in the paper, because this metric shows overall lane-keeping performance most robustly. However, by looking at the (inverse) minimum TLC instead of the mean, information can be obtained about the most critical or dangerous situation that was encountered in a segment. This metric is sensitive to outliers, so its results are noisier. However, it does allow comparison of the steering wheel settings based on a sort of 'worst case scenario'. In Fig. G.7 the inverse minimum TLC is shown, and in Fig. G.8 is zoomed in on the results on wide roads. It can be seen that on wide roads, performance is best (i.e. lowest $TLC^{-1}$) with high $K_{SW}$. Interestingly,

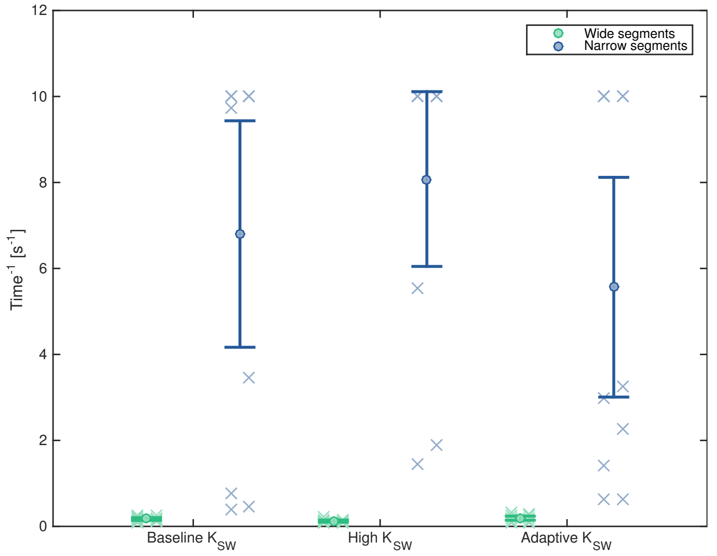


Figure G.7: Inverse minimum time-to-lane crossing (TLC$^{-1}$), cut off at 10 seconds

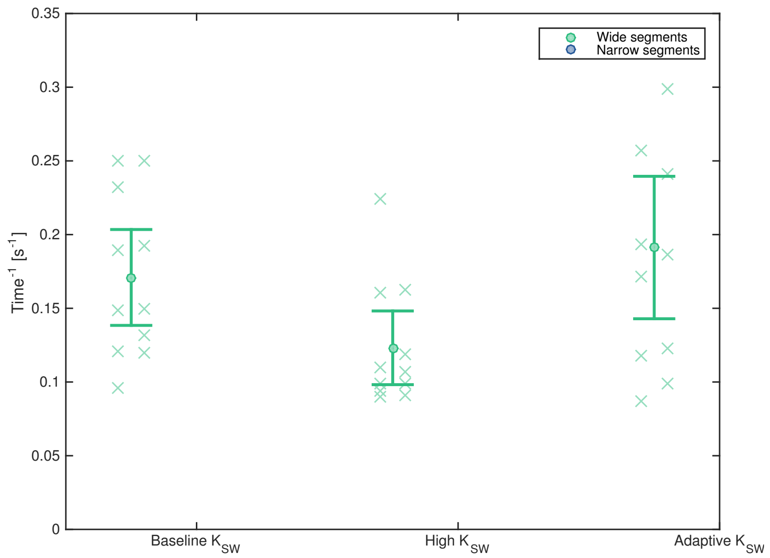


Figure G.8: Inverse minimum time-to-lane crossing (TLC$^{-1}$), zoomed in to show wide road results

on narrow roads, subjects perform better with adaptive $K_{SW}$ than high $K_{SW}$. This is remarkable, since the steering wheel has the same stiffness both situations. On none of the other metrics, a difference was found between baseline and adaptive $K_{SW}$ on wide roads, or between high and adaptive $K_{SW}$ on narrow roads. The reason for these findings is thus unclear. However, the fact that subjects less often experience a highly critical situation with adaptive $K_{SW}$ may help explain why its subjective ratings were higher.

