MSc. Thesis

Design and real-world evaluation of lane-keeping support for truck drivers

H. A. L. G. Roozendaal

Technische Universiteit Delft

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Design and real-world evaluation of lane-keeping support for truck drivers

by

H. A. L. G. Roozendaal

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Thesis committee:	Dr. ir. D. A. Abbink,	TU Delft, supervisor
	Dr. Ir. J. C. F. de Winter,	TU Delft
	Ir. T. Melman,	TU Delft
	E. J. Johansson,	Volvo Trucks, supervisor

This thesis is confidential and cannot be made public until December 7, 2020.

Preface

Technological advances in the automotive industry push human-driven vehicles into autonomy. The world is gradually preparing for fully autonomous vehicles. Although the technology will be available within a few years, will the human be ready for it?

An intermediate stage is needed where intelligent vehicles and humans interact in such a way that humans start to trust the technology, and technology is allowed to develop based on human driving behaviour. This paves the way for wide implementation of Advanced Driver Assistance Systems (ADAS) that assist drivers when prompted by the driver or when most necessary to avoid accidents, and do so in both a safe and pleasant manner.

In current literature I found many simulator studies that evaluated and proved the safety benefits of ADAS, however not so many where evaluated in real-life where driver acceptance towards automation is of key importance (entire literature survey is added to Appendix G). In this MSc. thesis I designed and evaluated three haptic lane-keeping support designs based on their potential to be implemented in real life.

This thesis report is part of the fulfillment of the master degree Mechanical Engineering with a specialization in Vehicle Engineering at the Delft University of Technology. The relevant support systems' Simulink models, and Matlab code used for the data and statistical analyses have been uploaded to the Mechanical Engineering repository.

H. A. L. G. Roozendaal
Delft, November 2017

Acknowledgments

First, I would like to thank my supervisors Emma Johansson (Volvo Group Trucks Technology), Bastiaan Petermeijer (TU Delft), and David Abbink (TU Delft) for their enthusiasm and help during my MSc. thesis. Emma's open attitude is what got me into Volvo Trucks but also allowed me to design this research in a way that fit my literature findings and met the demands set by the TU Delft for a MSc. thesis. Her continuous devotion was of tremendous help during the preparations and execution of the experiment and during the writing of the report. Bastiaan's approachability and flexibility was enormously appreciated throughout the entire study. His experience and knowledge in this research field added to the advanced both the literature and the actual thesis study. David's been an inspiration to me since I started my master program at the TU Delft. His understanding and knowledge about haptics has been of great contribution to this project, and his enthusiasm was a constant motivator to get the most out of this research. Also I would like to thank Timo Melman for reviewing my paper short before final submissions.

This work was conducted at Volvo Group Trucks Technology in Gothenburg in close collaboration with the University of Technology Delft. Special thanks go out to Pontus Larsson, Wilhelm Wiberg, Mats Sköld, Robert Sjödell, António Craveiro, Claudia Wege and all other involved employees and the resources that were made available to make this research happen.

Jeroen Roozendaal was hired and supervised by Emma within the FFI project HARMONISE: Safe interaction with different levels of automation. David and Bastiaan's efforts were supported by VIDI grant 14127, funded by TTW, part of the Dutch National Science Foundation.

Finally I would like to thank Emelie Widerström for her encouragement and my parents for their continuous support throughout my entire studies, without you guys I would never have been in this position.

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Thesis Paper

Design and real-world evaluation of three types of haptic lane-keeping support systems for truck drivers

Jeroen Roozendaal

Abstract—Designing lane-keeping assistance (LKA) systems that are both effective and well-liked by drivers is a highly challenging process, that is not well understood. This is illustrated by a wide variety of market releases of LKA systems, and a large body of literature illustrating different designs and various evaluation methodologies that are often performed in driving simulators. As a result, it is unclear how design choices impact driver steering behaviour and acceptance, and extrapolate this to real-world driving where driver distraction is often a reality. This study presents a detailed evaluation methodology to compare three haptic LKA designs in a single real-world truck driving study. These designs are constructed based on two haptic LKA approaches found in literature; continuous support and bandwidth support. It is hypothesized that continuous support is favored over bandwidth support but that both LKA approaches are effective and well-liked when implemented in real-life and show to be particularly effective for distracted drivers. Two of the evaluated systems were triggered to generate haptic torques only when the predicted lateral error exceeded a bandwidth of 0.4 m: a single-bandwidth system (SB); that shuts off the guidance when the predicted lateral error returned within the bandwidth, and a double bandwidth system (DB); that shuts off the guidance when a second inner bandwidth (close to lane center) is reached [38]. The third evaluated system generated continuous haptic torques towards the lane center: a continuous double bandwidth system (CDB). Sixteen participants drove four trials on a private test-circuit; one trial without and three trials with haptic support. For each support system, participants drove both a distracted and a non-distracted condition. The results show that compared to manual control, all three support systems provided equal benefits in terms of accuracy and prevention of large lateral errors (>0.7m). When a lane departure did occur both DB and CDB support systems showed shorter lane departure times with smaller lateral errors compared to manual driving. The DB and CDB support systems showed high driver acceptance and reduced large swerving behaviour that was observed during distracted driving. All three support systems however lacked effectiveness and driver acceptance during curves. Ultimately the CDB support system was the overall preferred haptic LKA design. This study shows the potential for DB and CDB support to be used in real-life, however higher driver satisfaction can be achieved when the support systems are able to cope with humans' driving behaviour during curves.

Index Terms—Haptic shared control, lane keeping assist, steering wheel feedback, continuous guidance, bandwidth guidance, driver acceptance, real-life experiment, secondary task, driver distraction

◆

1 INTRODUCTION

"ZERO accidents with Volvo Group products" is what Volvo Trucks pledged to the world in 2015 [15]. The ultimate goal of no fatalities in driving pushes vehicle manufacturers to design systems that result in high safety. One of the key aspects when aiming for high safety is the avoidance of unintended lane departures and the use of Advanced Driver Assistant Systems (ADAS) showed great potential reducing such incidents. In 2011 research towards the crash records of the Fatality Analysis Reporting System (FARS) showed lane departure warning/prevention systems can potentially prevent 31% of fatal single-vehicle crashes [24] and 15% of fatal side-swipe crashes for large trucks [25]. Unintended lane changes are more likely to happen with distracted or tired drivers as stated by Volvo Trucks; "Tired and distracted drivers are a danger to themselves and others. And tiredness is by far the most common cause of accidents involving trucks" [15].

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Distraction in general, but mainly due to visual-manual interaction with nomadic and build in vehicle devices, has shown to contribute to vehicle crashes [35] [46]. Olson et al. showed that drivers were engaged in non-driving related tasks in 71% of all crashes, 46% of all near-crashes, and 60% of all safety-critical events [35]. ADAS like lane departure warnings and lane-keeping assistance (LKA) have shown to significantly reduce such fatal crashes [24] [25]. However, even if ADAS systems have the potential to increase safety for both distracted and non-distracted drivers, the driver ultimately chooses whether to use such a system. Driver acceptance towards the support system is thus crucial for the system to have an effect. Designing lane-keeping assistance (LKA) systems that are both effective improving lane keeping performance and at the same time accepted by drivers, is a highly challenging process that is not well understood. This is illustrated by a wide variety of market releases of LKA systems [26], and a large body of literature illustrating different designs and various evaluation methodologies that are often performed in driving simulators. As a result, it is unclear how design choices impact objective driver behaviour and acceptance, and how drivers extrapolate this to real-world driving (Appendix G: Literature survey). Johansson et al. showed a wide implementation for LKA

- *H.A.L.G Roozendaal was with VOLVO Trucks and the Department of Cognitive Robotics Faculty 3mE, Delft University of Technology*
  E-mail: H.A.L.G.Roozendaal@student.tudelft.nl

systems among personal vehicles but not so much for the Truck segment [26]. The focus of this study is on the three design challenges; safety, distraction and acceptance, with a detailed evaluation methodology to compare different haptic LKA designs in a single real-world truck driving study.

1.1 Lateral support design approaches

Lane keeping support for vehicles can be presented through two fundamentally different approaches. For the first approach the driver shares the control with the system as continuous guidance will be exerted through the steering wheel; haptic shared control [1] [13] [18] [33] [38]. The second approach makes use of a position threshold, within the boundaries of this threshold the system acts as a manual controller but when this threshold is exceeded the support will be activated; a so called haptic bandwidth support system. [31] [38] [41] [43].

Continuous support

Studies with implemented haptic shared controllers showed improved lane keeping performance compared to manual control [14] [18] [32] [38]. Comparable continuous systems with higher support torques result in similar but stronger lane keeping performance effects [13] [28]. Apart from that, haptic shared control is argued to provide transparency about the automation functionality. According to Abbink et al. [1] haptic shared control enables the driver to constantly interact with the system in order to be aware of the system functional limitations. The continuous guidance have also showed to come with some downsides. Due to personal variability in drivers' preferred lane position the lane centered controller can result in driver conflicts meaning the system provided opposite feedback torques as were expected by the driver [13] [22] [33]. Also Petermeijer et al. [38] showed that continuous guidance is more prone to aftereffects when compared to manual driving or bandwidth guidance.

Bandwidth support

Most continuous support systems use the lane center as a reference point for the guidance output (Appendix G: Literature survey). The system then always guides towards an optimal lane position. However research has shown that human drivers rather control tasks based on satisficing (i.e., swerving the lane within personal tolerable limits) than optimizing behavior (i.e., absolute lane centered position) [19]. According to Godthelp et al. [17] human drivers prefer to choose a self judged safe lane position and apply corrective steering when they exceed this limit. The bandwidth controller is based on this principle and previous research has shown improvement in both lane keeping performance and acceptance [34] [38]. One of the benefits of the bandwidth guidance is that the driver will not be affected when driving tolerable and will only be corrected when necessary. However the difficulty of bandwidth guidance is to determine where this necessity is positioned. If the guidance interferes too late there is too few time and space for correction. However corrections presented to the driver too early can be perceived as false alarms [37]. Research showed that binary support can be annoying and difficult to interpret [44]. Adding a hysteresis filter over the bandwidth guidance as was presented by Petermeijer et al. [38] is a good example of how bandwidth guidance can be modified to accomplish better satisfaction among drivers.

1.2 System acceptance

A recent study towards the use of Advanced Driver Assistance Systems (ADAS) showed that one of the main reasons for disuse of ADAS on highways is due to an unpleasant or faulty system [20]. As mentioned by Van der Laan in 1997; it is unproductive to invest effort in designing and building an intelligent co-driver if the system is never switched on, or even disabled [45]. Since the driver is ultimately responsible for the driving task and chooses whether to use a system, the acceptance towards a guidance system is of high importance for a system to have any effect. Few studies evaluate the driver acceptance (Appendix G: Literature survey) but the ones that do, emphasize the importance of driver acceptance when introducing haptic driving support to the real world [4] [6] [38]. High satisfaction ratings for both the continuous guidance systems and the hysteresis bandwidth guidance system are shown by Petermeijer et al. [38], showing the potential of both systems to result in high acceptance.

1.3 Distraction

According to earlier presented accident statistics, over 71% of drivers were engaged in non-driving related tasks at the time of crashing [35]. The driver inattention [10] is most frequently caused by passenger related distraction and visual-manual tasks (i.e., the use of mobile devices) [29] [35] [46]. In contrast to the protective effect of cognitive loading tasks, visual-manual tasks have been shown to contribute to accidents [46]. In the last few years many European countries banned the use mobile devices while driving a vehicle. This however does not mean that drivers are now more committed to the driving task. The distraction moved to on-board information or media systems, like searching for a favorite music song, looking for a phone-contact or typing the address of a destination in a navigation system [4]. Even if such distraction will be banned there will be others ways to distract the driver like roadside events or passengers in the vehicle. The challenge for automotive manufacturers is to design their safety systems in a way that works for both attentive and inattentive drivers.

1.4 Aim and hypotheses

The aim of this study was to evaluate the lane keeping performance and driver acceptance of continuous and bandwidth systems, with and without driver distraction, in a real-life driving experiment. It is hypothesized that both continuous and bandwidth guidance result in improved lane keeping performance when compared to manual driving. Positive acceptance ratings are expected for both types of support systems, combined with higher secondary task performance when compared to manual driving. It is also expected that these benefits will be shown for both distracted and non-distracted driving. Due to continuous lane centering the continuous support is expected to result in

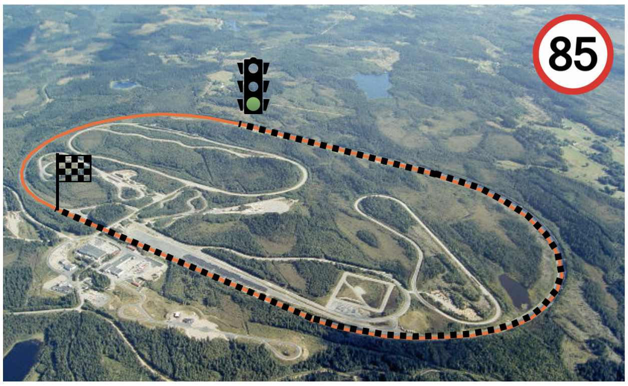


Fig. 1: Main-track of Volvo Cars' private test facility named "Hällered"

both the highest lane keeping performance and secondary task performance, where bandwidth guidance is expected to score highest on driver acceptance due to less driver conflicts within the manual controlled zone.

This study is performed in collaboration with Volvo Trucks and evaluates three versions of haptic lane keeping support in a real-life experiment on a private test facility; two bandwidth versions and one continuous support version. Two of the support options were developed in previous studies; the continuous guidance [33] and the hysteresis double bandwidth system [38]. The third and second bandwidth system, uses a single bandwidth with a constant amount of directional torque once activated.

Understanding how design choices impact objective driver behaviour and acceptance, is crucial for real-world application of support systems. The presented study, focuses on three design challenges; safety, distraction and acceptance, and is aimed to evaluate the three presented haptic LKA designs on their potential for real-world application.

2 METHOD

2.1 Experiment design

A 4x2 within-subjects, repeated measures design was used to evaluate the support types (3 support types and manual driving) with secondary task involvement (with and without Surrogate Reference Task (SURT)). All participants drove one trial with using each of the following three support options: Single Bandwidth (SB), Double bandwidth (DB), Continuous Double Bandwidth (CDB), and manual control. The support systems were counterbalanced across participants using the 'Latin Square' method. The participants drove two laps per support type; one lap with and one without the SURT. Each participant also drove one additional lap with SB, DB and CDB where the participant was allowed to evaluate the system further by approaching or crossing lane boundaries. The primary and secondary task were counterbalanced across the 3 laps. After each trial the truck was parked next to test-track for participants to fill in a questionnaire regarding the driven support system.

The participants drove on the 'main-track' of a Volvo Cars private test facility named 'Hällered' shown in figure 1, also used by Volvo Trucks. This main track track is a 6300m long, four-lane wide, right-turned, oval track with lane widths of 3.6m. On this main track vehicles are being exposed to their engineering limits by driving extreme speeds on the "fast lanes" (outer two banked lanes 3-4) and intensive highway braking (inner lane number 1). During the experiment such vehicle test were ongoing. Trucks are only allowed to drive on the inner lanes 1 and 2. The participants were instructed to drive on lane 2 and were instructed to prioritize on-track safety by checking the vehicles surroundings for hazardous situations caused by other traffic. When a lane change towards lane 1 had to be made to cope with other traffic, that specific experiment lap was reseted and redone. All involved Hällered track rules can be found in Appendix B. The evaluated trajectory was identical for each trial and consisted of two straights and one curve as can be seen in figure 1. The trial always started on the beginning of the first straight and ended at the end of the second straight. During the second curve, support was always deactivated and experimental settings were changed to prepare for the next lap of that trial. The participants drove with a fixed speed of 85-km/h using the trucks onboard Cruise Control (CC).

During one of the laps of each trial, the participants had to commit to a secondary task; SURT [23] [39] to evoke distracted driving.

2.2 Participants

Sixteen participants (2 women and 14 men) between 26 and 58 years old ($M = 42.6, SD = 8.8$), licensed to drive a truck, licensed to drive at the Hällered test facility, volunteered to take part in the experiment. All participants were employed by Volvo and had prior knowledge of ADAS.

2.3 Apparatus

The Experiment was conducted in a Volvo FH 16 8x4 Rigid truck as shown in figure 2.

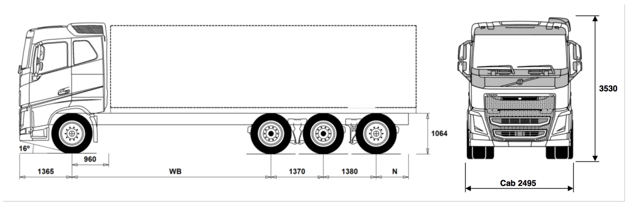
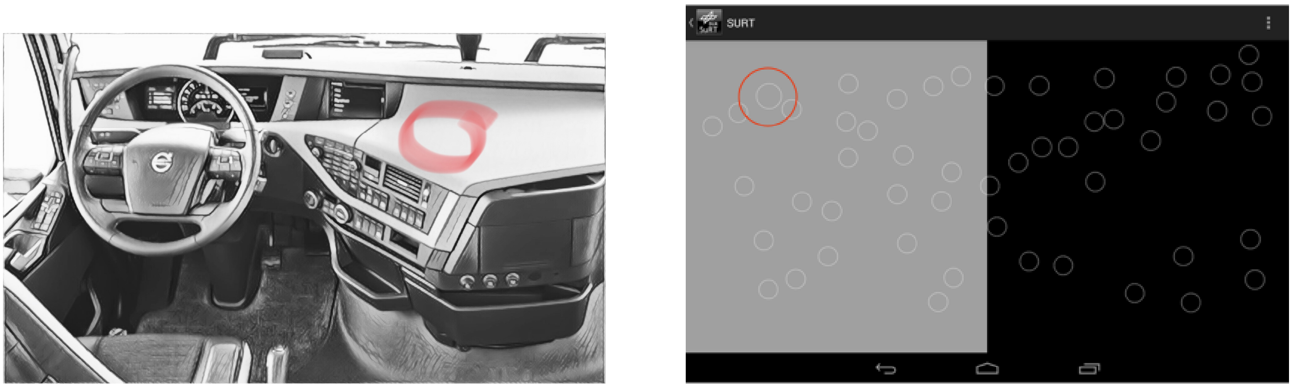


Fig. 2: Type and dimension specification truck used for experiment: Volvo FH 16 8x4 - Rigid

This specific truck was modified for experimental use and is equipped with AutoBox hardware [9]. This hardware allows a software package called dSpace [9] to influence the vehicles actuators and other vehicle hardware like window-wipers or headlights. Selectable vehicle sensory data could be accessed after installing Vector-hardware (CAN/LIN-interface block) and software (CANalyzer application) [16]. The truck is equipped with an active steering wheel, influenceable through the dSpace software. The vehicle is among other systems, equipped with an automatic gearbox and original Volvo Cruise Control (CC).

Metrics with respect to the vehicle's state and the vehicle's lane position were logged at a frequency of 10Hz. The



(a) Cabin sketch with tablet location for secondary-task (SURT) indicated by red circle

(b) Printscreen of secondary-task (SURT), red circle showing task target

Fig. 3: Secondary-task (SURT) visualization

secondary task (SURT) was presented on an on-board tablet facing towards the driver on the top and slightly on the left side of the middle of the dashboard as indicated in figure 3a. The tablet screen is filled with small circles where one of the circles was bigger than the others. The bigger circle was randomly positioned on either the left or right side of the screen. After a participant's input this input was highlighted and continuously, a new set of circles would appear on random locations ready for the next input as visualized in figure 3b. For the secondary task (SURT) the reaction time of each hit and a true/false indication was recorded. Pre-, between systems-, and post-questionnaires (respectively Appendix D, E and F) were gathered containing information about respectively the participant and its experience with ADAS, standardized usefulness and satisfaction acceptance scale ('Vanderlaan' [45]) and System Usability Scale (SUS) [7] questionnaires (aimed at the different support options) and a questionnaire about the overall preferred support system. An on-board driver facing camera recorded participants' behavior during all trials. The camera was only allowed to record inside cabin events due to secrecy rules on the Hällered test facility. 'GoPro' [21] camera units were used for the recordings.

2.4 Procedure and instructions

The participants were welcomed in a track-side office where they were asked to read and sign a written consent form (Appendix C), including an explanation of the purpose and the procedure of the experiment. The participants were talked through the consent-form in which they were informed that a haptic support system will support them in a lateral control task by torques exerted through the steering wheel. Then the participant filled out the pre-questionnaire (Appendix D) regarding demographics and participants' experience with truck driving and ADAS. The experiment procedure is visualized in figure 4

Next, the participants were escorted to the truck where they were asked to take place in the driver's seat to talk them through the vehicle's information cluster and controls. The experimenter then repeated the explanation of the driving tasks and safety rules on the test-track and informed that questions regarding the working principles of the support systems where not answered until after the experiment. Subsequently the participants were asked to drive to the beginning of the test track, using the short drive towards the start (approximately 500m) to get familiarized with the vehicle. The participants were then asked to enter the main-track which they accessed just before one of the two curves. Once entered they were asked to set the CruiseControl to 85 km/h and proceed to lane 2 when safe. When the participant reached the beginning of the straight the participants were asked to flash the main-beam as an annotation in the measurement data. After the annotation the experimenter activated the relevant support system. Before the end of the second straight the participants were again asked to flash the main-beam on which the experimenter de-activated the support system. With the main-beam signal measured, a clear beginning and end of each lap was documented in the data logs. After each lap, consisting of two straights and one curve, the experimenter used the second curve to ask the participants to rate their overall self-perceived driving performance (combined performance of driver and system) on a scale from 1 to 10 according to the HASTE scale [36]. The experimenter documented this as the HASTE-score per support and task setting. Depending on the counterbalanced schedule, the remaining time in the second curve was used by the experimenter to prepare the SURT, which was then activated at the beginning of the first straight together with the relevant support system. This process was repeated until the last lap of the trial where the participants were allowed to explore the effect of the system when near or when crossing the lane boundaries. During this last lap the participants were specifically asked to comment on the activation time, support intensity and overall feeling of the systems correction. These comments, along with all the other comments made during the entire trial, were documented by a third person assisting the experimenter. After each trial the participants were asked to leave the main-track and park on a nearby parking area intended for short, between experiment, parking. There they were asked to fill in the between-systems-questionnaire, while the experimenter used that time to reset the trucks settings and prepare for the next trials support type settings. The between-system-questionnaire was not filled in after the

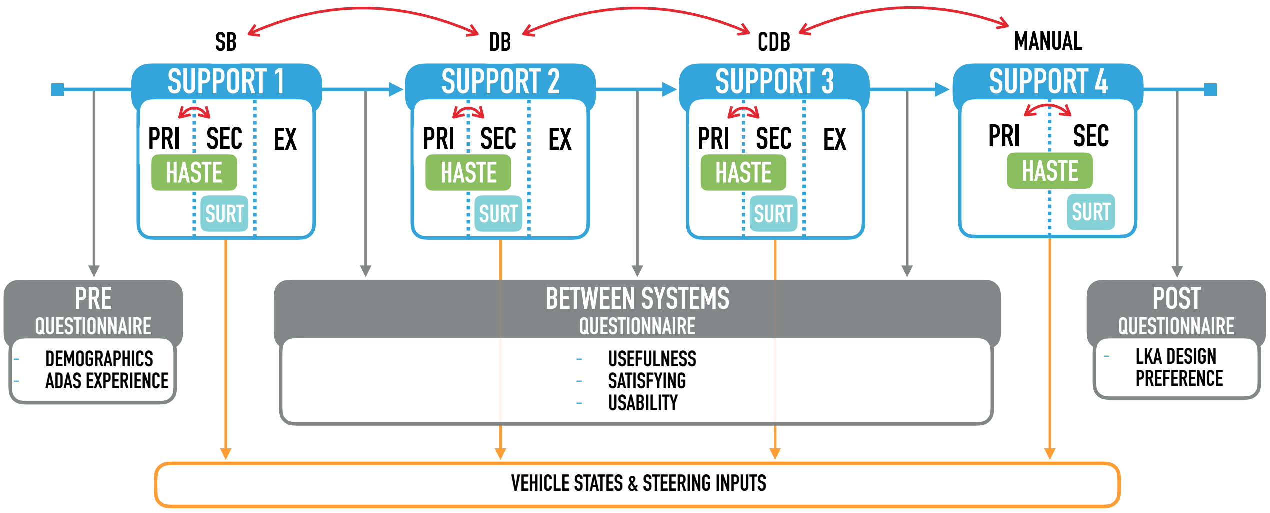


Fig. 4: Visualization of experimental procedure. SB; Single Bandwidth, DB; Double Bandwidth, CDB; Continuous Double Bandwidth, PRI; Primary task, SEC; Secondary task, EX; Exploratory task. Red arrows represent the changing order of the assessed support systems and the presence of the secondary task, blue arrows represent breaks between the experiment's support systems, gray blocks represent questionnaires taken before, between, and post experiment support conditions, orange block represent vehicle state measures and steering wheel inputs taken during experiment conditions, green blocks represent self-reported HASTE-score taken after PRI and SEC task, and the light blue blocks represent the SURT-score from the secondary task.

manual driven laps. This process repeated itself until all trials were completed. Ultimately the same parking area was used to fill in the post-questionnaire before returning to the side track office.

