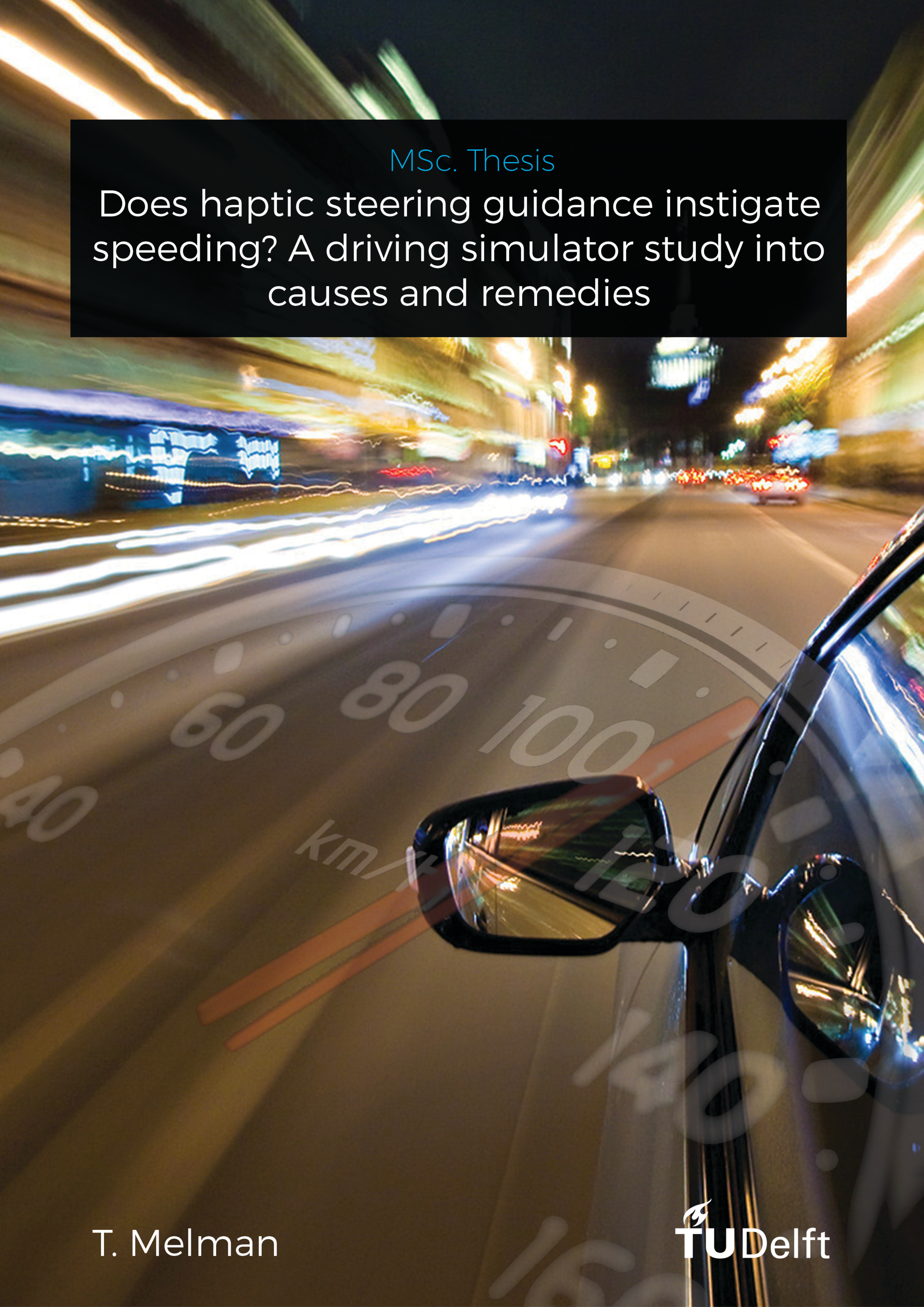

MSc. Thesis

Does haptic steering guidance instigate speeding? A driving simulator study into causes and remedies

T. Melman

TU Delft

Cover image adopted from:
Fotokeren (2015, November). Night high speed car fun [Digital image]. Retrieved May 23, 2016, from http://fotokeren.net/night-high-speed-car-fun/

MSc. Thesis

Does haptic steering guidance instigate speeding? A driving simulator study into causes and remedies

by

T. Melman

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on June 3rd, 2016

Student number:	4090241	
Project duration:	September 1, 2015 – June 3, 2016	
Thesis committee:	Dr. ir. D.A. Abbink,	TU Delft, supervisor
	Dr. ir. J.C.F. de Winter,	TU Delft, supervisor
	Prof Dr. M.P. Hagenzieker,	TU Delft, external member
	Dr. ir. E.R. Boer,	Entropy Control, Inc., external member

Preface

"Automation does not simply supplant human activity but rather changes it, often in ways unintended and unanticipated by the designers of automation"
(Parasuraman et al. 2000)

Driving a car has become a major part of our life. To assist drivers during this task new Advanced Driver Assistance Systems (ADAS) are developed to increase safety and comfort. In reality, however, these safety benefits are often diminished because of adaptations by the driver, such as adopting a higher speed or driving closer to the vehicle in front. In current literature, I found many theories trying to explain why people adapt, but few studies investigating ways to prevent these negative adaptations from occurring (entire literature study is available at `http://repository.tudelft.nl/` for more detail). In this MSc. thesis I took the first step from explaining towards preventing behavioral adaptation, with the aim to make novel ADAS more effective in terms of safety.

This thesis report is part of the fulfillment for the Master degree of Biomechanical Design at the Delft University of Technology. The driving simulator code, Matlab code used for the data analysis, and statistical analyses have been submitted to the BioMechanical Engineering depository on a USB stick, which is available on request.

T. Melman
Delft, May 2016

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First, I would like to thank both my supervisors David Abbink and Joost de Winter for their enthusiasm and support during my MSc. thesis. David always knew how to motivate me, and was there to oversee the bigger picture, whereas Joost, with his keen eye for details, assisted me with tremendous devotion, especially during the last couple of weeks in order to send my thesis to a journal before my graduation. Although we had many memorable discussions, one moment in particular deserves to be mentioned in this acknowledgment; at Sunday evening prior to my experiment, I had some serious concerns. That very same evening, both helped me out, and took these concerns away. Despite the late hour, both were available to help me when I needed them the most. I believe that is what great supervision means!

I also would like to thank Dimitra Dodou, Bastiaan Petermeijer, and Marco Stijnman for reviewing my paper. Emma Heitbrink for designing my front page. Special thanks to Sjors Oudshoorn for the many hours of discussions. Finally, I would like to thank Melissa, Nadine, and my parents because without your support and encouragements I would not have been in this position. Thank you!

T. Melman
Delft, May 2016

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Journal Paper

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Does haptic steering guidance instigate speeding? A driving simulator study into causes and remedies

T. Melman, J. C. F. de Winter, & D. A. Abbink

Abstract— An important issue in road traffic safety is that drivers show adverse behavioral adaptation (BA) to driver assistance systems. Haptic steering guidance is an upcoming assistance system which facilitates lane-keeping performance while keeping drivers in the loop, and which may be particularly prone to BA. Thus far, most experiments on haptic steering guidance have measured driver performance while the vehicle speed was kept constant, and so the degree of BA could not be established. The aim of the present driving simulator study was to examine whether haptic steering guidance causes BA in the form of speeding, and to evaluate two types of haptic steering guidance designed not to suffer from BA. Twenty-four participants drove a 1.8 m wide car for 13.9 km on a curved road, with cones demarcating a single 2.2 m narrow lane. Participants completed four conditions in a counterbalanced design: no guidance (Manual), continuous haptic guidance (Cont), continuous guidance that linearly reduced feedback gains from full guidance at 125 km/h towards manual control at 130 km/h and above (ContRF), and haptic guidance provided only when the predicted lateral position was outside a bandwidth (Band). Participants were familiarized with each condition prior to the experimental runs and were instructed to drive as they normally would do while minimizing the number of cone hits. Compared to Manual, the Cont condition yielded a significantly higher driving speed (on average by 7 km/h), whereas ContRF and Band did not. All three guidance conditions yielded better lane-keeping performance than Manual, whereas Cont and ContRF yielded lower self-reported workload than Manual. In conclusion, continuous steering guidance entices drivers to increase their speed, thereby diminishing its potential safety benefits. It is possible to prevent BA while retaining safety benefits by making a design adjustment either in lateral (Band) or in longitudinal (ContRF) direction.

Index Terms— Behavioral adaptation, haptic steering guidance, human-automation interaction, driving simulator

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1. INTRODUCTION

Advanced Driver Assistance Systems (ADAS) support drivers in task such as lane keeping, car following, braking, and obstacle avoidance (e.g., Eichelberger and Mccartt, 2016; Ferguson et al., 2008). Generally, ADAS are developed with the goal to increase comfort and safety, and numerous simulator-based and test-track studies indeed have shown such benefits (cf. Bengler et al., 2014; Piao and McDonald, 2008). In reality, however, the anticipated safety benefits are often diminished because of adaptations by the driver, such as adopting a higher speed, driving closer to a lead vehicle, or performing distractive non-driving tasks as compared to driving without ADAS (Hiraoka, Masui, & Nishikawa, 2010; Martens & Jenssen, 2012; Mehler, Reimer, Lavallière, Dobres, & Coughlin, 2014; Saad, 2006).

The ability to adapt is intrinsic to humans, and although adaptation can arguably have positive effects in certain situations (e.g., close following may be beneficial in terms of highway capacity), most transportation researchers are concerned with adaptations that degrade the safety benefits that can be achieved with ADAS. For example, Sagberg et al. (1996) observed a reduced time headway among 213 taxis equipped with an Anti-lock Braking System (ABS), compared to taxis without ABS. Their results suggest that the taxi drivers misused the fact that ABS reduces the braking distance by driving closer to the vehicle in front. Such adaptation with negative consequences is called Behavioral Adaptation (BA) (OECD, 1990), and has been implicated in many types of ADAS including not only ABS, but also adaptive cruise control (Panou, Bekiaris, & Papakostopoulos, 2007), lane departure warning systems (Rudin-Brown & Noy, 2002), and collision avoidance systems (Janssen & Nilsson, 1993).

The psychological mechanisms behind BA are yet to be elucidated, but it has been postulated that drivers exhibit a trade-off between two conflicting motivations, namely arriving at a destination in time (efficiency) versus avoiding dangerous situations (safety), and whereby the driver's level of subjective risk (Näätänen & Summala, 1974; Wilde, 2013; Wilde, 1998), task difficulty (Fuller, 2005), or time/safety margins (Gibson & Crooks, 1938; van Winsum, de Waard, & Brookhuis, 1999) are important homeostatic variables. Accordingly, drivers adopt a higher speed or a shorter headway when the driving task becomes easier, less risky, or less temporally demanding due to a change in the road-vehicle-driver system, such as improved environmental conditions (e.g., increased speed that occurs when adding road lighting; Assum et al., 1999) or increased controllability of the car itself (e.g., increased speed and shorter headway time adopted when driving with an adaptive cruise control; Dragutinovic et al., 2005). The magnitude of the BA effects is thought to depend on

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- T. Melman, J.C.F. de Winter and D.A. Abbink are part of the Department of Mechanical Engineering, Faculty of 3mE, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands.
  E-mail: T.Melman@student.tudelft.nl

the time driven with the ADAS, the driver's attitude towards the ADAS (e.g., whether the driver uses the system to drive to the limit), driver experience, and the design of ADAS (Carsten, Lai, Barnard, Jamson, & Merat, 2012; Saad, Hjälmdahl, Cañas, & Alonso, 2004; Sullivan, Flannagan, Pradhan, & Bao, 2016). One supposedly important predictor of BA is the ADAS' noticeability: It has been said that ADAS which cause directly noticeable differences in the road-vehicle-driver system suffer from BA to a greater extent than ADAS that do not (Elvik, Vaa, Hoye, & Sorensen, 2004). That is, if drivers are more aware of the ADAS' interference it is more likely that they will adapt their behavior. For example, larger BA effects have been demonstrated for driving with a night vision enhancement system than when implementing a non-visible feature such as electronic stability control (e.g., Hiraoka et al., 2010; Jiménez et al., 2008). Based on these findings it is expected that ADAS that continuously interact with the driver are more likely to suffer from BA than for instance emergency systems.

