

Specialization: BioMechanical Design  
Title: **The Power of Haptic Guidance**  
Author: Stephan de Nijs BSc.  
Student ID: 1151444

Title (in Dutch) De kracht van haptische besturing

Assignment: ME2590-32 MSc Thesis

Supervisors: Dr.ir. D.A. Abbink  
Dr.ir. M. Mulder

Date: August 19, 2011

# **PREFACE**

This is the final report of the Master Thesis (part of course code ME2590-32) of Stephan de Nijs BSc. with the working title "The Power of Haptic Guidance".

The goal of this research was to design an experiment and gather empirical data that could give insight in the amount of steering control information that can be provided through haptic guidance. A visual occlusion experiment has been performed with the fixed base driving simulator at the HMI-lab of the Aerospace Engineering Faculty of Delft University of Technology.

After deliberation with my supervisors David Abbink, Mark Mulder and professor Frans van der Helm it was chosen to write this report in the form of a scientific paper.

This report starts with this paper and continues with an appendix which contains a more elaborate explanation concerning the experiment design (appendix A), the approach that was used for the analysis (appendix B) and the subjective questionnaire (appendix C) that was performed during the experiment for this final project.

I would like to thank my supervisors, David and Mark, for their assistance and patience during this project. Without their guidance I would have been unable to reach this destination.

Their support, well needed motivational speeches, constructive criticism and enthusiasm were invaluable to me during the events leading up to this report.

Delft, University of Technology

S.Y. de Nijs BSc

August 19, 2011

# The Power of Haptic Guidance

Stephan de Nijs BSc. [S.Y.denijs@student.tudelft.nl]  
Delft University of Technology

## ABSTRACT

**Background:** Haptic guidance is a continuous form of haptic feedback where the driver obtains information through small corrective forces on control inputs, such as the steering wheel. Haptic guidance for automotive steering has shown promising results such as improved primary task performance, reduced visual workload and reduced control activity.

Despite these promising results, it remains unknown how much information on curve negotiation is provided by haptic guidance when combined with full visual or reduced visual information.

**Objective:** The goal of this research is to gather empirical data to investigate the capability of haptic guidance to present essential steering control information for curve negotiation to drivers when essential visual information is removed.

**Method:** Previous research identified a far and near visual point for providing drivers with essential visual control information. This research removed essential visual control information while haptic guidance was presented to the subjects. The visual information was removed by occluding all visuals above  $7.5^\circ$  down from the true horizon for the near visual condition and all visuals beneath  $1.68^\circ$  down from the true horizon for the far visual condition. This corresponds to 0.34 seconds and 1.53 seconds look-ahead time respectively when driving at  $20 \text{ ms}^{-1}$ . It was hypothesized that the designed haptic guidance would be able to compensate for this loss of visual information.

**Results:** While using haptic guidance, driving performance and control activity show a significant performance increase for all visual conditions. For the experimental conditions tested, control effort only increases for full visual and slightly for the far visual condition. The summed absolute lateral position is increased to better than baseline performance for all visual conditions, however time to line crossing performance is not increased to better than baseline performance for the near visual condition.

**Conclusion:** Based on the empirical data it can be concluded that haptic guidance is capable of providing drivers with essential control information, although driving performance does not match that of full visual feedback without haptic guidance. It also appears that drivers are more likely to accept haptic guidance if essential visual information is removed.

**Application:** With this empirical data new mathematical and cognitive driver models can be developed that incorporate haptic feedback which can be useful in the future development of autonomous systems based on human driving behavior.

Keywords: haptic guidance, curve negotiation, control information, visual occlusion

## I - INTRODUCTION

Driving is a task which relies heavily on visual roadway information. Distractions inside the vehicle as well as outside the vehicle can misdirect the driver's visual attention. These distractions are the main cause of accidents. Previous research proposed continuous haptic guidance as a way to offer an additional feedback loop to drivers. Several benefits of haptic guidance can be found in literature (Mulder et al, 2008; Brandt et al, 2007; Griffiths & Gillespie, 2005) including increased driving performance while reducing drivers control activity and increasing driver comfort. It is important to note that, when visual feedback was present during these previous experiments, human subjects were provided with full visual information. It remains unknown to what extent haptic guidance can restore performance or reduce control effort when visual feedback is degraded or partially unavailable

The goal of this research is to gather empirical data to investigate the capability of haptic guidance to present essential steering control information to drivers which is usually provided visually. This empirical data is gathered by an experiment where essential visual control information used when steering is removed.

### 1.1 Manual control, Automated control, shared control and haptic guidance.

Drivers conventionally operate the car themselves by using only manual control. The driver can look at the situation and choose an appropriate driving strategy based on the environment. This also means that the driver can bend or break the rules for safe driving. Since many accidents are caused by human error one solution is taking the human out of the loop and automate the system. Taking the human out of the control loop completely removes any flexibility

coming from drivers and requires a perfect system model equipped with perfect sensors. At present day full automation requires drivers to take a supervisory task upon themselves. This form of automation brings several problems along described widely in literature (Sarter, Woods & Billings, 1997; Abbink, Boer & Mulder, 2008; Lee & See, 2004). Furthermore, humans are reluctant to give up autonomy when it comes to driving, yet the introduction of automatic control features could significantly increase vehicle and highway safety and efficiency.

Another solution to increase driving safety is shared control which combines the precision of automated control and flexibility of manual control. With the introduction of steer-by-wire systems in future vehicles, steering wheels will need to be motorized in order for drivers to form an internal model on the linkage between steering wheel and tire angle. This also adds the possibility to share control between drivers and an automatic controller that guides drivers to an optimal steering wheel angle by generating additional corrective forces. Shared control with the use of continuous haptic feedback is called haptic guidance or shared haptic guidance and has already been successfully implemented by Mulder et al. (2008), Forsyth & Maclean (2006), Abbink & Mulder (2010) and Griffiths & Gillespie (2005). Promising results include reduced visual workload, increased performance, reduced control activity and an increase of driver comfort. However this came at the expense of increased control effort. Note that the forces used to guide drivers are small and easily overridden.

## 1.2 Essential control information and its incorporation into driver models

Despite all promising results of continuous haptic guidance it is still unknown how people use the information provided by this support system compared to the information provided visually. A visual occlusion experiment performed by Griffiths & Gillespie (2005) showed a reduction in mental load, so a secondary task could be performed better. The question remains how haptic guidance helps drivers to obtain essential steering control information while negotiating curves.

This question can be answered by mathematical driver and cognition models which are based on empirical data. However such models do not incorporate haptic guidance yet. Mathematical driver and cognition models are very useful to develop better autonomous systems based on human driving behavior (Goodrich & Boer, 2000). They are important to predict behavior, and quantify it in control-theoretic parameters. Plöchl (2007) gives an overview of such models. These models are based on control information found in literature which is essential for safe driving. Control information can be provided by driving cues at different sensory levels: not only visual, but also auditory, vestibular, tactile and proprioceptive. Literature claims that the cues used for driving are mainly visual, see Sivak (1996) for an overview, and all these models are based on the assumption

that visual information provides the most important cues for vehicle control.

Land & Horwood (1995) showed that drivers need to sample visual information both close by (near point) and further down the road (far point), in order to obtain good driving performance by partially occluding visual information. If only near point visual information is available drivers have to increase their efforts to track the curves. If only a far point is available, curve tracking improves with little control effort. However, this occurs at the cost of larger deviations in lane position. If a visual near and far point are present, without showing the visual middle points, driving performance approaches that of full visual information. Salvucci (2006) gives a more detailed model of the two-level control based on the perception of these two salient visual points.

With haptic guidance, drivers are presented with a look-ahead controller that provides additional future (far) and present (near) information for lateral vehicle control. This means haptic guidance can be a source of essential control information for curve negotiation. To build models which incorporates additional information provided by haptic guidance and predicts driving behavior it is essential to understand how the additional information provided by haptic guidance is used. The goal of this research is to gather empirical data to investigate the capability of haptic guidance to present essential steering control information to drivers for curve negotiation.

## 1.3 Hypotheses

It is hypothesized that the removal of visual information – either near or far visual information – can adequately be compensated for by the addition of haptic guidance. Furthermore, the removal of far information can be compensated for with haptic guidance better than the removal of near visual information, since the tested haptic guidance controller is a ‘look-ahead’ controller, i.e. its control actions are based on predictions of future position and heading errors.

Table I summarizes the expected effect of haptic guidance on different visual and haptic conditions.

TABLE I  
Experimental Hypotheses for effect of Haptic guidance (H)  
on metrics for Visual conditions (V)

	$V_{full}$	$HV_{full}$	$V_{near}$	$HV_{near}$	$V_{far}$	$HV_{far}$
SALP	baseline	better	similar	better	worse	similar
TLC	baseline	better	worse	similar	similar	better
SRR	baseline	better	worse	similar	similar	better
maxFsw	baseline	more	more	more	similar	more
$\sigma$ Fsw	baseline	more	more	more	similar	more

## II - METHOD

### 2.1 Experiment design

To test the hypotheses, two independent variables, haptic feedback (H) and visual feedback (V) are combined to yield 6 different conditions. The haptic feedback (H) is either on or off:  $H = \{\text{on}, \text{off}\}$ . The visual feedback (V) is full, near or far:  $V = \{\text{full}, \text{near}, \text{far}\}$ . With visual feedback this means occluding part of the screen. With full feedback the subject will get all the visible information available. For the near visual feedback all visual information above  $7.5^\circ$  down from the true horizon will be occluded and for far visual feedback all visual information beneath  $1.68^\circ$  down from the true horizon will be occluded (fig. 1). This corresponds to 0.34 seconds and 1.53 seconds look-ahead time respectively when driving at  $20 \text{ ms}^{-1}$ . There should be no discussion that people are not able to drive without feedback. This condition will not be tested. The conditions without haptic feedback have already been investigated to some extent by Land & Lee (1994) and will be repeated in order to verify our research. The condition with full haptic feedback and full visual feedback has been researched by Mulder et al. (2008).

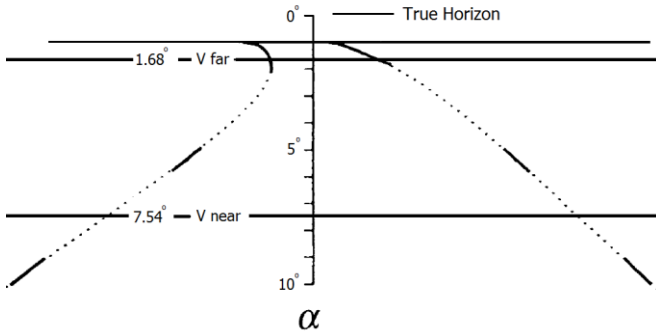


Fig. 1 Adapted from Land & Horwood (1995)

3 Curve types  $R = \{150\text{m}, 200\text{m}, 300\text{m}\}$  or  $c_r = \{7\text{km}^{-1}, 5\text{km}^{-1}, 3\text{km}^{-1}\}$  or difficulty = {difficult, normal, easy} respectively, were used to generate tracks. A track was generated by placing the curve types in a random order followed by a straight sections with a random length between 100 and 200m. 6 repetitions of each curve type (3 left, 3 right) were used for each track.