During the lap without the secondary task the participants were asked to drive the truck as they would do in normal life, only concerning about keeping the truck within the lane boundaries. During the lap with the secondary task the participants were instructed to "keep the truck within the lane boundaries while committing to the secondary task". All licensed Hällered-drivers are personal responsible to always prioritize safety over experimental tasks. The total experiment lasted about 1 hour and 45 minutes per participant.

2.5 Applied steering wheel support

Three different control algorithms were used that calculated the guidance torque ($T_{guidance}$ [Nm]) that was superimposed on the steering wheel (visualized in figure 5). An algorithm predicted the lateral error ($e_{lateral,future}$ [m]) and the heading error ($e_{heading,future}$ [rad]) of the truck with respect to the lane center. The future states of these errors were calculated by assuming a constant steering wheel angle for 0.6s into the future (look-ahead time). During tuning of the algorithms this look-ahead time was set below the originally designed 1.0 s [38] to increase the stability of the algorithm during curves. Also the $T_{guidance}$ was determined to be comfortable at 1.5Nm.

The SB algorithm used the $e_{lateral,future}$ to calculate the $T_{guidance}$. The algorithm was designed to only exert the predetermined $T_{guidance}$ when $|e_{lateral,future}|$ ($|e_{lat}|$) exceeded 0.4m as shown in equation 1.

$$T_g = \begin{cases} 0 & \text{if} \quad |e_{lat}| < 0.40 \\ 1.5 & \text{if} \quad |e_{lat}| \geq 0.40 \end{cases} \tag{1}$$

The DB algorithm used the $e_{lateral,future}$ in two states of operation. In the initial state, the system was designed to only exert $T_{guidance}$ when $e_{lateral,future}$ exceeded 0.4m as shown in equation 2. The support gains were $D_1 = 2.8$, $K_f = 1.2$. The support gains were determined during a test-trial prior to the experiment and are relatively high compared to previous research [38]. This is the result of the truck's larger diameter steering wheel that has a negative effect on the amount of steering wheel forces transfered to the driver as shown in figure 6. Also because of the width of the truck (2.45m) the effective lane-margin is almost twice as small compared to normal vehicles. Therefore the guidance system had to be more effective on a shorter section of the lane to reduce big lane departures.

$$T_{g,state1} = \begin{cases} 0 & \text{if} \quad |e_{lat}| < 0.40 \\ (e_{lat} \cdot D_1) \cdot K_f & \text{if} \quad |e_{lat}| \geq 0.40 \end{cases} \tag{2}$$

When $e_{lateral,future}$ became greater than 0.4m, the system switches to the second state where the controller exerts $T_{guidance}$ until $e_{lateral,future}$ is smaller then 0.15m as shown in equation 3. Therefore the system behaves as a hysteresis system that once activated guides the truck back the middle of the lane.

$$T_{g,state2} = \begin{cases} 0 & \text{if} \quad |e_{lat}| < 0.15 \\ (e_{lat} \cdot D_1) \cdot K_f & \text{if} \quad |e_{lat}| \geq 0.15 \end{cases} \tag{3}$$

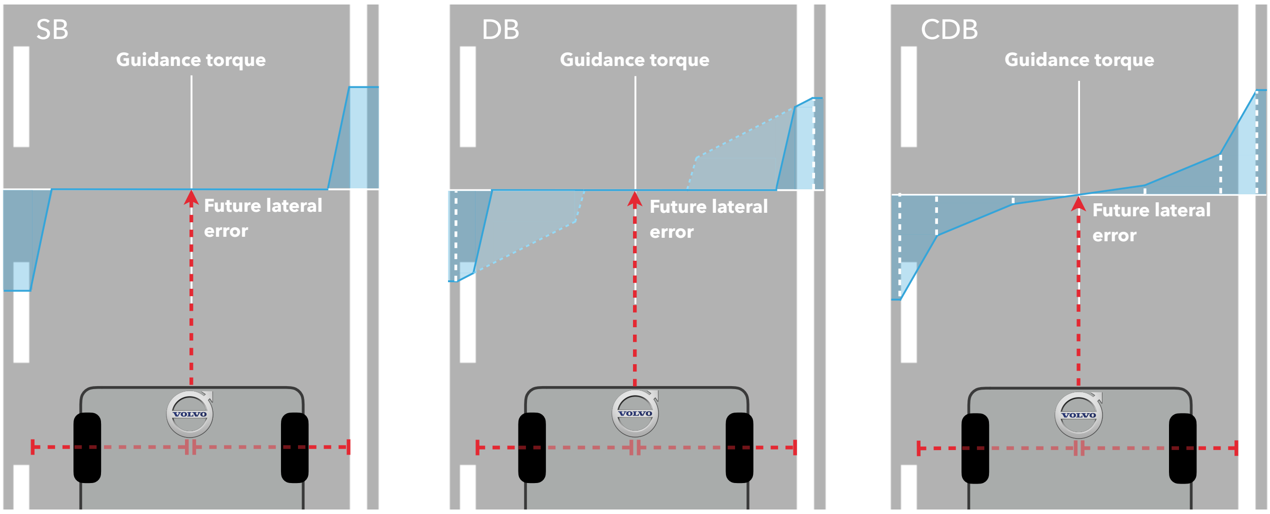


Fig. 5: The three support system designs, illustrating the guidance torque as a function of future lateral error, for a single set of initial conditions (lateral error and heading error of zero). From left to right the support systems; Single Bandwidth (SB), Double Bandwidth (DB) and Continuous Double Bandwidth (CDB). The red arrows symbolize the future state of the truck's lateral error (as was calculated from the left and right distance from the truck center to the lanes, at the position of the truck's front axle) as the truck is symbolized by the black square with the Volvo emblem. SB is shown on the left, DB in the middle and CDB on the right

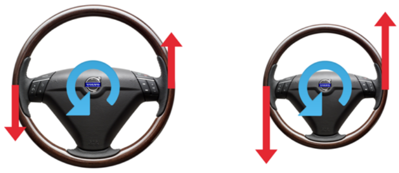


Fig. 6: Smaller steering-forces at the rim of a truck steering-wheel (left) for equal amount $T_{guidance}$ compared to a normal passenger car steering-wheel (right)

The CDB system uses both $e_{lateral,future}$ and $e_{heading,future}$ to calculate $T_{guidance}$ similar to Petermeijer et al. [38]. However for this study $e_{lateral,future}$ boundaries were used to apply different gain settings, similar to the $e_{lateral,future}$ boundaries seen in SB and DB guidance as shown in equation 4. The support gains D_1 and K_f were similar to DB. The other gain settings were $D_2 = 2$, $D_3 = 3.5$ and $P = 4$.

$$T_g = \begin{cases} (e_{lat} \cdot D_2 + e_{head} \cdot P) \cdot K_f & \text{if} \quad |e_{lat}| < 0.15 \\ (e_{lat} \cdot D_1 + e_{head} \cdot P) \cdot K_f & \text{if} \quad |e_{lat}| \geq 0.15 \\ & \text{and } |e_{lat}| < 0.40 \\ (e_{lat} \cdot D_3 + e_{head} \cdot P) \cdot K_f & \text{if} \quad |e_{lat}| \geq 0.40 \end{cases} \tag{4}$$

2.6 Dependent measures

The data was analyzed separately for straight and curved sections. The following measures were calculated per participant, for each support type in each lap of the experiment. The lateral position is the measured current position of the front axle.

- Mean absolute lateral position (meters). This measure describes the lane keeping accuracy.
- Standard deviation of the absolute lateral position (meters). The standard deviation is determined for each participant. The mean of these standard deviations then describe the swerving behavior with respect to the drivers preferred/mean lane position.
- Number of lane departures (#). This describes the effectiveness of the guidance systems to stay within the lane.
- Mean duration of the lane departures (seconds). If lane departures took place this measure averages the duration of each lane departure.
- Mean maximum lateral position during lane departure (meters). If lane departures took place this measure averages the maximum value of each lane departure.
- Standard deviation steering wheel-angle (degrees). The standard deviation is determined for each participant. The means of these standard deviations then describe if participants use different steering behaviour when using the support feedback. Some drivers can for example show low standard deviations indicating near constant steering wheel-angles while others can show high standard deviations indicating they were making long subtle steering wheel-angle deviations or many extreme steering wheel-angle deviations. This measures therefore shows the variability in the way drivers use the guidance system.
- Number of steering wheel reversals, larger then 2 degrees, per minute (reversals/min.). This commonly used measure, also knows as Steering Wheel Reversal Rate (SWRR), describes the driver's control activity. A steering wheel reversal takes place when a driver tries to aim for a certain lane position. Many reversals means a high control activity to achieve this

position.

- Overall system preference. The post-questionnaire asked the drivers to order the three guidance systems from most favorite to least favorite. When a system was rated most favorite it scored 2 points, when placed in the middle it scored 1 point and when placed last it scored 0 point. The points were summed to result in a quantitative overall preference score.

The following measures were calculated per participant, for each trial of the experiment.

- The HASTE-score, used in the HASTE project [36], is the self-reported performance indicator on a scale from 1 to 10 (in this study a performance indicator of combined driver and guidance system). This score is an overall performance indicator and is therefore dependent on driving circumstances. High driver demands, i.e., during the secondary task, is therefore likely to result in a lower self-reported performance score.
- Standardized acceptance questionnaire ('Vanderlaan' [45]). The from +2 to -2 ranging satisfying and usefulness scores (based on a Likert scale which is the sum of the responses of several Likert items) where determined by averaging five scores that made up the usefulness-score (item 1, Useful-Useless; item 3, Bad-Good; item 5, Effective-Superfluous; item 7, Assisting-Worthless; item 9, Raising Alertness-Sleep Inducing) and four scores that made up the satisfying-score (item 2, Pleasant-Unpleasant; item 4, Nice-Annoying; item 6, Irritating-Likeable; item 8, Undesireable-Desireable). Item 3, 6 and 8 have mirrored scores from -2 to +2.
- Usability scores from the System Usability Scale questionnaire. Seven questions regarding the systems usability were asked to the participants (Appendix E). Each question could be answered based on a Likert scale. The five Likert items used are; 1, Strongly disagree; 2, Disagree; 3, Neither agree nor disagree; 4, Agree; 5, Strongly agree. The scores of negative aimed usability questions were subtracted from five and one point was subtracted from the scores of positive aimed usability questions. The added up total score is then multiplied by 3.6 to result in a score out of 100. A study conducted by Bangor et al. in 2009 [2] concluded that a score of at least 70 corresponds to a usable system.
- SURT score: Response time for hits (i.e. correct answers). [39]. This value describes the participants' devotion to the secondary task. A higher SURT score corresponds to a higher driver devotion to the secondary task.

In order to investigate the effectiveness of the lane keeping support systems the distribution and standard deviation of the lateral position for all participants for the distracted and non-distracted lap for both straights and curves were separately compared, as well as measures of the number of lane departures and the mean duration and mean max lateral error of these lane departures. SURT-scores were compared to evaluate secondary task devotion per support system. In order to evaluate the acceptance of the support systems subjective usefulness, satisfying, usability and performance scores were compared. On top of that steering wheel-angle measures were compared to investigate the drivers' steering wheel behavior and control activity.

2.7 Analysis

For each dependent measure a 2x2 cell (task x road-section) was made. Task corresponds to the distracted or non-distracted driver setting and road-section corresponds to the separation of straights and curves. Each cell digit consists of a 16x4 matrix (participant x support option). For all measures except for two (mean length and mean max lateral error of the lane departures), these 4 matrices were submitted to an analysis of variance (Factorial Repeated Measures ANOVA), with the two tasks (with and without secondary task) and the four support types (Manual, SB, DB, CDB) as the within-subject variables. Since lane-departures were not always present the measures regarding the lane departures did not always contain data. In order to cope with the empty data arrays, a Factorial Mixed ANOVA was used with the tasks and support types as the within-subject factors. Ninety-five percent confidence intervals of the supplied means were calculated to investigate the statistical significance among pairs of the support systems and corresponding tasks. The ANOVA's calculated the; significance levels p and main effect levels F between support options, task and the interaction of the two (Support*Task). A pairwise comparison was done to indicate which pairs resulted in significant effects. The post questionnaire was analyzed to result in the overall LKA design preference of the participants. Driver comments were sorted per support system and distinguished between secondary task involvement.

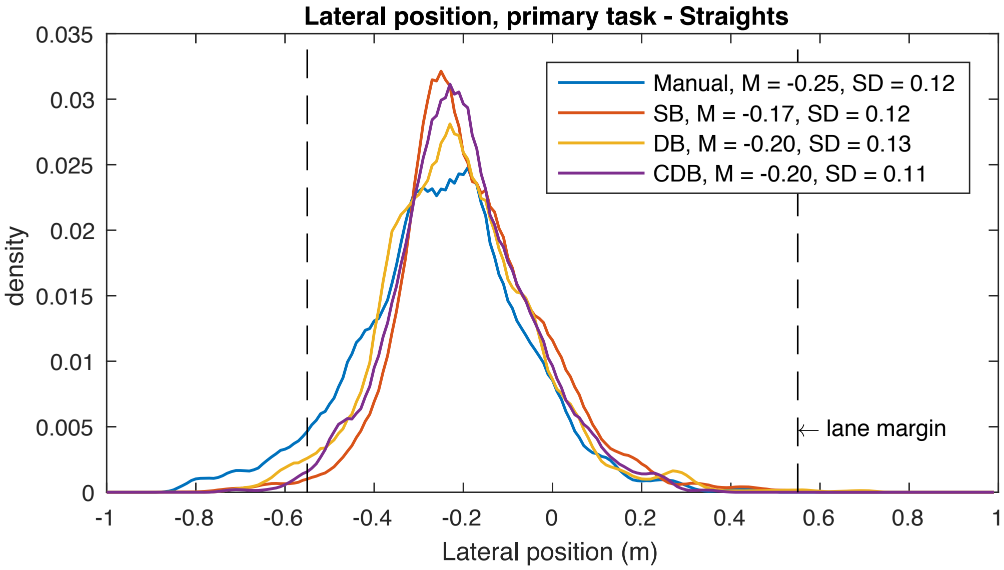
3 RESULTS

3.1 Distribution of lateral position

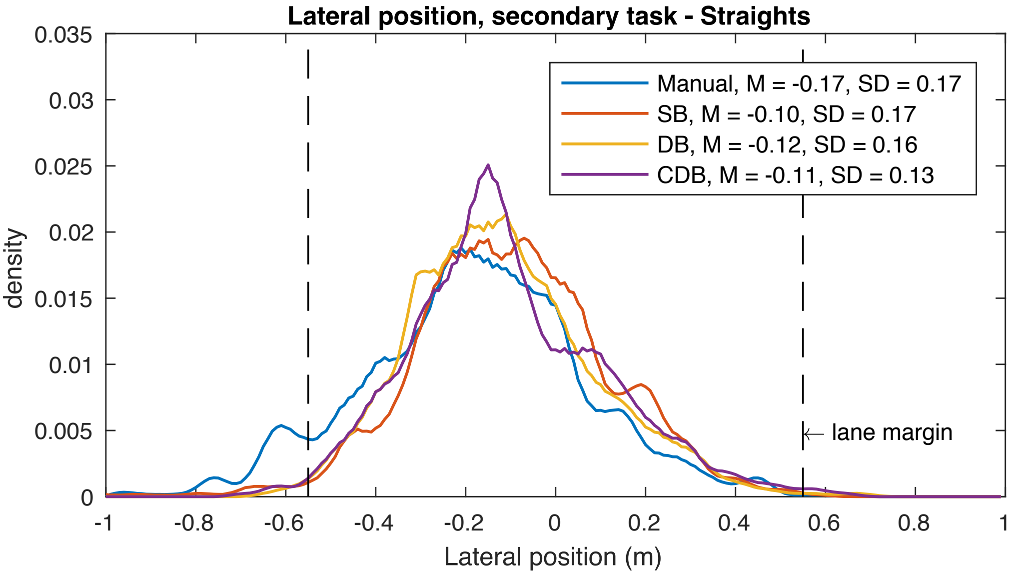
For all three support systems and manual control, the distribution of lateral position over the straight parts of the trajectory is shown in figure 7. Non-distracted drivers (figure 7a) using any of the support systems result in a narrower position distribution compared manual driving. During distraction (figure 7b) this effect is only seen for the CDB support.

Independent of distraction figure 7 show the mean lateral position shifting towards the lane center (improved means) when using guidance systems. Participants prefer a lateral position that is 0.25m left of the lane center when not distracted and 0.17m left of the lane center when distracted. The support systems show to reduce the lateral positions outside the lane boundaries independent of driver distraction, which were observed during manual driving (figure 7 show for manual driving the highest position distribution outside the left lane margin).

The support systems did not show improved lateral positions compared to manual driving for the curved road sections. The mean lateral position shifts from a left side lane position during straights (Manual mean $= -0.25$m,



(a) Distribution lateral position on straights, all support types, non-distracted driver (primary task)



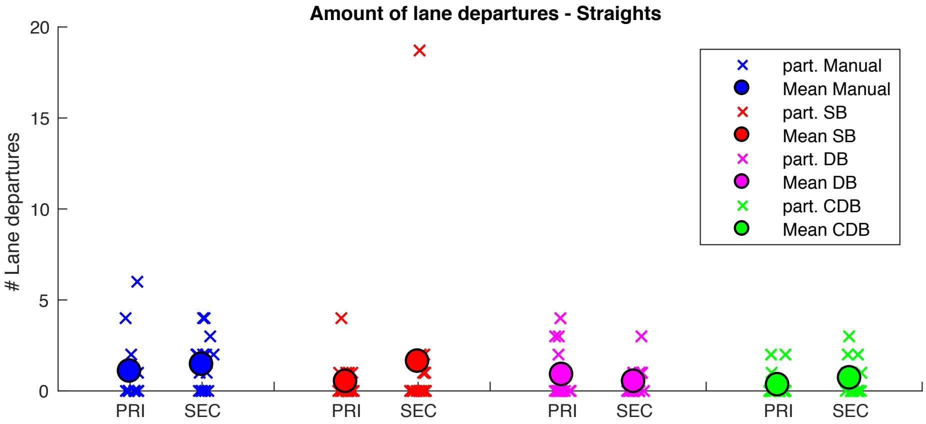
(b) Distribution lateral position on straights, all support types, distracted driver (secondary task)

Fig. 7: Distribution of the lateral position (m) of all participants per support system (i.e., Manual, Single Bandwidth, Double Bandwidth, Continuous Double Bandwidth) for the straight road sections for distracted (secondary task) and non-distracted (primary task) driver. The truck's lane margins are indicated by the dashed lines. They represent the distance between the truck and lane markings when the truck is positioned in the center of the lane. Bins are 0.01 m, the area under each of the four curves equals 1.

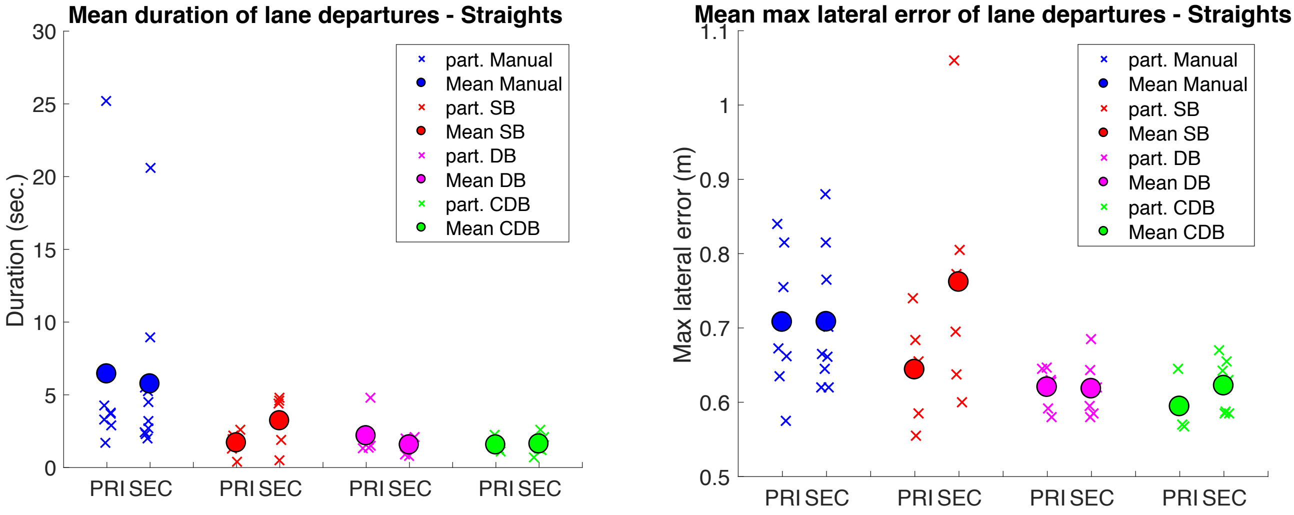
SB mean $= -0.17$m, DB mean $=-0.20$m, CDB mean $= -0.20$m; figure 7a) to a slightly left sided lane position during curves (Manual mean $= -0.07$m, SB mean $= -0.02$m, DB mean $= -0.07$m, CDB mean $= -0.08$m) as was seen in the mean values on all four support types for the non-distracted task. During the distracted task in curves the mean lane position moved even further to right. As can be seen in the mean values when comparing the straight (Manual mean $= -0.17$m, SB mean $= -0.10$m, DB mean $= -0.12$m, CDB mean $= -0.11$m) to the curved road sections (Manual mean $= 0.08$m, SB mean $= 0.09$m, DB mean $= 0.06$m, CDB mean $= 0.03$m). The curved road section resulted in a mean position on the right side of the lane center. During distraction manual driving again resulted in a higher distribution outside the lane margin compared to the support systems (this time outside the right lane margin).

3.2 Straight road sections

Table 1 shows the means and standard deviations of the dependent measures across participants for the four driving



(a) Amount lane departures (#)



(b) Mean duration lane departures (sec.)

(c) Mean max. lateral error lane departure (m)

Fig. 8: Lane departure information for a non-distracted (PRI) and a distracted (SEC) driver during straights sections of the track

support types for both with and without secondary task, during the straight road sections. The significance levels and main-effect levels of the ANOVA's are are shown in the table under respectively the p and F values. The outcome of the pairwise comparison was added in the last columns of the table and if an effect was present this is indicated by a x under the corresponding pair.

Performance measures

Engaging in SURT did not significantly affect participants' mean lateral position (p-task < 0.069). Engaging in SURT however did affect the standard deviation (p-task < 0.012), indicating participants have increased swirling behavior while distracted while resulting in similar mean lateral position as when not distracted. SB and CDB yielded in better lane keeping performance (lower mean absolute lateral error ($p < 0.001$) and lower standard deviations of the absolute lateral position per participant ($p < 0.005$)) compared to manual driving. During distraction participants had a larger standard deviation from their mean position compared to non-distracted driving (non-distracted $M = 0.104$m, distracted $M = 0.121$m). This effect was strongest for the Manual and SB support type as can be seen in the significance level of the interaction effect. This indicates that participants show increased swerving behavior when distracted, but DB and CDB reduce this swirling behavior resulting in a more constant lateral driving position.

All support systems yielded similar amounts of lane departures (figure 8a; non-distracted $M = 0.782$ lane departures per lap, distracted $M = 1.058$ lane departures per lap). However the mean duration and the mean maximum lateral error of the lane departures did show significant differences between the support systems (duration; $p < 0.017$, max lateral error; $p < 0.010$). Lower departure times and and smaller lateral errors were observed when using DB and CDB compared to manual driving, indicating effective haptic support resulting in improved safety as can be seen in figure 8b and 8c. The distraction task did not significantly affect duration and maximum lateral error of the lane departures (duration; $p < 0.956$, max lateral error $p < 0.172$).