One type of ADAS which is growing in popularity and which may be particularly prone to BA is haptic steering guidance. The philosophy of haptic steering guidance is to use the control interfaces as channels for continuous communication and interaction between the driver and an intelligent vehicle, thereby keeping the driver informed and involved in the driving task, and mitigating the out-of-the-loop problems that occur in hands-free automated driving (Abbink et al., 2012; Flemisch et al., 2008; Griffiths and Gillespie, 2005; Johns et al., 2016; Mars et al., 2014a; O'Malley et al., 2006; Soualmi et al., 2014, and see Petermeijer et al., 2015b for a review). Concretely, haptic steering guidance continuously assists drivers during a steering task by providing torques on the steering wheel based on the target steering behavior of an automated controller. Previous research has shown beneficial effects in terms of improved lane-keeping performance, increased safety margins (in terms of time-to-line crossing), and reduced self-reported workload for driving with steering guidance as compared to unsupported driving (Mars et al., 2014b; Mulder, Abbink, & Boer, 2012; O'Malley et al., 2006). In summary, due to the continuous interaction, increased controllability, and reduced workload, haptic steering guidance may be highly susceptible to BA.

Recently, researchers have started to investigate the hypothesis that the beneficial effects of haptic guidance might be accompanied by unintended side effects, such as over-reliance. A driving simulator study by Petermeijer et al. (2015a) found that drivers showed dangerous short-term steering oscillations, also called 'aftereffects', after the steering guidance failed just before entering a curve. However, as with most research on haptic steering guidance (e.g., Griffiths and Gillespie, 2005; Mohellebi et al., 2009; Mulder et al., 2012), the vehicle speed in this study was held constant. It is yet unknown whether participants driving with haptic steering guidance will show BA in terms of increased driving speed. The only study on this topic found no BA with continuous haptic steering guidance compared to manual driving (Mars et al., 2014b). This study compared two groups of participants in a driving simulator for about three hours in total; one group drove with haptic steering guidance and the other drove without. No statistically significant speed difference was found between the two groups; however due to the between-subject design and the generally large individual variability in driving speed this particular study may have lacked the statistical power to detect speed differences that possibly exist in the population.

The aim of the present research was two-fold. Our first aim was to test the hypothesis that haptic steering guidance causes BA operationalized as driving speed. Driving speed has traditionally been a prime measure of BA with clear effects on road safety (Elvik, 2013). An increase of speed reduces a driver's time to respond in case of an emergency scenario, increases the probability of being involved in a crash, affects the driver's severity of injury if a crash occurs, and often forgotten, increases the severity of injury of (vulnerable) road users that are hit by the driver (Aarts & Van Schagen, 2006; Elvik, Christensen, & Amundsen, 2004; Hedlund, 2000).

Our second aim, anticipating on the hypothesized BA caused by haptic steering guidance, was to investigate the effectiveness of two types of haptic steering guidance that were developed to mitigate speeding without compromising the beneficial effects of guidance on safety and comfort. The first design (Band) incorporates a lateral bandwidth whereby the guidance engages only when the vehicle deviates substantially from the lane center. This design was previously tested at a constant driving speed and was found to mitigate effects of over-reliance in case the technology suddenly failed (Petermeijer et al., 2015a). The second design is a longitudinal boundary system (ContRF) that removes the continuous guidance when driving faster than a pre-defined speed threshold. Both of these fundamentally different systems were hypothesized to reduce speeding: the Band condition is equivalent to driving manually unless making a large lateral error (thereby providing guidance only when needed) and the ContRF condition provides guidance in normal conditions, but ceases to function when the driver adopts a high speed (thereby removing the benefits of guidance when driving fast).

This study evaluated driving behavior when driving with three haptic steering guidance systems on a narrow road with cones along the entire road, compared to unsupported driving. Prior to each guidance condition, drivers were familiarized with the working mechanisms of the steering guidance. This was done because a BA effect may not appear immediately but rather appears after a familiarization period that allows drivers to update their mental model of the system (Beggiato, Pereira, Petzoldt, & Krems, 2015; Bianchi Piccinini, Rodrigues, Leitao, & Simoes, 2014; Martens & Jenssen, 2012; Saad, 2004; Sullivan et al., 2016). To enhance the familiarization process, each guidance condition was explained to the participants in detail. During the actual experiment, drivers were instructed to drive as they normally would while minimizing the number of cones hit. Drivers received real-time feedback on their lane-keeping performance: a cone hit was indicated by means of a red dot appearing on the screen. The augmented feedback (i.e., red dot) and narrow road were assumed to enhance the subjective risk and noticeability of the lane-keeping benefits of the haptic guidance, and to discourage participants from driving at full speed (cf. Zhai et al., 2004). Due to these factors, it was expected that if haptic steering guidance suffers from BA, this effect would be detected sooner. To investigate the potential risks of speeding, a sharp curve was introduced at the end of the trial trajectory.

In summary, the aim of this study was to investigate the effect of three different designs of haptic steering guidance on speeding. It was hypothesized that when driving with continuous steering guidance participants would adopt a higher speed than when driving without support. Moreover, a lateral and longitudinal alternative steering guidance were tested. Both designs were hypothesized to not suffer from speed adaptations while retaining a high lane-keeping performance compared to unsupported driving. In order to offer a comprehensive evaluation and comparison between conditions, each design was assessed with respect to five categories of measures: speed, lane-keeping accuracy, safety margin, workload, and system acceptance.

2. METHOD

2.1. Participants

Twenty-four participants (7 female) between 23 and 52 years old (*M* = 28.0, *SD* = 9.6) with normal or corrected-to-normal vision volunteered for a driving simulator experiment. All participants had their driver's license for at least five years. In response to the question how often they drove in the past 12 months, 6 participants reported to drive every day, 4 drove 4–6 days a week, 5 drove 1–3 days per week, 5 drove once a month, 3 drove less than once a month, and 1 never. Regarding mileage in the past 12 months, the most frequently selected response category was 1.001–5.000 km (8 respondents), followed by 10.001–15.000 km (6 respondents), and 25.001–35.000 km (3 respondents).

2.2. Apparatus

The experiment was conducted in a fixed-base simulator at the Control and Simulation Department at the faculty of Aerospace Engineering, Delft University of Technology. The steering wheel was electronically actuated by a MOOG FCS ECol8000 S Actuator running at 2500 Hz. Vehicle dynamics were simulated with a single-track model (heavy sedan of 1.8 m wide), having an automatic gearbox, and a maximum speed of 160 km/h. The scenery was visualized using three LCD projectors with a horizontal and vertical field-of-view of respectively 180° and 40°. The visuals were refreshed at 50 Hz, whereas the simulation and data logging were updated at 100 Hz. A car front was visualized to facilitate perception of the car's position relative to the road boundaries. Car vibrations ('road rumble') were simulated with a seat shaker implemented in the driver's seat.

2.3. Designs of Haptic Steering Guidance

In addition to the Manual condition that simulated natural self-alignment torques, three different methods were used to provide superimposed haptic guidance torques on the steering wheel. Each of these three methods used a two-level algorithm which was identical to previously published research (Abbink & Mulder, 2009; Mulder, Abbink, & Boer, 2008; Petermeijer et al., 2015a). The first level calculated the desired steering angle based on a two-parameter model that predicts the future lateral error between the lane center and the middle of the car (e_{future_lat}) and the future heading error of the car ($e_{future\_heading}$), at a look-ahead time of 0.7 s. The first level was identical for each of the three tested guidance conditions. At the second level, the two variables calculated in the first step were converted to feedback torques according to an algorithm that was different for each of the three guidance conditions.

2.3.1. Continuous Steering Guidance (Cont)

The system Cont forms the baseline for the haptic steering guidance. It provides continuous feedback torques on the steering wheel using the two-level architecture described above, for which the second level is shown in Equation 1.

$$T_{feedback} = \left(e_{future\_lat} \cdot D + e_{future\_heading} \cdot P\right) \cdot K_f \qquad (1)$$

The feedback gains were identical to Mulder et al. (2008), namely K_f = 2.0, D = 0.08, and P = 0.9. This system guides towards the lane center, instead of guiding away from lane boundaries like several marketed lane-keeping assistance systems do.

2.3.2. Continuous Steering Guidance with a Reducing Feedback Gain (ContRF)

The ContRF is a speed-dependent version of the continuous guidance Cont. At speeds below 125 km/h the ContRF condition functions identically to Cont. If the speed is greater than 125 km/h, the feedback torque ($T_{feedback}$) linearly reduces to zero, and beyond speeds of 130 km/h it is identical to the Manual condition (see Equation 2). The working principle of ContRF is to remove the guidance when driving at excessive speeds, thereby theoretically mitigating speed adaptation. The boundary of 125–130 km/h was chosen based on results of pilot studies.

$$T_{feedback} = \begin{cases} \left(e_{future\_lat} \cdot D + e_{future\_heading} \cdot P\right) \cdot K_f & for\ v < 125 \\ \left(e_{future\_lat} \cdot D + e_{future\_heading} \cdot P\right) \cdot K_f \cdot \dfrac{130 - v}{5} & for\ 125 \le v \le 130 \\ 0 & for\ v > 130 \end{cases} \qquad (2)$$

2.3.3. Bandwidth Guidance (Band)

The bandwidth guidance is similar to the 'double bandwidth' system previously introduced by Petermeijer et al. (2015a). This design was shown to mitigate over-reliance on haptic guidance, and may be a viable solution to speed adaptation as well. The Band condition has two states of operation. In State 1 the Band system does not exert any torque when the virtual car is in the lane (i.e., absolute e_{future_lat} is smaller than 0.2 m). Once the e_{future_lat} exceeds this threshold, the system switches to State 2. In State 2 the system exerts torque until the absolute e_{future_lat} is below 0.1 m of the lane center, as shown in Equations 3 and 4.

$$T_{state1\_feedback} = \begin{cases} 0 & for\ |e_{future\_lat}| < 0.2 \\ e_{future\_lat} \cdot D \cdot K_f & for\ |e_{future\_lat}| \geq 0.2 \end{cases} \quad (3)$$

$$T_{state2\_feedback} = \begin{cases} 0 & for\ |e_{future\_lat}| < 0.1 \\ e_{future\_lat} \cdot D \cdot K_f & for\ |e_{future\_lat}| \geq 0.1 \end{cases} \quad (4)$$

2.4. Road Environment

All participants drove each trial on the same narrow single-lane road (2.2 m wide and 13.9 km long), assisted by one of the four conditions. The road width of 2.2 m and car width of 1.8 m allowed 0.2 meters on both sides of the car before a cone would be hit. The first 12 km of the trajectory contained three types of curves with inner radii of 1.500 m, 750 m, and 500 m, respectively. This road design assured that no braking was required before curves (i.e., curves could be taken full throttle), and that the lateral accelerations stayed at all times in the linear region where the simulated car dynamics are valid (Dixon, 1988). To investigate the downsides of potential speeding, a sharp curve to the right was introduced at the end of the trajectory (inner radius of 300 m and 300 m long) for which the physically maximum speed was approximately 125 km/h. That is, driving faster than 125 km/h would result in the car veering off the road on the outside of the curve. Before each experimental trial, participants were familiarized with the guidance by means of a training run. The roads of the training runs were identical to the first three quarters of the road in the subsequent experimental trials (10.5 km long). Speed perception was complemented by means of trees alongside the road. Cones were placed along the entire road with a distance between cones of 8 m. A cone hit was visualized with a red dot on the side where the car hit a cone (Figure 1). Apart from the trees and cones, no obstacles or other road users were simulated.