### 2.2 Subjects

The experiment was performed by total of 16 subjects. 2 subjects were excluded from analysis for not meeting the age and drivers license requirements. 2 other subject were excluded from analysis due to misinterpretation of the experiment instructions which resulted in outlier driving behavior.

The analysis was performed on a group of 10 male and 2 female subjects, with mean age = 24,  $\sigma = 2.6$ . Although this number seems small in order to obtain statistical relevant data, it actually suffices since all subjects are required to negotiate a random curve. Each curve can be treated as in

independent repeated event which gives statistical power on how people negotiate curves.

All subjects are in possession of a drivers license for mean years = 5,  $\sigma = 2$ . and have no known medical issues that could impair driving skills. The subjects participated voluntarily, and did not receive financial compensation for their efforts.

### 2.3 Apparatus

All experiments will be performed in a fixed based driving simulator at the faculty of Aerospace Engineering at Delft University of Technology. This driving simulator is capable of providing haptic guidance and has audio of engine sounds. The test subjects will drive on a simulated one lane curved road with a fixed speed. This means the driver will only use the steering wheel of the driving simulator and no pedal interaction is required.

The driving scene consisted of a single lane road with a road width of 4m and was displayed by 4 beamer on a wall in front and at the sides of the driver. The displayed image had a vertical resolution of 768 pixels which placed the true horizon at 452 pixels from the top of the screen. Visuals were occluded by using a mask that blacked out the visual information above 627 pixels from top for  $V_{\text{near}}$  and under 492 pixels from top for  $V_{\text{far}}$ . The screen was located at 290 cm from the driver. A 1:1 ratio was assumed to determine the size of the masks and calculate the look-ahead times at a driver eye-height of 0.9m. All beamers had a resolution of 1024x768 pixels and used the same masks for occlusion.

Since the information provided by haptic guidance is only compared to visual information no additional simulator fidelity was required for this experiment.

#### 2.3.1 Haptic Guidance Design

The haptic guidance system was adapted from Mulder et al. (2008). The haptic guidance will be based on the lateral error between the reference path (defined here as the lane centre) and the position of the vehicle at a certain time in the future. Forsyth, 2006; Brandt, 2007; Rossetter, 2002 used this 'look-ahead time' principle to enable stable vehicle control. In this study the look-ahead time was set at 0.7 seconds. The future vehicle position at this look-ahead time was predicted by assuming a constant steering input during that time.

By scaling the predicted lateral error by a constant gain  $K_f$ , the magnitude of the torque was determined. This concept of shared control has been explored before by Griffith (2004) and Steele (2001) in steering and by O'Malley (2006) in performance enhancement in virtual environments.

The current lateral error is scaled by a constant gain  $K_s$  and determines the stiffness of the steering wheel.

There is no controller conceivable where stiffness feedback alone can assist the driver; increasing the steering wheel stiffness  $K_s$  will merely make it more difficult to steer away from the center position of the steering wheel, while for effective error rejection it will be necessary to be able to turn the steering wheel away from the center position. Therefore, for stiffness feedback to be effective, it needs to be

combined with force feedback. During this experiment the gains  $K_f = 2$  and  $K_s = 0.005$  were used.

## 2.4 Experiment protocol

Subjects get a beforehand briefing on the experiment tasks as well as a training to familiarize themselves with the simulator and the haptic guidance controller. A questionnaire before the experiment will ask for personal information, driving experience and attitude against ADAS. A questionnaire after each condition will ask for subjective mental load and personal experience during the experiment. After all conditions were completed comments could be given and the attitude against ADAS was evaluated again.

The experiment will be divided into 2 sets of conditions. One without the presence of haptic guidance and the other with the presence of haptic guidance. The conditions are randomized within the set and the two sets are interchanged with each subject. Each set will start with two training sessions to explore the simulator. During the first training subjects will be asked to explore the steering wheel settings, during the second training subjects are asked to drive normal as they would during the experiment.

### 2.4.1 Task Instruction

The subjects are instructed they're driving on a single lane road without traffic and asked to drive as they normally would do without violating any traffic laws or engage in any dangerous driving behavior. They were instructed to keep both hands on the steering wheel at all times in a ten-to-two position.

## 2.5 Dependent measures

The effect of haptic guidance (H) is evaluated for several metrics. For driving performance these are Summed Absolute Lane Position (SALP) and Time-to-Line-Crossing (TLC), for control activity Steering wheel Reversal Rate (SRR) and for control effort the maximum steering wheel force ( $maxF_{sw}$ ) and the standard deviation of the steering wheel force ( $\sigma F_{sw}$ ).

### 2.5.1 Performance: Summed Absolute Lateral Position (SALP)

To evaluate in-lane driving performance the summed absolute lateral position (SALP) is calculated. The lateral position is determined as the distance from reference line. By summing the absolute lateral position the amount and time deviated from the reference line can be determined.

During this experiment the road center line is taken as the reference line. However, since subjects weren't asked to stay as close to the road's center but to drive as they normally would, this metric might not prove as useful as thought. A subject could have a certain lateral position preference other than the road's center which would result in unnecessary bad score for in-lane position.

Despite this fact this metric is still used to determine in-lane driving performance. Subjects drove in a single lane road and deviation from the center lane is thus limited. Next to

that the differences between conditions of all subject combined are of such magnitude that they can't be explained solely to individual lateral position preferences.

### 2.5.2 Performance: Time-to-Lane-Crossing (TLC)

TLC was calculated based on the method described by Winsum (2000).

$$TLC = \frac{y}{\dot{y} + \ddot{y}} \quad (1)$$

Godthelp (1986) shows that TLC is suited to describe the quality of anticipatory steering actions. The minimum TLC was calculated for the left and right bound of the road at each data point. The minimum value of the two was taken to represent the minimum TLC at that data point. By taking the 100 lowest data points of each curve, calculate their mean and standard deviation and subtracting this standard deviation from the mean the minimum TLC is calculated that was used for the plots.

### 2.5.3 Control Activity: Steering wheel Reversal Rate (SRR)

SRR indicates control activity by showing the frequency of steering wheel reversals. SRR has been linked to driving task demand by previous research (MacDonald, 1980). A minimum angle difference of the steering wheel of  $2^\circ$  was used to count as a reversal.

### 2.5.4 Control Effort: standard deviation of steering wheel force ( $\sigma F_{sw}$ )

Research where a haptic support system was used for car following showed that, when drivers actively yield to guiding forces presented by the support system, the standard deviation of measured control forces decreases (Abbink, 2006; Mulder, 2007).

### 2.5.5 Control Effort: Maximum steering wheel force ( $maxF_{sw}$ )

The peak steering wheel forces give insight in the control forces that are needed during each condition.

The maximum steering wheel force used for these plots was determined by taking the 100 highest data points of each curve, calculate the mean and standard deviation and adding this standard deviation to the mean.

### 2.5.6 Subjective workload

To evaluate the subjective workload for each condition, subject are asked to fill out a NASA-TLX questionnaire. Each condition is evaluated on six workload related factors and are combined to derive workload index using a weighted sum of the related factors.

## III – RESULTS

A repeated measures ANOVA was applied to reveal any significant differences. Sphericity was checked using Mauchly's test and corrected if necessary using the Greenhouse-Geisser estimates of sphericity. All pair-wise comparisons were significant  $p < 0.008$ . The results are summarized in table II, table III and table IV

TABLE II  
Statistical results of main effect for conditions Haptics (H) and Visual (V)  
and contrasts for  $V_{near}$  and  $V_{far}$  compared to baseline

	Main Effect H	Main effect V	Contrast $V_{near}$ vs baseline	Contrast $V_{far}$ vs baseline
SALP	$F(1, 215) = 368.14$ $p < 0.001$	$F(1.89, 406.57) = 41.85$ $p < 0.001$	$F(1, 215) = 66.70$ $p < 0.001$	$F(1, 215) = 43.41$ $p < 0.001$
TLC	$F(1, 215) = 283.22$ $p < 0.001$	$F(2, 430) = 513.47$ $p < 0.001$	$F(1, 215) = 823.74$ $p < 0.001$	$F(1, 215) = 5.33$ $p = 0.022$
SRR	$F(1, 215) = 352.57$ $p < 0.001$	$F(2, 430) = 333.83$ $p < 0.001$	$F(1, 215) = 630.11$ $p < 0.001$	$F(1, 215) = 93.67$ $p < 0.001$
maxFsw	$F(1, 215) = 9.60$ $p = 0.002$	$F(1.81, 389.78) = 174.12$ $p < 0.001$	$F(1, 215) = 12.92$ $p < 0.001$	$F(1, 215) = 281.12$ $p < 0.001$
$\sigma$ Fsw	$F(1, 215) = 7.48$ $p = 0.007$	$F(2, 430) = 70.60$ $p < 0.001$	$F(1, 215) = 39.77$ $p < 0.001$	$F(1, 215) = 31.47$ $p < 0.001$

TABLE III  
Statistical results of main effect for interaction between conditions Haptics (H) and Visual (V)  
and contrasts for interaction between conditions Haptics (H) and Visual (V)  
for  $V_{near}$  and  $V_{far}$  compared to baseline

	Main interaction effect V x H	Contrast interaction VxH, $V_{near}$ vs Baseline ( $V_{full}$ )	Contrast interaction VxH, $V_{far}$ vs Baseline ( $V_{full}$ )
SALP	$F(1.82, 390.45) = 11.00$ $p < 0.001$	$F(1, 215) = 17.67$ $p < 0.001$	$F(1, 215) = 19.72$ $p < 0.001$
TLC	$F(1.911, 410.93) = 33.78$ $p < 0.001$	$F(1, 215) = 54.94$ $p < 0.001$	$F(1, 215) = 45.18$ $p < 0.001$
SRR	$F(1.88, 404.54) = 24.20$ $p < 0.001$	$F(1, 215) = 54.83$ $p < 0.001$	$F(1, 215) = 18.01$ $p < 0.001$
maxFsw	$F(1.94, 417.92) = 176.46$ $p < 0.001$	$F(1, 215) = 54.67$ $p < 0.001$	$F(1, 215) = 141.01$ $p < 0.001$
$\sigma$ Fsw	$F(1.94, 416.44) = 127.49$ $p < 0.001$	$F(1, 215) = 219.97$ $p < 0.001$	$F(1, 215) = 62.57$ $p < 0.001$

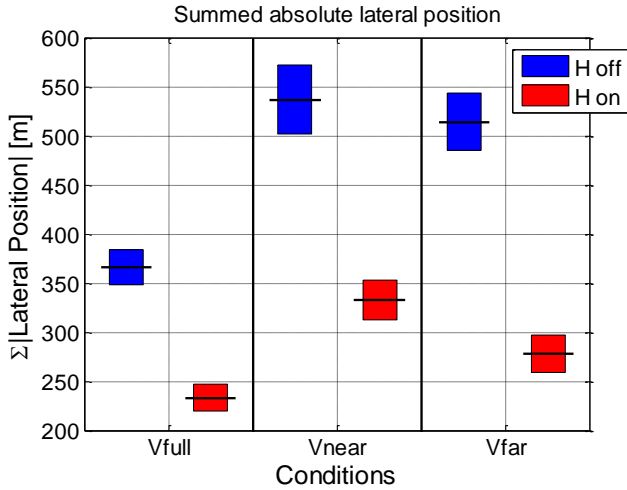
TABLE IV

Experimental Results for effect of Haptic guidance (H) on metrics for Visual conditions (V). **Bold** indicates different from hypothesis.