TABLE 1: Means and standard deviations of vehicle state measures - Straights

	Primary task (a)				Secondary task (b)							Pairwise comparison support						Pairwise comparison support*task			
	Mean / (Std.)				Mean / (Std.)																
Variable	Man. (1)	SB (2)	DB (3)	CDB (4)	Man. (1)	SB (2)	DB (3)	CDB (4)	Support p / (F)	Task p / (F)	Support*Task p / (F)	1-2	1-3	1-4	2-3	2-4	3-4	a/b-1	a/b-2	a/b-3	a/b-4
Mean absolute position (m)	0.269 (0.024)	0.204 (0.014)	0.229 (0.017)	0.214 (0.016)	0.243 (0.025)	0.191 (0.010)	0.195 (0.014)	0.201 (0.016)	0.001 (7.163)	0.069 (3.880)	0.566 (0.636)	x		x							
Standard deviation absolute position (m)	0.110 (0.008)	0.096 (0.005)	0.110 (0.007)	0.100 (0.006)	0.133 (0.008)	0.126 (0.008)	0.115 (0.007)	0.108 (0.007)	0.005 (1.716)	0.012 (2.505)	0.045 (2.810)	x		x				x	x		
Amount lane departures (#)	1.063 (0.423)	0.500 (0.258)	0.875 (0.340)	0.313 (0.176)	1.438 (0.353)	1.607 (1.154)	0.500 (0.204)	0.688 (0.237)	0.370 (0.961)	0.286 (1.227)	0.450 (0.780)										
Mean duration lane departure (sec.)	6.430 (1.460)	1.690 (1.846)	2.176 (1.686)	1.550 (2.384)	5.743 (1.306)	3.208 (1.686)	1.550 (1.686)	1.614 (1.561)	0.017 (3.793)	0.956 (0.003)	0.905 (0.187)		x	x							
Mean max lateral error lane departure (m)	0.708 (0.033)	0.644 (0.039)	0.620 (0.035)	0.594 (0.050)	0.708 (0.029)	0.762 (0.035)	0.618 (0.035)	0.622 (0.033)	0.010 (4.295)	0.172 (1.931)	0.313 (1.223)		x	x							
Standard deviation steeringwheel-angle (deg)	2.600 (0.174)	2.812 (0.201)	2.640 (0.199)	2.455 (0.171)	2.127 (0.161)	2.648 (0.212)	2.292 (0.150)	2.077 (0.270)	0.024[1] (3.694)	0.148 (2.386)	0.482 (0.839)										
Steeringwheel Reversal Rate (rev./min.)	10.442 (0.842)	14.287 (1.546)	11.890 (1.013)	10.532 (0.826)	13.017 (1.304)	14.439 (1.139)	12.152 (0.712)	12.717 (0.746)	0.002 (6.009)	0.077 (3.694)	0.357 (1.081)					x					

Note. All measures are calculated for the trajectory existing of two straights and one constant curve. Man. = manual driving; SB = Single Bandwidth; DB = Double Bandwidth; CDB = Continuous Double Bandwidth. One participant driving with the DB system had no measurement recordings whatsoever because of hardware failure; connection towards the data-recorder failed.

TABLE 2: Means and standard deviations of HASTE and SURT scores - Straights & Curve

	Primary task (a)				Secondary task (b)							Pairwise comparison support						Pairwise comparison support*task			
	Mean / (Std.)				Mean / (Std.)																
Variable	Man. (1)	SB (2)	DB (3)	CDB (4)	Man. (1)	SB (2)	DB (3)	CDB (4)	Support p / (F)	Task p / (F)	Support*Task p / (F)	1-2	1-3	1-4	2-3	2-4	3-4	a/b-1	a/b-2	a/b-3	a/b-4
HASTE (0-10)	8.000 (0.408)	7.125 (0.375)	8.250 (0.281)	8.313 (0.472)	5.563 (0.447)	5.875 (0.427)	6.313 (0.454)	6.188 (0.467)	0.042 (3.064)	0.001 (17.907)	0.014 (3.922)				x				x		
SURT (# hits)	-	-	-	-	93.876 (9.767)	89.067 (8.010)	95.200 (7.478)	95.933 (7.122)	0.674 (0.415)	-	-										

Note. All measures are calculated for the trajectory existing of two straights and one constant curve. Man. = manual driving; SB = Single Bandwidth; DB = Double Bandwidth; CDB = Continuous Double Bandwidth.

TABLE 3: Means and standard deviations of vehicle state measures - Curve

	Primary task (a)				Secondary task (b)							Pairwise comparison support						Pairwise comparison support*task			
	Mean / (Std.)				Mean / (Std.)																
Variable	Man. (1)	SB (2)	DB (3)	CDB (4)	Man. (1)	SB (2)	DB (3)	CDB (4)	Support p / (F)	Task p / (F)	Support*Task p / (F)	1-2	1-3	1-4	2-3	2-4	3-4	a/b-1	a/b-2	a/b-3	a/b-4
Mean absolute position (m)	0.172 (0.015)	0.141 (0.012)	0.165 (0.014)	0.155 (0.015)	0.224 (0.032)	0.165 (0.013)	0.175 (0.016)	0.189 (0.017)	0.008 (5.435)	0.072 (3.793)	0.436 (0.927)	x		x							
Standard deviation absolute position (m)	0.113 (0.009)	0.089 (0.004)	0.108 (0.010)	0.096 (0.008)	0.142 (0.016)	0.109 (0.010)	0.108 (0.008)	0.114 (0.008)	0.003 (3.457)	0.068 (0.978)	0.311 (0.417)	x		x							
Amount lane departures (#)	0.200 (0.107)	0.067 (0.067)	0.467 (0.215)	0.400 (0.335)	0.933 (0.463)	0.133 (0.091)	0.200 (0.107)	0.400 (0.163)	0.141 (1.933)	0.456 (0.587)	0.182 (1.742)										
Mean duration lane departure (sec.)	3.800 (0.794)	1.650 (0.972)	2.800 (0.794)	1.570 (0.972)	2.450 (0.486)	2.113 (0.794)	1.380 (0.615)	1.460 (0.615)	0.163 (1.870)	0.280 (1.224)	0.561 (0.701)										
Mean max lateral error or lane departure (m)	0.747 (0.043)	0.653 (0.053)	0.756 (0.043)	0.627 (0.053)	0.657 (0.028)	0.641 (0.043)	0.600 (0.033)	0.625 (0.033)	0.264 (1.419)	0.035 (5.079)	0.199 (1.648)										
Standard deviation steeringwheel-angle (deg)	2.364 (0.279)	2.718 (0.222)	2.851 (0.321)	2.792 (0.295)	2.169 (0.118)	2.546 (0.211)	2.497 (0.179)	2.177 (0.164)	0.029^1 (3.532)	0.192 (1.915)	0.529 (0.702)										
Steeringwheel Reversal Rate (rev./min.)	11.174 (0.924)	13.276 (1.535)	12.119 (1.176)	19.907 (1.054)	14.939 (1.100)	15.574 (1.536)	14.709 (1.342)	10.447 (1.036)	0.004 (5.182)	0.016 (7.737)	0.338 (1.148)					x					

*Note.*All measures are calculated for the trajectory existing of two straights and one constant curve. Man. = manual driving; SB = Single Bandwidth; DB = Double Bandwidth; CDB = Continuous Double Bandwidth. One participant driving with the DB system had no measurement recordings whatsoever because of hardware failure; connection towards the data-recorder failed.

TABLE 4: Means and standard deviations of subjective measures - Straights & Curve

	Primary task (a)					Pairwise comparison support					
	Mean / (Std.)										
Variable	Man. (1)	SB (2)	DB (3)	CDB (4)	Support p / (F)	1-2	1-3	1-4	2-3	2-4	4-4
Vanderlaan Usefulness (-2 to +2)	-	0.188 (0.097)	0.238 (0.074)	0.263 (0.072)	0.667 (0.327)						
Vanderlaan Satisfying (-2 to +2)	-	-0.234 (0.138)	0.188 (0.128)	0.359 (0.082)	$1{\cdot}10^{-9}$ (11.524)				x	x	
System Usability Scale (0-100)	-	62.000 (3.291)	70.250 (3.405)	71.750 (3.435)	$1{\cdot}10^{-15}$ (11.425)				x	x	

*Note.*All measures are calculated for the trajectory existing of two straights and one constant curve. Man. = manual driving; SB = Single Bandwidth; DB = Double Bandwidth; CDB = Continuous Double Bandwidth.

Control activity

A significant effect was found when comparing participants mean standard deviation of the steering wheel-angle between the four support types ($p < 0.024$), mainly resulting from the high mean values of the SB system. Apparently the participants had more trouble controlling the truck with the SB setting as shown by the high amount of steering wheel reversals. The post-hoc comparison ('Bonferroni') however did not show pairwise significance. The variability in how participants use the system is therefore similar for all support systems compared to manual driving for both a distracted or a non-distracted driver.

All support systems show similar reversal rates compared to manual driving whether distracted or not. In other words the secondary task did not affect the participants' control activity and all support systems showed similar control activity as the participants did during manual control. The control activity was however significantly lower for CDB when compared to SB ($p < 0.019$) indicating a higher activity was needed to use SB, potentially indicating increased comfort using CDB compared to SB. Interesting is that when participants are distracted the support types manual driving, DB and CDB show similar mean amounts of steering wheel reversals, however manual driving shows an almost double standard deviation. In other words driving manually while distracted showed larger individual differences; some participants showed active and others more relaxed steering.

3.3 Curved road sections

Table 3 shows the means and standard deviations of the dependent measures across participants for the four support systems during the curved road sections, just like table 3 did for the straight road sections.

Performance measures

Distraction during driving did not affect participants' mean absolute lateral position ($p < 0.072$). Contrary to the straight road sections, the standard deviation of the absolute lateral error was not affected by the distraction task during curves ($p < 0.068$). Similar to the results found for straight sections, SB and CDB yielded in better lane keeping performance (due to a lower mean absolute lateral position error ($p < 0.008$) and lower standard deviations of this error ($p < 0.003$) per participant) compared to manual driving. The reduced swirling effect for DB and CDB (that was observed during straight road sections) is however not shown during curved road sections.

Just like the straights road sections, the amount of lane departures did not differ between the four support types independent of driver distraction (support systems; $p < 0.141$, distraction; $p < 0.163$). During curved road sections the guidance systems were not effective in reducing the mean lane departure duration or the mean maximum lateral error of the lane departure. The mean maximum lateral error was however affected by the distraction of the participant ($p < 0.035$). During distraction the mean maximum lateral error was lower compared without distraction. This was caused by high mean values during the manual ($M = 0.747$) and DB support ($M = 0.765$). Table 3 shows an overall low amount of lane departures during curves (even without support ($M = 0.200$ lane departures per trial-lap)). Because the low amount of lane departures during curves the measures regarding the lane departures that did occur can be sensitive to large variations. Manual driving and the DB support without distraction resulted in respectively 3 and 7 lane departures total. For these two support types, mean the duration and mean maximum lateral error of lane departures thus show to be sensitive to outliers which potentially explains the counter-intuitive result.

Control activity measures

Similar to straight road sections, a significant effect was found when comparing participants' mean standard deviation of the steering wheel-angle between the four support types during the curved road section ($p < 0.029$). However the 'Bonferroni-correction' again diminishes this effect. The variability in how participants use the system is thus similar for all support systems compared to manual driving for both a distracted or a non-distracted driver.

All support systems show similar reversal rates compared to manual driving. The distraction thus did not affect the participants' control activity and all support systems showed similar control activity as the participants did during manual control. The control activity was however significantly lower for CDB support compared to SB support ($p < 0.025$). The lower control activity suggests more relaxed steering behaviour using CDB support compared to SB support. Interesting is that the distraction task resulted in an overall higher control activity when compared to straight road sections ($p < 0.016$). The larger effect on control activity during curves suggest a more challenging driving circumstance. This circumstance demands more steering wheel corrections, which are further increased when participants are distracted.

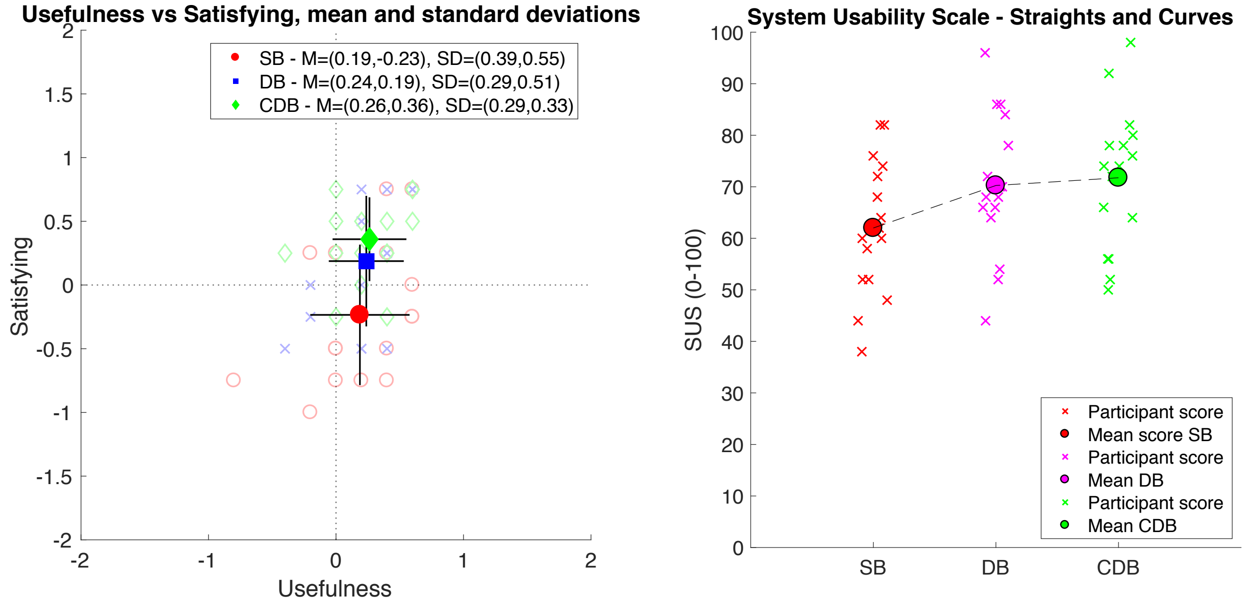
3.4 Straight and curved road sections

Table 2 and 4 show the means and standard deviations of the dependent measures across participants for the four support types for measures where the straight and curved road sections were combined.

Driver acceptance measures

The HASTE rating is lower for distracted driving compared to non-distracted driving ($p < 0.001$). The DB support has higher performance ratings when compared to the SB support ($p < 0.023$). Also an interaction effect is shown for the SB support when distracted vs. non-distracted ($p < 0.014$). This means that the addition of support yielded improved self-rated performance for the DB and CDB support systems but not so much for SB support during non-distracted driving.

The between-experiment questionnaire resulted in three driver acceptance ratings; usefulness, satisfaction and usability. Figure 9a shows the usefulness and satisfaction scores from the 'Vanderlaan' questionnaire. All support systems result in a similar positive mean usefulness scores ($p < 0.667$). However only the DB and CDB support systems result in a positive mean satisfying score. The driver satisfaction for the DB and CDB support are significantly



(a) Overall means and standard deviations Usefulness (horizontal) and Satisfying (vertical) ratings for SB (red), DB (blue) and CDB (green) support systems

(b) System Usability Scale on a scale from 0-100 per participant with the overall mean per support system; SB (red), DB (pink), CDB (green)

Fig. 9: Driver acceptance ratings for the support systems SB, DB and CDB: left; System Usability Scale, right; VanderLaan acceptance questionnaire

high compared to the SB support (SB-DB; $p < 0.014$, SB-CDB; $p < 0.001$) therefore they are more likely to be accepted in real life compared to the SB support. Fig. 9a also shows smaller standard deviations and thus narrower spreads in participant ratings for the DB and CDB (std-DB $= (0.29, 0.51)$, std-CDB $= (0.29, 0.33)$) support compared to the SB support (std-SB $= (0.39, 0.55)$). Figure 9b shows the SUS for the straight and curved road sections combined. The DB and CDB support systems scored significantly higher on usability compared to the SB system ($p < 1 \cdot 10^{-15}$). As mentioned in section 2.6 a SUS of at least 70 qualifies as a usable system which means both DB ($M = 70.25$) and CDB ($M = 71.75$) qualified usable however SB ($M = 62.00$) did not.

Table 1 show no significant effects ($p < 0.674$) for the SURT, therefore indicating similar distraction levels from the SURT during all four support types.

The post-questionnaire (Appendix F) showed an overall participant preference for the CDB support, with an overall preference score of 21. Nine out of sixteen participants placed the CDB system as their first preference, three participants as their second preference and four participants placed it their last preference. The DB support has an overall preference score of 17 and is the second favorite option of the drivers. Four participants placed it as their first choice, nine as their second choice and three as their last choice. The SB option scores lowest compared to the DB and CDB option with an overall score of 10. Three participants placed the system as their first choice, three as their second choice and more then half of the participants (nine) placed it as their least preferable choice.

4 DISCUSSION

Three haptic support options were evaluated based on lane keeping performance, control activity and driver acceptance. The support options were evaluated separately for straight and curved road sections during distracted and non-distracted driving.

4.1 Benefits and limitations

Only the Continuous Double Bandwidth (CDB) support system showed a more accurate lane distribution during both straight and curved road sections. The other support options (Single Bandwidth (SB) and Double Bandwidth (DB)) also showed a narrower lane distribution during straights however did not achieve this during curved road sections. Participants supported by SB and CDB support yielded more accurate lane keeping performance compared to steering manually for both straight and curved road sections (based on their mean lateral position). This corresponds to empirical findings for continuous support from previous studies (Flemish et al. [13], Mulder et al. [33], Petermeijer et al. [38]). The increased lane accuracy was stronger for the straight compared to the curved road sections. This indicates that more frequent guidance yields improved lane-keeping accuracy (similar to findings from Petermeijer et al. [38]). Results show that all support types (including manual driving) yielded equal numbers of lane departures, however the duration and the maximum lateral error of a lane departure are significantly lower when the driver is supported by DB or CDB systems compared to manual driving, consistent with findings from Petermeijer et al. [38]. Since the number of lane departures is consistent, it implies that the support options not only increases awareness about the lane boundary being crossed but also actively reduces the intensity (duration and lateral error) of the lane departure. This effect was however not shown during curved road sections. This can be explained by the low number of lane departures for manual driving and all three support options during curves. This resulted in fewer data-samples compared to non lane departure related measures, which made the measures (duration and max lateral error of the lane departures) sensitive to outliers during curves and therefore unreliable. A higher sample-size potentially leads to more reliable results, in order to evaluate the support systems' effectiveness to avoiding large lane departures during curves.

All three support systems resulted in similar steering wheel-angle variability, and steering wheel reversal rates compared to manual driving, indicating similar efficiency in steering tactics and control activity. An example of two different steering tactics is a driver that uses a near constant steering wheel angle or a driver that uses lots of different steering wheel angle inputs around a certain mean. Both drivers end up with similar mean steering wheel-angle values, however they used the system in a different way as seen by the number of steering wheel reversals. The similar variability of the steering wheel-angle combined with similar steering wheel reversal rates indicate a corresponding response between drivers, on how to control the support systems efficiently (usability). This corresponds to the drivers self-reported System Usability Scale scores, that showed high usability of DB and CDB guidance compared to SB guidance. SB guidance scored low on this scale indicating more misinterpretation among drivers on how to use this system. This is again seen in the objective data where the SB guidance showed higher steering wheel-angle variance compared to CDB guidance. The CDB guidance is thus easier to understand by the drivers and results in the lower control activity compared to SB guidance. The continuity of the support plays an important roll in this since its easier to understand a systems intention without an activation bandwidth. Humans are better able to understand a systems intentions and limitations when continuously supported [1]. Therefore humans are better able to integrate haptic with visual information, consistent with findings from Ernst et al. [12].

During straight sections, drivers showed a preferred off-centered lane position towards the left for all four support types, which means a smaller effective lane margin. A small effective lane margin means a higher probability of lane departure and therefore affects traffic safety. The use of haptic support systems SB and CDB improved the lane accuracy (mean lateral position error towards zero and smaller standard deviation) and therefore increases the effective lane margin, meaning a higher safety margin to avoid an unintended lane departure. During curves the guidance systems SB and CDB again improved the lane accuracy. Drivers however yielded a mean lateral position towards the right side of the lane center, therefore effective lane margins were larger during curved road sections compared to straights.

4.2 Benefits and limitations during distracted driving

Results (standard deviation of the lateral position) indicate that visually distracted drivers showed increased swerving behavior on straight road sections compared to non-distracted drivers, corresponding with findings from several studies [4] [8] [11] [40]. However when supported by DB or CDB guidance this effect is significantly reduced. This corresponds to findings of Blaschke et al. [4] that showed smaller maximum lateral deviations and less lane departures for distracted driving with the use of haptic lane-keeping support (both bandwidth and continuous support) compared to without. This shows the benefits of using DB and CDB support on lane-keeping performance are higher when driving distracted. Distracted drivers cause larger lateral errors therefore the guidance systems have more effect compared to non-distracted drivers. Driving with the DB system, means the driver essentially only receives corrective support when boundaries of acceptable lane performance are exceeded. Until then the system basically acts as a manual system. This is almost similar to the CDB support, where the amount of exerted torque when driving acceptable was tuned to be low but increases significantly when lane margin are close to being exceeded. Since both support systems exert most of the steering support when the lane margins are almost exceeded, the support systems are more useful to correct for driver errors, which is more likely to occur when the driver is distracted. Both systems therefore find their true potential by correcting large human errors instead of constant improvement of the lane accuracy [m].

Distracted, all three support systems do not directly improve lane keeping accuracy but show an effect of reducing the lateral error during lane departures. Drivers mentioned driver-support conflicts (Appendix H: Driver comments). The higher control activity [rev./min.] that was observed during the curved road sections can be explained by drivers trying to correct for or cope with such conflicts. This indicates that the support algorithms are not well capable of determining an acceptable lane position during curves. Drivers show different approaches in committing to a corner and do not always prefer the lane centered position, as was reported by Mulder et al. [33]. When the support algorithms use this lane center position as a control target it is likely that a conflict between driver and system will arise. A haptic architecture that offers manual tuning of the haptic support, or a controller that tunes these settings on its own, can be ways to overcome such conflicts as is acknowledged and investigated by Boink et al. [5]. In an attempt to apply an individualized controller on curve negotiation they found that too high steering wheel torques during individualized support resulted in an overall preference for a non-individualized system. Further research towards implementing individualized control like the study of van Paasen et al. [27] is needed to reduce conflicts during curves negotiation in order to ultimately result in improved lane-keeping performance with high acceptance.

The pitfall of a system that is working too well is behavioral adaptation. When the support systems are increasing safety margins and work without many driver conflicts, the driver might rely too much on the system as was reported in a study towards behavioural adaptation resulted from the use of support system by Smiley et al. [42] [30]. Over-reliance has the potentially to results in unwanted aftereffects as was shown by Petermeijer et al. [38]. This study simulated a system malfunction before a curved road section which resulted in large lane departures with the use of continuous support but not so much using bandwidth support. The dead-zone (no guidance torques) in the bandwidth support maintains high driver involvement allowing the driver to detect and respond earlier to potential system malfunction, therefore reducing the effect of behavioural adaptation.

The distraction task resulted in similar scores over all four support types, indicating equal devotion to the secondary task for all support options. In future work it would be interesting to evaluate not only the number of secondary task hits but also the reaction times of participants between secondary task hits as a workload indicator, as bandwidth support resulted in higher reaction times when compared to continuous support by Petermeijer et. al [38]. The study ([38]) however did not result in different reaction times of the support systems when compared to manual driving but did show shorter reaction times for continuous support vs. bandwidth support.

4.3 System acceptance

Implementation of haptic support to the real world requires driver acceptance. One of the factors that influences driver acceptance is a driver that is unaware of a systems limitations. This is observed in driver comments during the experiment that emphasized the importance of proper system understanding to achieve proper human-system integration. Drivers expectancies towards a systems corrective capabilities should match the, by the systems, applied correction. If not the case, human-system conflicts are likely to arise. Such conflicts can lead to annoyance or distrust, and these should be avoided in order to increase driver acceptance. This is similar to other studies that reported driver annoyance because the system was too difficult to interpret [38] [44]. This study showed corresponding driver comments during curved road sections regarding the system not living up to participants' expectations, or misinterpretation of the provided steering support.

The 'Vanderlaan' questionnaire showed positive usefulness scores for all three support systems. Most drivers thus acknowledged the benefits the system brings to the driving task. Since the effect of the guidance systems is larger during distracted driving it is possible that drivers assessed the usefulness of the system on the ability to correct the driver when distracted. It also resulted in higher (positive) satisfaction scores for both DB and CDB compared to SB that scored negative on satisfaction. The SB support had a similar low satisfaction score in an earlier study by Petermeijer et al. [38] where the SB support scored approximately 0 in range from +2 to -2. The reason this study resulted in a even lower satisfaction score for SB support is likely caused by the constant amount of steering torque exerted to the steering wheel when the lateral position treshold was exceeded, where Petermeijer et al. used a linear relation between lateral position to determine the amount of guidance torque exerted to the steering wheel. This was observed in drivers comments regarding a dislike to the binary torques and the way the support torque steps-in: "This was the worst. Quite clearly a gap taking over quite harshly. Less respectful to me as a driver", "More uncomfortable and more annoying to drive with", "it applies support too strong, perhaps it could send the support more stepwise". The SB system provides support shorter compared to double bandwidth which guides the driver back towards middle of the lane. The presence of only one treshold compared to two (Band2 in Petermeijer et al. [38] and DB in this study) and the constant amount of guidance torque instead of linear progressing are therefore most likely the reason of low (negative) driver satisfaction score for SB support in this study. The CDB support resulted in a smaller standard deviation on satisfaction ratings compared to both DB and SB support. This indicates accurate satisfaction ratings for CDB, where this was not the case for DB and SB support that showed more individual differences in satisfaction ratings. CDB support therefore not only showed the highest satisfaction ratings but also showed to be more equally well liked by different drivers.