2.5. Experimental Design

The four conditions were compared in a counterbalanced within-subjects design: no guidance (Manual), ContRF, Band, and Cont. Prior to the experiment participants read and signed an informed consent form, explaining the purpose, instructions, and procedures of the study (Appendix B). Participants were informed about the availability of each steering guidance and were told to keep both hands on the steering wheel in a ten-to-two position at all times. Participants were instructed to drive as they normally would and to minimize the number of cone hits. No speed advice was given and any questions regarding speed were not answered.

Before entering the driving simulator, participants filled out a personal detail questionnaire regarding their driving experience and a Driver Behaviour Questionnaire (DBQ) containing seven violation items (de Winter & Dodou, 2016) (Appendix E). Prior to each trial, a training run of approximately six minutes was performed (i.e., fixed road distance of 10.5 km). Six minutes was considered sufficient to become familiar with a guidance system (McGehee, Lee, Rizzo, Dawson, & Bateman, 2004). To enhance the familiarization process, two actions were taken. First, the experimenter explained the working mechanism of each guidance, but not the underlying hypothesis. Second, participants were stimulated to experience the guidance's working mechanism by allowing them to drive without negative consequences (i.e., cone hits were not counted but still visualized). To emphasize the importance of understanding each guidance condition, the experimenter orally motivated the driver to experience the mechanism of each guidance condition at least once. For ContRF this meant that the driving speed was at least once above 130 km/h, so that the participants could feel the steering guidance being absent when driving fast; for Cont this came down to driving with large lateral errors to feel the feedback force increasing; for Band drivers were asked to let go of the steering wheel to observe that the guidance turns on just before hitting the cones.

Figure 1. Simulator environment including the car front and cone hit warning (i.e., red dot).

After each trial, participants were informed about the number of cone hits and were requested to step out of the simulator for a 5 min break and to fill out three questionnaires: a NASA Task Load Index (NASA-TLX) (Hart & Staveland, 1988) to assess workload (Appendix C), an acceptance questionnaire (Van der Laan, Heino, & De Waard, 1997) to assess satisfaction and usefulness of the guidance (Appendix D), and a simulator sickness item (Appendix C). In the latter, participants needed to indicate whether they were feeling simulator sickness on a scale from 1 to 6 (1 = no sign of symptoms, 2 = arising symptoms, 3 = slightly nauseous, 4 = nauseous, 5 = very nauseous, 6 = vomiting). A response of 4 or higher would stop the experiment. The total experiment, including filling out all questionnaires, took approximately 1.5 hours per participant.

2.6. Dependent Measures

The data measured on the first and last 400 m of the trajectory were discarded, because of the initial accelerations and final decelerations of the simulated vehicle. This resulted in a 13.1 km long trajectory that was used in the analysis. The dependent measures that were calculated were categorized into speed, performance, workload, safety, and system acceptance.

2.6.1. Vehicle Speed

- *Mean Speed* (km/h). This was the primary BA effect of interest.

2.6.2. Performance

- *Percentage Time Off-Road* (TOR) (%). Which is the amount of time that the car drives outside the cone boundaries (i.e., the middle of the car deviates more than 0.2 m from the lane center), expressed as a percentage of the total driving time.
- *Mean and Maximum Absolute Lateral Error* (m). The absolute lateral error was defined as the distance from the middle of the car towards the center of the lane. The absolute lateral error and TOR are measures of lane-keeping accuracy.
- *Mean time needed to get back in lane* (s). The time needed from the moment the car crosses the cone boundary (i.e., center of the car within 0.2 m of the lane center) to the time the car is back within the cone boundaries for at least 5 s. This serves as measure of controllability.

2.6.3. Workload

- *NASA TLX Subjective Workload* (%). After each trial, participants were asked to indicate their workload on six items: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. Items were scored on a 21-point scale from *very low to very high*, except for Performance, which ranged from *perfect to failure*. The overall workload was calculated as the arithmetic mean of the six items (Cain, 2007; Hart & Staveland, 1988).
- *Steering Reversal Rate* (SRR) (reversals/s). SRR is defined as the number of times that the steering wheel is reversed by a magnitude greater than 2 deg (McLean & Hoffmann, 1975), and can be considered an objective measure for workload (Johansson et al., 2004). The SRR was calculated by determining the local minima and maxima of the steering wheel angle, and if the difference between two adjacent peaks was greater than 2 deg, it was counted as a reversal.
- *Mean Absolute Feedback Torque* (Nm). The feedback torque is the torque superimposed on the driver by the haptic steering guidance. A high mean feedback torque means that more guidance was applied.
- *Mean Absolute Driver Torque* (Nm). The driver torque is the torque applied by the driver on the steering wheel, and was considered as a measure of the driver's physical effort.

2.6.4. Safety Margins

- *Median Time to Line Crossing* (TLC) (s). The median TLC was approximated using the lateral speed and lateral acceleration (Van Winsum et al., 2000). The TLC was set at 0 s when driving outside the lane boundaries.

2.6.5. System Acceptance

An acceptance questionnaire (Van der Laan et al., 1997) was used to assess system acceptance on two dimensions, a *usefulness scale* and an affective *satisfaction scale*. This questionnaire consisted of nine items, scored between +2 and −2. The *usefulness scale* was obtained by taking the average score for the items: Useful-Useless, Bad-Good*, Effective-Superfluous, Assisting-Worthless, and Raising Alertness-Sleep-inducing. The *satisfaction scale* is the average score for the items: Pleasant-Unpleasant, Nice-Annoying, Irritating-Likable*, and Undesirable-Desirable*. Appropriate sign reversals were conducted for the items indicated with an asterisk.

2.7. Statistical Analyses

For each dependent measure, a matrix of 24 x 4 numbers was obtained (24 participants and 4 conditions). This matrix was rank-transformed according to Conover and Iman (1981). The rank-transformed matrix, consisting of numbers from 1 to 96, was submitted to a repeated measures ANOVA with the four conditions as within-subjects factor. Bonferroni corrections were applied to the six pairwise comparisons between the conditions.

3. RESULTS

During the training run, all participants had experienced the mechanism of each guidance condition at least once. This exploratory behavior during training was not analyzed.

3.1. Vehicle Speed

Table 1 shows the means and standard deviations for all dependent measures, the results of repeated measures ANOVA, and the pairwise comparisons. Drivers adopted significantly different speeds among the four conditions, $F(3,69) = 5.96$, $p = .001$. When supported by Cont, participants drove significantly faster (on average by 7 km/h) compared to ContRF and Manual. This speed difference occurred both on straights and in curves (Figure 2). No statistically significant speed differences were observed between Manual and the two guidance conditions that were hypothesized not to suffer from BA (i.e., ContRF and Band).

Ninety-five percent of the time drivers did not exceed the lower speed threshold (125 km/h) when driving with ContRF, effectively resulting in an identical guidance as the continuous guidance. A majority of 14 out of 24 participants in the ContRF condition never exceeded the lower speed threshold of 125 km/h (Figure 3). Even though ContRF and Cont effectively were identical conditions for most

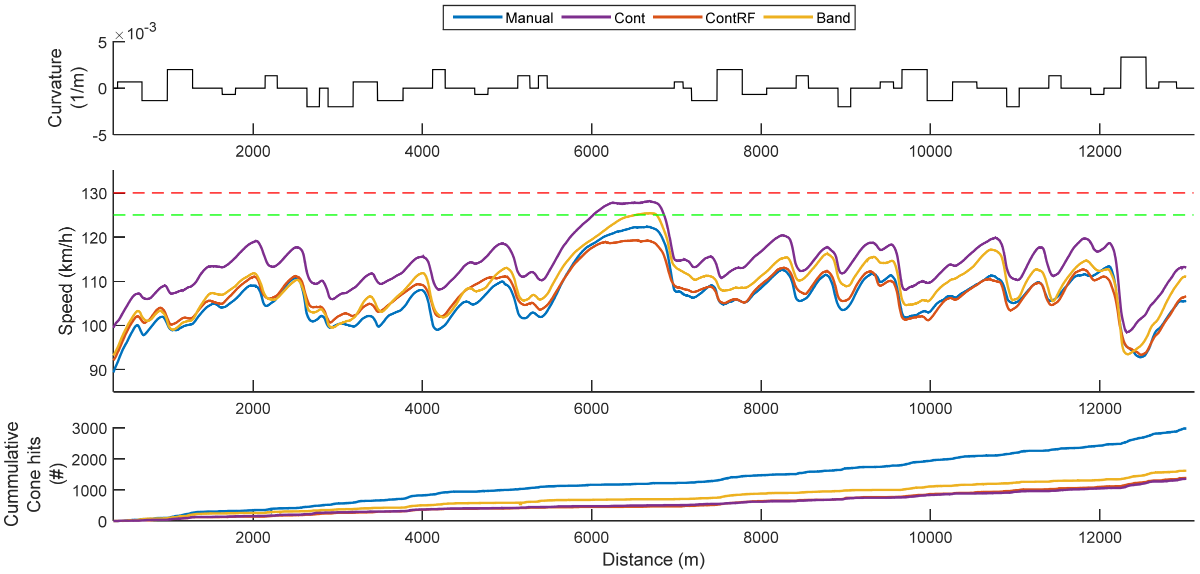

Figure 2. Top: curvature (1/curve radius) of the trajectory. Middle: mean speed across all participants per condition. The horizontal dotted lines indicate the speed thresholds of the ContRF condition. Bottom: cumulative number of cone hits for all participants combined per condition. Cones were 8 m apart. The cone hit results for the Cont and ContRF conditions are overlapping.