## G.3. Effort

Next to the standard deviations of torques on the measured road segments (std(T), as reported in the paper), the effects of steering wheel stiffness and road width were also analyzed on the non-excited frequencies ($f_{\text{no power}}$) only. Applying Parseval's Theorem, variance can be calculated as the sum of the power spectral densities of the torques ($\hat{S}_{TT}$) on these frequencies [2]:

$$\sigma_T = 2\sqrt{\sum_{f\,=\,0\text{ Hz}}^{f\,=\,20\text{ Hz}} \hat{S}_{TT}(f_{\text{no power}})} \tag{G.1}$$

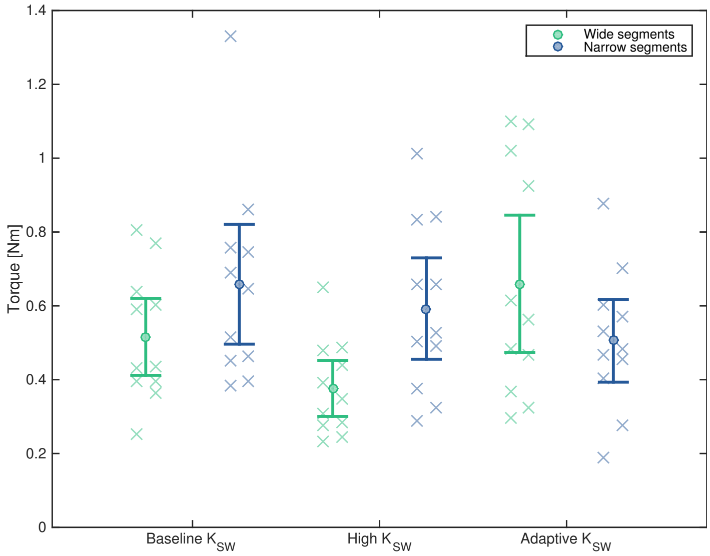


Figure G.9: Standard deviation of torques on non-excited frequencies

The results are shown in Fig. G.9. As can be seen, the effects of steering wheel stiffness $K_{SW}$ are not as clear as those on std(T). The only significant effects were of road width ($t(10) = -4.561$, $p < 0.01$ with baseline $K_{SW}$, and $t(10) = -3.557$, $p < 0.01$ with high $K_{SW}$). Adaptive $K_{SW}$ still results in constant effort between road widths. As a check, the variance of the steering angles was also analysed only at non-excited frequencies, and a clear influence of $K_{SW}$ was visible. So perhaps subjects chose to keep their force levels more or less constant, while making larger steering wheel angles with lower $K_{SW}$. This would verify that indeed, with both steering wheel systems, subjects performed a 'force task' [1] while driving.
As the other metrics could not be as easily compared without including the effects of perturbations, it was chosen not to report these results.

## G.4. Acceptance

Finally, the results from the Van der Laan questionnaire are plotted in Fig. G.10 and G.11. Note that these results include both narrow and wide segments; no distinction was made in the questionnaire (see Appendix F). Subjects thus evaluated the steering wheel systems based on their experience on both straight segment types. Interestingly, as reported in the paper, they seemed to be most satisfied with adaptive $K_{SW}$, while also rating it the most useful.