The positive satisfaction scores of the DB and CDB support systems are promising findings for real life implementation but the systems have room for further improvements. Drivers commented positively about both guidance options, where some drivers preferred the freedom provided by the bandwidth support gap, where others preferred the smooth transitions of the continuous support. For both systems the drivers however mentioned the benefit of having a system more tunable to personal preference: DB; "Easy to steer jointly with the system. More maneuverability within the lane than CDB", DB; "I like being able to have a dead zone in the middle where I can control the truck on my own.", CDB; "Like it better this way. More subtle, more smooth. The level of the force is like something that would occur naturally.", CDB; "Engage a lot smoother, more comfortable, but gives me less confidence, need to be more concentrated (compared to DB)", CDB; "I would like to be positioned where I want". Clearly some drives prefer the DB support where others prefer the CDB support. The overall driver system preferences were evaluated based on the results from the after-questionnaire. This showed a first preference for the CDB support and a second preference for DB. Since both these systems score similar in lane keeping performance, satisfying and usefulness scores, it comes down to individual driver preference; bandwidth support with interventions only when needed (with personal preferences regarding timing and the amount of support), or continuous support with smoother support transactions that may affect driver confidence.

Drivers reported lots of conflicts in the curved road section, similar as was shown by Mulder et al. [33]. Three examples of comments from different drivers during curves: "the system keeps me on the left side of lane and does not allow me to move to inside (right side) where I want to be", "I do not know exactly where it wants me", "I want to be on the inside (of the curve) but it forces me to be on the middle.", "during straights I preferred steering support but during curves I preferred manual driving". This showed that the support systems did not live up to the drivers expectancies, resulting in many human-system conflicts during curves, which led to low system acceptance and even preference for manual driving in the curved road sections. During the straight road sections this was however not the case and drivers commented positively on both of the support systems: "pleasant to use, not intrusive and still very useful", "stable on the straights, good position inside the lane, a nice smooth ride", "It is like having good suspension, that helps to make the drive more comfortable, but you need to experience it for some time to assess that". This indicates that the support systems' capabilities are better aligned with the driver's expectancies during straight road sections, and challenges arise with individual driver preferences in curve negotiation, as mentioned in section 4.2, and as was reported by Boink et al. [5] and van Paasen et al. [27].

As mentioned in section 4.1, the system usability scale was lowest for the SB support compared to the DB and CDB support systems, indicating less efficient steering tactics among drivers when using the SB system. This is in agreement with the comments made by drivers using the SB support mentioned above. The higher scores for the DB and CDB support systems indicate sufficient ease of use and learnability of the systems. This is in agreement with the findings from the standard deviation of the steering wheel-angle that showed similar driving behaviour among drivers using the same system.

According to the self-reported HASTE-score (overall driving performance driver-system combined) the SB support was less capable increasing self-reported driver performance compared to DB and CDB support when driving without distraction. This can be explained by the number of driver reported conflicts when using the SB system. When the driver is non-distracted s/he is likely more aware of arising conflicts compared driving with a higher workload, during distraction. When the attention is shifted to the secondary task it is possible that the driver is more concerned about his/her lateral vehicle control and therefore will give way to the provided corrective support instead of fighting it which results in a conflict. Such priority towards lateral performance when distracted is similar to findings from Östlund et al. [36] and Beede et al. [3] where drivers under high cognitive load prioritized lateral vehicle control over peripheral driving task in an effort to protect their lane keeping performance.

5 CONCLUSION

Three haptic support systems were evaluated during normal and distracted driving based on two key factors relevant to real-life implementation; lane keeping performance, and driver acceptance. A double bandwidth (DB) support system and a continuous double bandwidth (CDB) support system have shown to be able to achieve a more accurate lane position and reduce large lane departures (> 0.7m) compared to driving without a support system, while both systems resulted in high self-reported driver acceptance. These safety benefits of the support systems are to a greater extent beneficial when the driver is distracted: larger swerving behaviour was observed during distracted driving which was reduced by the use of both the DB and the CDB support systems. The CDB support system however scored highest on driver satisfaction and system usability, showed to be more comfortable compared to SB support, and was overall preferred based as resulted from a post-experiment questionnaire. The single bandwidth support system resulted in a more accurate lane position compared to manual driving however did not reduce large lane departures and scored significantly low on satisfying and usability scores compared to both the DB and the CDB support systems. During curved road sections all support systems were unsuccessful reducing large lane departures, while participants commented on more driver-support conflicts. Both DB and CDB support systems have shown to have the potential of improving traffic safety by being well-liked while reducing large unintended lane departures where this was not the case for the single bandwidth .

Future research should investigate the application of controllers that adapt to individual driver preferences, to bandwidth and continuous support. This potentially improves the performance of the support systems during curved road sections. It is also encouraged to study the best threshold limits and the best ways to fade-in and fade-out support feedback, in order to maximize driver acceptance while benefiting from improved lateral performance.

ACKNOWLEDGMENTS

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KEY POINTS

- Both double bandwidth (DB) and continuous double bandwidth (CDB) improved lane accuracy and prevented large lateral position errors (> 0.7m).
- DB and CDB support showed high self-reported driver acceptance ratings with an overall driver preference for the CDB support system.
- Driver distraction resulted in large swerving behaviour which was reduced by the use of both the DB and the CDB support systems.
- Single bandwidth support showed improved lane accuracy but was unsuccessful reducing large lane departures and was rated low on driver acceptance.
- During curved road sections all support systems were unsuccessful reducing large lane departures and participants commented on more driver support conflicts.

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A

Simulink models - Support structures

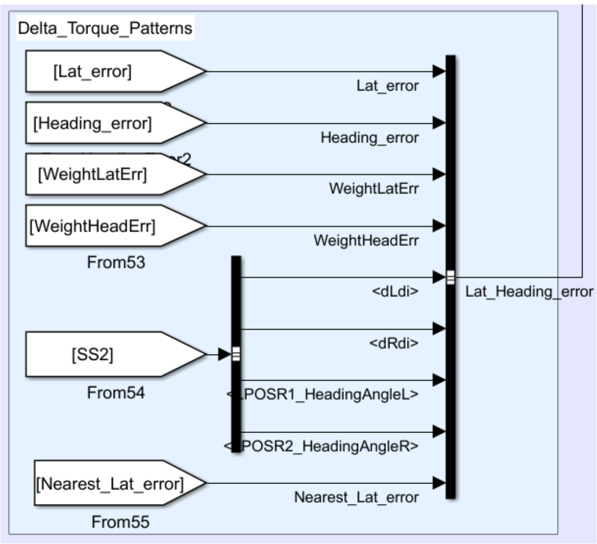


Figure A.1: Simulink print-screen of sensory inputs for support algorithms

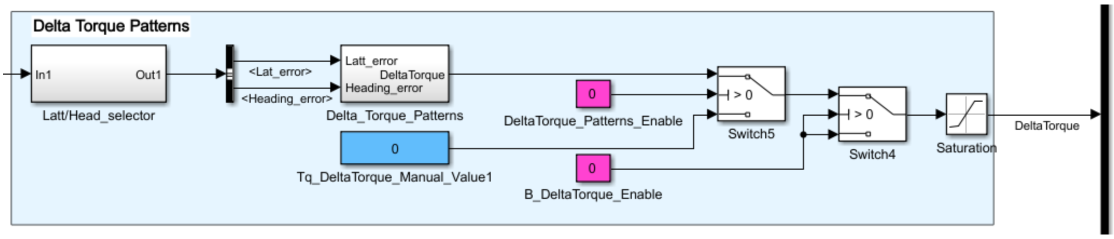


Figure A.2: Simulink print-screen of delta torque activation and overall saturation for driver and road safety

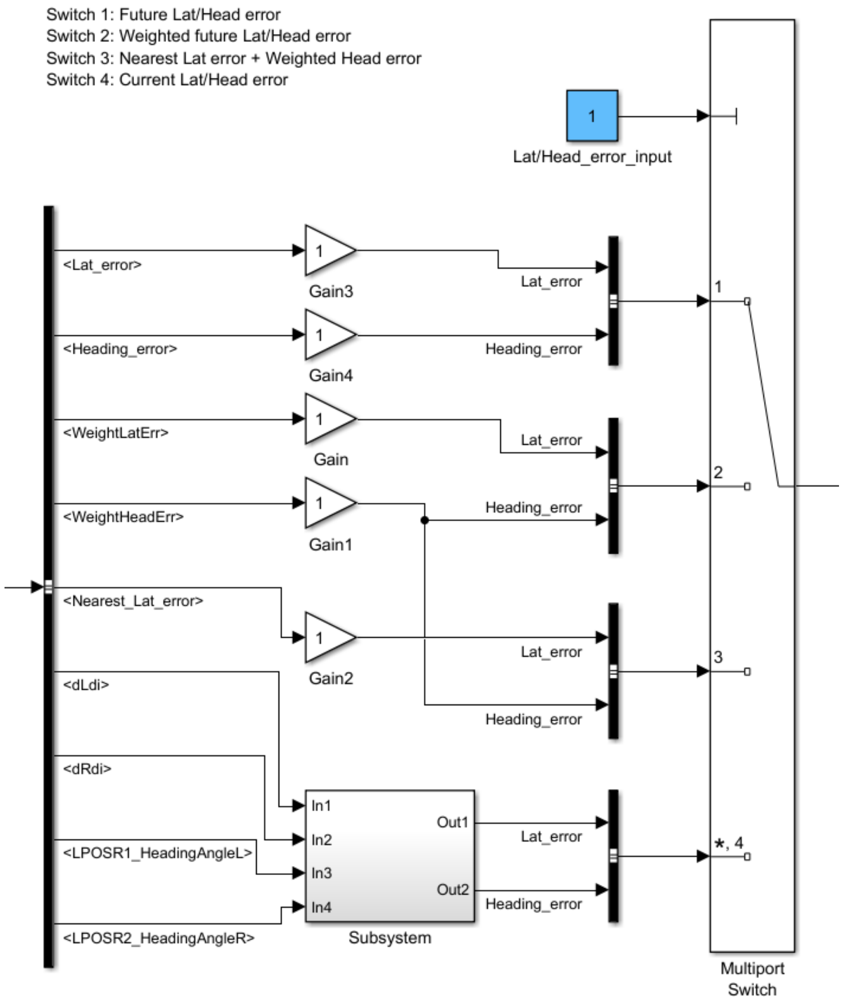


Figure A.3: Simulink print-screen of selector for sensory inputs combinations

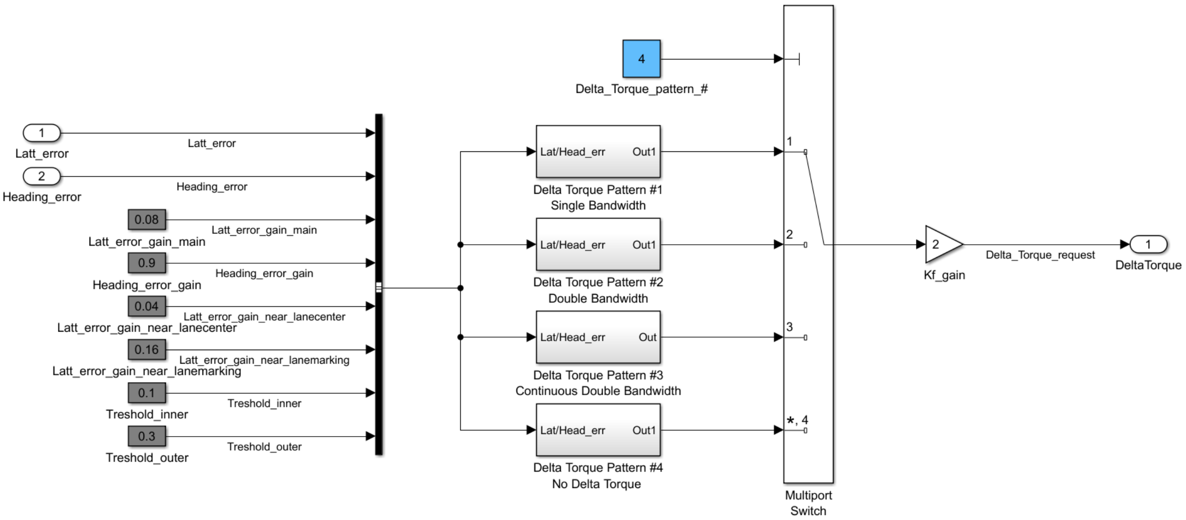
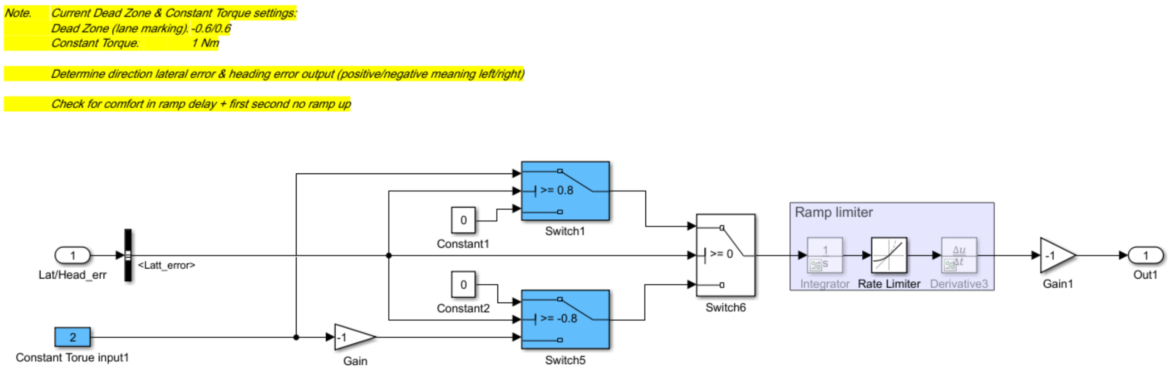


Figure A.4: Simulink print-screen of inputs for support algorithms gains based on literature findings. Gains are adapted after tuning prior to experiment and new gain values can be found in the rapport under section 2.5

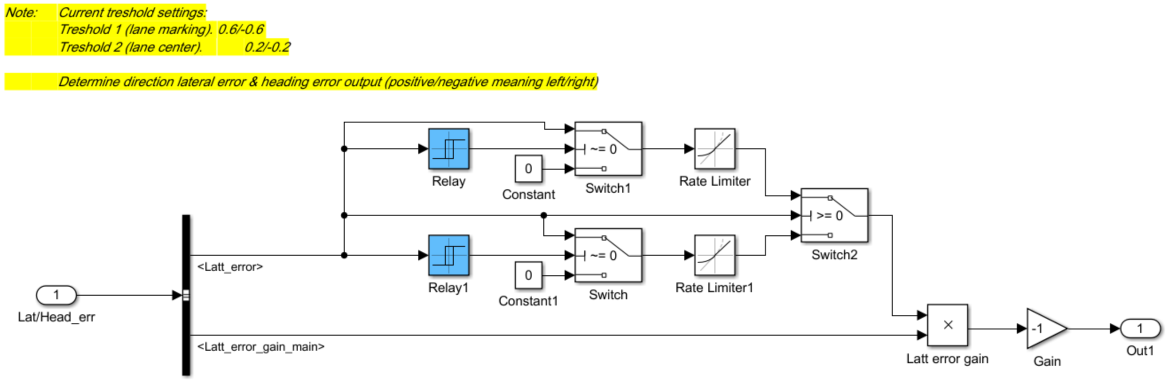


Note. Current Dead Zone & Constant Torque settings:
Dead Zone (lane marking): -0.6/0.6
Constant Torque: 1 Nm

Determine direction lateral error & heading error output (positive/negative meaning left/right)

Check for comfort in ramp delay + first second no ramp up

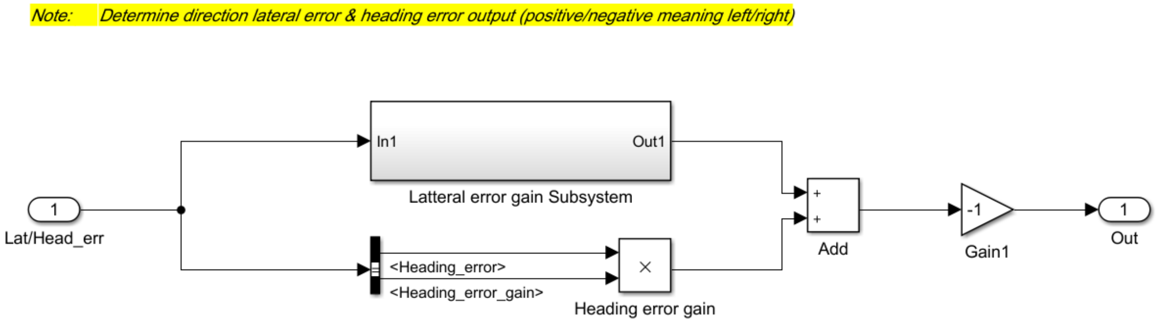
Figure A.5: Simulink print-screen of single bandwidth (SB) support structure



Note: Current treshold settings:
Treshold 1 (lane marking): 0.6/-0.6
Treshold 2 (lane center): 0.2/-0.2

Determine direction lateral error & heading error output (positive/negative meaning left/right)

Figure A.6: Simulink print-screen of double bandwidth (DB) support structure



Note: Determine direction lateral error & heading error output (positive/negative meaning left/right)

Figure A.7: Simulink print-screen of continuous double bandwidth (CDB) support structure including heading error

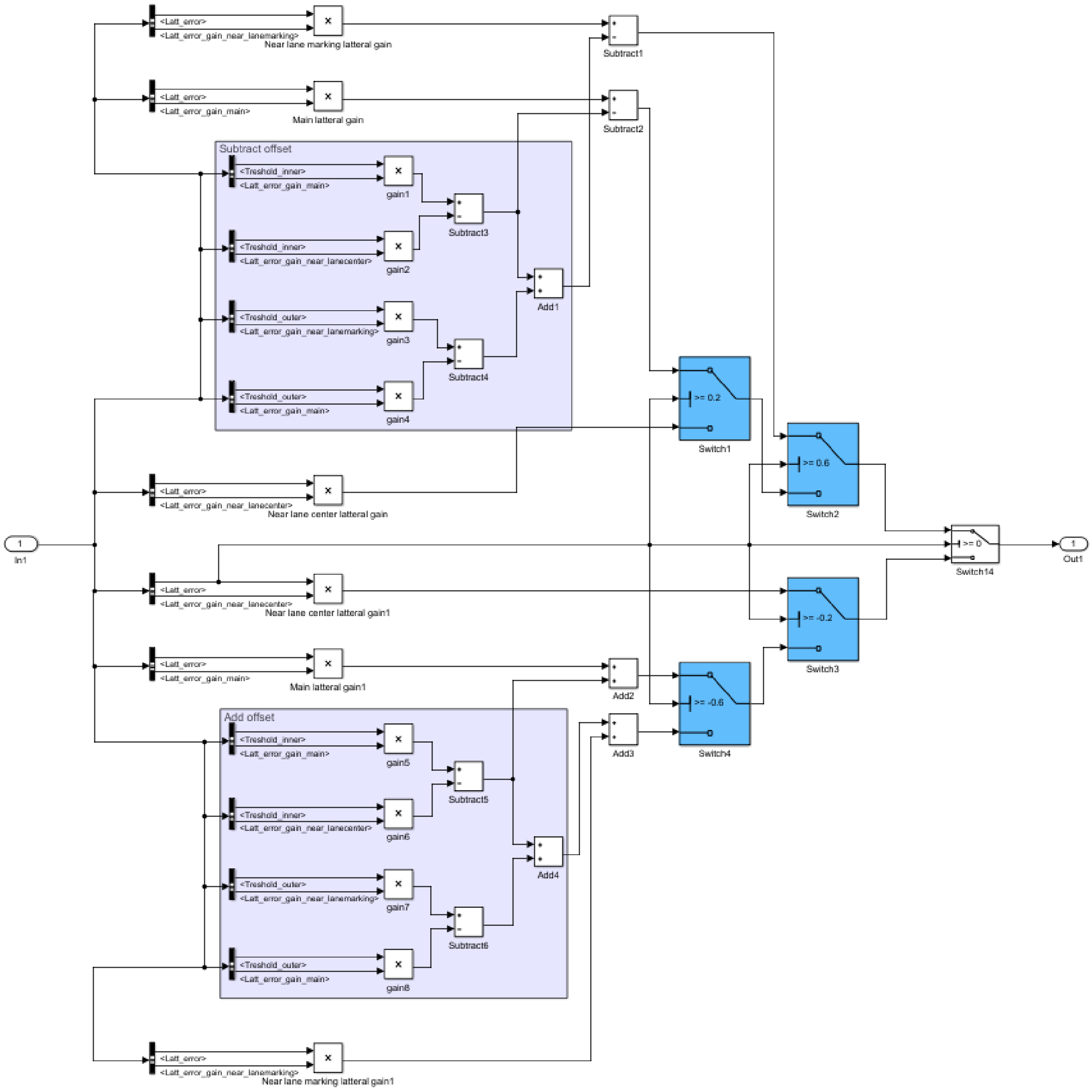


Figure A.8: Simulink print-screen of continuous double bandwidth (CDB) support structure, inside subsystem

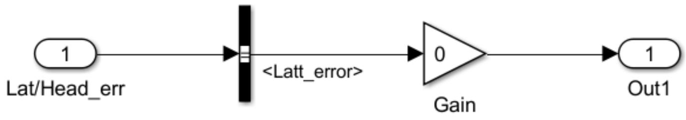


Figure A.9: Simulink print-screen of manual support structure, delta torque set to 0

B

Track rules Hällered

Licensed Hällered drivers are obliged to follow a course where they are taught about the following types of rules:

- Safety procedure in case of accident/emergency
- Regulations on the various road types; speed thresholds, direction of driving, shared space
- Regulations on what permit is needed for each lane on high speed track, And what vehicles are prohibited on certain lanes.
- Communication with back-office/traffic control and between drivers in different vehicles.
- Procedures for entering and exiting a specific track.

C

Consent-form

VOLVO

Information
&
Consent form

Research study information

Volvo Technology (VOLVO) kindly ask you to participate in a research study on different types of lateral steering support. It is a part of our safety research and your participation is of great importance.

Your consent is necessary for us to be able to process data. If you accept to participate you need to read this document and give a written consent on the attached Consent form (Appendix B).

Description of study

The purpose of this study is to evaluate 3 settings of a function presenting different steering force in the steering wheel (non is intended to be driven with hands-off steering wheel). While you drive with these we will be collecting vehicle data, video data of you as a driver, subjective information via questionnaires and interviews as well as performance on a secondary task.

Your participation involves the following tasks:

- To drive a Volvo FH truck at Hällered on the High Speed Track in lane number 2.
- To keep the speed threshold by using cruise control (set speed should be 85 km/h).
- To follow the lane appointed by the test leaders. Normally the lane no. 2.
- To perform a lane change when told by the test leaders (from lane 2 to lane 1). Do not drive in lane 3 and 4.
- To use high beam lights when told by the test leaders (for annotation purpose only).
- To perform a so called secondary task (a game presented on a phone in the truck cabin) when prompted by the test leader. This one should be performed as fast and accurate as you possibly can. You should of course still keep the priority of driving safely.
- To estimate your *'level* of driving performance*'* during the drive when you are prompted by the test leader to do this. 1 is very bad and 10 is very good. You should take into account the sum of you and the system presenting lateral support when rating the overall driving performance.
- To answer questionnaires before and after driving.
- You will drive with three different version of lateral support with and without a secondary task.

The truck is equipped with:

- A tablet where the secondary task is presented.
- A camera to record visual behavior in the truck
- A vehicle data logger, logging lane position, speed & steering wheel angle & steering wheel torque

The recorded data will be used internally as well as presented in aggregated form externally.

Participation and withdrawal

Your participation in this study is voluntary. You have the right to withdraw at any time without giving any reason. If you choose to withdraw, all data transfer to the research partners will be stopped. Please note, however, that any information obtained from you prior to your withdrawal will still be used.

Risks

The experiment will take place on a closed test track. However, other tests might be going on in parallel and you are obliged to give way for faster moving vehicles and pay attention to road boundaries, still standing vehicles, humans or objects etc as you would do in real traffic conditions.

Personal data

When participating in this study personal data will be collected. Apart from the logged information, all background information (age and gender etc.) will be collected and stored for future analysis.

All information related to you as person will be treated according to the Swedish national privacy legislation (1998:204), PuL based on EU Directive 95/46/EC.

Conclusions from this study could be published, however all published data will be anonymized, your identity will not be revealed unless you give your written consent.

Collected data will be stored by the project member. Volvo is responsible for protection of the personal records.

In case of authority decisions, the project might be forced to release research records collected during this clinic. Apart from these, collected information will be handled within the research project according to your written consent.

If requested you can get access to information collected about yourself and your driving within this research study.