	$V_{full}$	$HV_{full}$	$V_{near}$	$HV_{near}$	$V_{far}$	$HV_{far}$
SALP	baseline	better	<b>worse</b>	better	worse	<b>better</b>
TLC	baseline	better	worse	<b>worse</b>	<b>worse</b>	better
SRR	baseline	better	worse	<b>worse</b>	<b>worse</b>	better
maxFsw	baseline	more	more	<b>less</b>	<b>more</b>	more
$\sigma Fsw$	baseline	more	more	<b>less</b>	<b>more</b>	more

### 3.1.1 Performance: Summed Absolute Lateral Position (SALP)

There is a significant decrease in SALP in the presence of haptic guidance  $F(1, 215)=368.14$ ,  $p<0.001$ . There was also a main effect of visual conditions  $F(1.89, 406.57)=41.85$ ,  $p<0.001$ . Contrasts revealed that SALP for  $V_{near}$   $F(1, 215)=66.70$ ,  $p<0.001$  and for  $V_{far}$   $F(1, 215)=43.41$ ,  $p<0.001$  were significantly higher than for full visual feedback, see Fig. 2.

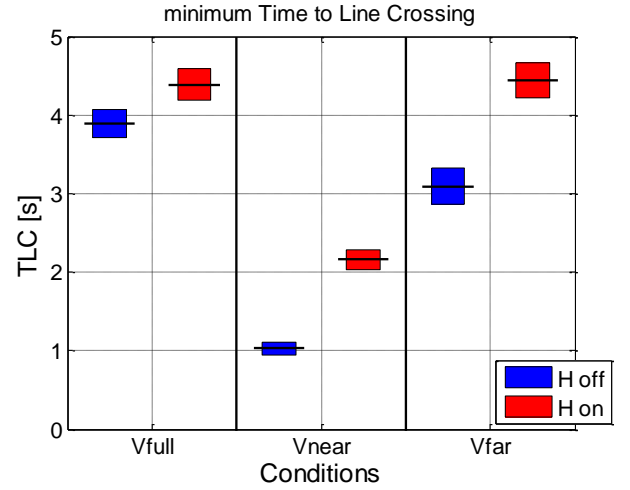


**Fig. 2 Summed Absolute Lateral Position (SALP) marking for all conditions and 95% confidence intervals.**

There is a significant interaction effect between the visual conditions and presence of haptic guidance  $F(1.82, 390.45)=11.00$ ,  $p<0.001$ . To break down this interaction, contrast were performed comparing all visual condition with presence of haptic guidance to the baseline, full visual condition and no presence of haptic guidance. This revealed a significant interaction when comparing the presence of haptic guidance for both  $V_{near}$   $F(1, 215)=17.67$ ,  $p<0.001$  and  $V_{far}$   $F(1, 215)=19.72$ ,  $p<0.001$  to full visual feedback without the presence of haptic guidance.

### 3.1.2 Performance: Minimum Time to Line Crossing (TLC)

There is a significant increase in TLC in the presence of haptic guidance  $(1, 215)=283.22$ ,  $p<0.001$ . There was also a main effect of visual conditions  $F(2, 430)=513.47$ ,  $p<0.001$ . Contrasts revealed that TLC for  $V_{near}$   $F(1, 215)=823.74$ ,  $p<0.001$  022 was significantly lower and for  $V_{far}$   $F(1, 215)=5.33$ ,  $p=0.022$  significantly higher than for full visual feedback, see Fig. 3.



**Fig. 3 Mean minimum TLC to road bounds marking for all conditions and 95% confidence intervals.**

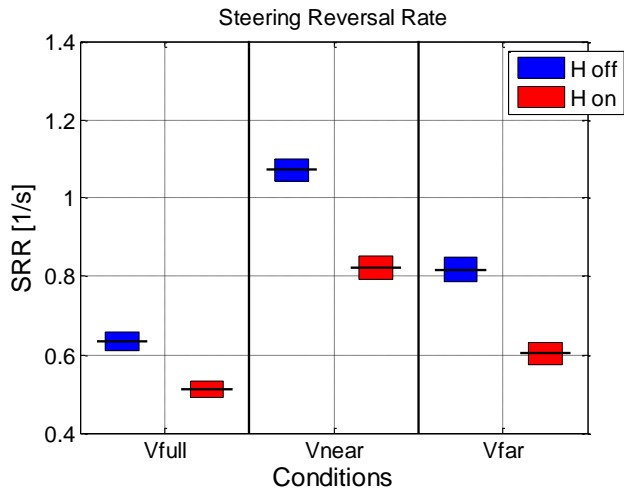
There is a significant interaction effect between the visual conditions and presence of haptic  $F(1.911, 41093)=33.78$ ,  $p<0.001$ . To break down this interaction, contrast were performed comparing all visual condition with presence of haptic guidance to the baseline, full visual condition and no presence of haptic guidance. This revealed a significant interaction when comparing the presence of haptic guidance for both  $V_{near}$   $F(1, 215)=54.94$ ,  $p<0.001$  and  $V_{far}$   $F(1, 215)=45.18$ ,  $p<0.001$  to full visual feedback without the presence of haptic guidance.

### 3.2 Control Activity: Steering Reversal Rate (SRR)

There is a significant decrease in SRR in the presence of haptic guidance  $F(1, 215)=352.57$ ,  $p<0.001$ . There was also significant main effect of visual condition  $F(2, 430)=333.83$ ,  $p<0.001$ . Contrasts revealed that SRR for  $V_{near}$   $F(1, 215)=630.11$ ,  $p<0.001$  and for  $V_{far}$   $F(1, 215)=93.67$ ,  $p<0.001$  were significantly higher than for full visual feedback, see Fig. 4. There is a significant interaction effect between type of visual feedback and type of presence of haptic guidance  $F(1.88, 404.54)=24.20$ ,  $p<0.001$ . To break down this interaction, contrast were performed comparing all visual condition with presence of haptic guidance on to the baseline, full visual condition and no presence of haptic guidance. This revealed a significant interaction when



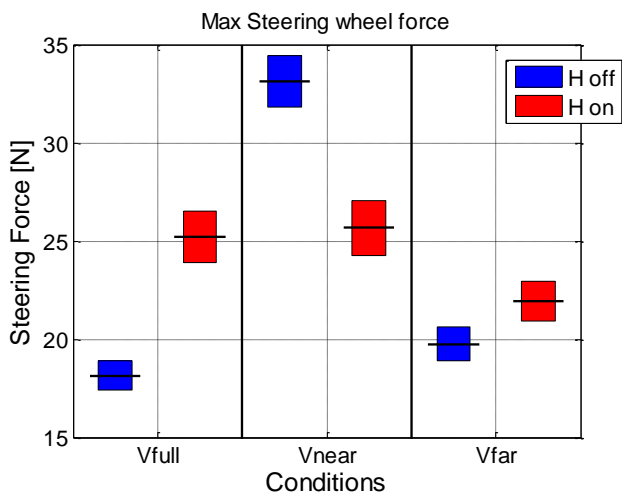
comparing the presence of haptic guidance for both  $V_{near}$   $F(1, 215)= 54.83$ ,  $p<0.001$  and  $V_{far}$   $F(1, 215)=18.01$ ,  $p<0.001$  to full visual feedback without the presence of haptic guidance.



**Fig. 4 Mean SRR (2° gap values) marking for all conditions and 95% confidence intervals.**

### 3.3.1 Control Effort: Maximum Steering Wheel Force (maxFsw)

There is a significant main effect of visual condition  $F(1.81, 389.78)=174.12$ ,  $p<0.001$ . Maximum Steering wheel Force increased in the presence of haptic guidance on/off  $F(1, 215)=9.60$ ,  $p=0.002$ . Contrasts revealed that maximum steering wheel force for  $V_{near}$   $F(1, 215)= 12.92$ ,  $p<0.001$  and for  $V_{far}$   $F(1, 215)=281.12$ ,  $p<0.001$  were significantly higher than for full visual feedback, see Fig. 5.



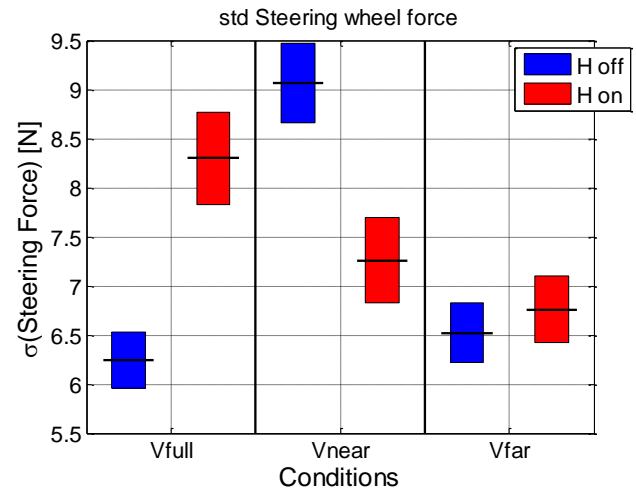
**Fig. 5 Mean maximum steering wheel force marking for all conditions and 95% confidence intervals**

There was a significant interaction effect between type of visual feedback and type of presence of haptic guidance  $F(1.94,417.92)=176.46$ ,  $p<0.001$ . To break down this interaction, contrast were performed comparing all visual condition with presence of haptic guidance on to the baseline, full visual condition and no presence of haptic guidance . This revealed a significant interaction when comparing the presence of haptic guidance for both  $V_{near}$   $F(1, 215)= 54.67$ ,  $p<0.001$  and  $V_{far}$   $F(1, 215)=141.01$ ,  $p<0.001$  to full visual feedback without the presence of haptic guidance.

### 3.3.2 Control Effort: Standard Deviation of Steering Wheel Force ( $\sigma Fsw$ )

There is a significant main effect of visual condition  $F(2, 430)=70.60$ ,  $p<0.001$  and presence of haptic guidance on/off  $F(1, 215)=7.48$ ,  $p=0.007$ . Contrasts revealed that standard deviation of steering wheel forces for  $V_{near}$   $F(1, 215)= 39.77$ ,  $p<0.001$  and for  $V_{far}$   $F(1, 215)=31.47$ ,  $p<0.001$  were significantly higher than for full visual feedback, see Fig. 6.

There was a significant interaction effect between type of visual feedback and type of presence of haptic guidance  $F(1.94,416.44)=127.494$ ,  $p<0.001$ .



**Fig. 6 Mean standard deviation of steering wheel force marking for all conditions and 95% confidence intervals**

To break down this interaction, contrast were performed comparing all visual condition with presence of haptic guidance on to the baseline, full visual condition and no presence of haptic guidance . This revealed a significant interaction when comparing the presence of haptic guidance for both  $V_{near}$   $F(1, 215)= 219.97$ ,  $p<0.001$  and  $V_{far}$   $F(1, 215)=62.57$ ,  $p<0.001$  to full visual feedback without the presence of haptic guidance.