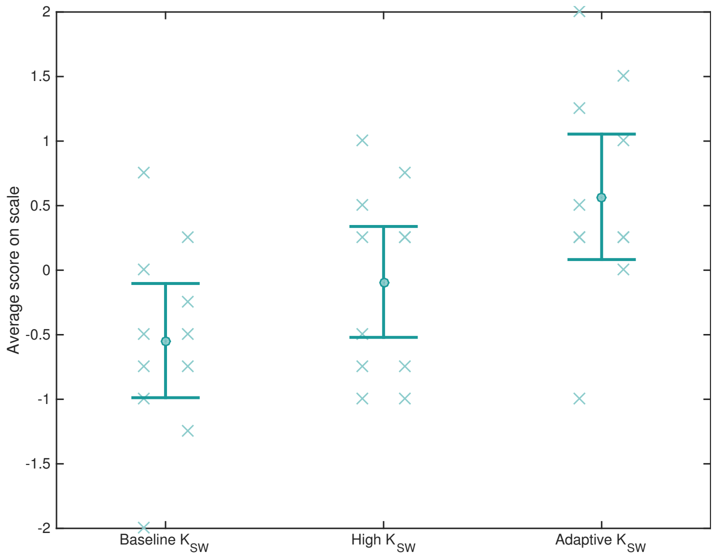


Figure G.10: Subjectively rated satisfaction

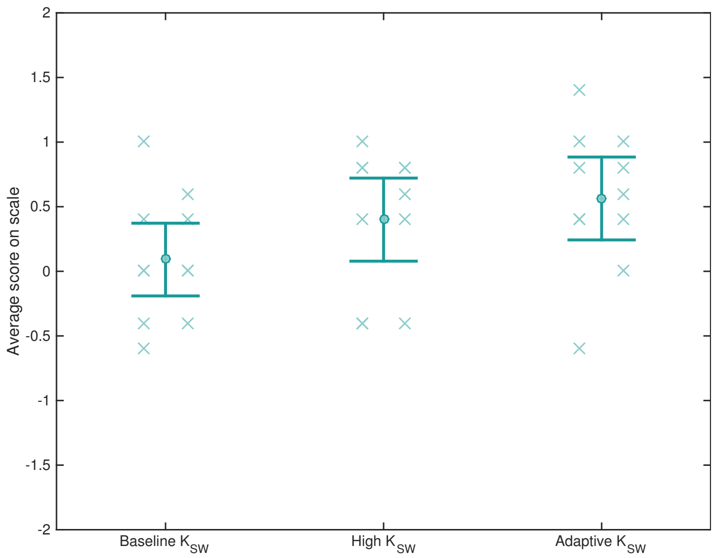


Figure G.11: Subjectively rated usefulness

# Bibliography

[1] DA Abbink, M Mulder, and MM van Paassen. Measurements of Muscle Use during Steering Wheel manipulation. *Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics*, pages 1652–1657, 2011. ISSN 1062922X. doi: 10.1109/ICSMC.2011.6083908.

[2] D.B. Percival and a.T. Walden. Wavelet Methods for Time Series Analysis. *Cambridge University Press*, page 594, 2000.

# H

# Individual trend analysis

By looking at the results from all the subjects together, sensitivity to individual trade-offs is lost. For example, half the participants might increase their neuromuscular stiffness $K_{NMS}$ with increased steering wheel stiffness $K_{SW}$, while also improving their respective task performance. At the same time, the other half of the subjects might have lowered their $K_{NMS}$, while keeping performance constant. When looking at all the results together, the effects of $K_{SW}$ on $K_{NMS}$ will be averaged out, and no clear trends will be seen in performance. If the two groups could be separated based on what kind of trade-off's they make, differing strategies might be found that give more insight into the results.
To that end, individual trends were analysed to identify if specific strategies were applied while performing the driving tasks. The analysis consists of two parts: first, it was attempted to categorise subjects based on their trade-off between effort and performance, and then, individual differences between conditions are analysed.

## H.1. Individual trade-offs

First, scatter plots were made of effort versus performance to categorise subjects. On the x-axis, increasing effort is plotted: neuromuscular stiffness ($K_{NMS}$), steering reversal rate (SRR) or standard deviation of torques (std(T)). On the y-axis, decreasing performance is plotted: inverse mean time-to-lane crossing ($TLC^{-1}$), number of hit cones (#HIT) and standard deviation of lateral error (std($\epsilon$)).
Fig. H.1 indicates that when the data of a subject are above the average trade-off, that means they

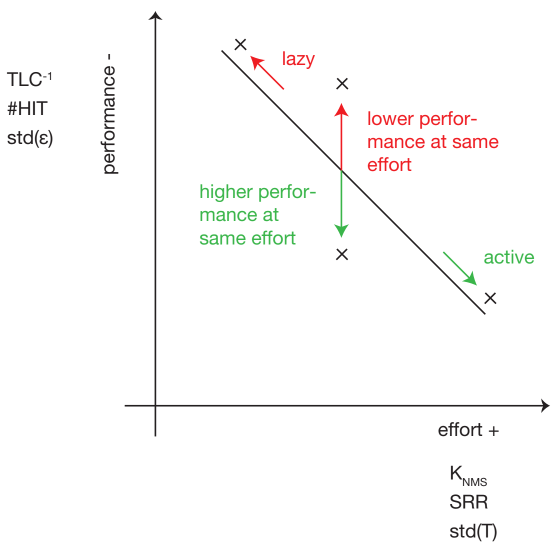


Figure H.1: Scatter plot of effort vs. performance metrics to show individual w.r.t. average trade-off

perform worse at the same level of effort. Similarly, when they are below the trade-off, they are relatively good at the task. Also, participants that are on the lower right side on the trade-off line can be regarded as more active, and those on the upper left side as lazier.