Appendix A

Contacts

If you have questions concerning data collection or the study in general, please contact:

Emma Johansson
Volvo Group Trucks Technology (GTT)
Advanced Technology & Research, BF46020
Office phone: +46(0)73-902 85 79
Email: emma.johansson@volvo.com
Website: www.volvogroup.com

If you have questions concerning the personal record collected about you during this research study please contact:

Marianne Carlsson
Controller of personal data at Volvo Group Trucks Technology (VOLVO),
Legal entity: Volvo Technology.
Volvo Information Technology AB
Dept. DE50600, VBBVN
405 08 Göteborg, Sweden
Office phone: +46 31 3224600
Email: marianne.carlsson@volvo.com

Project-ID: HARMONISE Date: 2017 w25-26, **TP ID:**___

Appendix B

Consent form

I have read and understood the information concerning this research study. It is clear what is expected of me in this study and I have been given the possibility to ask questions if anything has been unclear to me. I am informed about my right to withdraw without giving any reason.

I hereby agree to participate in the above described research study. I agree to have my personal data stored and processed by Volvo.

☐ Yes
☐ No

I also agree to have video recordings or pictures being published or shown in public events (e.g. research reports or conferences)

☐ Yes
☐ No

Place: __________________________ Date: ______________________

Signature: ____

Printed name: ____

Witnessed by: ____

Printed name: ____

Thank you!

We appreciate your participation.

D

Pre-questionnaire

Introductory questionnaire for experiment on automated driving - Demographics

*Required

Untitled title

1. **participant ID** *

____

2. **Gender** *

Mark only one oval.

○ Male
○ Female

3. **Year of birth** *

____

4. **What year did you obtain your driving license?** *

Mark only one oval.

○ B: ____________
○ C: ____________

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

Mark only one oval.

○ Several times a week
○ Several times a month
○ Several times every 6 months
○ Several times a year
○ Never

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

Mark only one oval.

○ Several times a week
○ Several times a month
○ Several times every 6 months
○ Several times a year
○ Never

7. **About how many kilometers did you drive the car in the last 12 months?** *

Mark only one oval.

○ 1 - 1000 km
○ 1001 - 10.000 km
○ 10.001 - 25.000 km
○ 25.001 - 50.000 km
○ 50.001 - 100.000 km
○ Over 100.000 km

ADAS

8. **Do you have experience with ADAS**

Mark only one oval.

○ Yes
○ No

9. **If yes; which ADAS?**

Tick all that apply.

☐ Cruise Control
☐ Adaptive Cruise Control
☐ Lane Departure Warning (acoustic, visual and/or haptic vibration in seat or steering wheel)
☐ Lane Keeping Assist (active steering support)
☐ Forward Collision Warning
☐ Driver Alert System
☐ Lane Change Support
☐ Automatic Brake Assist (CW-EB)
☐ Other: ____

10. **I would consider 'Force Feedback' on Lane Keeping Assist to be useful in a truck (see picture)** *

Mark only one oval.

	1	2	3	4	5	
Not useful	○	○	○	○	○	Useful

11. *

Mark only one oval.

	1	2	3	4	5	
Not pleasant	○	○	○	○	○	Pleasant

E

Between-experiment-questionnaire

Questionnaire between Feedback patterns

*Required

1. **Participant ID?** *

2. **Feedback pattern** *

   Mark only one oval.

   ○ NF
   ○ SB
   ○ DB
   ○ CDB

Acceptance

3. **What are your first thoughts about driving with this 'Force Feedback' option?**

4. **The 'Force Feedback' in this trial was easy to feel.**

   Mark only one oval.

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

5. **(Without taking the lane change into account) I find the 'Force Feedback' in the last trial:**

   Mark only one oval.

	1	2	3	4	5	
Useless	○	○	○	○	○	Useful

6. *Mark only one oval.*

	1	2	3	4	5	
Unpleasant	○	○	○	○	○	Pleasant

7. *Mark only one oval.*

	1	2	3	4	5	
Bad	○	○	○	○	○	Good

8. *Mark only one oval.*

	1	2	3	4	5	
Nice	○	○	○	○	○	Annoying

9. *Mark only one oval.*

	1	2	3	4	5	
Effective	○	○	○	○	○	Superfluous

10. *Mark only one oval.*

	1	2	3	4	5	
Irritating	○	○	○	○	○	Likeable

11. *Mark only one oval.*

	1	2	3	4	5	
Assisting	○	○	○	○	○	Worthless

12. *Mark only one oval.*

	1	2	3	4	5	
Undesirable	○	○	○	○	○	Desirable

13. *Mark only one oval.*

	1	2	3	4	5	
Raising Alertness	○	○	○	○	○	Sleep-inducing

System usability scale

14. **I felt I was in control of the driving task.**

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

15. **I felt the system was in control of the driving task.**

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

16. **I agreed with the vehicles direction that I was guided towards by the 'Force Feedback'.**

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

17. **I felt very confident using this torque feedback.**

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

18. **I felt safe performing the secondary task (while having the 'Force Feedback')**

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

19. **I found this torque feedback system very cumbersome/awkward to use**

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

20. **I needed to learn a lot of things before I could get going with this torque feedback.**

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

21. **What would you like to be changed in this support system if you would design it?**

F

Post-questionnaire

After experiment Questionnaire

1. **Participant ID?**

2. **Rank the 'Force Feedback' patterns and provide short reasoning.**

G

Literature survey

The effect of LKA Control Structures on driver Acceptance in active steering support for ADAS

H.A.L.G. Roozendaal

Literature Survey

Delft
University of
Technology

The effect of LKA Control Structures on driver Acceptance in active steering support for ADAS

Literature Survey
Vehicle Engineering

H.A.L.G. Roozendaal

November 7, 2017

Faculty of Mechanical, Maritime and Materials Engineering (3mE)
Delft University of Technology

Delft
University of
Technology

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Chapter 1

Introduction

Safety is one of the primary aspects of the driving task. Driving from A to B is a means of people's busy work and social life and stressful circumstances can directly affect driver focus towards the driving task. A results of combining driving with peoples busy life possibly explains why most accidents are caused by tiredness, distraction or lack of concentration. A system not affected by such longterm degrading effects, silently watching over the driver task and ultimately assisting at imminent dangers can significantly reduce these risk factors. These so called Advanced Driver Assistant Systems (ADAS), like active Lane Keeping Assist (LKA), therefore show potential to significantly improve traffic safety.
In the last decade the research and development towards such ADAS increased, and different methods for exerting assistant feedback (eg., through pedals or the steering wheel [9],[2]) have been proven to improve driver safety by monitoring, alerting or acting on the above risk factors [10],[11].

The automotive industry is trying to keep up with promising research outcomes but is simultaneously held back by safety regulations. The real-life implementation of such support systems showed not to be as straightforward as proof of concept studies performed in a simulator. Implementation in public vehicles goes hand in hand with increased system demands manufactures are obliged to follow. An example of a criteria list manufactures are oblige to follow is the "Road Vehicles - Functional Safety" ISO document that was latest revised in 2011, also known as ISO26262. One of the goals of this document is to ensure functional safety aspects throughout the entire development process are below an in the document determined risk assessment. This includes risk assessments concerning implementation, integration, verification, validation, and configuration. Such system demands are both expensive and time consuming to overcome and therefore affect the amount of support system that can be tested in real life. According to the ISO document an acceptable level of safety can only be achieved if the human aspect is properly integrated in the support system. Therefore development of a steering support system for real life implementation should be divided in two important aspects; the systems performance to increase a specific safety aspect and the cooperation between system and driver to complement one another in the driving task. The first aspect, increased performance, can easily but mistakenly be the main focus in the design of new support system. Since the driver is the one controlling the support system and ultimately responsible for the driver task, its acceptance towards a support system should be just as important as the systems safety performance aspect. A system build specific for risk reduction may result in better lane keeping performance but can without proper integration with the human still be evaluated as annoying or not satisfying therefore unlikely to be activated during a driving task as was mentioned by Parasuraman et al. [12].

Most big automotive manufacturers (like Mercedes, Audi, BMW, Volkswagen and Volvo) managed to implement a ISO26262 approved lane keeping support system that uses directional steering support. Simulator studies however evaluate more elaborate control structures compared to the ones now seen in real-life. Forsyth et al. [11] for example showed that advanced driver models are able to predict trajectories in a way that is both safe and satisfying for the driver. Abbink et al. [13] evaluated the combination of force and stiffness feedback to a control structure and Petermeijer et al. [6] evaluated the addition of an automation free zone. Blaschke et al. [4] implemented such more complex control structures in real life and found self-reported increased safety and helpfulness scores. These studies show potential for development of more complex control structures that can result in higher driver acceptance compared to less complex structures that can be found in real-life.

A gab can thus be defined between complex control structures evaluated in simulator studies that have the potential to increase driver acceptance, and control structures that are nowadays implemented in real-life. The aim of this literature survey is to look into this gab. It is to provide an overview of available control structures and show their effectiveness to improve lane keeping performance and drivers acceptance in simulator studies and real-life. The following research question including four subquestions will be answered to do so.

How do different LKA control structures affect lane keeping performance and driver acceptance in active steering support for vehicles?

Subquestions:

- What haptic LKA model structures are currently available or being developed within scientific literature?
- How are lane performance and driver acceptance evaluated within scientific literature?
- How do the found control structures affect the lane keeping performance?
- How do the found control structures affect the driver acceptance?

This survey will answer these questions by first addressing to the method in chapter 2. In this chapter the selection method of relevant papers will be addressed. In the following chapter the found published research will be explained by focusing on the above subquestions; what systems are available (section 3-3), how have these systems been evaluated based on performance and acceptance (section 3-4) and how are the different model structures affecting the driver performance and acceptance (section 3-5). The survey ends with a discussion about potential interesting control structures in chapter 4 and a short conclusions in chapter 5.

Chapter 2

Method

In order to find relevant literature related to the research question a software package called "Publish or Perish" was used [14]. This software uses manual search term inputs and cross reference them over selectable literature search engines, in this case; "Google Scholar", "Web of Science" and "Scopus". The used search terms were selected to find literature about LKA control structures and the effects they have on lane keeping performance and driver acceptance. Combinations of the following search terms were used; Haptic Shared Control, Lane Keeping Assist, Lane Keeping Support, Steering Support, Active Steering Support, Haptic Steering Feedback, Torque Feedback Steering, Driver Acceptance, Lane Keeping Performance, Lane Keeping Performance.
This search was performed mid March 2017 and a list of 500+ papers were the result. To limit down the result a criteria was introduced stating that the studies needed to be published in a scientific journal or had to be selected as a conference paper and needed to have at least 5 referrals. The abstract of the resulting papers were read to verify whether they fulfilled the inclusion criteria (exact criteria and explanation can be found below). A more thorough evaluation was done on the resulting ten papers and they were placed into a mind-map where they were linked based on control structures, experimental setups, experimental measures, driver acceptance and results as can be seen in Appendix C.

The following four inclusion criteria were used:

1. The experiment was designed to evaluate lateral control of the driver
2. The experiment was tested and evaluated in a real vehicle or in a driving like simulated environment
3. Participants were able to continuously control the vehicles lateral movement
4. Lane keeping feedback was provided through an actuated steering wheel

Since lane keeping control structures are usually a collaboration between feedback system and driver input (human-in-loop) the performance and acceptance effect of such systems is best measured when the driver faces a realistic driving experience. The first two criteria are there to specify the resulting papers towards just that: lateral vehicle control during a realistic driving experience.

Since this survey focuses on performance and acceptance in a man-machine shared control system, the third criteria; the driver should always be in control of the the vehicles lateral movement, is introduced. Without this criteria the control structure would be categorized as partly self-driving and entirely different criteria (like robustness, safety margins and path planning) would then define performance and acceptance of the overall system.

The fourth criteria is to make sure focus is put on active steering based on controlled torque corrections. Other ways of providing lane keeping assistance can for example be vibrations in the steering wheel which more classifies as a warning system in stead of a active guidance/assist system.

Lateral support systems often result in driver-system conflicts that affect the acceptance towards a system. Such conflicts arise when the system is exerting feedback to the driver that is unpleasant or unnecessary. Such conflicts can be reduced in two ways. One option is to lower the amount of conflicts by applying an advanced driver model (for example with predictive path planning). This was done by Nilsson et al. [15] where it was hypothesized that less conflicts will be present if the envisioned driver-model would exhibit a human-like control behavior. The second is to reduce the effect of a conflict by addressing the feedback forces as was done by Mars et al. [5]An exclusion criterium is introduced to evaluate the latter; reducing the conflict by evaluating the effect of different control structures.

Exclusion criterium:

1. An advanced driver model (with feed forward control or path prediction) was used to evaluate the lane keeping performance.

The papers that met the criteria are evaluated on three levels namely:

1. *Experimental set-up*, categorizes the experiments in simulator or real-life experiments
2. *Control structures*, are the different controller profiles on which the feedback amount is calculated. For example is the profile linear or constant, is the profile continuous or does it use bandwidths.
3. *Experimental measures*, evaluates the experimental measures used to assess the performance and acceptance of the system.

Finally the effect of the control structures on lane keeping performance and driver acceptance are evaluated by looking at the impact of the control structures on the objective and subjective measures taken in the studies.

Chapter 3

Results

3-1 Search results

The literature search resulted in 64 journal and conference papers of potential interest. Of these 35 are related to the Human Driver Model, 27 to Haptic Shared Control and the left over two about predictive guidance and environmental perception. Of these, eleven met the inclusion criteria. Five of these were available in scientific journals [6][16][4][17][3] and the remaining six were available in conference proceedings [1][18][7][8][5][19].

3-2 Study characteristics

Of the eleven studies two were conducted in real vehicles [4][18]. Eight studies used a medium fidelity driving simulator [1][6][17][7][8][5][19][3], and one study used a high-fidelity driving simulator[20]. A simulator was considered of medium-fidelity when it had wide field of view but no motion base. A high-fidelity simulator included both a moving base and a wide field of view. The same categorization was used by de Winter et al. [21]. The remaining study qualifies as a literature survey and uses both real vehicle and simulator data [16]. On overview of the study characteristics can be found in table 3-1.

Table 3-1: Study characteristics

Medium-fidelity simulator	[1][6][17][7][8][5][19][3]
High-fidelity simulator	[20]
Real-life vehicle	[4][18]

3-3 Lane Keeping Assist control structures

3-3-1 Constant vs proportional feedback

After evaluating the the included studies on amount of torque feedback, two types could be distinguished; constant torque feedback and proportional feedback. Constant torque feedback was defined as:

- Activated when a certain external variable exceeded a treshold
- When active a constant amount of steering torque was applied, so in other words independent on current vehicle state
- A steering system that acts as a warning system and simultaneously acts as a lane keeping system by assisting the driver in making the appropriate action (positive or negative steering torque)

An example of such a system is a steering assist system that provides a constant amount of directional steering torque (negative, positive for left and right) when the lateral position nears the lane markings as can be found in a research conducted by Navarro in 2006 and 2008 [19][3]. In these studies steering assistance is provided with a constant torque frequency, in the study referred to as *Motor Priming*.

The proportional feedback is a wider used system within the selected studies and was defined as:

- A steering support that, when activated, is linear dependent on a measure indicating the current driver state

An example of such a system is the LKA system used by Fritz et al.[18]. Here the amount of steering wheel torque is depending on two state variables of the vehicle, specifically; lateral position and the yaw angle, up to certain saturation point (maximum applied steering torque). A similar approach was used in seven other studies [1][6][17][18][7][8][5][4]. Itoh et al.[20] also used a proportional controller but in stead of controlling the steering wheel torque they controlled the steering angle needed to follow a specified trajectory.

3-3-2 Continuous vs Bandwidth support

A second evaluative perspective was a comparison based on system activation. Therefore the feedback systems are classified as continuous and bandwidth feedback. Here a system is classified as continuous when there is continuous lateral support, where a bandwidth system works with certain treshold values on which the feedback is activated. Of the selected studies, 8 apply a continuous controller [1][4][6][17][18][7][8][5] and 5 apply a bandwidth controller [6][4][7][19][3].
A table cross referencing the papers on amount of feedback and activation of the feedback can be found in table 3-2.

As the table shows there are two studies comparing the differences between continuous and bandwidth feedback [6][4]. From the selected literature there is no paper that evaluates the differences between constant and proportional feedback.

Table 3-2: Cross reference amount of feedback and activation of feedback

	Continuous feedback	Bandwidth feedback
Constant feedback		[19][3]
Proportional feedback	[1][6][4][17][18][7][8][5]	[6][4]

3-3-3 Controller in- & outputs

The selected studies are evaluated from a third perspective; the controller in- and outputs. Different control parameters and parameter combinations are found within selected literature. An oversight of these can be found in table 3-3.

All selected studies used the lateral off-set as at least one of the inputs for the controller. Where 5 studies combined the lateral off-set with the vehicles heading [6][18][7][17][5], and two of these studies also added the lateral acceleration to this combination [17][5]. Only two studies [1][4] calculated the Time to Lane Crossing and combined this measure with the lateral off-set as controller inputs.
For the controller output two clear categorizations can be made; steering angle, and steering wheel torque. The steering angle is defined as the actual steering angle of the tires compared the centerline of the lane, which means that the output of the controller is the steering angle necessary to follow a certain trajectory. The steering wheel torque is defined as a torque that is placed on the steering wheel. Most studies (five out of nine) chosen the steering wheel torque as a controller output [1][6][4][17][5], where the left over 4 applied a steering angle correction to vehicle [18][7][8][19].

3-4 Control structures evaluation

3-4-1 Measures

Different measures where use to evaluate the effectiveness of the control structures found in the selected studies. In this section the selected studies are evaluated on dependent experimental measures.

Table 3-3: Controller in- & outputs

	Controller input	Controller output
Lateral error	[4][8][19][3]	
Lateral error + vehicle heading	[6][18][7]	
Lateral error + vehicle heading + lateral acceleration	[17][5]	
Lateral error + TLC	[1][4]	
Steering angle (tires)		[18][7][8][19][3]
Steering wheel torque		[1][6][4][17][5]

Dependent measures

An oversight of the dependent measures used in the selected studies can be found in table 3-4. However not indicated in the table, a distinction should be made between objective and subjective measures. From the selected literature two (Petermeijer 2015 [6] and Mars 2014 [17]) used subjective measures. The 3 subjective measures used in Petermeijer 2015 are gathered by two after trial questionnaires. Both questionnaires (NASA-TLX and Vanderlaan) are standardized questionnaires and are commonly used among HMI studies. The NASA-TLX questionnaire qualifies as a multidimensional assessment tool that rates the perceived workload in order to assess a task, a system or team effectiveness [22]. The Vanderlaan questionnaire qualifies as an acceptance tool and results in two subjective results; a *Satisfaction* rating and *Usefulness* rating [23]. Mars et al. [17] used a somewhat creative subjective measure for visibility by evaluating the frequency of the screen wipers.
The other selected studies focus purely on objective measures. The most used objective measure for lane keeping is the vehicles lateral error ($e_{lateral}$). Different variations on this measure are used. Mulder et al. for example, used the RMS (Root Mean Square) of the $e_{lateral}$ [1] where Petermeijer, Blaschke, Mars, and Brandt used the mean (M), the standard deviation (SD) or the maximum (Max) of the $e_{lateral}$ [6][4][17][7][5]. Another common used objective measure for lane keeping is the TLC (Time to Line Crossing). This measure uses a small look ahead time and with this determines the time until the lane marking is crossed based on the vehicles speed, lateral position, heading and road curvature. The TLC can be calculated based on the *center* of the vehicle or based on the *shoulder* of the vehicle [1]. Lateral performance can also be evaluated in more abstract way as was shown by Katzourakis et al. [8]. Here the percentage of road departures were evaluated.
The objective measures are not necessarily based on lane keeping performance. Mulder et al. [1] categorized their objective measures in three subcategories; *Performance*, *Control activity* and *Control effort*. Two examples of control activity measures found in the selected papers are the SD of the steering wheel angle (θ_c) and the SRR (Steering Wheel Reversal Rate). The latter is basically the frequency of the reversal of the steering wheel. The steering angle difference to define a reversal usually consists of a treshold between 0.5 and 4 degrees. An example of control effort is the measured steering wheel force as was found in Mulder et al. [1].

3-5 The effect of the control structures

3-5-1 Effect on lane keeping performance

Constant & proportional

Only two of the selected studies evaluated constant torque guidance [19][3] but did not evaluate the effect differences compared to a proportional control structure. This study compared three types of driver assistance for lateral control; *auditory control*, *vibrational control* and *motor priming control*. Also combinations of driver assistance were evaluated. The outcome of the study is that *motor priming control* resulted in the highest lane keeping performance scores (by the means of duration of a certain $e_{lateral}$ treshold) compared the other assistance types. This means corrective steering can have a positive effect on the lane keeping task provided

Table 3-4: Evaluation per experiment

	Measure	Dedicated to	Type
Navarro 2007 [2]	Time$_{LaneDeparture}$	Perf.	Ob.
Navarro 2010 [3]	Time$_{LaneDeparture}$	Perf.	Ob.
	Time$_{Steeringreaction}$	Perf.	Ob.
	Max a$_{Steeringwheel}$	Perf.	Ob.
	Overshoot $e_{lateral}$	Perf.	Ob.
Petermeijer 2015 [6]	M $e_{\|lateral\|}$	Perf.	Ob.
	Max $e_{\|lateral\|}$	Perf.	Ob.
	SD $e_{lateral}$	Perf.	Ob.
	Min $\|TLC\|$	Perf.	Ob.
	M $\|T_c\|$	Accep.	Ob.
	M $\|v_{steering}\|$	Accep.	Ob.
	M $t_{reaction}$	Other	Ob.
	NASA-TLX	Accep.	Sub.
	Vdl-Satisfaction	Accep.	Sub.
	Vdl-Usefulness	Accep.	Sub.
Blaschke 2009 [4]	Max $e_{lateral}$	Perf.	Ob.
	Safety-scale (1-5)	Accep.	Sub.
	Helpfulness-scale (1-5)	Accep.	Sub.
Mars 2014 [17]	SRR	Accep.	Ob.
	M $e_{\|lateral\|}$	Perf.	Ob.
	SD $e_{\|lateral\|}$	Perf.	Ob.
	Visual request	Other	Ob.
Mulder 2008 [1]	RMS $e_{lateral}$	Perf.	Ob.
	TLC$_{centerline}$	Perf.	Ob.
	TLC$_{shoulderline}$	Perf.	Ob.
	SD θ_c	Accep.	Ob.
	SRR	Accep.	Ob.
	SD F_c	Accep.	Ob.
Fritz 2004 [18]	-	-	-
Brandt 2007 [7]	M $e_{lateralplanned}$	Perf.	Ob.
Katzourakis 2011 [8]	% road departures	Perf.	Ob.
Mars 2014 [5]	SD $e_{lateral}$	Perf.	Ob.

*M = mean, SD = Standard Deviation, Max = maximum, Min = minimum, RMS = Root Mean Square, SRR = Steering Wheel Reversal Rate, Vdl = Vanderlaan, Accep. = Acceptance, Perf. = Performance, Ob. = Objective, Sub. = Subjective to the driver with a constant control structure but does not say anything about the benefit compared to a proportional system. The other studies using a proportional control structure also result in increased lateral performance compared to a manual lane keeping task, thus adding to the believe that active steering assist increases the lane keeping performance in general. However the effect differences between the constant and proportional controller are not evaluated in available literature.

Bandwidth & Continuous

A schematic overview of the performance effects between bandwidth and continuous control structures can be found in table 3-5. The continuous control structure shows improved lateral performance compared to manual driving in almost all conducted studies. Mulder et al. showed this based on the mean RMS $e_{lateral}$, the mean SD of the steering angle and the minimum TLC [1]. The simultaneously present lower SRR also implicates less steering activity. Corresponding findings about increased lateral performance were found by Navarro et al. [2][3], Mulder et al. [1], Blaschke et al. [4], Mars et al. [5] and Petermeijer et al. [6]. Results show that continuous haptic shared control reduced lateral position variability/SD when compared with unassisted driving.

From the eight studies that evaluated the proportional feedback two did it by comparing a bandwidth control structure to a continuous control structure [6][4]. Both studies evaluate the absolute maximum lateral position and result in similar findings. The guidance is equally effective to reduce the absolute maximum lateral position compared to a baseline trial. However Blaschke [4] compares two types of bandwidth settings, standard assistance and early assistance (bandwidth closer to lane center), and the two show different results. The early assistance shows similar results as the continuous feedback however the standard assistance result in a higher absolute maximum lateral position, thus showing the impact of the bandwidth settings.

Petermeijer [6] however also found significant effects indicating that continuous feedback result in more accurate lane keeping performance (in terms of lateral position and time to lane crossing) compared to manual steering or bandwidth feedback. That result indicates that a more frequent or stronger guidance force implies improved lane-keeping performance. This corresponds to earlier findings of Brand [7] and Katzourakis [8] (with Katzourakis the feedback forces were to small to result in significant performance changes).