### 3.4 Subjective results

10 out of 12 subjects indicated that they liked the system. Subjects indicated that while driving with both full visual feedback and haptic feedback they got their information mean= 62%, $\sigma$ =20% from vision and mean=38%, $\sigma$ =20% from haptics. The subjective workloads of subjects are summarised in table V.

TABLE V

Summarized results of subjective workload questionnaire. Workload index is weighted sum of individual scores. The increase in workload indices compared to baseline are expressed as a percentage.

Workload Index [1 low- 20 high]	H off	H on
Vfull	4,8	4,0
Vnear	12,3	9,4
Vfar	7,7	5,9
increase compared to baseline [%]	H off	H on
Vfull	baseline	-16
Vnear	158	97
Vfar	61	23

## IV – DISCUSSION

### 4.1 Effect of haptic guidance on driving performance

Using haptic guidance improves the in-lane performance metric Summed Absolute Lateral Position (SALP) for all visual conditions compared to baseline performance (i.e. full visual information without haptic guidance). However the SALP for  $V_{near}$  is higher than for  $V_{far}$ . These results do not agree with Land & Horwood (1995) who stated that a better in lane performance is obtained for  $V_{near}$ .

This can be explained by the fact that Land & Horwood (1995) used a lower speed of  $16.9 \text{ ms}^{-1}$  for their experiment, while a speed of  $20 \text{ ms}^{-1}$  was used for this experiment. Also difference in curve types can be the cause for this result. Land & Horwood used a track that was modeled after a real road in Edinburgh with unknown curvatures. The most difficult curve used for this experiment was  $R=150\text{m}$ . It is very unlikely that one would find such a small curve radius on real roads where driving at  $20 \text{ ms}^{-1}$  or higher is legal.

It should be noted that SALP isn't an absolute performance metric. Subjects could prefer a different in-lane position other than the road center causing a higher SALP. Having a haptic feedback that guides drivers to the road center automatically decreases SALP. However, the decrease in SALP cannot be explained solely to the presence of haptic guidance. When the controller drove the tracks without human interaction the SALP was higher than any of the results set by humans without support.

In the end SALP isn't the best performance metric for human curve negotiating behavior due to individual preferences in lateral position and curve cutting behavior.

The results for Time to Line Crossing (TLC) show an increase of performance for all visual conditions when haptic guidance is added. Since TLC gives a general description of curve negotiation and could be used to describe the quality of anticipatory steering actions (Godthelp, 1986) it is a better performance metric for research on human curve negotiating behavior than SALP. For  $V_{near}$  there is no preview information to anticipate on. Without preview information drivers cannot anticipate steering actions and can only react to upcoming curves. This results in a 'bang-bang' control action where the steering wheel is turned suddenly when a curve is detected and returns suddenly when the curve ends, in both cases causing a large overshoot. (see Fig. 7)

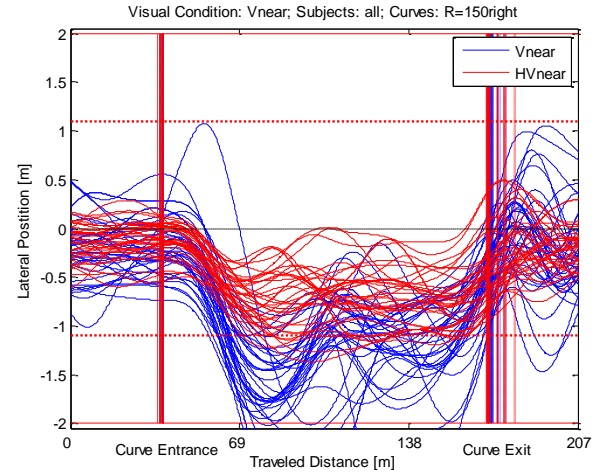


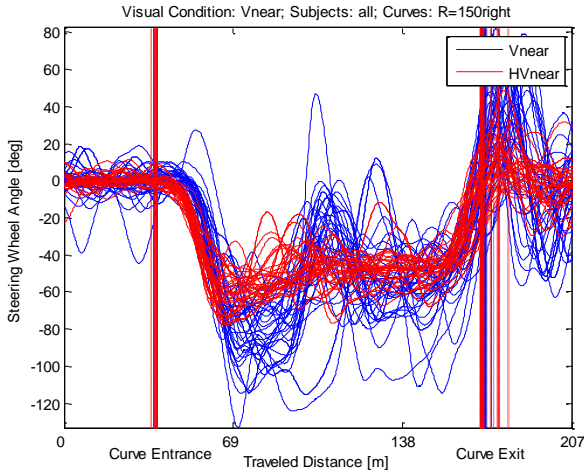
Fig. 7 Lateral position for all right curves with radius=150m for  $V_{near}$ , with and without haptic guidance. Vertical blue and red lines indicate start and end of each curve.

This result was also found by Land & Horwood (1995). Raw data plots of lateral position (fig. 7) and steering wheel angle (fig. 8) indicate that when using haptic guidance, drivers initiate their steering actions slightly sooner, steered smoother and more consistently, thereby reducing lateral overshoot.

Minimum TLC improves with the presence of haptic guidance. However, for the experimental conditions studied, continuous haptic guidance does not provide enough information to restore  $V_{near}$  to baseline performance. Although haptic guidance provides much of the required information to steer, it appears that it does not match the information capability of visual feedback.

### 4.2 Effect of haptic guidance on control activity

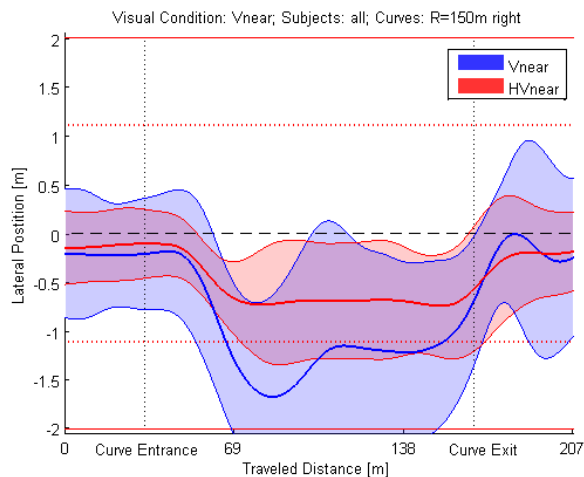
SRR improves when subjects are supported by haptic guidance for the all visual conditions. Corresponding results were found by Mulder et al. (2008), who used haptic guidance while having full visual information. As expected the SRR for  $V_{near}$  is higher than for  $V_{far}$ . This concurs with the results of Land & Horwood (1995), who state that steering became 'jerky' when far visual information was removed. Although  $HV_{near}$  results into a smooth and



**Fig. 8 Steering wheel angle for all right curves with radius=150m for  $V_{near}$ , with and without haptic guidance. Vertical blue and red lines indicate start and end of each curve.**

consistent steering wheel behavior (also see Fig. 8), SRR is not reduced to baseline performance. Also for  $V_{far}$  SRR is worse compared to baseline performance. Here  $HV_{far}$  is capable to reduce SRR to baseline performance.

Since SRR has been linked to driving task demand (MacDonald, 1980), the SRR could indicate a higher workload which corresponds to the subjective results where subjects indicated the task to be more demanding and frustrating. For  $V_{near}$  and  $HV_{near}$  this corresponds to subjective results. From table V it can be seen that the subjective workload increased by 160% and 100% compared to baseline for  $V_{near}$  and  $HV_{near}$  respectively.



**Fig. 9 Mean lateral position with 95% confidence band for all right curves with radius=150m for  $V_{near}$ , with and without haptic guidance. Vertical black lines indicate mean beginning and end of all curves.**

$V_{far}$  increased subjective workload by 61% while  $HV_{far}$  only increased subjective workload by 23% compared to baseline while SRR is reduced to better than baseline performance. As expected  $HV_{full}$  reduced subjective workload by 16% compared to baseline. This means a very high SRR can be linked to a higher subjective workload, while a lower SRR cannot be linked directly to subjective workload. Comparative results were obtained by MacDonald (1980) where the relation of SRR to driver task demand depended on the subject's capacity to cope with the level of task difficulty relative to the task itself.

#### 4.3 Effect of haptic guidance on control effort

Control forces increase for  $V_{full}$ . This can also be seen in previous research by Mulder et al. (2008). However, for  $V_{near}$  the forces decrease. Previous research has always shown increase in steering wheel forces when using haptic guidance.

Research where a haptic support system was used for car following showed that, when drivers actively yield to guiding forces presented by the support system, the standard deviation of measured control forces decreases (Abbink, 2006; Mulder, 2007).

The decrease in standard deviation of steering wheel forces could indicate that drivers are more likely to yield to the guiding forces when there is a lack of visual information.

All results were obtained with a controller that was able to guide drivers through the most difficult corner (see Fig. 9). This resulted in a controller that could cause high steering wheel forces when subject disagreed with the control actions. When interpreting these results, keep in mind that these forces are not absolute values when using haptic guidance. When using a controller that guides drivers to the road center higher forces can be expected when drivers deviate from the controller's path.

##### 4.4.1 Research limitations and future work

Subjects indicated they liked the system but wished they could turn it off. This could be caused by the increased control effort seen when haptic guidance is combined with full visual feedback. This is of course not the idea of a well designed ADAS. A well designed ADAS should be able to assist the driver at all times when needed.

Future experiment could investigate the minimal controller settings that are able to negotiate roadway information to drivers. A more sophisticated approach is a system that assists the driver depending on the driver's real time mental workload.

The experiment took place in a simplified driving environment in a simulator that didn't require pedal interaction. This results in a low mental load where subjects could fully focus on their primary driving tasks. During such conditions visual feedback is able to provide all the required information. However, it is expected that the power of haptic feedback for driving can be even better observed when

drivers are occupied with a visually and mentally demanding secondary driving task.

The road's center was taken as the reference line for the haptic controller during this experiment. Although the haptic controller naturally incorporates cutting corners due the look ahead time, it still doesn't match with driver's road preference. A reference line that is based on driver's in lane position preferences could result in lower control forces and reduce drivers need to turn the ADAS off. A more sophisticated approach would be a reference line that learns drivers in-lane position preferences. By coupling the reference line to a Global Positioning System a reference line for known curves can be extrapolated to unknown curves.

For all subjects this experiment was their first introduction of driving with haptic guidance. Although subject were able to drive using haptic guidance, not all of them might have understood how the information provided can be used best, despite the training before experimental data was gathered. It is possible that long term use of haptic guidance could change the way drivers use the information.

The force feedback gain translates future lateral error into guiding forces on the steering wheel and the stiffness feedback gain translates present lateral error into a change of steering wheel stiffness. Both these feedback gains were fixed during this experiment. However, another benefit of haptic guidance is that control authority could be negotiated between the driver and the automated controller by adjusting these feedback gain. By changing the feedback gains the guiding forces can be adapted to individual and time dependent differences in neuromuscular properties. Changing these feedback gains could also make it possible to assist drivers with their task only if necessary while using forces that match individual driver preferences. This could lead to a driver support system that will not intrude on individual driving preferences for in-lane position and curve cutting behavior. A non intruding controller will increase driver acceptance, while safety can be improved during critical situations.