All possible combinations of performance and effort metrics were plotted, for both narrow and for wide segments. If subjects were clearly more above or below the trade-off line than most others, they would be categorised as ‘good’ or ‘bad’ for that combination. Similarly, if data were located near either one of the ends of the line, those subjects would be labelled ‘active’ or ‘lazy’ with respect to the plotted metrics. An example of a trade-off is shown in Fig. H.2 and H.3, on a wide and narrow road, respectively.

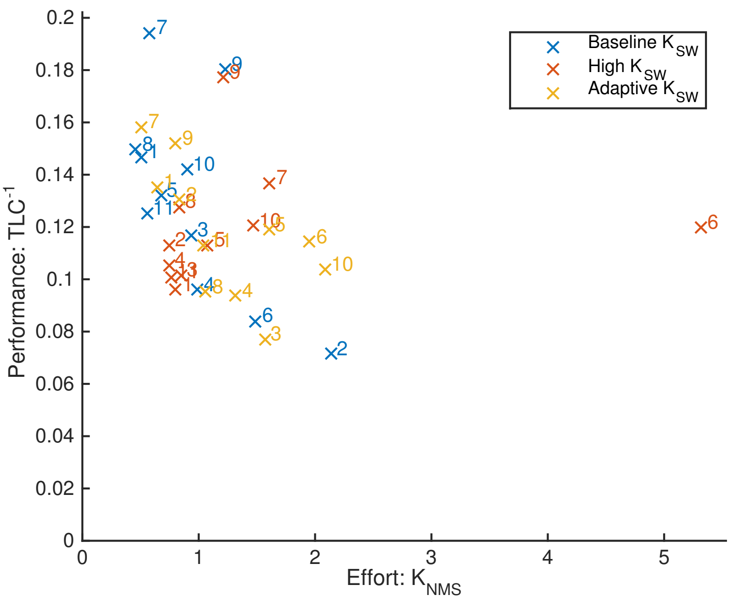


Figure H.2: Example of a trade-off on a wide road: neuromuscular stiffness ($K_{NMS}$) versus performance (inverse mean time-to-lane crossing, $TLC^{-1}$).

It was found that subject number 7, 8 (on narrow roads) and 9 scored ‘bad’ or ‘lazy’ at most of the combinations. Subject 3, 4, and 6 often scored ‘good’ or ‘active’, and subject 5 was particularly active with respect to std(T). To check if these results could be attributed to driving experience and/or driving frequency, they were compared to the personal details that subjects had provided. No such relationship appeared to exist. Neither did the other characteristics (age, gender, weight and height) seem to have affected the outcomes.

As a side note, it should be mentioned that the average trade-off lines were not very reliable. They were fitted using a first-degree least-squares method. Results differed between adaptive steering wheel stiffness and the corresponding baseline (wide segments) or high stiffness (narrow segments). Besides, with most combinations of metrics, the data was widely spread. Therefore it was chosen not to plot them in Fig. H.2 and H.3. Some of the trade-off lines had a positive slope, meaning that performance decreased with higher effort. In those cases, cause and effect might have been reversed: worse performance leads to higher effort, instead of the other way around. After all, performance was affected by the experimental conditions.

## **H.2.** Individual trends

Next, the effects of steering wheel stiffness and road width were analysed within each subject. In the metrics plots, the data points that belonged to one subject were connected and the lines were numbered. As an example, the resulting plots for drivers’ neuromuscular compliance are shown in Fig. H.4 - H.6.