The continuous control structure however does not only show benefits compared the bandwidth structure. Petermeijer showed, by introducing a system failure, that aftereffects arose with the continuous structure where neither of the bandwidth structures yielded identifiable after effects.

3-5-2 Effect on driver acceptance

Constant & proportional

The only selected study that evaluated a constant control structure [19] lacked subjective measures in order to compare acceptance ratings between a constant or a proportional controller. Petermeijer however touched this topic by briefly addressing annoyance [6]. Some of

Table 3-5: Performance effects of bandwidth and continuous control structures compared to manual control and each other from [1] [2] [3] [4] [5] [6] [7] [8]

	compared to Manual control	*compared to* Bandwidth control	*compared to* Continuous control
Bandwidth control	↓ M $e_{lateral}$, ↓ Max $\|e_{lateral}\|$, ↑ TLC	-	↓ aftereffects
Continuous control	↓ RMS $e_{lateral}$, ↓ SD $e_{lateral}$, ↓ Max $\|e_{lateral}\|$, ↓ M SD θ_c, ↑ Min TLC	↓ M $e_{lateral}$, ↓ Max $\|e_{lateral}\|$, ↑ TLC	-

*↑ = increased effect, ↓ = decreased effect

Table 3-6: Acceptance effects of bandwidth and continuous control compared to manual control and each other from [1] [2] [3] [4] [5] [6] [7] [8]

	compared to Manual control	*compared to* Bandwidth control	*compared to* Continuous control
Bandwidth control	↑ Vdl-Usefulness, ↑ Safety, ↑ Helpfulness	-	-
Continuous control	↓, SD θ_c, ↓ SRR, ↑ M SD F_c, ↓ NASA-TLX, ↑ Vdl-Usefulness, ↑ Safety, ↑ Helpfulness	↑ Vdl-Satisfaction	-

*↑ = increased effect, ↓ = decreased effect

the drivers reported annoyance and pointed at the difficult to interpret binary behavior of the bandwidth controller. Similar responses were found in a study by Suzuki and Jansson [24] when binary torque pulses were provided when a lateral error was exceeded.

Continuous & Bandwidth

Again a schematic overview of acceptance effects is presented in table 3-6.
Three of the nine studies evaluated subjective measures to elaborate on acceptance towards the control structure. Mulder implicates smoother control with the continuous control structure compared to manual control because of reduced control activity [1]. This was derived from a significant reduction in the steering angle variance SD θ_c and the SRR. The same study also evaluated control effort by comparing the mean standard deviation of the steering force. This however showed increased steering forces with the continuous control structure compared to manual control indicating a mismatch between the drivers desired steering actions and those of the guidance system. Petermeijer et al. found similar effects that showed large individual differences in how drivers respond to the continuous control structures [6]. Some drivers resisted the steering feedback, whereas others gave way to them.
Petermeijer evaluated three more subjective measures related to acceptance; driver workload (NASA-TLX), system satisfaction and system usefulness. The continuous control structure yielded in significant decreased workload ratings compared to manual control. The study also shows that drivers found continuous control structures more satisfactory than bandwidth structures. The usefulness scale showed that both bandwidth and continuous feedback systems were considered more useful than manual control. Blaschke et al. [4] reports significant positive subjective scores for increased overall safety and the control structures helpfulness. He asked drivers to rate these factors on scale from 1 to 5. Both control structures show significant effects to manual driving, but the study lacks a pair-wise comparison in order to evaluate differences between the bandwidth and continuous control structure.

Chapter 4

Discussion

4-1 Control structures

The following subsections will address the effects of the evaluated control structures in order to answer the research question of this literature survey; How do different LKA control structures affect lane keeping performance and driver acceptance in active steering support for vehicles?

4-1-1 Bandwidth

The importance of acceptance of new support systems was emphasized in a study of Petermeijer [6], who based this on drivers reporting annoyance and difficulties with feedback interpretation towards his single bandwidth control structure. A double bandwidth system was introduced as an example of how a bandwidth system can be modified to accomplish better acceptance among drivers. The simulator study showed improved mean, maximum and standard deviation of the lateral error (most likely caused by the second more narrow bandwidth), increased absolute steering torque for the double bandwidth controller (possibly explained by drivers fighting the longer lasting guidance towards lane center) but however no improvements in satisfying or usefulness scores. Interesting enough Blaschke [4] found subjective significant results in a real-life experiment for improved safety and helpfulness (based on t-test against midpoint of rating scale) but also found an increased effect between the two types of bandwidth feedback he used. Apparently the real-life study showed an effect in acceptance where the simulator study did not. Therefore it would be interesting to see how usefulness and satisfying ratings of the bandwidth structures used in Petermeijer et al. [6] are effected if tested in real life. These are however the only two studies that evaluate acceptance between a variety of bandwidth and continuous controllers in a simulator and real-life. As can be seen in table 4-1 different controller inputs where used among the studies therefore the study results cannot properly be compared.
Both studies showed improved subjective acceptance effects (usefulness/helpfulness, feeling of safety) when compared to manual steering and therefore overall improved acceptance can be expected when implemented in real life.

Table 4-1: Literature overview - Simulator vs. Real-life studies, Bandwidth vs Continuous controllers

			Controller input			Controller output		
			$e_{lateral}$	$e_{lateral}$ + $e_{heading}$	$e_{lateral}$ + $e_{heading}$ + $_{other}$	Steering angle (tires)	Steering wheel torque	
Simulator	Continuous	Ob.	[8]	[7]	[1] [5] [17]	[7] [8]	[1] [5] [17]	
		Ob. + Sub.		[6]			[6]	
	Bandwidth	Ob.	[19]			[19]		
		Ob. + Sub.		[6]			[6]	
Real-life	Continuous	Ob.		[18]		[18]		
		Ob. + Sub.			[4]		[4]	**RQ**
	Bandwidth	Ob.						
		Ob. + Sub.			[4]		[4]	**RQ**

* Ob. = evaluated on objective measures
Ob. + Sub. = evaluated on both objective and subjective measures

4-1-2 Continuous

Table 4-1 shows that most studies focus on the use of a continuous control structure in stead of a bandwidth structure. The reason can likely be the improved lateral performance (mean, max and variance of lateral error, improved TLC) that numerous simulator studies showed [25][26][6]. Based on acceptance measures the continuous structure shows decreased steering wheel velocity indicating smoother steering behavior compared to bandwidth control. The acceptance measures however also showed higher absolute steering torques for continuous control thus possibly indicating a higher amount of driver-system conflicts. A possible reason is personal driver preferences. Some drivers may like the constant steering support where others prefer freedom (deadzone or non-feedback) in the driving task when near the lane center. Another reason can be linked to finding of Abbink et al. [13] that concluded that optimal control guidance yields lower acceptance if multiple trajectory paths are available. In a lane keeping task there is no such thing as an optimal trajectory since the only constraint is to avoid crossing the lane boundaries. Also the preferred trajectory shows variability per person so to fit an “one path fits all” path is difficult to achieve.

The earlier mentioned “deadzone” in provided feedback shows to have another important effect; it reduces a potential after effect during a hypothetical system failure [6]. Petermeijer et al. commented that when using a bandwidth controller the driver cannot become dependent on the system, however they argued that the TLC of the continuous system in the shutdown curve is still higher compared to the nominal driving TLC’s in manual and bandwidth systems. This argument however does not hold-up in real-life implementation where its about a systems effectiveness to avoid accidents. Over reliance towards a system that has the possibility to fail would still result in a higher safety risk compared to a system where this effect is not present.

4-1-3 Bandwidth compared to continuous

Both control structures show great potential for real-life implementation but can still be improved to increase driver acceptance. Both Petermeijer and Blaschke use a driver model that use a linear increasing output depending on vehicle state parameters. Shyrokau et al. [27] concluded that both professional and normal drivers prefer steering feedback as a linear stiffness damping model. Applying this to the control structures used by Petermeijer et al. [6] and Blaschke et al. [4] can possibly result in higher driver acceptance. Overall the evaluated studies show the continuous control structure to most likely be the better option when evaluating performance and acceptance measures. Both studies that compared continuous with bandwidth feedback (Petermeijer et al. [6] and Blaschke et al. [4]) show the highest lane keeping performance with a continuous control structure and Petermeijer et al. [6] also showed a significant affect for higher satisfaction when comparing a bandwidth structure with a continuous structure. The after effect of the use of a continuous support structure is however a downsides of this method. The increased risk after system malfunction should be taken into account when implementing this system in real-life. The automation free zone within the bandwidth control structure can hypothetically result in reduced driver-system conflicts and thus be beneficial for acceptance. This however goes hand in hand with a transition when the feedback is later activated, which when not properly tuned can result in discomfort [17]. With continuous feedback this transition effect will not be present.

4-1-4 Feedback intensity

Multiple studies [6][17][25][26] address the 'magic' balance between lane keeping performance and comfortability in the amount of applied steering feedback. Mars et al. [17] argued that the driver comfort seem to increase up to 31% of shared control (balance between driver and system responsible for necessary applied steering wheel torque) and that safety, control and attention seem to maximize around 11%. They concluded that driver prefer relative low level of haptic authority and that higher levels of haptic control are more of a benefit with low visibility. The importance of this feedback gain parameter is emphasized in by Mulder et al. [25], Abbink et al. [26] and Petermeijer et al. [6]. They found similar results that for an increased feedback gain during a continuous control structure the feedback imposed too much force on the steering wheel, leaving too little room for the human to contribute to the lane keeping task. It was also found that the high feedback gain resulted in the same levels of mean absolute driving torque compared to the lower gain continuous system but with a higher variance. In other words there were big individual differences in how drivers used the high gained system. Some resisted the feedback forces, where others gave way to them.

Since the bandwidth structure did not show these results an idea is to introduce a combination of the bandwidth system and the continuous system; the continuous double bandwidth system. Different road sections should use different gains settings. The middle section of the road can use a low gain settings (according to Mars et al. around 10% [17]) to maximize safety, control and attention while also resulting in feedback integration in the humans sensorimotor control loop [17]. This results in smoother steering activity which is subjectively rated safer and more comfortable compared to manual driving. This is mentioned by Abbink et al. [26] who emphasized the importance of matching neuromuscular settings to increases acceptance and prevention of HMI mismatches. The middle sections of the road should exert 'optimal' feedback settings (according to Mars et al. around 30% to remain within acceptable bandwidth [17]), up until comfort seem to still increase while simultaneously stronger feedback increases the driving performance (mean, max, standard deviation of lateral error and time to lane crossing [6][25][26]). Optimal feedback is put to bet use in this section since the correction can be made when there is still lateral space (before crossing of the lane boundary) for the driver to react to the feedback and restore to his preferred lane position, all within the by Mars et al. [17] estimated levels of driver comfort. The outer section of the lane can then even further increase the feedback intensity outside the levels of comfort for the driver to avoid potentially dangerous lane crossings.

4-1-5 Control structure output

When looking at table 4-1 the chosen controller outputs (steering angle or steering torque) seem to be around fifty-fifty. Some studies experiment with promising ideas like an increased steering angle out of the control of the driver [8] to assist in obstacle avoidance. However, I believe that in order to achieve high driver acceptance a certain transparency in the provided feedback is necessary. Different driving behavior corresponding to the same steering wheel input by the driver does not contribute to this transparency and can result in confusion of driver control.
Also the correct transfer of intended driver feedback benefits the transparency of a system. If the feedback is exerted as a vehicle steering angle, the vehicle dynamics can cause a hysteresis effect in the feedback received by the driver. By exerting the feedback as close to driver as possible, as a steering wheel torque, such hysteresis effects can be eliminated and a higher transparency can be achieved.

4-1-6 Real-life vs simulator

With a look at table 4-1 a gap can be identified in the amount of studies that are performed in real-life. As was mentioned before, in order for a system to be implemented in real-life the system needs to pass certain safety regulations and this is a time consuming and costly demand. This is one of the reasons why most studies are performed in simulators. Why would any scientist put additional effort towards a real-life experiment, if sufficient measurements can be obtained in a simulator in a controlled environment for a fraction of the costs. Nowadays simulators are able to reproduce close to real driving aspects with moving bases and virtual reality glasses and can also produce feedback outputs or driving scenarios that are unsafe to test in real-life. If the goal of a study is to evaluate driving performance, a simulator (even simplified fixed based simulators) can already be sufficient. However depending on the evaluation criteria a real-life experiment can prove itself beneficial. If it comes to evaluation of driver acceptance, a realistic driving environment can provide valuable information toward human system interaction for ADAS development, HMI integration and thus implementation.

4-2 Performance and acceptance measures

Combination of both table 3-4 and table 4-1 show that of all selected studies only three evaluate acceptance measures [9][6][4] and of these three only two evaluate not only objective measure but also subjective measures [6][4]. Table 3-4 show a relative low amount of acceptance measures compared to performance measures. However, with the earlier mentioned importance of proper human system integration (ISO26262) these measures should be equally important when being implemented in real-life. Subjective measures and documentation of driver comments during testing can proof to be valuable information to gain insight of the human subjective evaluation towards a control structure. Therefore more real-life studies should commit to evaluation of driver acceptance.

When comparing table 3-4, table 3-5 and table 3-6 an selection of important measures to evaluate performance and acceptance can be made. All selected papers use the lateral position error as an evaluation measure for performance. Interesting performance findings can be made when multiple of lateral error measures are cross referenced like the mean the maximum and the variance of the error as was done by Petermeijer et al. [6]. Another relevant performance measure used by Mulder et al. [9] and Petermeijer et al. [6] is the TLC (time to lane crossing). It is a transparent human like measure to evaluate system performance based on what McRuer [28] showed that the human as a controller prefers second order integrations as was mentioned by Macadam et al. [29].

Acceptance measures are focused towards steering wheel measures. In studies from Mulder et al. [9][25] and Petermeijer et al. [6] measures like steering wheel angles, forces, torques and speeds lead to interesting finding about the human driving behavior. For example is the driver fighting or giving way to feedback (mean and variance of steering wheel torque) or is there an increase or decrease in workload (steering wheel reversal rate). Subjective measures are, as mentioned before, just as important. Petermeijer et al. [6] used two standardized questionnaires to compare the objective data with self-reported data. This comparison can show if the objective evaluation as similar to how a driver perceives a system. Subjective questionnaires like the NASA-TLX and the Vanderlaan questionnaire are therefore important measures to take during a real-life evaluation of control structures.

Chapter 5

Conclusion

The presented literature survey evaluated eleven studies on the affect of lateral control structures on lane keeping performance and driver acceptance. The results indicate that both the bandwidth and the continuous control structure show improved lane keeping performance and driver acceptance enhancing potential compared to manual driving. Both control structures contain encouraging aspects affecting driver acceptance and performance. The automation free zone in a bandwidth controller potentially reduces the amount of driver-system conflicts where the continuous controller shows smooth feedback transition throughout the entire lane width. Too high feedback amounts in the control structures result in discomfort towards the system where too low feedback do not an show increased lane keeping affect. Therefore the feedback intensity of the control structures proves to be of significant influence to acceptance and performance. By introducing variating gain settings to specific lane sections and with that the introduction of linear spring damping steering behavior the acceptance towards the control structures can be further improved. Also increased transparency of exerted feedback can lead to higher acceptance. The control structures can accomplish this by providing the feedback as a steering wheel torque. This way the feedback forces are exerted as close to the human sensory system as possible.
Studies showed difference in subjective acceptance ratings between simulator and real-life experiments. This emphasizes the importance of real-life implementation of designed control structures. Also the evaluated studies showed a lack of acceptance measures and more specific, subjective acceptance measures for comparison with objective measures. This comparison can lead to better understanding of the effect that control structures have on driver acceptance.

Overall results indicate that control structures with potential to increase driver acceptance are mainly evaluated in a simulated environment. The implementation of such complex control structures in real life have the potential to reduces annoyance that is encountered in currently implemented support systems. This gab of real-life evaluated complex control structures can be closed by implementing the above lessons regarding the effect of control structures on lane keeping performance and driver acceptance to the development of new control structures to be evaluated in real-life.

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Appendices

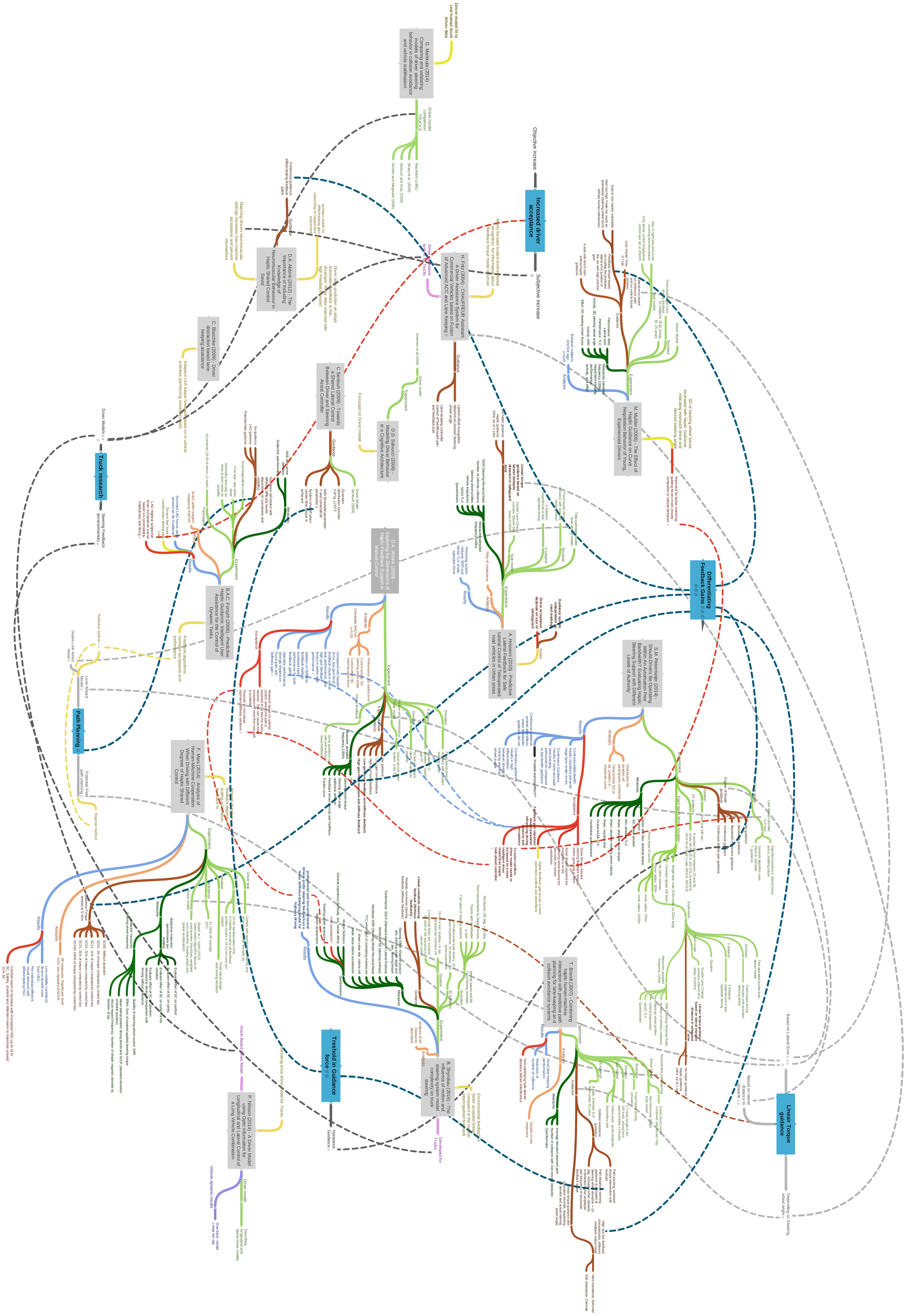
Appendix A - Experimental measures

First author	Year	Function	LKA model structure	Guidance scheme	Dependant measures	Independent measures	Number (M, F)	Age (years)	Heavy Vehicle	Results	Significance
H. Fritsche	1994	N/A	Car-following + Lane change	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
T. Pilutti	1991	State estimation	Driver state estimation on a road departure warning and intervention system	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
H. Fritz	2004	Guidance	Sensory based feed forward controller	Continuous guidance based on B. Ulmer 2001 (not published)	N/A	N/A	N/A	N/A	Yes	N/A	N/A
P. Griffiths (shared...)	2004	Guidance	Linear driver/controller input/output	Continuous guidance path following controller no sensory data	% LK performance, % Visual demand, reaction time	-	11	-	No	30%, 29%, -18ms	p<0,0001, p<0,0001, p=0,0009
P. Griffiths (sharing...)	2004	Guidance	Predicitve drive model Hess and Modjtahedzadeh (1990)	Continuous guidance based on current position of vehicle and orientation of surroundings (lane, obstacles)	RMS_lateralerror, % Hit cones, Reaction times, Avg_VisabilityDriver	With Haptic Assist, Without Haptic Assist (Baseline, Visual demand, Secondary task)	11 (9,2), W	20-63	No	Table 1, 2, 3 Paper	Table 1, 2, 3 Paper
A.C. Benjamin	2006	Guidance	Potential Field Guidance (PFG), Continuous Look-Ahead Guidance (LAG)	Continuous 1-DoF actuated feedback	MS_lateralerror	PFG, LAG	18 (12,6), W	19-33	No	PFG more power compared to others	-
D.D. Salvucci	2006	Model verification	Salvucci & Gray (2004) "two level control based on two salient visual points"	Continuous guidance towards salient point, also in smooth way during curve negotiation	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D. Toffin	2007	Human adaptation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N. Jordan	2007	Continuous vs Binary feedback	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
T. Brandt	2007	Guidance	Potential Field predicitive path planning	Continuoud linear characteristics with with a saturation treshold. For Path tracking an assistant torque intervention without treshold, departure warning is activated beyond a steering angle deviation of +/- 15 degrees (depending on speed however constant in this experiment), at collision avoidance guidance higher sinusoidal amplitudes are chosen	Objective: AvLatErrPlannedPath, #HitObsticles Subjective: questionaire; impression, strength vibration, thresholdimpression feeling vibration, workload, additional warning, acceptance towards safety and comfort	No Guidance, High guidance low guidance	16 (8,8)	18-60 (50% <35)	No	Postivie results towards acceptance and performance with activated system	N/A
C. Sentouh	2008	Guidance	Driver Model: 3-input model Sentouh (2009), Control input authority balanced using Gaussian distribution	Lineair time-invariant driver system with delay, neuromuscular system and visual and kinaestatic perception. Gaussian Distribution z=1 only driver input, z=0 purely controller input	LatErrDeviation, ControlActivation	Controller 1, Controller 2	N/A	N/A	No	Weighted authority succesfully minimizes system interference by limiting control interventions	N/A
C. Blaschke	2009	Guidance	Continuous vs multiple bandwith feedback	No assistance, early assistance, standard assistance and continuous assistance	LatError, survey about acceptance	Different types of IVIS;	30 (25,5)	31-65	No	Lateral Support adaptation while using IVIS helps lane keeping performance and is usefull to adapt LDW based on driver lateral performance	p = 0,00001 - 0,001
A. Amditis	2010	Further look ahead	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
F. Breyer	2010	Overreliance	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
K. Tsoi	2010	Guidance Lane change	Based on Mulder et. Al 2008: torque feedback based on Look Ahead Controller	Lateral and heading error between predicted state and reference lane (High low gain Kf)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D. Katzourakis	2011	Guidance	Direct controller output towards steering angle vehicle combined with HSC	Shared steeringwheel input based on desired estimated lsteral offset but controller has direct influence over vehicle steering angle in certain modes	N/A	N/A	N/A	N/A	N/A	N/A	N/A
F. Mars	2011	Design of Human controller	Distant visual cue to predict road curvature and parralelclose visual information to compensate for lateral position	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D.A. Abbink	2012	Accurate model for neuromuscular prediciton	N/A	N/A	Measured driver torque, The delivered HSC troque, Expected driver torque according to the HSC, LKA performance; RMS steering angle, RMS trajectory error	No hands, force task, Relax task	18 (18,0)	25,3 +-2,1	No	N/A	N/A
M. Itoh	2013	Acceptance Collision avoidance system	N/A	N/A	N/A	N/A	20 (12,8)	20 - 39	No	N/A	N/A
L. Saleh	2013	Guidance	Driver model based on F. Mars (2011)	Distant visual cue to predict road curvature and parralelclose visual information to compensate for lateral position	Absolut lateral deviation center lane, standard deviation lateral position, time to lane crossing, T_consistency, T_ressistance, T_contradiction	N/A	N/A	N/A	N/A	N/A	N/A
M. Kienle	2013	Side stick control input	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
W. Li	2013	Controller human-in-the-loop	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S.M. Petermeijer	2014	Guidance	Continuous vs bandwith HSC guidance (continuous indentical to Mulder (2012))	Superimposed guidance torque based on e_lateral_future in meters and e_heading_future in degrees	Mean+max absolut lateral position, Standard deviation lat position, Minimum TLC, Mean driver torqur, Mean steering wheel velocity, mean reaction time, NASA-TLX, Satisfaction and usefullness vanderlaan	Two types continuous guidance, two types bandwith guidance	32 (26,6) W	23-28	No	Continuous more accurate lanetracking performance, continuous aftereffects	Tables in paper
D.I. Katzourakis	2014	Guidance	Continuous haptic shared feedback vs shared feedback with direct influenceable wheel angle by controller	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
F. Mars (Driver adaptation to HSC...)	2014	Adaptation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
F. Mars (2014) Analysis of HM Coop.	2014	Guidance	Continuous based onL. Saleh (2012)	SDLP	RSS, Sum of squared applied torque, Mean lat position error (SDLP), visual request frequency	3 levels of visability conditions	21 (15,6)	32	No	N/A	N/A
G. Markkula	2014	Driver models TRUCK	4 Truck Driver models no LKA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P. Nilsson	2014	Driver Models TRUCK	Truck Driver models for lane change no LKA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Z. Zheng	2014	Car following model	Human factors in car following models	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S.M. Petermeijer	2015	Literature survey	HSC on driver performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N. Ryota	2015	Guidance Lat	gain-tuning control when performing lane-change	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S. Inou	2016	Guidance Lat	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
T. Qu	2016	Driver model predeictive	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
M. Mulder	2008	Guidance	Lat_err based on reference path and vehc. position certain time in future (look ahead time principle)	continuous guidance torque magnitude by scaling predicted lat error	TLC, RMS e_lat, Standard dev. Steering wheel angle deviation for low frequency control activity, Steeringwheel ReversalRate (RSS) for high frequency control activity, standard deviaton of measured steering Force for control effort	HF on/off, and with different gains	12 (6,6)	m;25, dev;2,1	No		x = 0,05
M. Tomizuka	1999	Driver model commercial vehicles	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S. Martini	2003	Vehicle model with trailer	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
L. Saleh	2011	Human Driver model	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
D.A. Abbink	2009	Guidance	Force feedback & Stiffness feedback		Standard deviation of measured steering angle; control activity, standard devitiation of steering wheel force; control effort, standard deviation of control error; performance + frequency domain analysis	Five haptic feedbaack conditions; No, F1, F2, K F1, K F2 Each case with and without visual feedback	9 (7,2)	m:25	No		
A. Hosseini	2016	Tele-operated guidance	Force feedback to avoid lateral collision depending on distance to obstacle	Continuous lineair with special torque curvature	SRR, # vehicle collision,	With and without haptic guidance	3 experienced tele-operators	-	No	Better performance compared to no guidance	-