#### 4.4.2 Future work: Man vs Machine

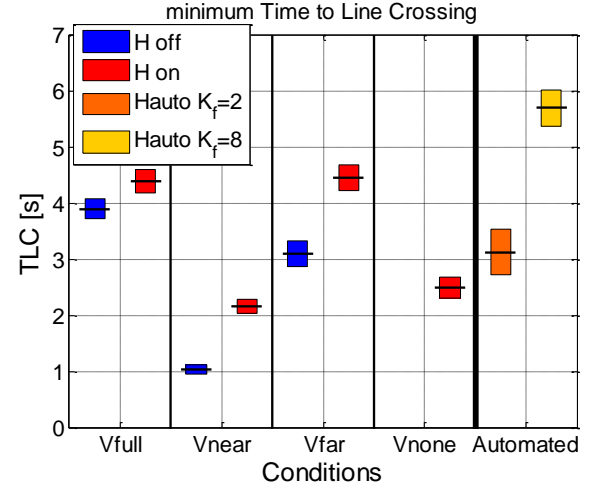
All the tracks were also completed by the haptic controller used during this experiment without human interaction (condition  $H_{\text{auto}} K_f=2$ ). This was repeated for a haptic controller with a higher force gain  $K_f=8$  (condition  $H_{\text{auto}} K_f=8$ ). Finally a condition was tested using the haptic controller with human interaction, but without any visual feedback (condition  $HV_{\text{none}}$ ). The results on minimum TLC can be seen in and Fig. 10 (last 3 columns).

The haptic guidance controller has a higher deviation when it is not interacting with humans. This appears strange since the controller should initiate each curve the same way.

However this controller might not be able to maneuver the vehicle to the roads center fast enough to position itself the same way for each corner.

The means give additional insight on the performance of humans compared to haptic guidance.

TLC performance of the automated controller matches  $V_{\text{far}}$ . Also the automated controller performs better without human interaction and better than  $HV_{\text{near}}$ . Even  $HV_{\text{none}}$  performs better than  $HV_{\text{near}}$ .



**Fig. 10 Mean minimum TLC to road bounds marking for all conditions and 95% confidence intervals.**

It can be seen that the haptic guidance controller used during the experiment needs to interact with humans having far visual feedback in order to establish good driving performance. It can also be seen that when a gain of  $K_f=8$  is used, which is basically a fully automated controller with guiding forces that are difficult to override, performance is better than any of the results set out by humans supported by haptic guidance, however at the cost of very little flexibility away from the optimal steering wheel angle. Due to time constraints the results of the automated controller compared to humans sharing control couldn't be investigated more thoroughly.

## V CONCLUSION

For the experimental conditions studied it can be concluded that:

- Haptic guidance increases driving performance for all visual conditions
- Haptic guidance is capable of providing essential steering control information. However, far visual information is needed to obtain the best results.
- For the full and far visual condition performance is restored to baseline while reducing control activity and increasing control effort. (As seen in Mulder et al., 2008)
- For the near visual condition steering behavior is 'jerky' (as seen in Land & Horwood, 1995). If haptic guidance is used, drivers initiate their steering actions sooner, steered smoother and more consistently, thereby reducing lateral overshoot for even the most difficult curves.

- For the near visual condition, haptic guidance is capable of partially restoring the performance to baseline (i.e. full visual information without haptic guidance) while reducing control activity and control effort.
- Subjects accept the guiding forces more when visual information is reduced.
- Sharing control between human drivers and a haptic guidance controller results into better driving performance while situational awareness to recover from unexpected events is maintained by keeping the driver in the control loop.

## REFERENCES

- D.A. Abbink, "Neuromuscular Analysis of Haptic Gas Pedal Feedback during Car Following," Ph.D. thesis, Department of Mechanical Engineering, Delft University of Technology, Delft, The Netherlands, 2006.
- Abbink, D.A., E.R. Boer, and M. Mulder. "Motivation for continuous haptic gas pedal feedback to support car following." In *Intelligent Vehicles Symposium*, 2008 IEEE, 283–290. IEEE, 2008.
- Abbink, D.A., and M. Mulder. "Exploring the dimensions of haptic feedback support in manual control." *Journal of Computing and Information Science in Engineering* 9, no. March (2009): 011006.
- Abbink, D.A., and M. Mulder. "Neuromuscular Analysis as a Guideline in designing Shared Control." *Control* (2010): 499-516.
- Brandt, T, T Sattel, and M. Bohm. "Combining haptic human-machine interaction with predictive path planning for lane-keeping and collision avoidance systems." In *Intelligent Vehicles Symposium*, 2007 IEEE, 13:582–587. IEEE, 2007.
- Forsyth, B A C, and K E Maclean. "Predictive Haptic Guidance: Intelligent User Assistance for the Control of Dynamic Tasks." *IEEE Transactions on Visualization and Computer Graphics* vol8, no. 1 (2006): pp103-113.
- Godthelp, H. "Vehicle Control During Curve Driving" *Human Factors*, 1986, 28(2), 211-221
- Goodrich, M. Boer, E. "Designing Human-Centered Automation: Tradeoffs in Collision Avoidance System Design". *IEEE Transactions on Intelligent Transportation Systems*, Vol. 1, No. 1, march 2000
- Griffiths, P, and R.B. Gillespie. "Shared control between human and machine: Haptic display of automation during manual control of vehicle heading." In *Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2004. HAPTICS'04. Proceedings. 12th International Symposium on, 27:358–366. IEEE, 2004.
- Griffiths, Paul G, R Brent Gillespie. "Sharing Control Between Humans and Automation Using Haptic Interface : Primary and Secondary Task Performance Benefits." *Human Factors* 47, no. 3 (2005): 574-590.
- Land, M F, and D N Lee. "Where we look when we steer.." *Nature* 369, no. 6483 (June 1994): 742-4.
- Land, M F and Horwood, J. "Which parts of the road guide steering?" *Letters to Nature* 337, 339 - 340 (28 September 1995)
- Lee, John D, and Katrina A See. "Human Factors : The Journal of the Human Factors and Ergonomics Society." *Trust in Automation : Designing for Appropriate Reliance.* Human Factors (2004).
- MacDonald W.A., Horrmann E.R. "Review of Relationships Between Steering Wheel Reversal Rate and Driving Task Demand". *Human Factors*, 1980, 22(6), 733-739
- M. Mulder, "Haptic Gas Pedal Feedback for Active Car-Following Support," Ph.D. thesis, Department of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands, 2007.
- Mulder, Mark, and David A Abbink. "The Effect of Haptic Guidance on Curve Negotiation Behavior of Young , Experienced Drivers." *Control* (2008): 1-6.
- McGehee, D.V., Lee, J.D., Rizzo, M., Dawson, J., and Bateman, K. (2004) Quantitative analysis of steering adaptation on a high performance fixed-base driving simulator. *Transportation Research Part F: Traffic Psychology and Behaviour*, vol 7, no 3, pp. 181-196.
- M.K. O'Malley, A. Gupta, M. Gen, and Y. Li, "Shared Control in Haptic Systems for Performance Enhancement and Training," *Journal of Dynamic Systems, Measurement, and Control*, vol 128, pp. 75–85, 2006.
- Plöchl, Manfred and Edelmann, Johannes(2007) 'Driver models in automobile dynamics application', *Vehicle System Dynamics*, 45: 7, 699 — 741
- Salvucci, Dario D, and Rob Gray. "A two-point visual control model of steering." *Perception* 33, no. 10 (2004): 1233-1248.
- Salvucci, Dario D." Modeling driver behaviour in a cognitive architecture". *HUMAN FACTORS*, Vol. 48, No. 2, Summer 2006, pp. 362–380

Steele M. Gillespie R. "Shared Control Between Human and Machine: Using a Haptic Steering Wheel to Aid in Land Vehicle Guidance," in Proceedings of Human Factors and Ergonomics Society, 45th Annual Meeting, 2001, pp. 1671 – 1675.

Sarter, N., Woods, D and Billings, C. "AUTOMATION SURPRISES." Human Factors (1997): 1-25.

Toffin, D. Reymond, G. Kemeny, A. Droulez, J. "Role of steering wheel feedback on driver performance: driving simulator and modeling analysis", Vehicle System Dynamics ISSN 0042-3114, 2007, vol. 45, no4, pp. 375-388, 2007.

van Winsum, W., Brookhuis, K.A., de Waard, D. "A comparison of different ways to approximate time-to-line crossing (TLC) during car driving". Accident Analysis and Prevention 32 (2000) 47–56



## Appendix: Thesis description

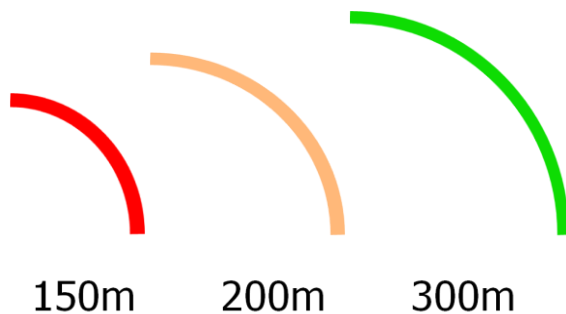
### Appendix A: Analysis

One of the most important aspects of this experiment are the corners and the data collected in them. The corners are the part of the road where the most action happens and where the biggest conflicts arise when sharing control between human and machine.

Since the corners are variables that change during the experiment it is important that the corners are created in a controlled manner. After the experiment the same precision of extracting the log data from the corners has to be applied to ensure that the data of subjects and between curves are allowed to be compared to each other and allow for statistical analysis.

For this experiment there has been chosen for the relatively simple time-domain approach. Although frequency-domain approach ensures a complete randomness of track generation over a full spectrum, the analysis of this approach might become tricky and is reserved for people with extensive experience in this field.

From literature there has been chosen for three types of corners:



Here the corner with a 150m radius is assigned as the difficult corner, meaning a lot of required control action and the 300m radius corner as the easy corner, meaning little control action required.

Although a radius of 150m at 20m/s isn't very realistic in real world roads, for the experiment this type of corner could provide us with the most useful (significant differences) information.

In order to get valuable statistical information from a relatively small group of subject we need to repeat the corners and place them in a random order in both left turns and right turns.

#### ***Track generation.***

There has been chosen to create a limited amount of tracks. Seven different tracks are generated and randomized over the conditions for each subject. In total there are seven different conditions that are tested during this experiment. This is done since it is easier to create a new configuration file which randomizes the tracks than to create a new track for each condition.

As an example we take a look at OcclusionTrack1 which can be seen in Fig. 11



**Fig. 11 Top view of OcclusionTrack1**

To create this track a radius vector had to be created and fed to a function that creates all additional road information points and 3D model information. When this additional information is calculated it is required to convert the current 3D model information into an Ogre-mesh 3D model that is used by the simulator at the HMI-lab.

The functions that create road information points and 3D model information were provided by Mark Mulder. The radius vector had to be created manually.