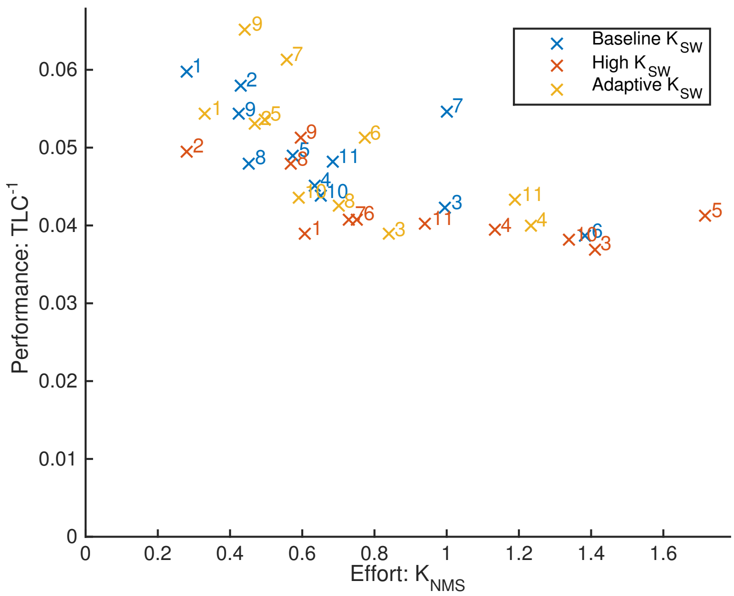


Figure H.3: Example of a trade-off on a narrow road: neuromuscular stiffness ($K_{NMS}$) versus performance (inverse mean time-to-lane crossing, $TLC^{-1}$).

For every participant, it was recorded whether a metric increased strongly ('++'), increased slightly ('+'), decreased slightly ('-'), or decreased strongly ('- -') when steering wheel stiffness was increased and when road width was decreased. For the results, see Table H.1.

As could be expected from the overall results, most subjects increased effort and decreased performance on narrow roads. Comparing high to baseline $K_{SW}$ showed that most subjects increased $K_{NMS}$ while decreasing SRR and mean $TLC^{-1}$. One of the subjects (number 2) that instead decreased $K_{NMS}$ showed worse than average performance, while others (subject 4 on narrow roads and subject 7 on wide roads) did not. In general, it seems like each person makes an individual trade-off between different effort and performance metrics, as there always is some sort of balance. However, there is no overlap in the way this is done, so clear strategies cannot be distinguished.

Next, the individual trends of the previously distinguished groups of subjects were considered. The underachieving subject 7, 8 and 9 did not appear to share an approach, or apply strategies that differed from those of the other participants. Neither did overachieving subject 3, 4 and 6.

## H.3. Personal preferences

Finally, the individual results of the Van der Laan questionnaire were analysed. It was found that there were roughly three types of responses:

- Ratings are lowest for baseline $K_{SW}$ and highest for adaptive $K_{SW}$ (the average outcome);
- Ratings are lowest for high $K_{SW}$;
- High $K_{SW}$ is favoured.

Clearly, the last two responses are contradicting, causing them to be averaged out when analysing all subjects' data together.

The individual responses of the previously distinguished groups were checked. Subject 7, 8 and 9, who did worse than average, all showed different results. Interestingly, subject 3, 4 and 6 who did better than average, all gave high $K_{SW}$ the lowest rating for satisfaction. Subject 3 and 4 also rated it as the least useful system, whereas subject 6 seemed to think all the systems were equally useful.