Appendix B - Inclusion criteria check

Paper; Year, First Author and Title	Subject	Long/Lat	Experimental data	Goal	Usefull	Table art.
1974 IEEE : Identification of human driver models in car following	Human Driver Models	Longitudinal	No	Control optimization	Maybe	No
1985 John A Michon : A Critical View of Driver Behavior Models: What Do We Know,	Human Driver Models	-	No	Survey available models '90	Maybe	No
1999 Van Winsum : The human element in car following models	Human Driver Models	Longitudinal	No	Car following human element; errors and distraction	Maybe	No
2007 Andersen : Optical information for car following: the driving by visual angle (DVA)	Human Driver Models	Longitudinal	Yes	Car following performance, drive by visual angle	Maybe	No
2007 Il Delice : Intelligent Modeling of Human Driver: A Survey	Human Driver Models	-	No	Survey; human smart control	Maybe	No
2007 Manched Plöchl : Driver models in automobile dynamics application	Human Driver Models	-	No	Overview driver models	Maybe	No
2008 Flemish : Cooperative Control and Active Interfaces for Vehicle Assistance and	Haptic Shared Control	-	No	Survey cooperative control and active interfaces for vehicle automation	Maybe	No
2008 S.H. Hamdar : Modeling behavior as a sequential risk taking task	Human Driver Models	Longitudinal	No	Car following performance, based on human risk assesment	Maybe	No
2009 Yang : Development of an errorable car-following driver model	Human Driver Models	Longitudinal	Yes	Car following human element; errors and distraction	Maybe	No
2010 L. Marchal-Crespo : The effect of haptic guidance, aging, and initial skill level on	Lateral Shared Control	Lateral	Yes	Haptic feedback training retention benefit	Maybe	No
2011 Correct and Faulty driver support from shared haptic control during evasive man	Haptic Shared Control	Lateral	Yes	Overridde abbility driver when HSC malfunctions	Maybe	No
2011 Jin : Visual angle model for car-following theory	Human Driver Models	Longitudinal	No	Car following performance, drive by visual angle	Maybe	No
2013 Flemish : Towards cooperative guidance and control of highly automated vehicle	Human Driver Models	-	No	General framework cooperative driving + prototype acceptance	Maybe	No
2014 Franck Mars : Analysis of human-machine cooperation when driving with differe	Haptic Shared Control	Lateral	Yes	5 Levels of HSC and performance measures	Maybe	No
2014 R. Boinck : Understanding and reducing conflicts between driver and haptic sha	Human Driver Models	Lateral	Yes	Adapting look ahead individual driver	Maybe	No
2014 Taheri Siavash : Steering Control Characteristics of Human Driver Coupled with	Human Driver Models	-	Yes	Driver models heavy vehicles	Maybe	No
2016 Shyrokau : The influence of motion and steering-system model complexity on tr	Human Driver Models	Lateral/Longitudinal		Truck simualtor influence on driver performance and personal assessment	Maybe	No
1989 John A Michon : Explanatory pitfalls and rule-based driver models	Human Driver Models	-	No	Theoretical	No	No
1994 Hans-Thomas Fritsche : A model for traffic simulation	Human Driver Models	-	Yes	Perceptual thresholds	No	Yes
1994 Thomas A Ranney : Models of driving behavior: A review of their evolution	Human Driver Models	-	No	Theoretical	No	No
1999 M. Tomizuka : Automated Lane Guidance for Commercial Vehicles	Driver model	Lateral	Yes	Developmemnt adaptive controller comercial vehicle	No	Yes
1999 T. Pilutti : Identification of driver state for lane-keeping assist	Human Driver Models	Lateral	Yes	Driver state estimation while using LKA	No	Yes
2001 Andrew Liu : MODELING AND PREDICTION OF HUMAN DRIVER BEHAVIOR	Human Driver Models	Lateral	Yes	State estimation to predict human behavior	No	No
2002 H Peng : Evaluation of Driver Assistance Systems—A Human Centered Approac	Human Driver Models	Lateral	Yes	Driver Model tested uppon Vehicle Stability Control	No	No
2003 MacAdam : Underdtanding and modeling the Human Driver	Human Driver Models	-	No		No	No
2003 S. Martini : Lateral Control of tractor-trailer vehicles	Vehicle model trailer	Lateral	No	Development of dynamical vehicle vehicle model with lat assistance	No	Yes
2004 Griffiths : Shared Control Between Human and Machine: Haptic Display of Auto	Haptic Shared Control	Lateral	Yes	Introduction HSC + experimental data	No	Yes
2005 AY Ungoren : An adaptive lateral preview driver model	Human Driver Models	Lateral/Longitudinal	Yes	Design of adaptive driving model for different driver representation	No	No
2005 Griffiths : Sharing Control Between Human and Automation using Haptic Interfac	Haptic Shared Control	Lateral/Longitudinal	Yes	Showcase HSC to improve driver performance	No	Yes
2006 J.M. Hoc : Human-machine cooperation in car driving for lateral safety : delegati	Human Driver Models	-		No paper	No	No
2007 D Toffin : Role of steering wheel feedback on driver performance: driving simulat	Lateral Shared Control	Lateral	Yes	Differentiating environmental Steering feedback	No	Yes
2007 N. Jordan : Lateral control support for car drivers: a human-machine cooperatio	Human focussed shared co	Lateral	Yes	Lateral support focussed on human interaction	No	Yes
2010 A. Admits : A Situation Adaptive Lane Keepig support system: Overview of the S	Lateral Shared Control	Lateral	No	Perception, decision, action layer	No	Yes
2010 F. Breyer : Negative Behavioral Adaptation to Lane-Keeping Assistance Systems	Lateral Shared Control	Lateral	Yes	Overtrust in system	No	Yes
2010 K.K. Tsoi : Balancing safety and support: Changing lanes with a haptic lane-kee	Lateral Shared Control	Lateral	Yes	HSC LKA + lane change assistance	No	Yes
2011 Franck Mars : Modeling the Visual and Motor Control of Steering With an Eye to	Human focussed shared co	Lateral	Yes	Visual anticipation road curvature and lat. Pos. compensdation in driver model	No	Yes
2011 L. Slaeh : Human-like cybernatic driver model for lane-keeping	Human Driver Models	Lateral	No	Human-like driver model for lane keeping	No	Yes
2011 Young : Lateral Control Assistance in Car Driving: Classification, review and futu	Lateral Shared Control	Lateral		Lateral Assistance devices by category	No	No
2013 Erlien : Safe Driving Envelopes for Shared Control of Ground Vehicles	Lateral Shared Control	Lateral	No	Control paper on obstacke avoidance and stability control	No	No
2013 L. Saleh : Shared Steering Control between a driver and an automation Stability	Lateral Shared Control	Lateral	Yes (1 person validation)	LKA in presdence of driver uncertainty	No	Yes
2013 M. Kienle : The ergonomic value of a bidirectional haptic interface when driving	Lateral Shared Control	Lateral	Yes	Performance when using HSC LKA	No	Yes
2013 Wenchao Lie : Synthesis for Human-in-the-Loop Control Systems	Human Driver Models	-	No	Semi-autonomus controller for human input in autonomous driving	No	Yes
2014 Corno : Road departure prevention in an Emergency Obstacle Avoidance Situat	Lateral Shared Control	Lateral	Yes	Lateral HSC compared with drive by wire direct steering angle control	No	Yes
2014 Lee : Combining Haptic Guidance and Haptic Disturbance : an Initial Study of hy	Haptic Shared Control	Lateral	Yes	HSC research guidance compared with disturbance	No	No
2014 Zutun Zheng : Incorporating human-factors in car-following models: A review of	Human Driver Models	Longitudinal	No	Survey: human driver models	No	Yes
2015 Nishimura Ryota : Haptic Shared Control in Steering Operation based on Coope	Human Driver Models	Lateral	No	Evaluation proposal most effective cooperation HSC man machine	No	Yes
2016 S. Inoue : Cooperative lateral control between driver and ADAS by haptic Share	Lateral Shared Control	Lateral	Yes	Addition of Yaw Moment Control	No	Yes
2016 Tin Qu : A stochastic model predictive control approach for modelling human dr	Human Driver Models	Lateral	Yes	Control approach human steering	No	Yes
2006 B.A.C. Forsyth : Predictive haptic guidance: intelligent user assistance for the co	Human Driver Models	Lateral	Yes	Predicitive haptic guidance look ahead	No	Yes
2006 Dario D Salvucci : Modeling Driver Behavior in a Cognitive Architecture	Human Driver Models	Lateral	Yes	Cognitive driver modeling, LK, curve negotiation, LC	No	Yes
2009 C. Sentouh : Towards a shared lateral Control between driver and Steering Assis	Human Driver Models	Lateral	Yes	SM Inlcuding Driver intentions and curve negotiation	No	Yes
2012 D.A. Abbink : The importance of including knowledge of neuromuscular behavio	Human Driver Models	Lateral	Yes	Neuromuscular response driver performance	No	Yes
2014 G. Markkula : Comparing and validating models of drivers steering behaviour in	Human Driver Models	Lateral	Yes	Four Truck Driver models from literature	No	Yes
2014 P. Nilsson : A Driver Model Using Optic Information for Longitudinal and Lateral	Human Driver Models	Lateral	No	High driver acceptance if driver model is human inspired	No	Yes
2016 A. Hosseini : Predictive Haptic Feedback for Lateral Control of Teleoperated Ro	Predicitive Haptic Guidance	Lateral	Yes	Predicitive haptic guidance look ahead	No	Yes
2004 H. Fritz : Chauffeur assistant: adriver assistance system for commercial vehicles	Environmental perception	Lateral/Longitudinal	Yes	Driver assistance Truck for LKA and ACC	Yes	Yes
2007 T. Brandt : Combining haptic human-machine interaction with predictive path pl	Lateral Shared Control	Lateral	Yes	Human interaction + path planning lateral	Yes	Yes
2008 Mulder : The effect of haptic guidance on curve negotiation	Lateral Shared Control	Lateral	Yes	HSC + lat ghuidance bandwiths	Yes	Yes
2009 D.A. Abbink : Exploring the Dimensions of Haptic Feedback Support in Manual	Lateral Shared Control	Lateral	Yes	Force Feedback vs Stiffness Feedback vs Force Stiffness Feedback	Yes	Yes
2009 Blaschke : Driver distraction based lane-keeping assistance	Lateral Shared Control	Lateral	Yes	More Effective driver ADAS due to incorparation driver state	Yes	Yes
2011 D. Kaztourakis : Shared control for road departure prevention	Lateral Shared Control	Lateral	Yes	Lateral HSC for LKA	Yes	Yes
2013 M. Itoh : Effectiveness and driver acceptance of a semi-autonomous forward ob	Lateral Shared Control	Lateral	Yes	Methods for determining driver acceptance	Yes	Yes
2014 S.M. Petermeijer : Should Drivers be Operating within an Automation-Free Band	Lateral Shared Control	Lateral	Yes	HSC Continuous vs bandwith feedback + experimental measures	Yes	Yes
2014 Franck Mars : Analysis of human-machine cooperation when driving with differe	Lateral Shared Control	Lateral	Yes	HSC different feedback cooperation	Yes	Yes
2014 Franck Mars : Driver Adaptation to haptic shared control of the steering wheel	Lateral Shared Control	Lateral	Yes	EXTENDED TIME PERIOD EXPERIMENT, adaptation to HSC lateral	Yes	Yes
2015 S.M. Petermeijer : The Effect of haptic support systems: a Literature Survey	Haptic Shared Control	Lateral/Longitudinal	No	Lay-out available HSC systems + experimental measures and outline	Yes	Yes

Appendix C - Mindmap relevant papers


Increased driver acceptance
Objective increase
Subjective increase
Truck research
Path Planning
Differentiating Feedback Gains
Treshold in Guidance force
Linear Torque guidance
G. Markkula (2014) - Comparing and validating models of driver steering behavior in collision avoidance and vehicle stabilization
H. Fritz (2004) - CHAUFFEUR Assistant - A Driver Assistance System for Commercial Vehicles based on Fusion of Advanced ACC and Lane Keeping
D.A. Abbink (2012) - The Importance of Including Knowledge of Neuromuscular Behaviour in Haptic Shared Control Design
C. Blaschke (2009) - Driver distraction based lane-keeping assistance
C. Sentouh (2009) - Towards a Shared Lateral Control Between Driver and Steering Assist Controller
D.D. Salvucci (2006) - Modeling Driver Behavior in a Cognitive Architecture
M. Mulder (2008) - The Effect of Haptic Guidance on Curve Negotiation Behavior of Young, Experienced Drivers
D.A. Abbink (2009) - Exploring the Dimensions of Haptic Feedback Support in Manual Control
B.A.C. Forsyth (2006) - Predictive Haptic Guidance: Intelligent User Assistance for the Control of Dynamic Tasks
A. Tsoukalas (2016) - Predictive Lateral Feedback for Safe Lateral Control of Heavy Vehicles in Urban areas
S.M. Petermeijer (2014) - Should Drivers Be Operating Within an Automation-Free Bandwidth? Evaluating Haptic Steering Support Systems With Different Levels of Authority
F. Mars (2014) - Analysis of Human-Machine Cooperation When Driving with Different Degrees of Haptic Shared Control
T. Brandt (2007) - Combining haptic human-machine interaction with predictive path planning for lane-keeping and collision avoidance systems
B. Shyrokau (2016) - The influence of motion and steering system model complexity on truck steering
P. Nilsson (2014) - A Driver Model Using Optic Information for Longitudinal and Lateral Control of a Long Vehicle Combination
Driver Models
Steering Feedback
Guidance
Experiment
Analysis
Results
Measures
Driver model
Vehicle dynamic model
Developed for Trucks
Vision Based Driver Model

H

Driver comments

All comments made by the participants during the experiment are categorized per participant, per support systems, distinguished between with and without SURT tasks. These comments are documented in an Excel file which is made available to the on-line repository.

Three random selected comments, per setting, per control task, are selected from all of the comments and are listed below.

SB, no SURT:

- “Backlash the same as DB, asymmetric in bends - outer didn’t push me back but more dangerous.”
- “Feels like it’s working against me. Sometimes it steers me back but not always (when testing on straight).”
- “I think it sends feedback too strong and maybe to early. Perhaps it could send it more stepwise instead”

DB, no SURT:

- “Not much difference(compared to CDB) Feels a bit lighter(the override forces) Otherwise performing really well. Easy to steer jointly with the system. More maneuverability within the lane than CDB”
- “Not sure how to describe it but it feels it’s helping me in a smoother way. That’s it, smoother. Now it lets me go over the lane on the left side (in curve). It didn’t do that on straight.”
- “Felt like it helped me in the corer but then kicks me on the straight. The system fights back when i counter steer for the headwind. Steers you back too aggressively.”

CDB, no SURT:

- “I want too feel I know when I’m setting out of the lane. Now its more like a rubber band. The system is a bit late. ”
- “This was barely noticeable, I barely noticed it. ”
- “Like it better this way. More subtle, softer more smooth. The level of the force is like something that would occur naturally.”

SB, with SURT:

- “I like the "remind me, keep your eyes on the road" feeling . The level of the torque could be lower. Maybe less sustained also for a specified duration (one second?)”
- “Too much of a force in STW. It seems the corrections are unnecessary strong in that early stage.”
- “Unpleasant distracting when it was doing it. Feels it reacts a lot sooner on left but on right it let me drive on the lane before reacting. I think its good in curves it feels very safe. It catches me.”

DB, with SURT:

- “I felt at least a difference in the steering wheel on this one and the first. This one follows the curves bends better than CDB byt has the backlash”
- “I felt this interfere a little bit early not it wasn’t just a safety system but also more a comfort system.”
- “There is a difference (to SB) but hard to explain. Feels more smooth in the movement. I wonder how much i can trust the system?”

CDB, with SURT:

- “Second task: It feels the system is correcting me.”
- “Not as aggressive as the SB more smooth. This is better than DB less "big" overtakes. Don’t know why it steers like this in curve”
- “More easy this time, too strong in lane when doing secondary task compared to first round (Note Emma: BL)”

Extensive results section

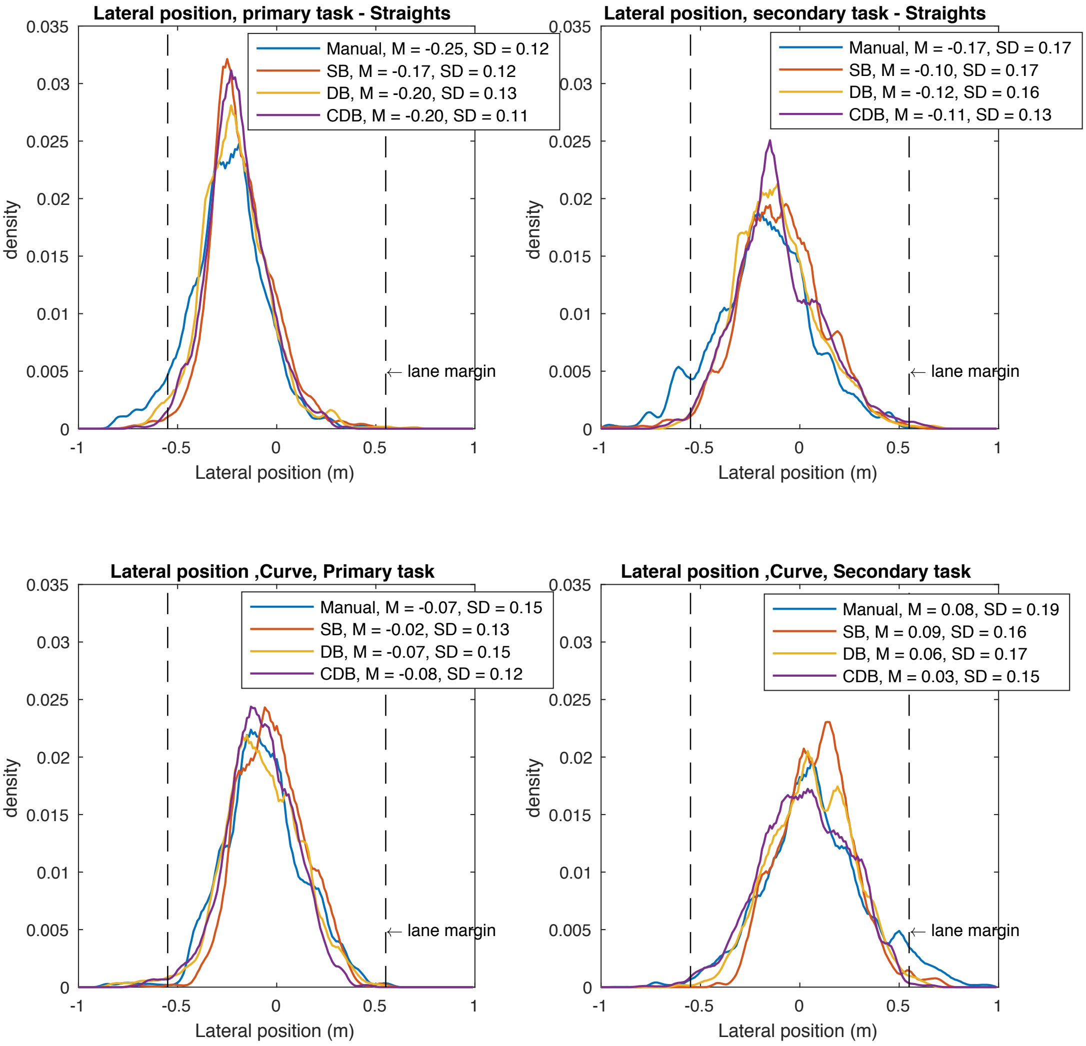


Figure I.1: Distribution of the lateral position (m) of all participants per condition (i.e., Manual, Single Bandwidth, Double Bandwidth, Continuous Double Bandwidth) for the straight and curved road sections for distracted (secondary task) and non-distracted (primary task) driver. The truck's lane margins are indicated by the dashed lines. They represent the distance between the truck and lane markings when the truck is positioned in the center of the lane. Bins are 0.01 m, the area under each of the four curves equals 1.

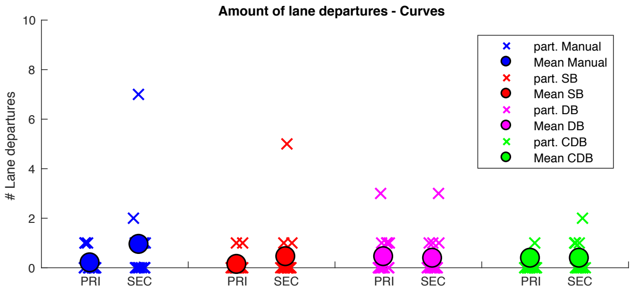


Figure I.2: Lane departure information for a non-distracted (PRI) and a distracted (SEC) driver during curved sections of the track; amount lane departures (#)

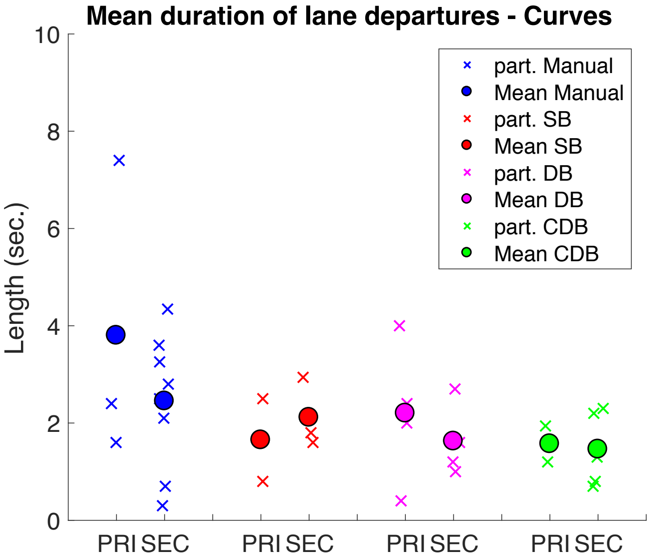


Figure I.3: Lane departure information for a non-distracted (PRI) and a distracted (SEC) driver during curved sections of the track; mean duration lane departures (sec.)