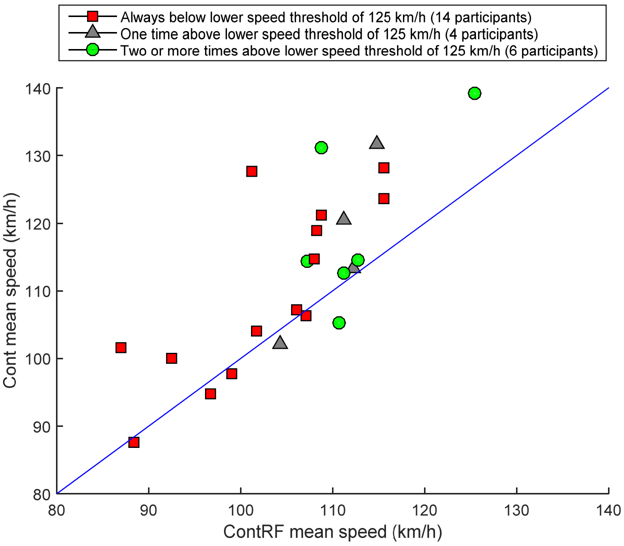

Figure 3. The participants' mean driving speeds (km/h) for the ContRF condition compared to Cont condition. The blue line indicates equal speed for both conditions. The different markers designate the number of times a participant exceeded the 125 km/h speed threshold when driving with ContRF. 18 out of the 24 participants drove faster with Cont than ContRF. 10 participants experienced the reduction of ContRF guidance (circles and triangles combined).

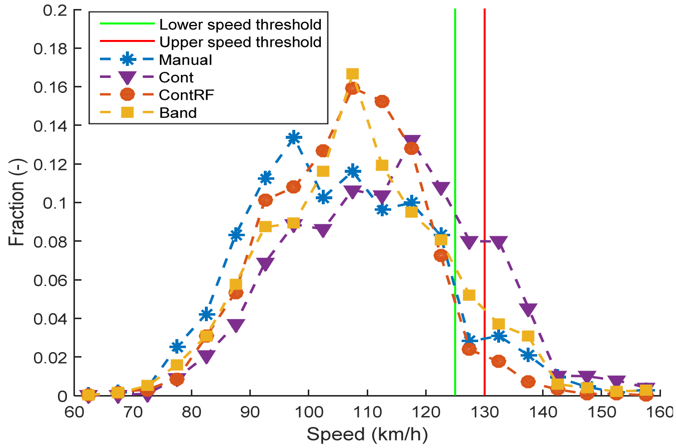

Figure 4. Speed distribution (km/h) of all participants combined. The bin width is 5 km/h. The fraction is plotted in the middle of each bin. The red and green lines indicate the speed thresholds of ContRF. The sum of all fractions equals 1 for each condition.

of the driving time, the speed distribution between these two conditions was notably different (Figure 4). Figure 4 shows a drop for the ContRF just before the lower speed threshold, whereas for the Cont condition, no such drop can be seen. Moreover, a larger fraction of the speed distribution of the Cont condition is located above the 125 km/h threshold as compared to the three other conditions (Manual = 9.8%, ContRF = 5.3%, Band = 13.4%, Cont = 23.8%).

3.2. Performance

All three steering guidance conditions showed better lane-keeping performance than the Manual condition in terms of a lower Time Off-Road (TOR), lower maximum absolute lateral error, and lower time to get back in lane (Table 1; Figure 2). Band and Manual yielded significantly higher mean absolute lateral errors than ContRF and Cont (Table 1), which may be caused by the fact that Band provided no guidance for on average 84% of the driving time and therefore mostly functioned identically to the Manual condition. No statistically significant differences in lane-keeping performance were found between ContRF and Cont.

Table 1. Means (*M*), standard deviations (*SD*), and results of the repeated measures ANOVA (*F, p*) per dependent measure.
x means $p \leq 0.05$, xx mean $p \leq 0.01$, xxx means $p \leq 0.001$.

	Manual (1)	ContRF (2)	Band (3)	Cont (4)		Pairwise comparisons					
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*p* value *F*(3,69)	1-2	1-3	1-4	2-3	2-4	3-4
Vehicle Speed											
Mean Speed	105.7	106.4	108.3	113.3	$p = 0.001$			xx		x	
(km/h)	(12.7)	(9.0)	(11.3)	(13.1)	$F = 5.96$						
Performance											
Percentage time off-road	7.21	3.32	3.92	3.40	$p = 2.51 \cdot 10^{-10}$	xxx	xxx	xxx			
(%)	(4.36)	(2.24)	(2.49)	(2.67)	$F = 22.68$						
Mean absolute lateral error	0.087	0.074	0.086	0.074	$p = 1.08 \cdot 10^{-11}$	xxx		xxx	xxx		xxx
(m)	(0.014)	(0.010)	(0.011)	(0.012)	$F = 27.10$						
Maximum absolute lateral error	0.47	0.33	0.37	0.38	$p = 2.17 \cdot 10^{-7}$	xxx	xx	xxx			
(m)	(0.15)	(0.06)	(0.14)	(0.24)	$F = 14.42$						
Mean time to get back in lane boundaries	3.19	2.03	2.00	1.72	$p = 4.41 \cdot 10^{-6}$	xx	x	xxx			
(s)	(1.64)	(1.16)	(1.07)	(0.73)	$F = 11.22$						
Workload											
Mean abs feedback torque		0.19	0.06	0.21	$p = 1.95 \cdot 10^{-22}$				xxx	x	xxx
(Nm)		(0.03)	(0.03)	(0.04)	$F = 179.15$						
Mean steering reversal rate	0.73	0.49	0.64	0.51	$p = 6.04 \cdot 10^{-14}$	xxx		xxx	xxx		xx
(reversals/s)	(0.23)	(0.17)	(0.17)	(0.17)	$F = 35.31$						
NASA TLX	47.78	33.26	42.19	32.81	$p = 2.64 \cdot 10^{-6}$	xxx		xx			
(%)	(12.12)	(11.70)	(16.07)	(13.19)	$F = 11.74$						
Driver torque	0.75	0.72	0.75	0.76	$p = 0.047$					x	
(Nm)	(0.07)	(0.06)	(0.06)	(0.08)	$F = 2.78$						
System Acceptance											
Satisfaction scale		0.88	0.52	0.79	$p = 0.076$						
(−2,2)		(0.52)	(0.69)	(0.73)	$F = 2.72$						
Usefulness scale		0.98	0.83	0.92	$p = 0.410$						
(−2,2)		(0.35)	(0.44)	(0.50)	$F = 0.92$						

Note. *F*(2,46) for the Mean abs feedback torque, satisfaction scale, and usefulness scale.

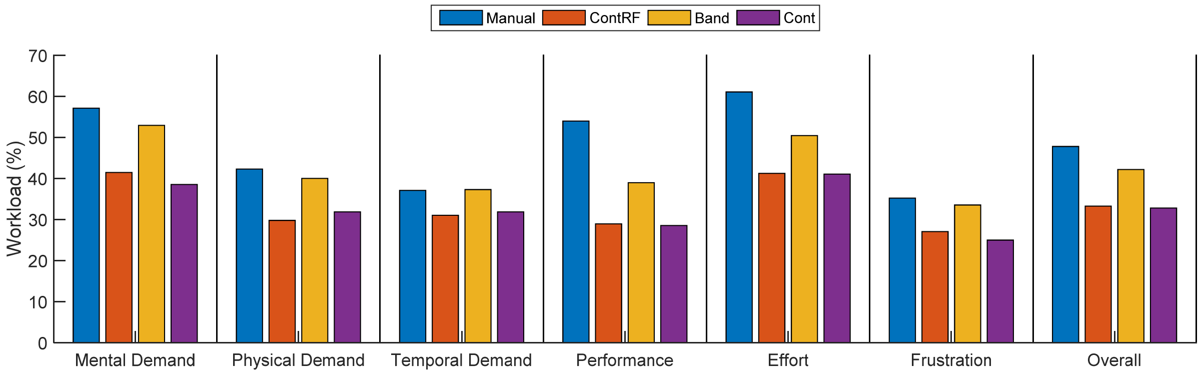

Figure 5. Mean scores on the NASA TLX.

3.3. Workload

Table 1 shows that the self-reported workload (NASA TLX score) and objective workload (SRR) were significantly higher for Band and Manual than for Cont and ContRF. For each of the six NASA TLX items, Cont and ContRF yielded lower workload scores than Manual and Band (Figure 5). The mean feedback torque provided by the guidance was significantly different between all conditions. Band yielded significantly less feedback torque (M = 0.06 Nm) than the continuous guidance conditions (ContRF M = 0.19 Nm and Cont M = 0.21 Nm). No feedback torque was applied during the Manual condition. Moreover, the results showed that lower physical effort (driver torque) was obtained for driving with ContRF than for driving with Cont guidance.

3.4. Safety Margins

Higher safety margins in terms of median TLC were found for ContRF and Cont compared to Manual and Band (Table 2). Additionally, slightly higher safety margins were adopted for ContRF than Cont, although not statistically significant (p = 0.071). Since TLC varies much during lane keeping, we performed a fine-grained analysis by binning the TLC values into four groups of safety margins: out of bound (TLC = 0 s), low safety margin (0 s < TLC ≤ 2 s), moderate safety margin (2 s < TLC ≤ 4 s), and high safety margin (TLC > 4 s). In the ContRF and Cont conditions, participants drove less often with a low safety margin but more often with a high safety margin, as compared to the Manual and Band condition. Overall driving with ContRF and Cont resulted in the highest safety margins in terms of median TLC and TLC > 4 s.

3.5. System Acceptance

The satisfaction score was lower for Band (M = 0.55) than for ContRF (M = 0.88) and Cont (M = 0.79), although not statistically significant, F(2,46) = 2.72, p = 0.076. No difference was found for the usefulness scale either (F(2,46) = 0.92, p = 0.410).

3.6. Sharp Curve

The performance measures were calculated separately for the 300 m long sharp curve segment at the end of the trajectory. The results did not show significant differences in lane-keeping performance between the four conditions. Nevertheless, the two largest absolute lateral errors (1.4 m and 0.6 m, respectively) were found for the two participants driving in the Cont condition. These two participants adopted relatively high speeds at the entrance of the sharp

Table 2. Means (*M*), standard deviations (*SD*), and results of the repeated measures ANOVA (*F*, *p*) for the time to line crossing (TLC). x means $p \leq 0.05$, xx mean $p \leq 0.01$, xxx means $p \leq 0.001$.

	Manual (1)	ContRF (2)	Band (3)	Cont (4)		Pairwise comparison					
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	p value *F*(3,69)	1-2	1-3	1-4	2-3	2-4	3-4
Median TLC (s)	1.32 (0.48)	2.09 (0.67)	1.36 (0.46)	1.89 (0.65)	$p = 4.73 \cdot 10^{-17}$ $F = 48.86$	xxx		xxx	xxx		xxx
Percentage low safety margin (0 s < TLC ≤ 2 s) (%)	54.20 (6.59)	46.87 (7.01)	56.32 (6.78)	49.27 (7.57)	$p = 1.61 \cdot 10^{-13}$ $F = 33.67$	xxx		xx	xxx	x	xxx
Percentage moderate safety margin (2 s < TLC ≤ 4 s) (%)	14.08 (2.68)	15.97 (1.47)	13.90 (2.26)	15.51 (1.75)	$p = 2.48 \cdot 10^{-7}$ $F = 14.24$	xx		x	xxx		xxx
Percentage high safety margin (TLC > 4 s) (%)	24.51 (6.46)	33.84 (6.84)	25.86 (5.68)	31.82 (7.22)	$p = 2.07 \cdot 10^{-16}$ $F = 45.83$	xxx		xxx	xxx		xxx

Note. The results for TLC = 0 are identical to the TOR results in Table 1.