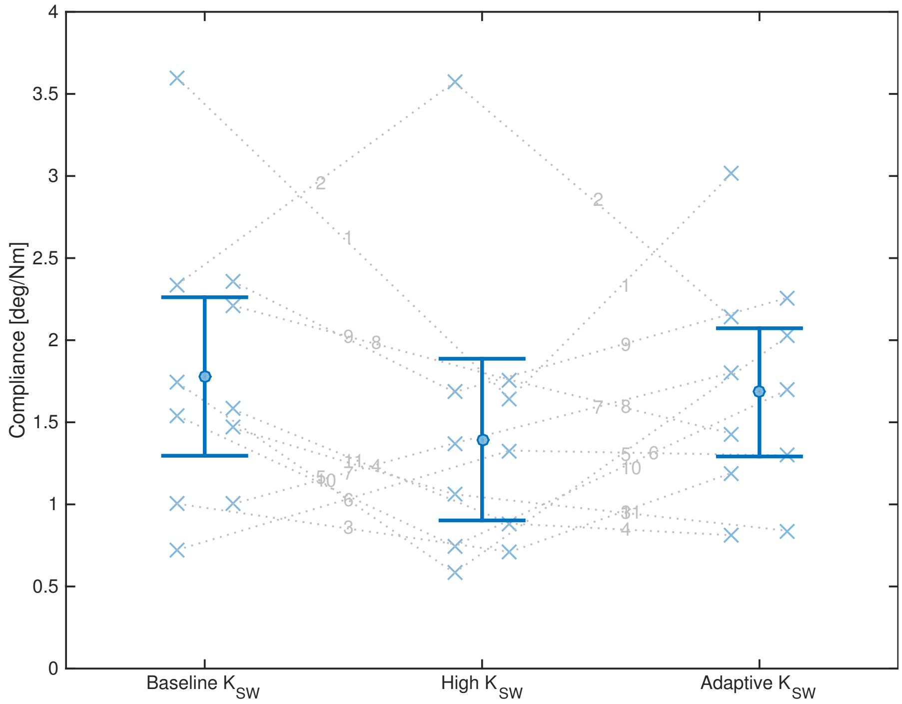


Figure H.4: Example of a metric plot that includes individual trends: neuromuscular compliance on a wide road.

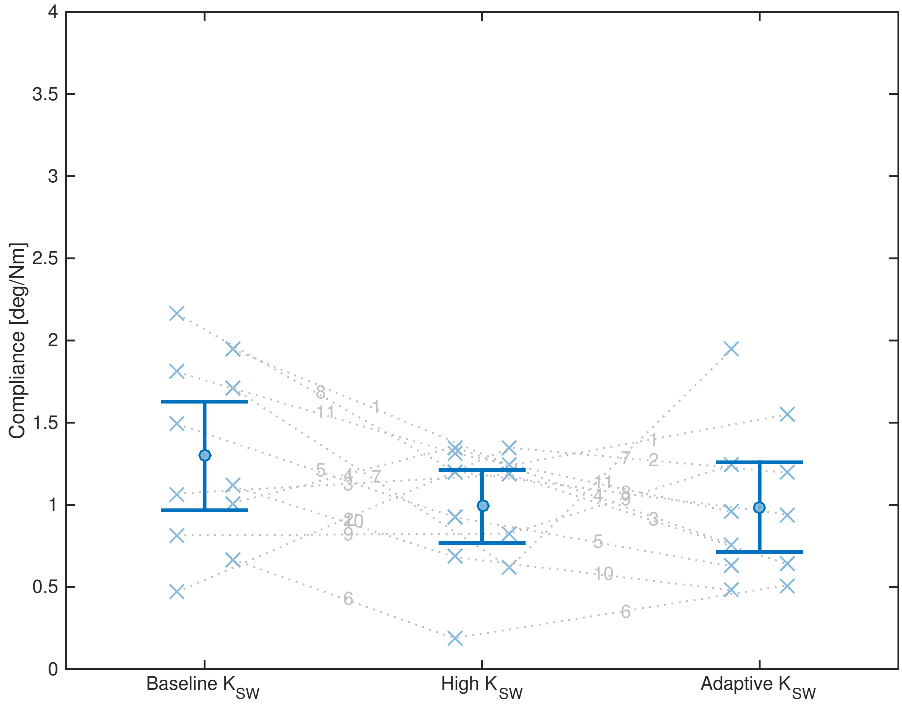


Figure H.5: Example of a metric plot that includes individual trends: neuromuscular compliance on a narrow road.