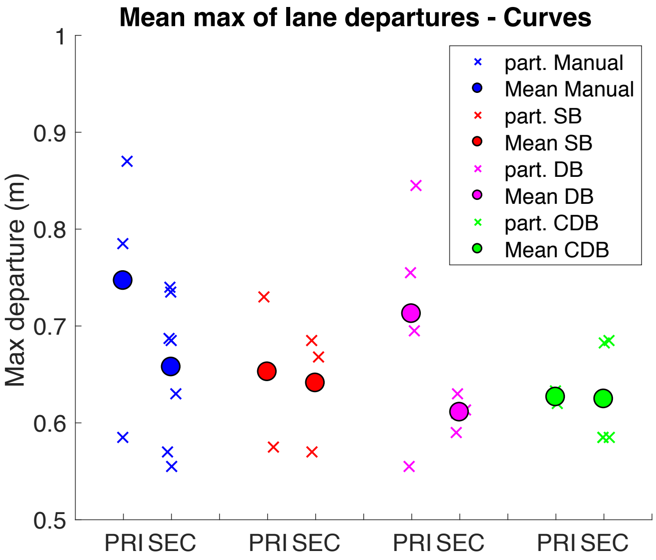


Figure I.4: Lane departure information for a non-distracted (PRI) and a distracted (SEC) driver during curved sections of the track; mean max. lateral error lane departure (m)

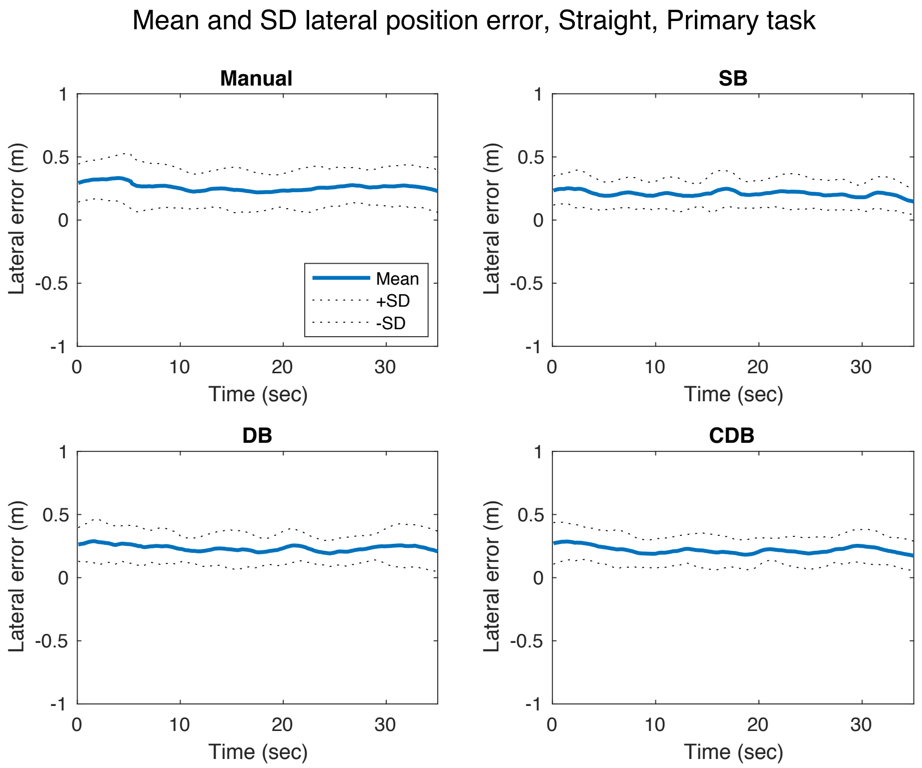


Figure I.5: Mean and SD of lateral position error for all support systems during straights, Primary task

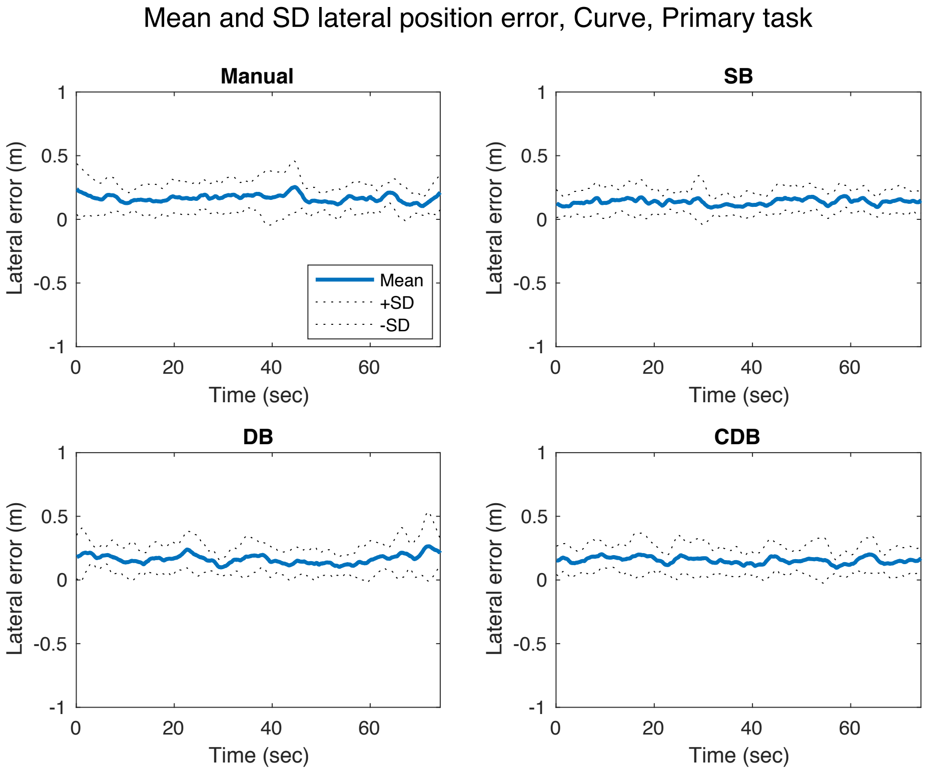


Figure I.6: Mean and SD of lateral position error for all support systems during curves, Primary task

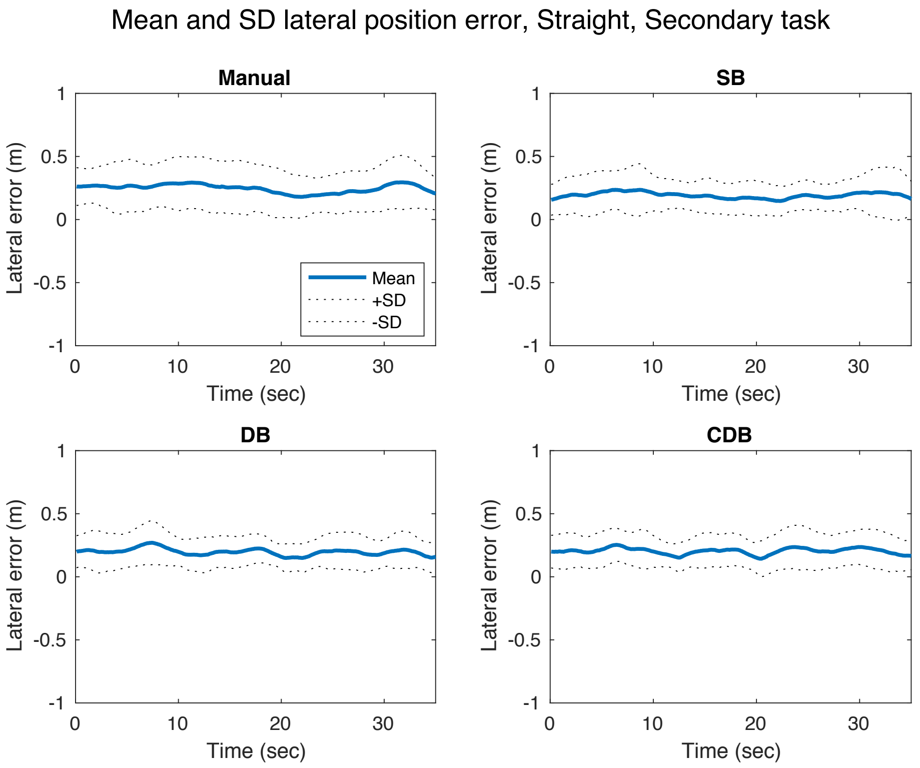


Figure I.7: Mean and SD of lateral position error for all support systems during straights, Secondary task

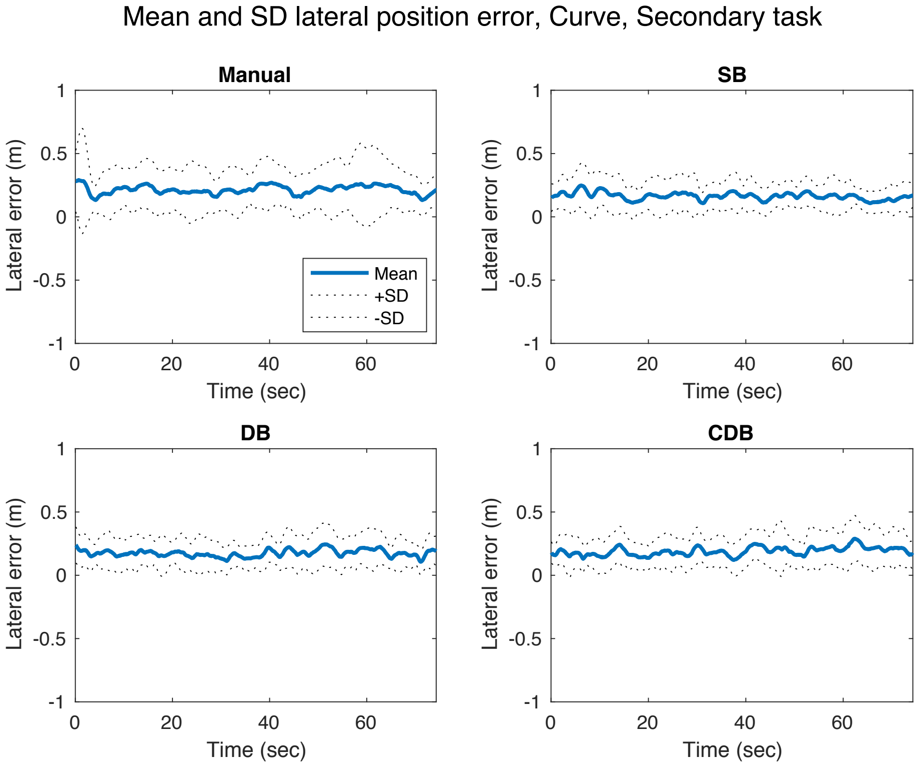


Figure I.8: Mean and SD of lateral position error for all support systems during curves, Secondary task

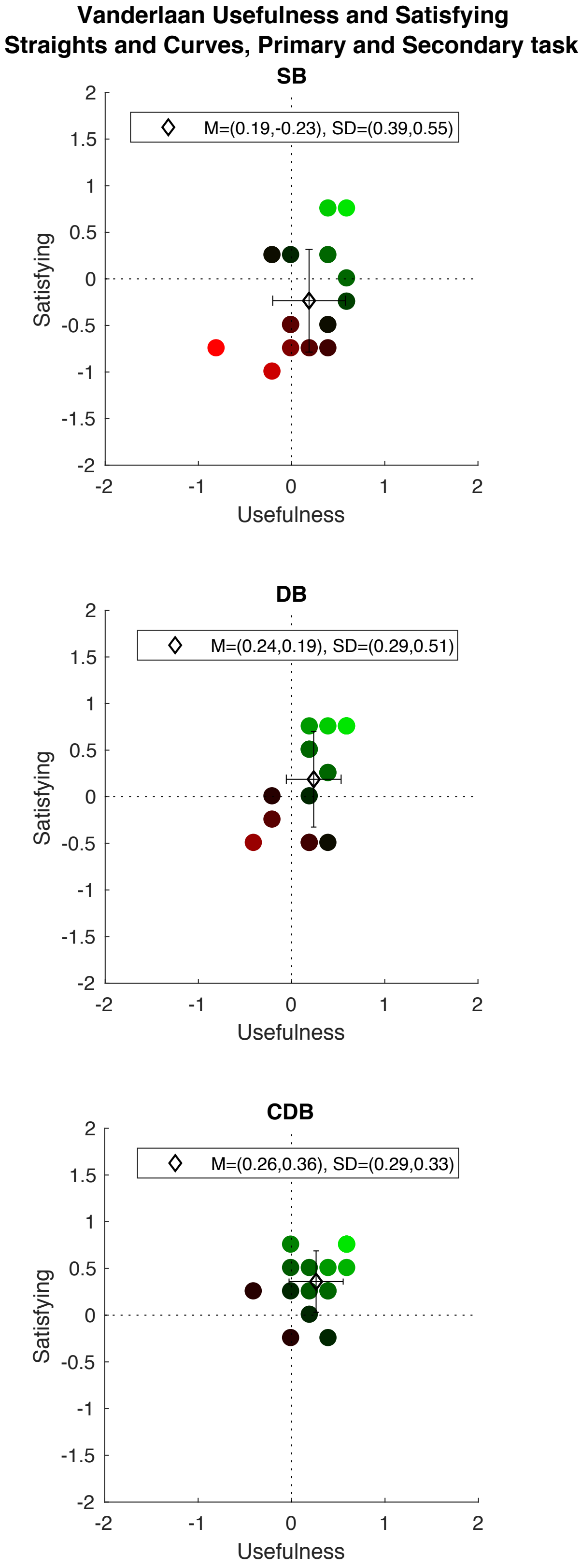


Figure I.9: Steering wheel reversal rates >2 deg. per participant for both straight and curved road sections

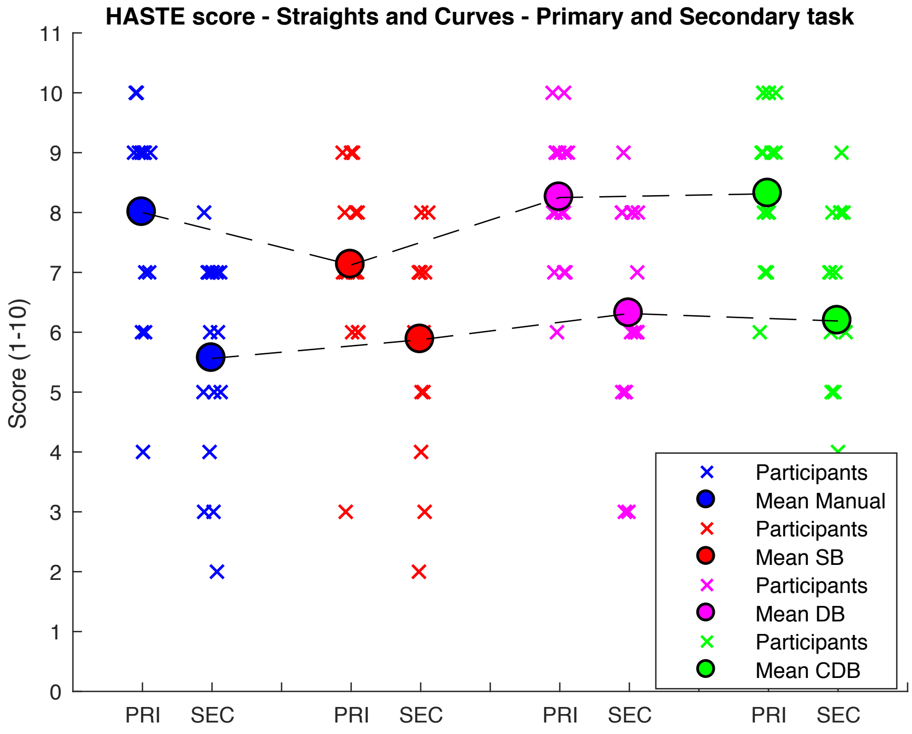


Figure I.10: HASTE-score (self-reported performance indicator of driver and support system combined) per participant (with overlap) and overall means per support system per experiment task

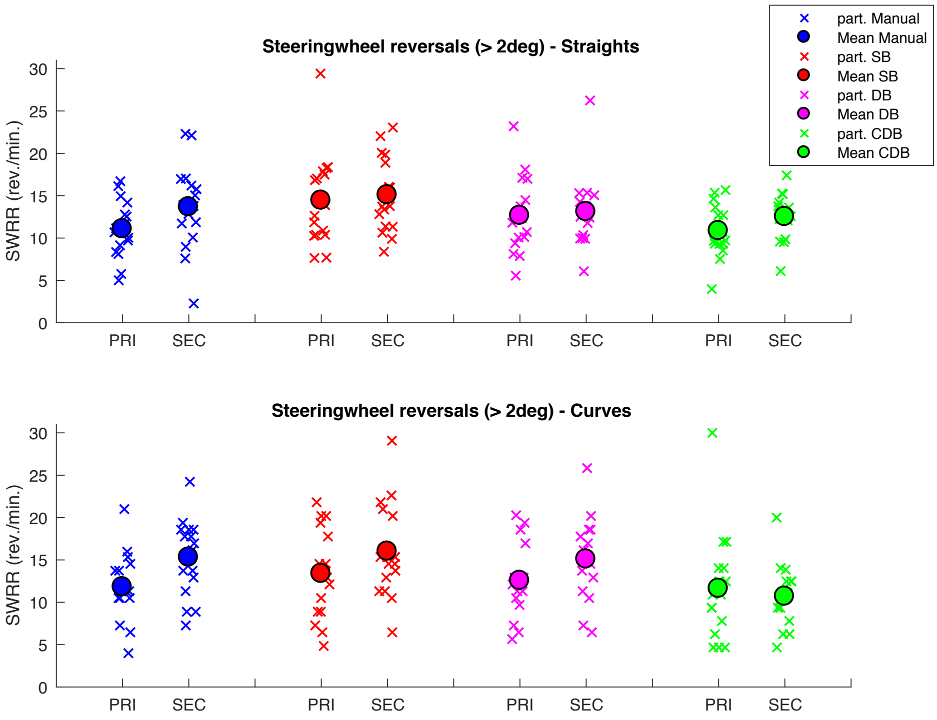


Figure I.11: Steering wheel reversal rates >2 deg. per participant for both straight and curved road sections

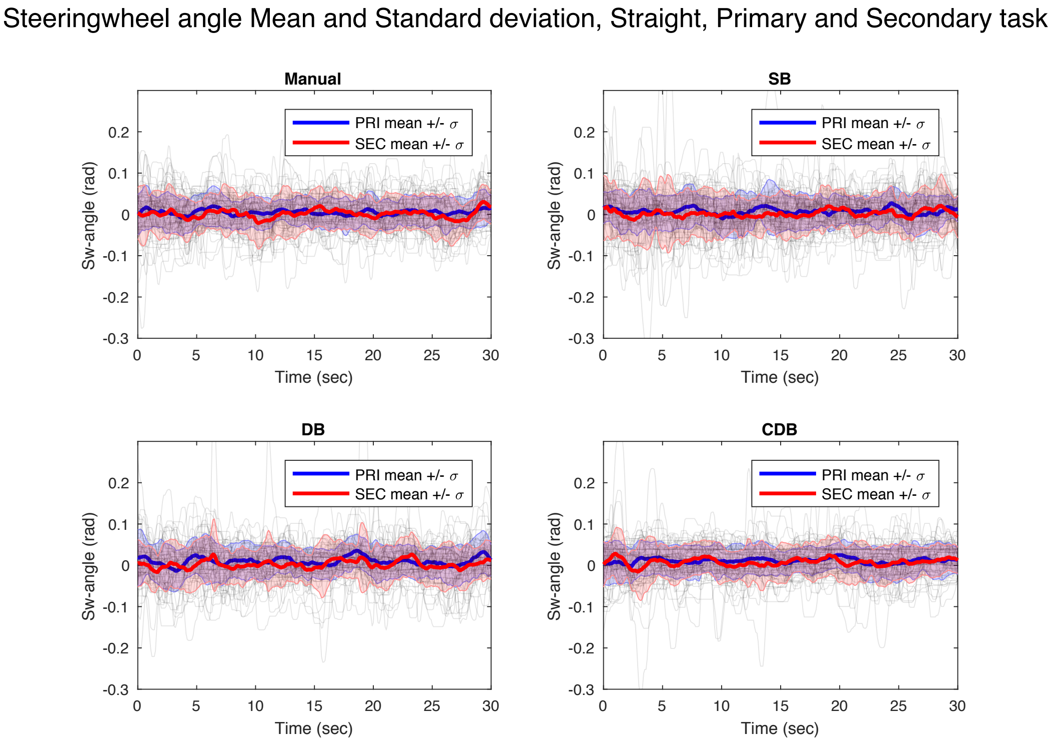


Figure I.12: Steering wheel-angle all participants and Mean +/- Std for all support systems during the two straights combined

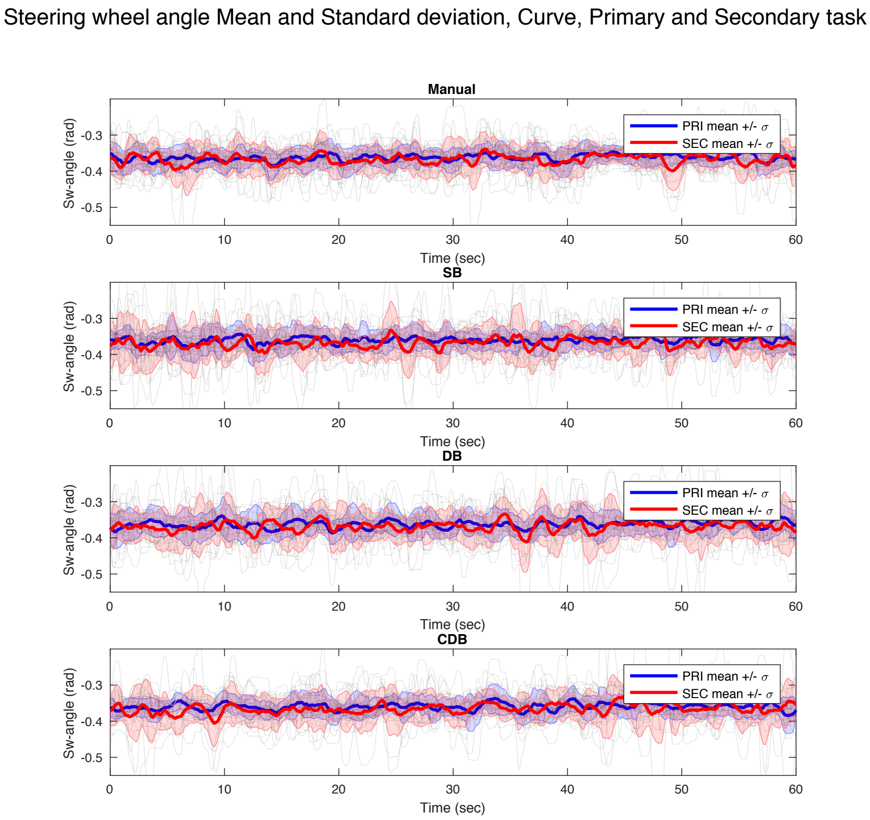


Figure I.13: Steering wheel-angle all participants and Mean +/- Std for all support systems during curves

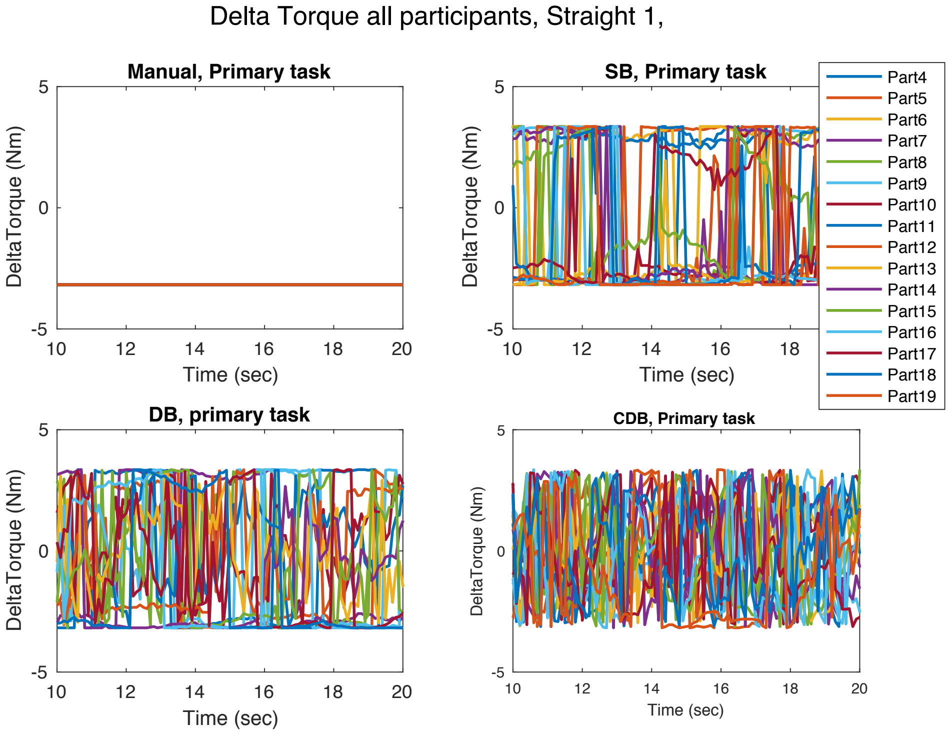


Figure I.14: An example of the by the support systems exerted absolute Delta Torques between 10 and 20 seconds of the first straight road section