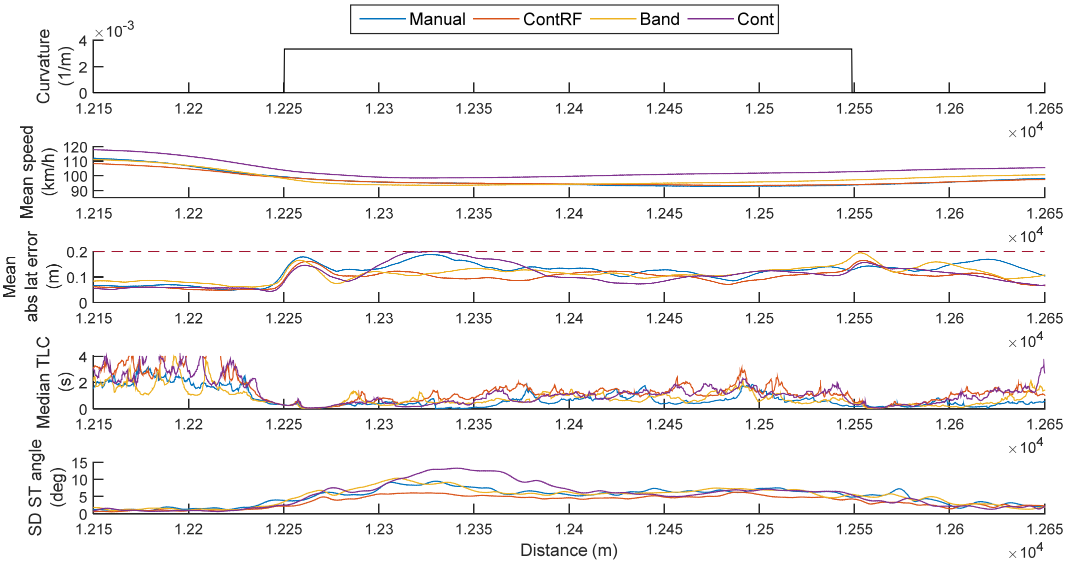

Figure 6. Mean speed (km/h), mean absolute lateral error (m), median TLC (s), and standard deviation of the steering wheel angle (deg) among the participants as a function of traveled distance in the sharp curve. The top figure shows the curvature (i.e., 1/radius in meters).

curve of 135 km/h (rank 1/96) and 117 km/h (rank 12/96), respectively. Figure 6 shows (1) the curvature, (2) the mean speed (km/h), (3) the mean absolute lateral error (m), (4) the median TLC (s), and (5) the standard deviation of the steering wheel angle among the participants as a function of travelled distance in the sharp curve. The sharp curve resulted in two distinct peaks in the mean absolute lateral error. The first peak (about 10 m into the curve) is caused by most participants slightly cutting the curve on the inside, whereas the second peak (70 m into the curve) is mainly caused by most participants veering to the outside of the curve. Critical safety margins (median TLC < 1 s) were observed for all conditions when entering the sharp curve. For continuous guidance, there were large steering angle differences between participants. Large mean maximum absolute lateral errors were obtained for the Cont (0.20 m) and Manual (0.19 m) condition compared to the ContRF (0.16 m) and Band (0.16 m) condition.

3.7. Supplementary Analyses

The Spearman correlation coefficients between the mean speed and the mean absolute lateral error were 0.40, 0.31, 0.14, and 0.11 for the Manual, ContRF, Band, and Cont conditions, respectively (see Appendix A). This suggests that the participant's speed moderately yet consistently influenced task performance, presumably due to a speed-accuracy trade-off (Zhai et al., 2004). In the simulator sickness item none of the participants responded greater than 3 (the number of responses being 1, 2, and 3 were 61, 27, and 8, respectively), and thus everyone finished the experiment. The Spearman correlation coefficients between the mean speed on the one hand, and the mean DBQ violations score, the driving frequency, and the mileage in the last 12 months, on the other, ranged between −0.06 and 0.25 (Appendix A). These findings suggest that the degree of behavioral adaptation is not associated with these personal characteristics in a practically significant manner.

4. DISCUSSION

4.1. Main Results

The aim of this study was to investigate the effects of haptic steering guidance on speeding, and to evaluate two varieties of haptic driver support that were designed to mitigate such speeding. To understand driving behavior better, we also tested the effects on lane-keeping performance, safety margins, workload, and driver acceptance. The mean speeds in the Manual, ContRF, Band, and Cont conditions were 105.7, 106.4, 108.3, and 113.3 km/h, respectively, with statistically significant differences between Cont and Manual and between Cont and ContRF. These results confirm the hypothesis that continuous haptic steering guidance causes drivers to driver faster, which diminishes the safety benefits of this assistive technology as compared to fixed-speed simulator studies. The results are in accordance with speeding results from earlier BA studies regarding other types of ADAS, such as obstacle avoidance systems and night vision enhancement system (Hiraoka et al., 2010; Janssen & Nilsson, 1993).

The laterally adjusted (Band) and longitudinally adjusted (ContRF) guidance conditions that were designed to mitigate speeding, both successfully prevented speeding while retaining a high lane-keeping performance. Compared to the Manual and Band conditions, participants driving with Cont and ContRF were better able to center the car in the middle of the road at a reduced workload. The results further showed that compared to the Manual condition, Cont provided increased safety margins in terms of TLC despite a higher mean speed (which correlates negatively with TLC, see supplementary materials), signifying that drivers apparently could afford to safely increase their speed due to the benefits offered by the haptic steering guidance. ContRF had even slightly higher safety margins than Cont, presumably due to the lower driving speed in this condition.

4.2. Effectiveness of ContRF in Preventing Speeding

Even though Cont and ContRF were effectively identical systems for 95% of the driving time, ContRF successfully prevented speed adaptation. The ContRF threshold of 125 km/h was well above the average speed of 108.4 km/h, which resulted in 14 participants not experiencing the reducing guidance during their trials (i.e., their speed was always below 125 km/h). The efficacy of the ContRF guidance despite the fact that drivers only rarely experienced it suggests that BA does not necessarily manifest itself as a function of *current* ADAS intervention and visibility but rather that *expected* (loss) of functionality offers a remedy against BA. The effects may be explained with the help of the theories of safety margins and risk compensation introduced above: arguably, drivers in the Cont condition speeded up compared to the Manual condition because the guidance lowered their subjective risk level and increased safety margins. With ContRF, participants did not experience such a risk reduction because they had been instructed and trained that the benefits of this assistive system would disappear when driving fast. Thus, it may be argued that the homeostatic equilibrium was shifted due to the imposed motivation to drive slower.

The working mechanism of the ContRF system may be further explained by means of an analogy previously introduced by Wilde (1998): on the one hand engineers make driving safer by offering forgiveness in case of an accident (e.g., seat belts, airbags, crashworthy car design, etc.), yet on the other hand they make the consequences of dangerous behavior more severe (e.g., by implementing speed bumps). A similar type of conflicting safety policy applies to the ContRF system, where on the one hand driving safety is enhanced by offering guidance on the steering wheel, yet speeding is discouraged by taking away the same guidance. Perhaps people need such opposing motivation to use ADAS in a responsible manner.

Nevertheless, it is difficult to establish whether the effectiveness of ContRF is caused by a ‘psychological’ homeostatic mechanism or by an actual ‘physical’ mechanism. Regarding such physical mechanisms it may be argued that the ContRF system gives feedback about the objective level of risk (speed) at a subcortical neuromuscular level (cf. Abbink et al., 2011). Future research should investigate whether physical or psychological mechanisms are underlying factors in BA preventive technologies. For example, to gain more insight into the cognitive factors behind a behavioral change, a verbal protocol method could be used (Banks, Stanton, & Harvey, 2014).

4.3. Speed Parameters of the ContRF system

The ContRF system does not necessarily represent the optimal solution to prevent BA and may be refined in various ways. In this study, the lower speed threshold was set fairly highly (125 km/h) with the reduction occurring over a relatively small speed range (125–130 km/h), in order to keep the benefits of continuous guidance and to ensure a noticeable feedback reduction. The question remains what would happen if one changes these design parameters. For example, it is possible to lower the speed thresholds towards the average speed in manual driving, so that almost all participants have to make a decision between using guidance versus adopting a high speed. Similarly, it is possible to conceive a system whereby the guidance diminishes over a broad speed range so that each driver has to achieve a trade-off along a continuum between safety and efficiency. These topics can be addressed in future research to improve the understanding of BA preventing technologies.

4.4. Effectiveness of the Band system

In accordance with previous research, driving with continuous guidance and bandwidth guidance was found to improve drivers’ lane-keeping performance compared to manual driving (Flemisch et al., 2008; Kienle, Dambock, Bubb, & Bengler, 2012; Marchal-Crespo, McHughen, Cramer, & Reinkensmeyer, 2010; Petermeijer et al. 2015a). The Band condition yielded improved TOR compared to Manual but did not improve the absolute lateral error. No differences in terms of workload were found between Manual and Band, presumably because Band and Manual were largely identical when driving inside the lane, with no haptic guidance offered in the Band condition on average for 84% of the time. The lack of BA effect for driving with bandwidth guidance is in line with a comprehensive field study which focused on BA conducted by Breyer et al. (2010). This study did not find evidence of BA for driving with a corrective steering system after a prolonged exposure to the system. Our bandwidth condition functioned similar to Breyer et al.’s corrective steering system by limiting lane crossings, yet allowing the driver to sway when driving within lane boundaries. This satisficing approach (i.e., keeping the driver fully in charge when driving in the lane; see also Goodrich et al., 2000; Summala, 2007), rather than an optimizing approach (i.e., continuous guidance), has the advantage that no BA occurs and no adverse steering aftereffects are evoked during a sudden transition of control to manual driving (Petermeijer et al., 2015a), but at the cost of a higher workload and worse lane-centering performance.

4.5. Experimental Conditions that Give Rise to Behavioral Adaptation

The speed adaptation of 7 km/h for continuous guidance is different from findings by Mars et al. (2014b) who did not find a statistically significant difference between a group of 12 participants driving with haptic steering guidance and another group of 12 participants driving manually. First, as mentioned in the introduction, large individual differences in speed make it unlikely to observe statistically significant effects in a between-subjects design. Second, in our experiment, the road was narrow and salient concurrent performance feedback was provided by means of a red dot when hitting a cone, whereas in the study by Mars et al. this was not the case. Due to the narrow road and knowledge-of-results feedback, drivers can be assumed to have been well aware of the improved lane-keeping performance facilitated by haptic guidance. The noticeability of the guidance benefits combined with the extended familiarization period could explain why strong speed differences were observed in the present 1.5-hour long experiment.

4.6. Risks of Behavioral Adaptation

Despite its higher speed, Cont yielded higher safety margins and better lane keeping performance (in terms of lower TOR, maximum lateral error, and absolute lateral error) than the Manual condition. This raises the fundamental question: why is BA regarded as undesirable if driving performance and safety margins are actually improved? When haptic steering guidance is within its operational limits it can indeed be considered favorable to unsupported driving. However, when haptic steering guidance is outside its operational limits a higher speed implies higher crash risk, higher injury severity, and lower time to respond. In fact for a given speed the crash risk may be even worse than in manual driving due to the aforementioned aftereffects (Petermeijer et al., 2015a). The adverse effects of speeding were illustrated by a large lane exit when entering a sharp curve at high speed (Figure 6). Having the unrealistic trust that haptic steering guidance (or any other intelligent vehicle or automated driving system for that matter) can anticipate sharp curves at all times, may lead to dangerous situations. The sharp curve is merely one example; there are numerous other examples like sensor failure, an obstacle on the road, or computer failure, that can unexpectedly push haptic steering guidance outside its operational envelope. The philosophy behind haptic steering guidance is to incorporate the best of both—a human's creative solutions combined with a machine's accurate and consistent performance. However, if drivers over-trust the machine and adopt an excessive speed the calibration in this team performance is off, which may in turn result in a loss of control.