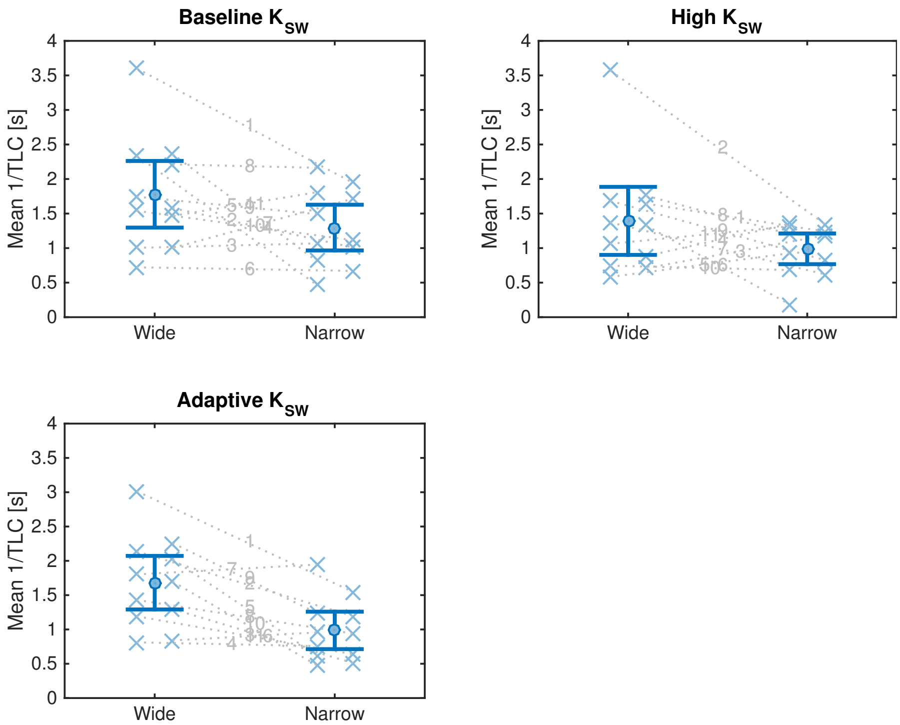


Figure H.6: Example of a metric plot that includes individual trends: neuromuscular compliance on a wide compared to a narrow road.

The only other subject that gave a similar response was subject 10, who although showing average performance, was not once labelled 'bad' or 'lazy'. Moreover, subject 3, 4, 6 and 10 all gave adaptive $K_{SW}$ the best scores. Summarizing, it appears that those who did good, were least fond of high $K_{SW}$ while favouring adaptive $K_{SW}$. The same subjects showed relatively high $K_{NMS}$ with high $K_{SW}$ on wide roads. A possible explanation could be that since they work harder themselves, the advantages of high $K_{SW}$ are eliminated in less critical situations. This demonstrates why adapting $K_{SW}$ to the situation is believed to be beneficial.

Table H.1: Individual trends

Subject 1

| | High w.r.t. baseline $K_{SW}$ | | Narrow w.r.t. wide road | |
|---|---|---|---|---|
| | Wide | Narrow | High $K_{SW}$ | Baseline $K_{SW}$ |
| $K_{NMS}$ | ++ | ++ | ++ | ++ |
| std(T) | = | = | + | + |
| SRR | = | - - | - | + |
| #HIT | = | ++ | ++ | ++ |
| $TLC^{-1}$ | - | + | ++ | ++ |
| std($\epsilon$) | - - | = | + | - |

Subject 2

| | High w.r.t. baseline $K_{SW}$ | | Narrow w.r.t. wide road | |
|---|---|---|---|---|
| | Wide | Narrow | High $K_{SW}$ | Baseline $K_{SW}$ |
| $K_{NMS}$ | - - | - - | ++ | ++ |
| std(T) | - | + | ++ | + |
| SRR | - | ++ | + | - - |
| #HIT | = | + | + | + |
| $TLC^{-1}$ | - - | ++ | ++ | ++ |
| std($\epsilon$) | - | ++ | + | - |

Subject 3

| | High w.r.t. baseline $K_{SW}$ | | Narrow w.r.t. wide road | |
|---|---|---|---|---|
| | Wide | Narrow | High $K_{SW}$ | Baseline $K_{SW}$ |
| $K_{NMS}$ | + | = | - | = |
| std(T) | - | - | + | + |
| SRR | - | - | + | ++ |
| #HIT | = | + | ++ | ++ |
| $TLC^{-1}$ | - | = | ++ | ++ |
| std($\epsilon$) | - | = | = | - |