This is done in a couple of steps

- 1) Calculate radius (including entrance and exit) of a full corner (3 types of corners)
- 2) Copy the corners and mirror them to create left and right corners ( $3 \text{ types} * 2 \text{ directions} * 6 \text{ repetitions} = 18 \text{ corner vectors}$ )
- 3) Randomly select a corner vector and add a random straight section between 100-200 meter
- 4) Add a straight section at the beginning of the track and at the end of the track for clearly defined start and end of the experiment.
- 5) When automated speed is required for the experiment, also add pedal position information to the road information.



The result can be seen in Fig. 11. This track was generated according to the steps described above. The other 6 tracks were generated in the same manner.

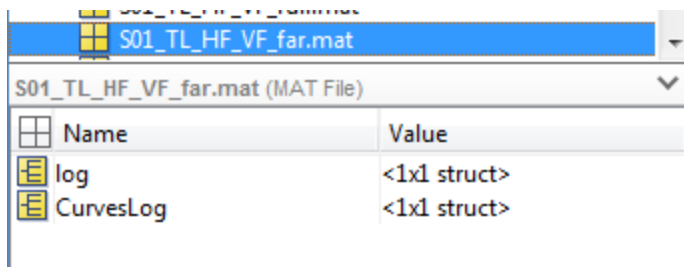
## **Data extraction**

### **SIMLOG to MATDATA**

Along each simulator an m-file is generated that reads the logdata into a matfile. However for to analyse the data of this experiment needs to be separated into individual curves. For this reason, the logdata is cut into individual data blocks belonging to each curve. A MAT file with this separated log data is generated for each condition for all subjects.

The data is cut in the following way

- If necessary, read simlog data into a structure named log and save this structure in a MAT file (this action is performed by the m-file generated by the simulator software). If the MAT file already exists it can be loaded to obtain the log structure in the MATLAB workspace.
- Search for a specific radius in log.radius
- Select data at specified radius and cut in 6 parts (or other specified nr of reps). The data is cut at the points where the data indices 'jump' from one curve to the next.
- Add specified amount of datapoints before corner and after corner to include entrance and exit behavior of corner
- Data of a single curve is saved along with the original indices of the log data and the indices of the data with the extended datapoints is saved in a new structure named 'curves'. Both the original 'log' structure as the new structure 'CurvesLog' are saved in a MAT with the name of the subject and the condition file in the MATDATA folder.



**Fig. 12 Contents of a MAT file from a single subject for a single task.**

Curves are extracted and stored in the order that they are found in the data:

1<sup>st</sup> radius- 1<sup>st</sup> rep  
 1<sup>st</sup> radius- 2<sup>nd</sup> rep  
 .....  
 1<sup>st</sup> radius- n<sup>th</sup> rep  
 ...  
 n<sup>th</sup> radius - 1<sup>st</sup> rep  
 .....  
 n<sup>th</sup> radius- n<sup>th</sup> rep

This means that the order of corners in the stored data does NOT match the order of the corners in the tracks, but they are sorted by the type and order that they appear in the track.

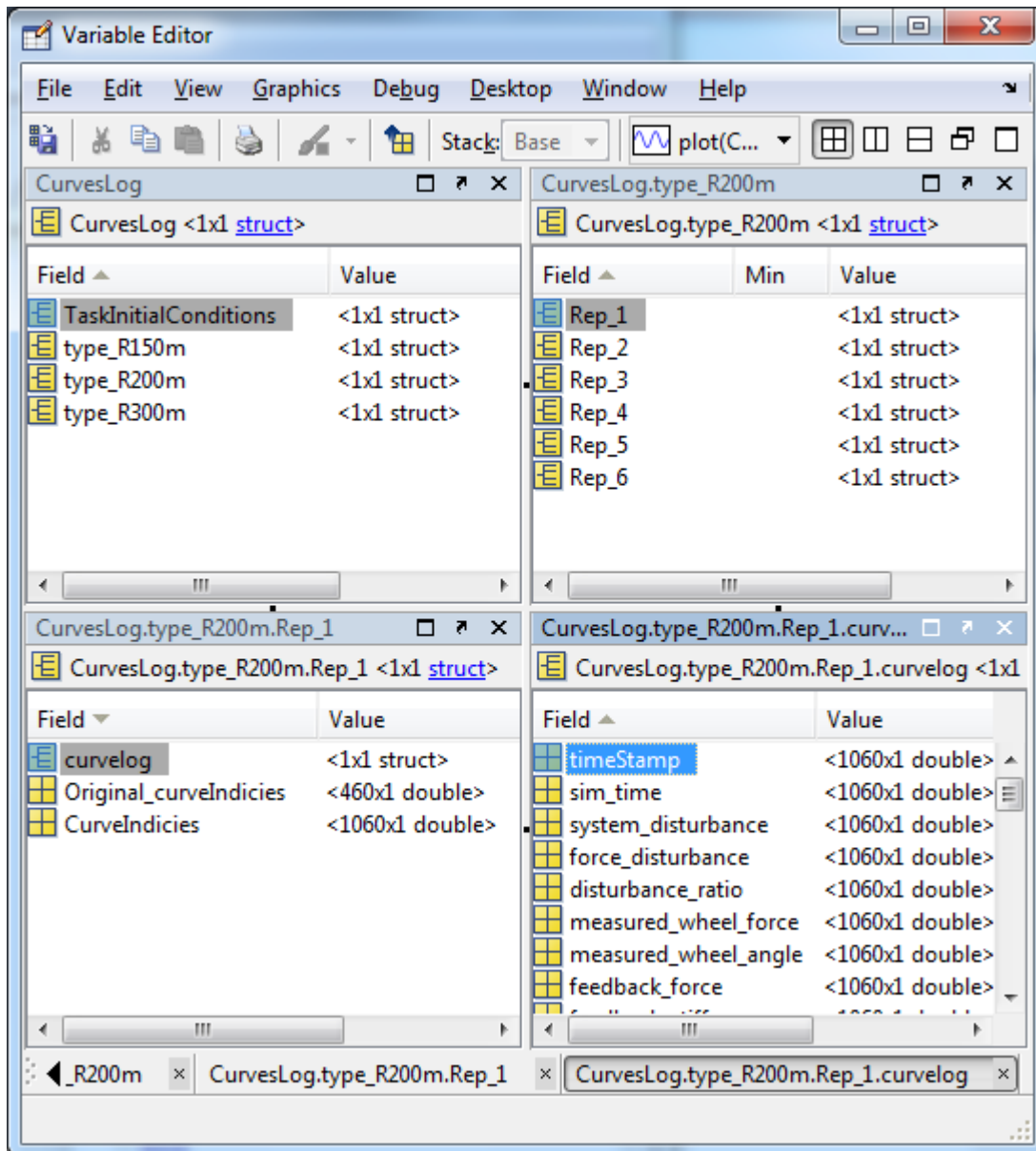


Fig. 13 Contents of a CurveLog from a single subject for a single task.

The Original\_curveIndicies contains the data indices of the original log data points with the specified radius.

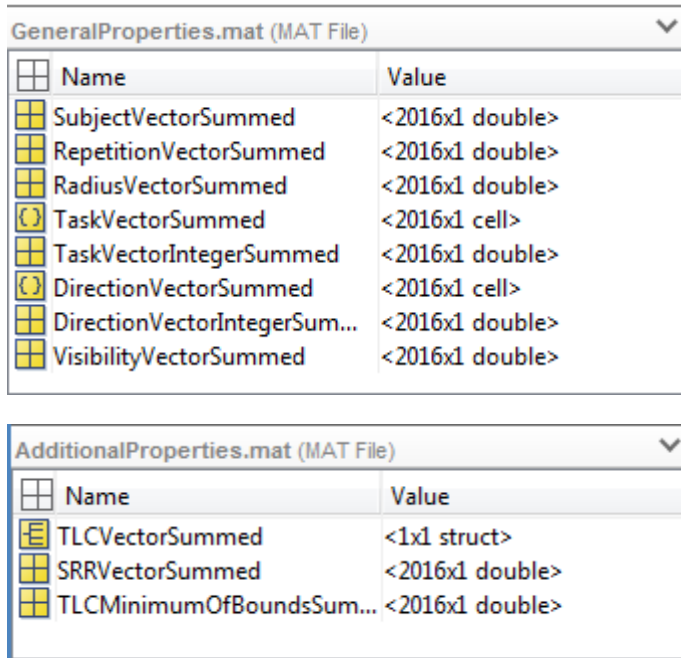
CurveIndicies contains the data indices of the original log data points with the specified radius and the indices of the data used to describe the curve entrance and exit.

From this point each curve from each subject and each condition can be compared. However no link between tracks exists. Detailed track information is lost in current data structure. However an order of tasks and tracks does exist in the 'Experiment Files' on the DATA DVD should this be necessary at a later stage.

## MATDATA to PropertyVectors

In order to create errorbar plots, all data of interest needs to be placed in single vectors. For this type of analysis there was chosen to reduce all data of interest into a row vector. Each element of the row vector represents a single property of a curve. These properties include general properties such as curve radius, direction, subject number, task identifiers, etc. but also performance metrics such as minimal Time to Line Crossing (TLC) and Steering wheel Reversal Rate.

In total there were 16 subjects, driving 7 different tracks, which consisted of 3 curve types that's were repeated 6 times. This results into vectors with size  $16 \times 7 \times 3 \times 6 = 2016$ .



Name	Value
SubjectVectorSummed	<2016x1 double>
RepetitionVectorSummed	<2016x1 double>
RadiusVectorSummed	<2016x1 double>
TaskVectorSummed	<2016x1 cell>
TaskVectorIntegerSummed	<2016x1 double>
DirectionVectorSummed	<2016x1 cell>
DirectionVectorIntegerSum...	<2016x1 double>
VisibilityVectorSummed	<2016x1 double>

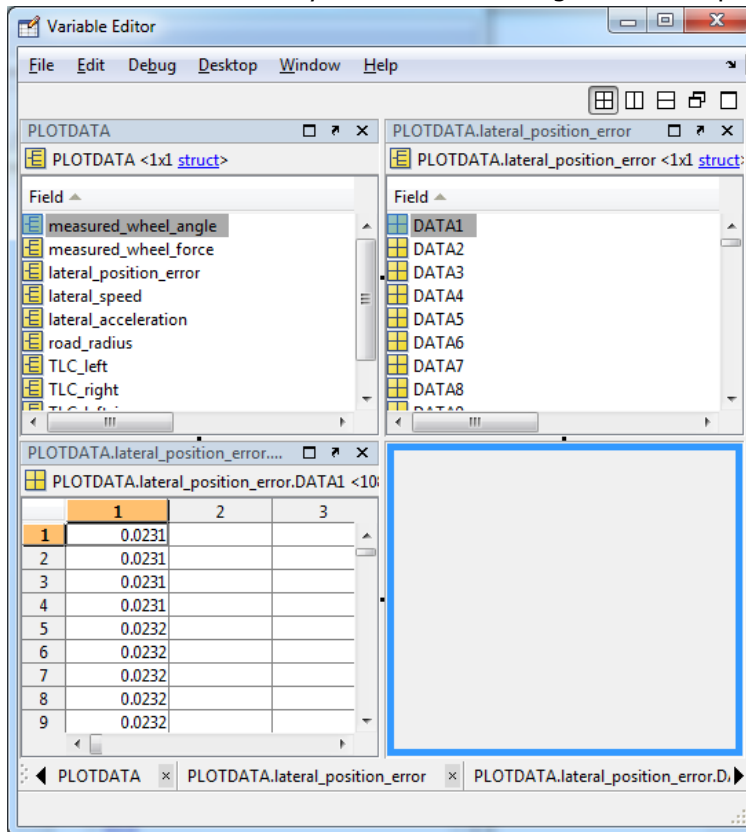
Name	Value
TLCVectorSummed	<1x1 struct>
SRRVectorSummed	<2016x1 double>
TLCMinimumOfBoundsSum...	<2016x1 double>

**Fig. 14** Generated property vectors

Each vector contains a single property for all curves. By combining property vectors and using the find function, the index numbers of curves with a certain properties can be combined. This is exactly the way that the error bar function obtains its data. But by combining this data retrieval method with entire curve logs could be handy when creating time plots that contain data from multiple subjects.