4.7. Self-Reported Satisfaction and Usefulness of the Haptic Steering Guidance

A support system should be perceived useful and satisficing to be accepted by drivers in a commercial vehicle. The results of the acceptance questionnaire showed that all three guidance conditions were well liked, with average scores above zero for both the usefulness and satisfaction dimensions, which ranged from +2 to −2. The Band system showed slightly and non-significantly lower acceptance than Cont and ContRF; it might be that participants experienced the sudden increase in feedback force when crossing a lane as annoying. It is interesting that the ContRF condition, which did not function above 130 km/h, did not show lower acceptance than the three other conditions. The relatively high acceptance for ContRF may have been caused by the fact that it took the guidance away in a gradual manner yet clearly communicated the ADAS functionality and availability. Alternatively, participants may have thought ContRF was helpful for the reason that it prevented them from driving excessively fast.

4.8. Temporal Effects of Behavioral Adaptation

During this study, participants were exposed to each condition for about 16 minutes, hence only measuring the initial and short-term BA effects. Previous research suggests that the degree of experience with the system is important in assessing BA (Martens & Jenssen, 2012; Panou et al., 2007). Considering that it has been found that trust in ADAS and mental models grow over periods of weeks or months (Beggiato et al., 2015), it is plausible that the speed difference between Cont and Manual may be even larger than 7 km/h in the long run. The correlations between the driving experience variables and the mean speed were small, which suggests that the degree of BA of a driver is not easily predictable from a person's driving characteristics. At present, the relation between short- and long-term BA effects is unknown (De Winter & Dodou, 2011), and it is recommended to obtain a better understanding of this topic by means of longitudinal studies.

4.9. Driving Simulator Versus On-Road Tests

The lane-keeping performance obtained in this study is slightly better than found in real cars, with a standard deviation of lateral position [SDLP] of about 0.10 m, whereas values of 0.15–0.20 m are typically observed in on-road experiments (see Veldstra et al., 2015; Verster and Roth, 2011). This difference may be caused by the narrow road and real-time feedback on performance. In addition, participants in our study adopted rather high mean speeds of 110 km/h despite the fact that the road was narrow and contained various moderately sharp curves. The relatively high speed in a driving simulator may be explained by incorrect speed perception or low subjective risk perception when driving in a simulator (De Winter, Van Leeuwen, & Happee, 2012; Wallis, Tichon, & Mildred, 2007). Drivers in a simulator do not experience a real risk of crashing, which is a downside of using a driving simulator opposed to a real car, especially because subjective risk is considered to be an important determinant of BA (Näätänen & Summala, 1974; Wilde, 1998). Nevertheless, simulators offer important advantages compared to tests in real cars. For example, it would be both technically challenging and unethical to expose participants to a sharp curve on a real road in a controlled manner. Moreover, the *relative* validity of driving simulators (i.e., the effect sizes between the pairwise comparisons) may still be considered valid, as was illustrated recently by Klüver et al. (2016). These authors found that participants had substantially different SDLP values between fixed base simulators, moving base simulators, and a real car but the effect sizes as a function of secondary task conditions were similar for these three hardware conditions. In our study, the lack of subjective risk was tried to be accounted for by prescribing a task that penalizes risky behavior (i.e., ‘minimize the number of cone hits’). Nevertheless, the fact remains that the environment in the current study was relatively uncomplicated, featuring a single-lane road and no other road users, and therefore further research should investigate the external validity of this simulator-based research.

4.10. Forced-paced versus Self-paced Experimental Designs

Finally, this research indicates that future ADAS developers should take into account human adaptations when assessing and designing new systems. The speed adaptation found in this study showed that driving at a constant speed, as is done in much ADAS research, may give a distorted view of a system’s benefits. Although fixing the speed is convenient because it homogenizes the chronological timing of events among participants, it also restricts drivers from adapting to a system in a realistic way.

4.11. Conclusions and Recommendations

In a driving simulator experiment, three designs of haptic guidance were compared to unsupported driving, with the aim of quantifying the influence of haptic steering guidance design on speeding. As hypothesized, continuous haptic steering guidance suffered from BA, in terms of an increased speed of 7 km/h compared to the Manual condition. We tested two fundamentally different remedial technologies (Band & ContRF): Band only provided feedback when driving out of bound, resulting in a system that was identical to Manual for 84% of the driving time, whereas ContRF provided continuous feedback in 95% of time. These two different approaches both successfully prevented BA while retaining the lane-keeping benefits, and self-reported system acceptance associated with continuous guidance. The differences in driving behavior were observed in 16 min of driving per condition; future research should address long-term effects and real-world fidelity, and assess which physical/biomechanical and psychological mechanisms are at play.

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A

Correlation Matrices

The Spearman correlation was calculated between all dependent measures for each condition (with one additional measure, the mean steering speed (deg/s)). The correlation results can be found in the tables below. The manual correlation matrix consist of 10 dependent measures, whereas the other three conditions contain 13 dependent measures, including the mean abs feedback torque, the usefulness scale, and the satisfying scale.

Spearman correlation Manual

	Mean speed	% TOR	Mean absolute lateral error	Peak absolute lateral error	Mean time needed to get back in lane boundaries	Median TLC	NASA TLX	SRR	Mean abs driver torque	Mean steering speed	DBQ	Mileage	Weekly driving
Mean speed	1.00												
% TOR	0.33	1.00											
Mean absolute lateral error	0.40	0.93	1.00										
Peak absolute lateral error	0.55	0.66	0.72	1.00									
Mean time needed to get back in lane boundaries	0.21	0.67	0.64	0.42	1.00								
Median TLC	-0.68	-0.72	-0.77	-0.71	-0.47	1.00							
NASA TLX	0.03	0.23	0.37	0.37	0.27	-0.27	1.00						
SRR	0.20	-0.16	-0.10	0.10	-0.21	-0.39	0.21	1.00					
Mean abs driver torque	0.92	0.30	0.37	0.51	0.23	-0.75	0.10	0.45	1.00				
Mean steering speed	0.37	-0.04	0.05	0.23	-0.14	-0.52	0.20	0.93	0.62	1.00			
DBQ	0.08	-0.07	-0.10	-0.02	-0.14	-0.03	0.09	0.06	0.19	0.12	1.00		
Mileage	0.25	0.03	0.05	0.04	0.18	-0.11	0.35	0.01	0.23	0.08	0.13	1.00	
Weekly driving	0.20	0.07	0.08	0.10	0.17	-0.11	0.26	-0.06	0.26	0.05	0.22	0.81	1.00

Spearman correlation ContRF

	Mean speed	% TOR	Mean absolute lateral error	Peak absolute lateral error	Mean time needed to get back in lane boundaries	Median TLC	NASA TLX	SRR	Mean abs feedback torque	Mean abs driver torque	Mean steering speed	usefulness scale	satisfying scale	DBQ	Mileage
Mean speed	1.00														
% TOR	0.19	1.00													
Mean absolute lateral error	0.31	0.86	1.00												
Peak absolute lateral error	0.00	0.83	0.59	1.00											
Mean time needed to get back in lane boundaries	0.26	0.66	0.44	0.50	1.00										
Median TLC	-0.54	-0.42	-0.46	-0.50	-0.28	1.00									
NASA TLX	0.11	0.33	0.40	0.15	0.22	-0.13	1.00								
SRR	0.15	-0.07	-0.08	0.09	0.05	-0.66	-0.17	1.00							
Mean abs feedback torque	0.19	0.73	0.76	0.59	0.33	-0.51	0.24	0.23	1.00						
Mean abs driver torque	0.77	0.06	0.14	0.05	0.20	-0.57	0.28	0.31	0.10	1.00					
Mean steering speed	0.29	-0.01	0.06	0.06	0.09	-0.69	-0.14	0.96	0.34	0.37	1.00				
usefulness scale	-0.11	-0.06	-0.20	0.15	-0.02	0.11	-0.24	-0.10	-0.03	0.13	-0.11	1.00			
satisfying scale	0.19	0.13	0.08	0.38	0.05	-0.30	-0.25	0.05	0.05	0.11	0.06	0.54	1.00		
DBQ	0.25	-0.22	-0.17	-0.05	-0.20	-0.30	-0.03	0.27	0.04	0.31	0.32	0.32	0.35	1.00	
Mileage	0.01	-0.11	0.08	-0.10	-0.06	-0.03	0.39	-0.08	-0.28	0.05	-0.09	-0.32	0.04	0.13	1.00
Weekly driving	-0.04	-0.02	0.27	-0.05	-0.14	-0.08	0.30	-0.12	0.03	-0.06	-0.07	-0.37	-0.07	0.22	0.81

Spearman correlation Band

	Mean speed	% TOR	Mean absolute lateral error	Peak absolute lateral error	Mean time needed to get back in lane boundaries	Median TLC	NASA TLX	SRR	Mean abs feedback torque	Mean abs driver torque	Mean steering speed	usefulness scale	satisfying scale	DBQ	Mileage	Weekly driving
Mean speed	1.00															
% TOR	0.10	1.00														
Mean absolute lateral error	0.14	0.87	1.00													
Peak absolute lateral error	0.32	0.77	0.63	1.00												
n time needed to get back in lane boundaries	0.10	0.89	0.71	0.67	1.00											
Median TLC	-0.65	-0.55	-0.39	-0.73	-0.55	1.00										
NASA TLX	0.33	0.41	0.39	0.52	0.31	-0.37	1.00									
SRR	0.27	-0.22	-0.44	0.13	-0.05	-0.44	0.04	1.00								
Mean abs feedback torque	0.36	0.89	0.81	0.73	0.83	-0.77	0.35	-0.04	1.00							
Mean abs driver torque	0.83	-0.04	-0.09	0.16	0.03	-0.63	0.28	0.54	0.28	1.00						
Mean steering speed	0.35	-0.10	-0.30	0.25	0.05	-0.53	0.08	0.97	0.09	0.56	1.00					
usefulness scale	0.04	-0.11	-0.09	-0.08	-0.16	-0.01	-0.32	-0.07	-0.07	-0.13	-0.04	1.00				
satisfying scale	-0.24	-0.15	-0.07	-0.22	-0.25	0.31	-0.62	-0.28	-0.20	-0.43	-0.28	0.63	1.00			
DBQ	0.07	-0.03	-0.09	0.06	-0.03	-0.15	0.04	0.36	-0.07	0.10	0.37	-0.04	-0.04	1.00		
Mileage	0.20	0.16	0.02	0.25	-0.05	-0.35	0.37	0.02	0.19	0.23	0.01	0.02	-0.25	0.13	1.00	
Weekly driving	0.20	0.17	0.04	0.11	0.07	-0.35	0.11	-0.03	0.21	0.26	-0.05	0.11	-0.13	0.22	0.81	1.00