Subject 4

| | High w.r.t. baseline $K_{SW}$ | | Narrow w.r.t. wide road | |
|---|---|---|---|---|
| | Wide | Narrow | High $K_{SW}$ | Baseline $K_{SW}$ |
| $K_{NMS}$ | + | - | - | - |
| std(T) | - | - | + | + |
| SRR | - | - | + | + |
| #HIT | = | - | + | ++ |
| $TLC^{-1}$ | + | + | ++ | ++ |
| std($\epsilon$) | + | + | - - | - |

Subject 5

| | High w.r.t. baseline $K_{SW}$ | | Narrow w.r.t. wide road | |
|---|---|---|---|---|
| | Wide | Narrow | High $K_{SW}$ | Baseline $K_{SW}$ |
| $K_{NMS}$ | ++ | + | - | = |
| std(T) | - | - | = | ++ |
| SRR | - | - | + | = |
| #HIT | = | - - | + | ++ |
| $TLC^{-1}$ | - - | - - | ++ | ++ |
| std($\epsilon$) | - | + | = | - |

Subject 6

| | High w.r.t. baseline $K_{SW}$ | | Narrow w.r.t. wide road | |
|---|---|---|---|---|
| | Wide | Narrow | High $K_{SW}$ | Baseline $K_{SW}$ |
| $K_{NMS}$ | - | ++ | ++ | = |
| std(T) | - | - | + | + |
| SRR | - | = | + | + |
| #HIT | = | + | ++ | = |
| $TLC^{-1}$ | + | + | ++ | ++ |
| std($\epsilon$) | ++ | + | - - | - |

Subject 7

| | High w.r.t. baseline $K_{SW}$ | | Narrow w.r.t. wide road | |
|---|---|---|---|---|
| | Wide | Narrow | High $K_{SW}$ | Baseline $K_{SW}$ |
| $K_{NMS}$ | - | ++ | + | - |
| std(T) | - | - - | + | ++ |
| SRR | - - | - | + | ++ |
| #HIT | = | + | ++ | ++ |
| $TLC^{-1}$ | - | - - | ++ | ++ |
| std($\epsilon$) | + | - - | - | + |

Subject 8

| | High w.r.t. baseline $K_{SW}$ | | Narrow w.r.t. wide road | |
|---|---|---|---|---|
| | Wide | Narrow | High $K_{SW}$ | Baseline $K_{SW}$ |
| $K_{NMS}$ | + | + | ++ | = |
| std(T) | = | = | + | + |
| SRR | = | - | + | + |
| #HIT | + | - - | ++ | ++ |
| $TLC^{-1}$ | + | + | + | ++ |
| std($\epsilon$) | ++ | - - | - - | + |

Subject 9

| | High w.r.t. baseline $K_{SW}$ | | Narrow w.r.t. wide road | |
|---|---|---|---|---|
| | Wide | Narrow | High $K_{SW}$ | Baseline $K_{SW}$ |
| $K_{NMS}$ | ++ | = | ++ | ++ |
| std(T) | = | - | + | + |
| SRR | = | = | + | + |
| #HIT | = | + | ++ | ++ |
| $TLC^{-1}$ | - | - - | ++ | ++ |
| std($\epsilon$) | - | - | - | - |

Subject 10

| | High w.r.t. baseline $K_{SW}$ | | Narrow w.r.t. wide road | |
|---|---|---|---|---|
| | Wide | Narrow | High $K_{SW}$ | Baseline $K_{SW}$ |
| $K_{NMS}$ | + | ++ | = | + |
| std(T) | - | - | + | + |
| SRR | = | - | = | + |
| #HIT | = | + | ++ | ++ |
| $TLC^{-1}$ | - | - - | ++ | ++ |
| std($\epsilon$) | - | + | = | - |

Subject 11

| | High w.r.t. baseline $K_{SW}$ | | Narrow w.r.t. wide road | |
|---|---|---|---|---|
| | Wide | Narrow | High $K_{SW}$ | Baseline $K_{SW}$ |
| $K_{NMS}$ | + | + | - | - |
| std(T) | - - | - | + | + |
| SRR | - | - | + | - |
| #HIT | = | - - | + | ++ |
| $TLC^{-1}$ | - | - | ++ | ++ |
| std($\epsilon$) | - | - | = | - |