## MATDATA to PLOTDATA

When a comparative time plot has to be made it is easier to access all data from a single mat file. For this reason a PLOTDATA structure is created in the same manner as the property vectors. However now the curve data of a single parameter is stored in a data slot at the same index as the property vectors. This makes it easy to retrieve curve log data with equal properties.



**Fig. 15** Contents of PLOTDATA where log data of several parameters can be found for all subjects

### IMPORTANT NOTE REGARDING INDEX SEARCHING:

When retrieving data with the help of property vectors it is important to always use the entire vectors. Otherwise a mismatch could occur between the indices found with certain properties and the indices of the data slots. This problem occurred when several subject were excluded from the data analysis (e.g. `find(radius(subjects_included)==150)` returns wrong indices.)

## Appendix B: Experiment Description

### *Haptic controller settings*

A haptic feedback controller already programmed into the simulator at the HMIlab is used during this experiment. This controller can be changed with several settings. Look-ahead-time (LAH), stiffness feedback gain  $K_s$  and force feedback gain  $K_f$ .

LAH combined with current speed determines how far ahead the vehicles road position is extrapolated based on the current steering wheel angle. The control forces are based on the error between the neutral position (here the road center) and the extrapolated position. These forces can be scaled using  $K_f$ . A high value of  $K_f$  will result in high control forces and allows little deviation from the optimal steering wheel input. A high value of  $K_f$  will approach a fully automated vehicle. A low  $K_f$  will provide small corrective forces but needs driver input to successfully negotiate a corner.  $K_s$  changes the stiffness of the steering wheel and determines how difficult it is to steer away from the center steering wheel position. For effective error rejection it will be necessary to be able to turn the steering wheel away from the center position. Therefore, for stiffness feedback to be effective, it needs to be combined with force feedback.

Choosing the right settings is highly influential on the results of the experiment. The settings were based on Mulder (2008). By trial and error the settings for this experiment were chosen.

It was found that using  $LAH=0.7$ ,  $K_f=2$  and  $K_s=0.005$  resulted in a haptic controller that provided settings suitable for this experiment. Changing LAH didn't result in a change in controller significant enough to use during this experiment.  $K_f=2$  results in a controller that provides most of the forces needed to negotiate a corner, however still requires driver input to stay within lane boundaries during cornering. This strong controller was chosen due to the lack of visual input. The experiment would give enough insightful information without the driver losing the ability to follow the track.

$K_s=0.005$  was chosen since it was successful in adding stiffness without overloading the haptic controller. A lower value could result in an unstable system and higher values could overload the controller hardware.

### *Configuration files*

The simulator works with configuration files stating the controller settings, vehicle initial state, track and log data. For easy control during the experiment a single configuration file per individual subject was chosen. This way the experiment could be performed a single step at a time with minimal room for human error.

The configuration files were generated automatically using a MATLAB script. By entering general information in this script the file was able to generate a randomized order of tracks and conditions.

There are two sets of conditions: without haptic feedback (VF) and with haptic feedback (HF). Each set is preceded by a training session where the subject can familiarize himself with the simulator and the steering wheel settings. In total there are 7 different conditions. VF contains a baseline condition (VF), a visual near condition (VF\_near) and a visual far condition (VF\_far). HF contains a full visual condition (HF\_VF), a visual near condition (HF\_VF\_near), a visual far condition (HF\_VF\_far) and a condition without visuals (HF).

Since each condition is only run once there are only 7 tracks required. Each track is randomized over each subject to increase interchangeability of the corner data. Further details on the track generation can be found in the analysis appendix. The training is performed on a special training course where each type of curve has to be negotiated once.

## ***Simulator description***

### ***Occlusion masks***

During this experiment parts of the visual feedback need to be occluded. There are many ways to occlude vision, but adapting the simulator software is the easiest and most precise.

Since only parts of the screen need to be occluded the beamer cannot simply be turned off.

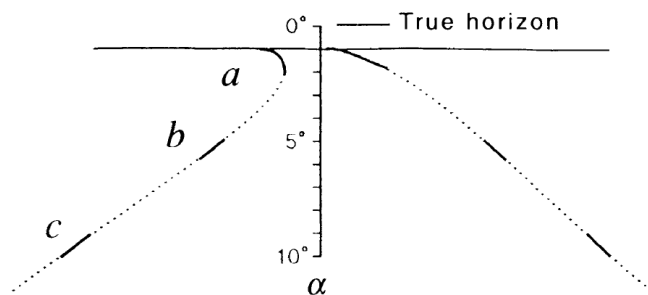
To occlude only parts of the screen masks need to be created that occlude the desired parts. Masks are images that are displayed on top of the rendered simulated environment.

The simulator software at the HMI-lab does come equipped standard with masks. However these mask mostly transparent to display a logo of the university. By adding additional masks into the simulator software, one can refer to a PNG image (resolution 1024\*768, same as screen resolution and 32 bit color depth) created with photo editor software (e.g. Paint.Net free software) which is partially transparent and partially black.

With the same software, more complex masks can be build such as the Screen\_size\_masks which can be used to approximate positions on screen in pixels.

One drawback of the masks used in this experiment is that they are present during entire run. This means they cannot be switched on and off during the experiment.

For this experiment the size of the masks need to be calculated very precise. They are based on the experiment by Land & Horwood. However, Land & Horwood describe their experiment in degrees from the true horizon, not in the required pixel size. Also Land & Horwood perform their experiment at 16.9m/s were this experiment uses a fixed speed of 20 m/s. This means some conversions need to be made.



Land & Horwood performed their experiment at 16.9 m/s. To keep the look ahead time equal the speed difference needs to be compensated.

The formula used to determine the correct angle for occlusion

$$\theta = \tan^{-1} \left( \frac{\text{Eye Height}}{V_{car} * LAH} \right)$$

$\theta$  = Degrees down from true horizon

When using the angles described in Land & Horwood the LAH can be determined using:

$\theta_A = 2$  degrees (VF far)

$\theta_c = 9$  degrees (VF near)

$V_{car} = 16.9$  m/s

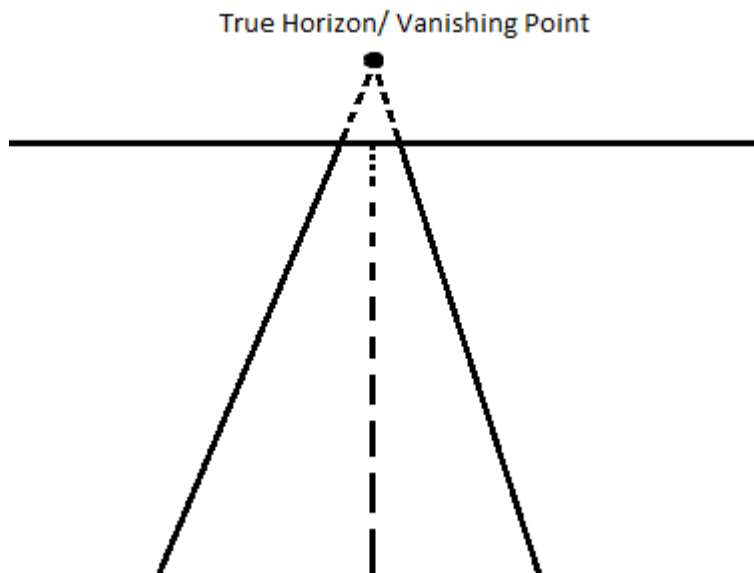
Eye Height = unknown

When keeping eye height (0.9m) and LAH the same this resulted in the new angles for the occlusion masks

$\theta_A = 1.68$  degrees (VF far)

$\theta_c = 7.54$  degrees (VF near)

Measurements revealed that the location of the horizon and that of the true horizon



**Fig. 16 True horizon (or vanishing point) is point where sidelines of a straight road would cross each other**

From measurement: True Horizon Approximately 5 pixels above 'normal' horizon

Screen resolution = 1024\*768 (2x front, 1x left, 1x right)

Normal horizon @ 457 pixels from top -> true horizon @ 452 pixels from top

Driver eye height approximately at true horizon (from tapeline measurement)

$\tan \theta * \text{Distance\_screen} = \text{distance\_from\_horizon}$

$\text{Screen\_vertical\_resolution} / \text{Screen\_height} = \text{pixels/cm}$

$786 / 200 = 3.84$  pixels/cm

Using the values found above resulted in the following occlusion masks



Fig. 17 Bottom occlusion at 492 pixels from top for Far visual condition



Fig. 18 Top occlusion at 627 pixels from top for Near visual condition

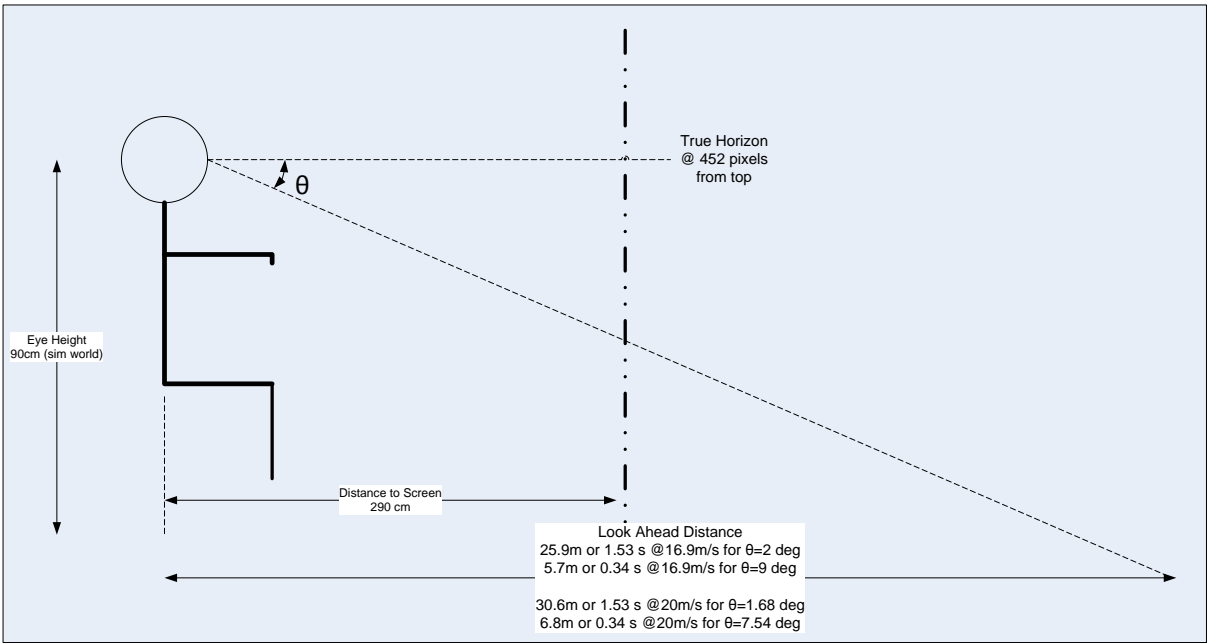


Fig. 19 Simplified drawing used to calculate occlusion masks height.