Spearman correlation Cont

	Mean speed	% TOR	Mean absolute lateral error	Peak absolute lateral error	Mean time needed to get back in lane boundaries	Median TLC	NASA TLX	SRR	Mean abs feedback torque	Mean abs driver torque	Mean steering speed	usefulness scale	satisfying scale	DBQ	Mileage
Mean speed	1.00														
% TOR	0.22	1.00													
Mean absolute lateral error	0.11	0.93	1.00												
Peak absolute lateral error	0.41	0.79	0.67	1.00											
Mean time needed to get back in lane boundaries	0.16	0.73	0.65	0.70	1.00										
Median TLC	-0.49	-0.60	-0.53	-0.56	-0.51	1.00									
NASA TLX	-0.08	0.28	0.26	0.24	0.16	-0.02	1.00								
SRR	0.03	0.16	0.18	0.04	0.29	-0.62	-0.15	1.00							
Mean abs feedback torque	0.45	0.84	0.79	0.66	0.60	-0.86	0.04	0.40	1.00						
Mean abs driver torque	0.90	0.32	0.19	0.42	0.35	-0.64	-0.05	0.21	0.59	1.00					
Mean steering speed	0.33	0.30	0.27	0.22	0.36	-0.77	-0.21	0.92	0.60	0.51	1.00				
usefulness scale	0.21	-0.44	-0.47	-0.31	-0.30	0.10	-0.50	-0.23	-0.20	0.22	-0.13	1.00			
satisfying scale	0.29	-0.28	-0.28	-0.12	-0.28	-0.06	-0.49	-0.09	-0.07	0.18	-0.01	0.70	1.00		
DBQ	0.11	-0.14	-0.15	-0.12	-0.19	-0.01	-0.19	0.00	-0.03	0.17	0.06	0.37	0.37	1.00	
Mileage	0.12	0.21	0.28	0.19	0.10	-0.09	0.44	-0.23	0.18	0.18	-0.08	-0.20	-0.41	0.13	1.00
Weekly driving	-0.06	0.27	0.35	0.15	0.20	-0.06	0.35	-0.15	0.18	0.06	-0.06	-0.24	-0.44	0.22	0.81

B

Informed Consent Form

Informed Consent Form in a driving simulator study

Researchers:
Timo Melman - Msc. Student
E-mail: t.melman@student.tudelft.nl
Tel: +316 11 437 963

dr.ir. D.A. Abbink - Supervisor
E-mail: d.a.abbink@tudelft.nl

dr.ir. J.C.F de Winter - Supervisor
E-mail: j.c.f.dewinter@tudelft.nl

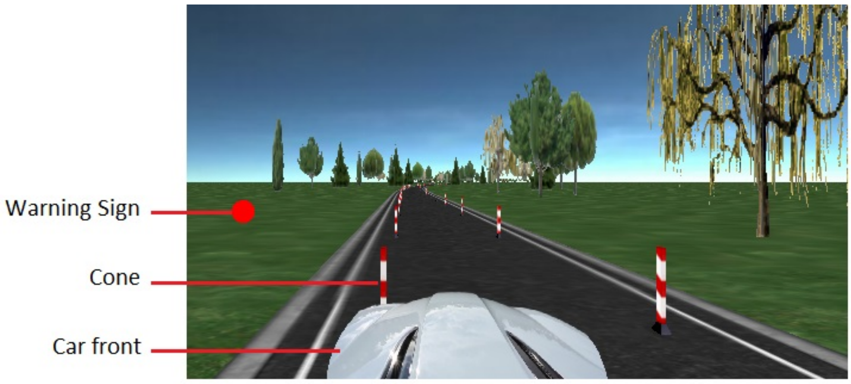
This document describes the purpose, procedures, benefits, risks and possible discomforts of a driving simulator study. It also describes the right to withdraw from the study at any time in any case. Before agreeing to participate in this study, it is important that the information provided in this document is fully read and understood.

Location of the experiment:
TU Delft, Faculty of Aerospace Engineering
Department of Control and Operations - Control and Simulation
HMI-lab, room 0.38
Kluyverweg 1, 2629 HS Delft

Purpose of the study: The purpose of this driving-simulator study is to investigate driving behaviour, subjective experience, workload and comfort of different haptic steering support systems. A haptic steering support system provides additional torques to the steering wheel in order to support the driver in the driving task (e.g. keeping the car in the lane). These guidance's can be designed in various ways. This study probes three different designs. The results will be statistically analysed and published in a Master thesis. Possibly in a scientific publication as well.

Procedure: You will be requested to seat in the driving simulator (a fixed-base driving simulator with a field of view of almost 180°) and will be briefed how to operate it. The simulator car has an automatic shifting gearbox. Therefore you do not have to use the clutch and gear shift. Moreover, you are requested to keep both hands on the steering wheel in a ten-to-two position at all time.

The experiment consist of 4 trials on a rural road. A trial will last approximately 8 minutes. Each trial will be supported by a different haptic controller (No controller, controller 1, controller 2, controller 3). Prior to each controller a 6 minute training run will be held. Use this time to familiarise yourself with



that particular controller.
During the real trials you are asked to drive as you normally would do and your aim is to minimise the number of cone hits (e.g. lane crossings). If a cone is hit, a red warning symbol appears *located at the side where the car hits a cone*. After each trail you are requested to get out of the simulator and fill out two questionnaires.

Task instructions: To stress this one more time. **During the entire track you are requested to drive as you normally would and try to minimise the number of cone hits.**

Duration: The total experiment, including filling out questionnaires, will approximately take 1.5 hour.

Risk and discomforts: Virtual environments like driving-simulators can cause different types of sicknesses: visuomotor dysfunctions (eyestrain, blurred vision, difficulty focusing), nausea, drowsiness, fatigue, or headache. These symptoms are similar to motion sickness. If you feel uncomfortable in any way, you are advised to stop the experiment or rest for several minutes. As mentioned above, you can stop the experiment and withdraw at any time, without negative consequences. If you do not feel well, then please take sufficient rest before leaving the laboratory.

Confidentiality: The collected data in this experiment is kept confidential and will be used for research purpose only. Throughout the study you will only be identified by a subject number only.

Right to refuse or withdraw: You participation is strictly voluntary and you may withdraw or stop the experiment at any time, without negative consequences.

Questions: If you have any question regarding this experiment, feel free to contact T. Melman (details are provided at the top of this document).

I have read and understood the information provided above
I give permission to process the data for the purpose described above
I voluntarily agree to participate in this study

Name of participant:

Signature: **date:**

C

NASA TLX Questionnaire

Figure 8.6

NASA Task Load Index

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

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

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

Very Low — Very High

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

Perfect — Failure

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

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Nausea: To what extend do you experience nausea? Please circle the statement that is most fitting to your condition:

1. Not experiencing any nausea, no sign of symptoms.
2. Arising symptoms (like a feeling in the abdomen), but no nausea.
3. Slightly nauseous
4. Nauseous.
5. Very nauseaous, retching.
6. Throwing up.

D

Acceptance Questionnaire

Van Der Laan Questionnaire

To be filled in by investigator:

Participant nr:	Haptic Controller	Date:

My judgments of the current system are ... (please tick a box on every line)

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

Comments on the experiment and system tested: (please provide any additional comments you may have)

- -

- -

- -

- -

- -

- -

- -

E

Generic Characteristics and Driver Behavior Questionnaire

Generic characteristics and DBQ

1. **Subject Number**
   To be filled in by investigator

2. **First name + Surname**

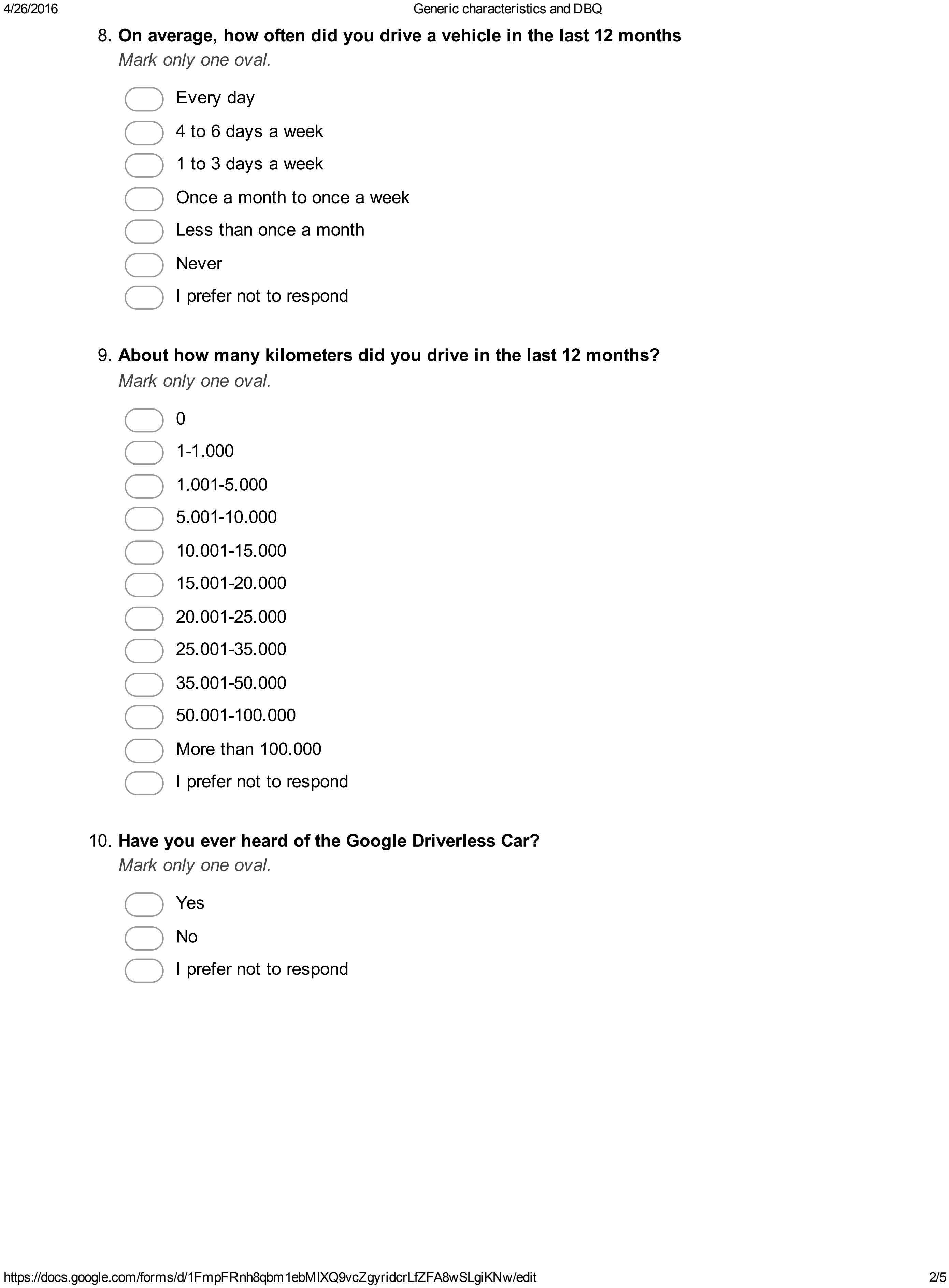
3. **E-mail address**

4. **What is your age**

5. **What is your gender?**
   Mark only one oval.
   - ○ Male
   - ○ Female
   - ○ I prefer not to respond

6. **What is your primary mode of transportation?**
   Mark only one oval.
   - ○ Private vehicle
   - ○ Public transportation
   - ○ Motorcycle
   - ○ Walking/cycling
   - ○ I prefer not to respond
   - ○ Other:

7. **At which age did you obtain your first driver's license?**



8. **On average, how often did you drive a vehicle in the last 12 months**

Mark only one oval.