## Typical configuration file

A typical configuration file looks as follows:

```
xml version="1.0" encoding="utf-8"?>
<Experiment>
  <Defaults>
    <Parameter name="log_file_path" type="string" value="./run-data/logs/OcclusionExperiment/" />
    <Parameter name="disturbance_path" type="string" value="./run-data/disturbances/" />
    <Parameter name="resource_group" type="string" value="General" />
    <Parameter name="car_eye_height" type="float" value="0.9" />
    <Parameter name="pedal_playback" type="bool" value="true" />
    <Parameter name="car_vx_body" type="float" value="20.0" />
    <Parameter name="car_x_world" type="float" value="0.0" />
    <Parameter name="car_y_world" type="float" value="1.0" />
  </Defaults>
  <Condition name="TRAINING_VF">
    <Parameter name="log_file_name" type="string" value="S01_TRAINING_VF" />
    <Parameter name="driving_scene" type="string" value="OcclusionTrainingTrack.scene" />
    <Parameter name="left_front_overlay" type="string" value="HMILabOverlays/MaskLeftFront" />
    <Parameter name="right_front_overlay" type="string"
value="HMILabOverlays/MaskRightFront" />
    <Parameter name="left_side_overlay" type="string" value="HMILabOverlays/MaskLeftSide" />
    <Parameter name="right_side_overlay" type="string" value="HMILabOverlays/MaskRightSide" />
    <Parameter name="idss_type" type="int" value="0" />
  </Condition>
  <Condition name="02_S01_VF_full">
    <Parameter name="log_file_name" type="string" value="S01_VF_full" />
    <Parameter name="driving_scene" type="string" value="OcclusionTrack2.scene" />
    <Parameter name="left_front_overlay" type="string" value="HMILabOverlays/MaskLeftFront" />
    <Parameter name="right_front_overlay" type="string"
value="HMILabOverlays/MaskRightFront" />
    <Parameter name="left_side_overlay" type="string" value="HMILabOverlays/MaskLeftSide" />
    <Parameter name="right_side_overlay" type="string" value="HMILabOverlays/MaskRightSide" />
    <Parameter name="idss_type" type="int" value="0" />
  </Condition>
  <Condition name="06_S01_HF_VF_full">
    <Parameter name="log_file_name" type="string" value="S01_HF_VF_full" />
    <Parameter name="driving_scene" type="string" value="OcclusionTrack5.scene" />
    <Parameter name="left_front_overlay" type="string" value="HMILabOverlays/MaskLeftFront" />
    <Parameter name="right_front_overlay" type="string"
value="HMILabOverlays/MaskRightFront" />
    <Parameter name="left_side_overlay" type="string" value="HMILabOverlays/MaskLeftSide" />
    <Parameter name="right_side_overlay" type="string" value="HMILabOverlays/MaskRightSide" />
    <Parameter name="idss_type" type="int" value="7" />
    <Parameter name="c_f" type="float" value="2" />
    <Parameter name="c_s" type="float" value="0.005" />
    <Parameter name="t_lookahead" type="float" value="0.7" />
  </Condition>
</Experiment>
```

## Appendix C: Subjective Questionnaires

All subjects were native Dutch. For this reason the questionnaire was in Dutch as well. After the experiment the results were manually entered into an Excel database called 'Subjective Results.xlsx' which can be found on the DATA DVD.

### Vragen VOOR experiment

Naam .....  
Leeftijd .....  
Geslacht man / vrouw

Bent u brildragend? Nee / verziend / bijziend

Heeft u lichamelijke klachten die rijvaardigheden kunnen beïnvloeden?

Neemt u medicijnen die rijvaardigheden kunnen beïnvloeden?

Jaar behalen rijbewijs .....  
Rij ervaring sindsdien (1 zeer weinig – 5 heel veel) .....  
Hoe vaak rijdt u auto? (1 zelden – 5 dagelijks) .....  
Type bestuurder (1 conservatief – 5 sportief) .....  
Bent u snel wagenziek? (1 nooit – 5 zeer snel) .....

Er is een Driver Support System (DSS) ontwikkelt welke de bestuurder helpt met het sturen. Hierbij zal er een kracht merkbaar zijn op het stuur. Tijdens het sturen door de bocht wordt de bestuurder continu geholpen om de auto de juiste kant op te sturen. Wat zou je ervan vinden als een dergelijk systeem in jouw auto geïnstalleerd zou worden

Mijn oordeel van het systeem voordat ik ermee gereden heb is:							
1	Bruikbaar	-	-	-	-	-	Onbruikbaar
2	Plezierig	-	-	-	-	-	Onplezierig
3	Slecht	-	-	-	-	-	Goed
4	Fijn	-	-	-	-	-	Storend
5	Effectief	-	-	-	-	-	Overbodig
6	Irritant	-	-	-	-	-	Handig
7	Behulpzaam	-	-	-	-	-	Waardeloos
8	Ongewenst	-	-	-	-	-	Gewenst
9	Verhoogt Alertheid	-	-	-	-	-	Slaapverwekkend

## Vragen NA experiment

Vond je het fijn om met het ontwikkelde stuursysteem te rijden?

Ja/Nee

Heb je tijdens het rijden nog een andere speciale strategie gebruikt om te sturen?

Nee/Ja namelijk:

.....

Kun je een schatting maken naar hoeveel je stuuracties gebaseerd waren op visuele informatie en hoeveel op haptische informatie?

Visuele Informatie + Haptische Informatie = 100%

..... + ..... = 100%

Hoe vond je het om zonder visuele informatie te rijden?

.....

Verwacht je dat een dergelijk systeem je stuurgedrag in de toekomst zou kunnen veranderen?

Nee/Ja namelijk:

.....

Zou je €500,- over hebben om dit stuursysteem in te laten bouwen in je auto?

Ja/Nee

### Mijn oordeel van het systeem nadat ik ermee gereden heb is:

1	Bruikbaar	-	-	-	-	-	Onbruikbaar
2	Plezierig	-	-	-	-	-	Onplezierig
3	Slecht	-	-	-	-	-	Goed
4	Fijn	-	-	-	-	-	Storend
5	Effectief	-	-	-	-	-	Overbodig
6	Irritant	-	-	-	-	-	Handig
7	Behulpzaam	-	-	-	-	-	Waardeloos
8	Ongewenst	-	-	-	-	-	Gewenst
9	Verhoogt Alertheid	-	-	-	-	-	Slaapverwekkend

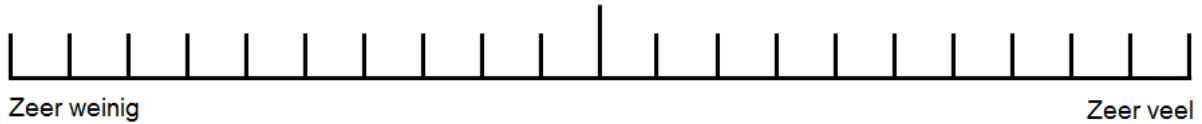
Naam:

Datum:

Taak: VF / VF<sub>n</sub> / VF<sub>f</sub> / HF / HF<sub>n</sub> / HF<sub>f</sub> / VFHF  
ProefpersoonNR:

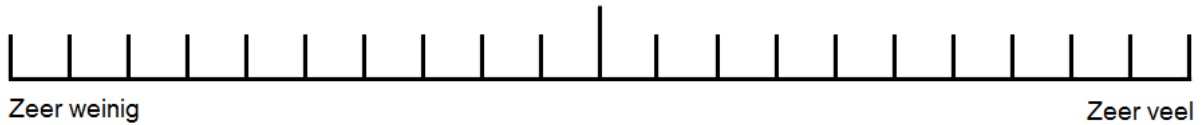
Mental belasting

Hoe belastend was de taak mentaal?



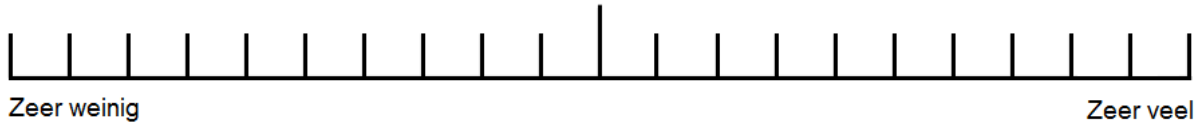
Fysieke belasting

Hoe belastend was de taak fysiek?



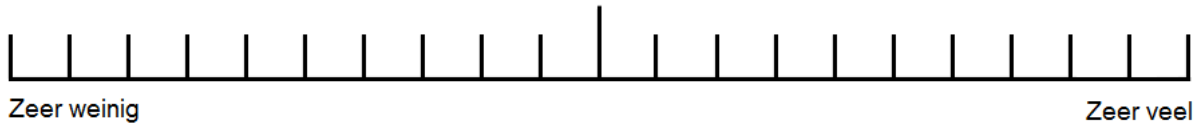
Tijd belasting

Hoe gehaast of opgejaagd was het tempo van de taak?



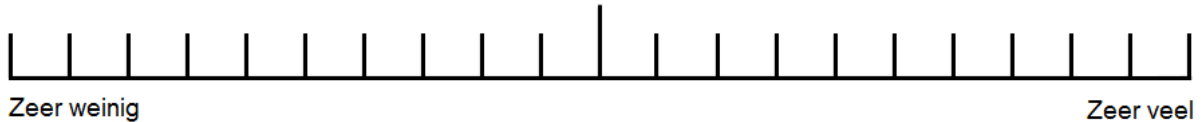
Prestatie

Hoe succesvol was je in de taak die je gevraagd was uit te voeren?



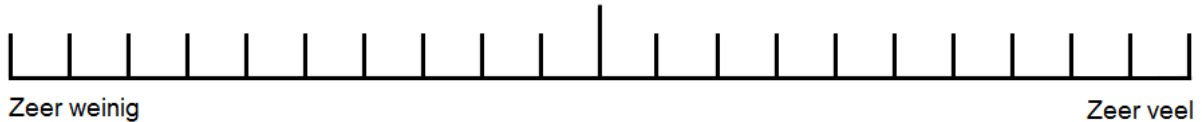
Moeite

Hoeveel moeite kostte het om de huidige prestaties neer te zetten?



Frustratie

Hoe onzeker, ontmoedigd, geïrriteerd, gestrest of geïrriteerd was je?



**Heb je tijdens het rijden een speciale strategie gebruikt om te sturen?**

Nee/Ja namelijk:

.....