○ Every day
○ 4 to 6 days a week
○ 1 to 3 days a week
○ Once a month to once a week
○ Less than once a month
○ Never
○ I prefer not to respond

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

Mark only one oval.

○ 0
○ 1-1.000
○ 1.001-5.000
○ 5.001-10.000
○ 10.001-15.000
○ 15.001-20.000
○ 20.001-25.000
○ 25.001-35.000
○ 35.001-50.000
○ 50.001-100.000
○ More than 100.000
○ I prefer not to respond

10. **Have you ever heard of the Google Driverless Car?**

Mark only one oval.

○ Yes
○ No
○ I prefer not to respond

11. **How many accidents were you involved in when driving a car in the last 3 years?**
(Please include all accidents, regardless of how they were caused, how slight they were, or where they happend)
Mark only one oval.

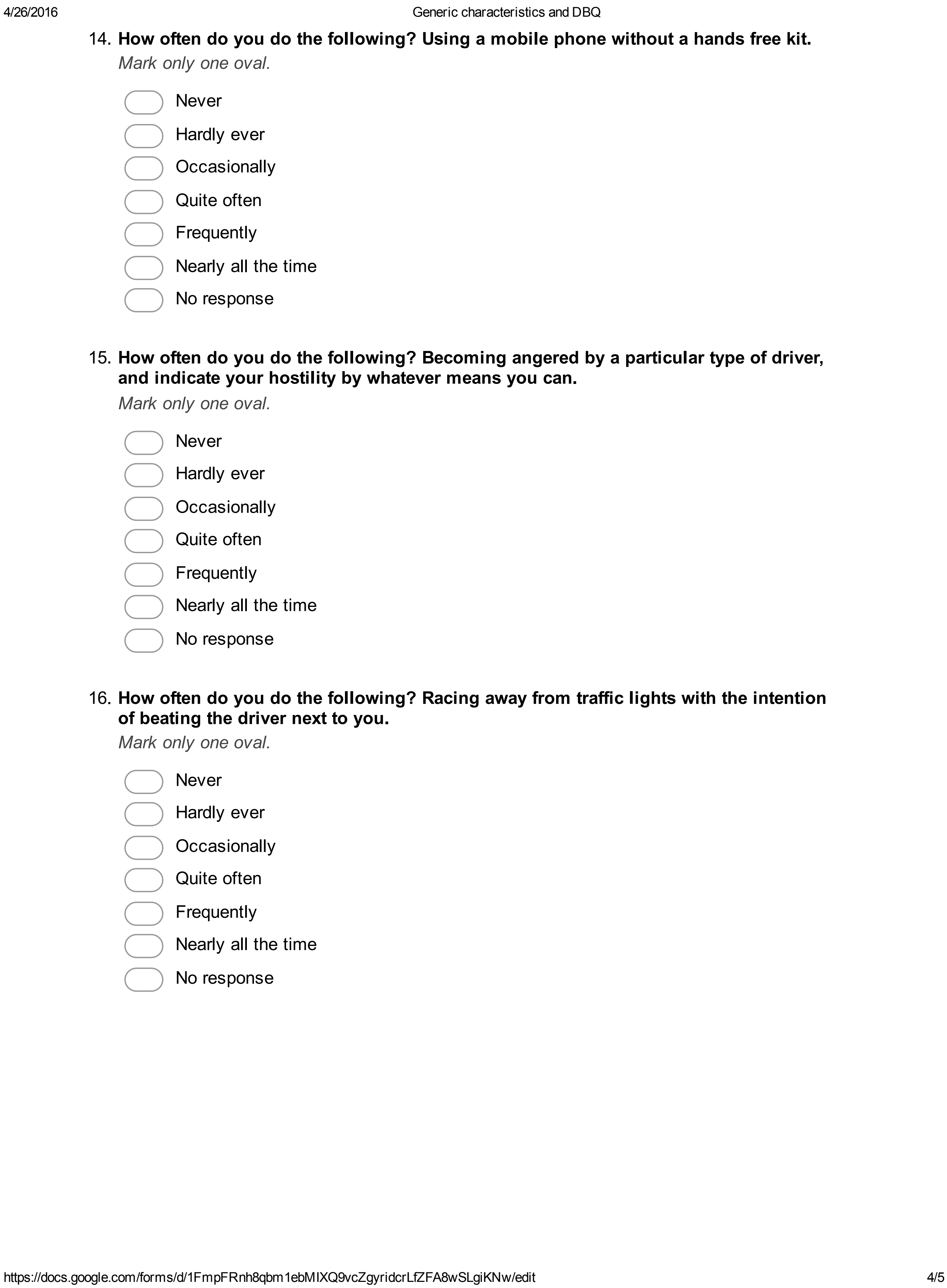
○ 0
○ 1
○ 2
○ 3
○ 4
○ 5
○ more than 5
○ I prefer not to respond

12. **How often do you do the following? Sounding your horn to indicate your annoyance with another road user.**
Mark only one oval.

○ Never
○ Hardly ever
○ Occasionally
○ Quite often
○ Frequently
○ Nearly all the time
○ No response

13. **How often do you do the following? Disregarding the speed limit on a residential road.**
Mark only one oval.

○ Never
○ Hardly ever
○ Occasionally
○ Quite often
○ Frequently
○ Nearly all the time
○ No response



14. **How often do you do the following? Using a mobile phone without a hands free kit.**

Mark only one oval.

- ○ Never
- ○ Hardly ever
- ○ Occasionally
- ○ Quite often
- ○ Frequently
- ○ Nearly all the time
- ○ No response

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

Mark only one oval.

- ○ Never
- ○ Hardly ever
- ○ Occasionally
- ○ Quite often
- ○ Frequently
- ○ Nearly all the time
- ○ No response

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

Mark only one oval.

- ○ Never
- ○ Hardly ever
- ○ Occasionally
- ○ Quite often
- ○ Frequently
- ○ Nearly all the time
- ○ No response

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

Mark only one oval.

○ Never
○ Hardly ever
○ Occasionally
○ Quite often
○ Frequently
○ Nearly all the time
○ No response

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

Mark only one oval.

○ Never
○ Hardly ever
○ Occasionally
○ Quite often
○ Frequently
○ Nearly all the time
○ No response

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Extensive Results Section

This appendix shows the results and figures that couldn’t be included in the paper. It contains the analysis of the following topics:

- Statistical analysis of the dependent measures that were not included in the paper
- Extensive speed results
- Extensive performance results
- Extensive safety margins results (in terms of TLC)
- Speed-accuracy trade-off
- Questionnaire results
- Workload
- Curve versus Straight segments
- ContRF guidance
- Sharp curve analyses
- Learning effect
- Lateral acceleration

Statistical analysis

The metrics that were analyzed but not explained in the paper can be found in table 1.

Table 1: Means (M), standard deviations (SD), and effect size of the repeated measures ANOVA (F,p) for the dependent measures. x means p ≤ 0.05, xx means p ≤ 0.01, XXX means p ≤ 0.001.

	Manual (1)	ContRF (2)	Band (3)	Cont (4)		Pairwise comparison					
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*p*-value F(3.69)	1-2	1-3	1-4	2-3	2-4	3-4
ContRF influence											
Total time above 125 km/h threshold (s)	36.49 (77.40)	21.36 (39.94)	51.78 (84.88)	86.61 (110.14)	*p* = 0.001 *F* = 5.94			x		xx	
Mean time needed to get below 125 km/h threshold (s)	12.00 (22.16)	7.92 (13.41)	25.39 (64.05)	25.43 (31.97)	*p* = 0.013 *F* = 3.87					x	
Curve and straight											
Curve mean speed (km/h)	102.7 (12.6)	103.7 (8.8)	105.2 (11.3)	110.2 (13.2)	*p* = 0.001 F = 2.04			xx		x	
Straight mean speed (km/h)	108.7 (13.0)	109.1 (9.6)	111.5 (11.9)	116.3 (13.3)	*p* = 1.00E-04 *F* = 7.93			xx		xx	
Curve percentage time off-road (%)	9.32 (5.67)	4.72 (3.75)	5.50 (3.96)	4.33 (3.35)	*p* = 1.97E-08 F = 17.17	xxx	xx	xxx			
Straight percentage time off-road (%)	5.19 (3.43)	2.01 (1.24)	2.40 (1.54)	2.52 (2.53)	*p* = 3.12E-08 *F* = 16.63	xxx	xxx	xxx			
Sharp curve											
Sharp curve mean speed (km/h)	94.1 (14.6)	94.5 (12.9)	94.6 (15.2)	100.2 (14.9)	*p* = 0.116 *F* = 2.04						
Sharp curve TOR (%)	23.35 (18.01)	13.94 (13.85)	14.19 (12.67)	16.10 (15.72)	*p* = 0.117 *F* = 2.03						
Sharp curve abs lateral error (m)	0.13 (0.06)	0.11 (0.04)	0.12 (0.03)	0.12 (0.09)	*p* = 0.214 F = 1.53						

Extensive speed results

Mean and standard deviation of the speed

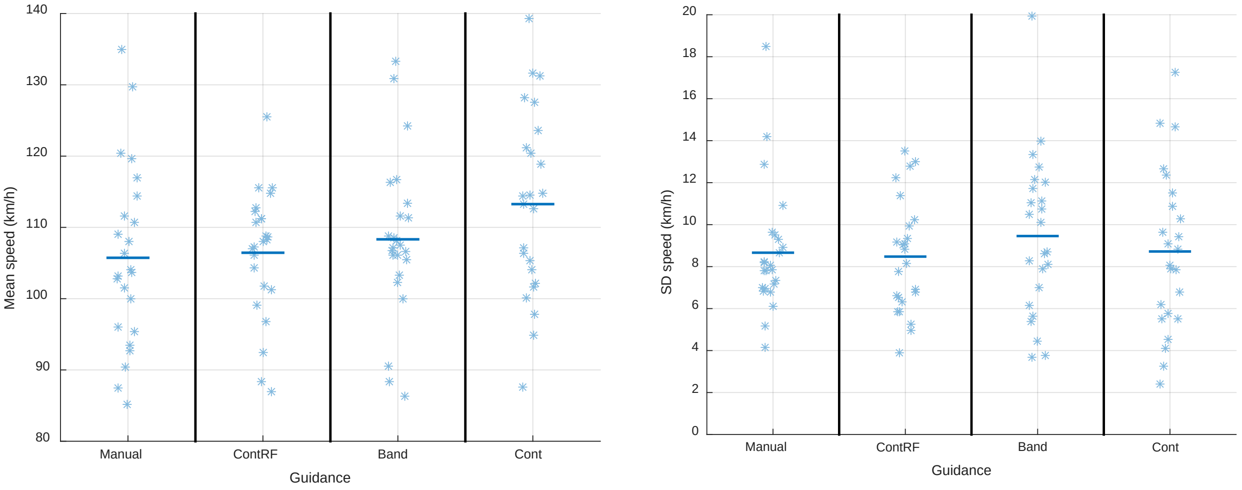


Figure 1: Left figure: Mean speed of individual participants (stars) and mean speed across all participants (horizontal line) per condition. Right figure: SD speed of individual participants (stars) and mean speed STD across all participants (horizontal line) per condition

Scatter plot of the mean speed per participant

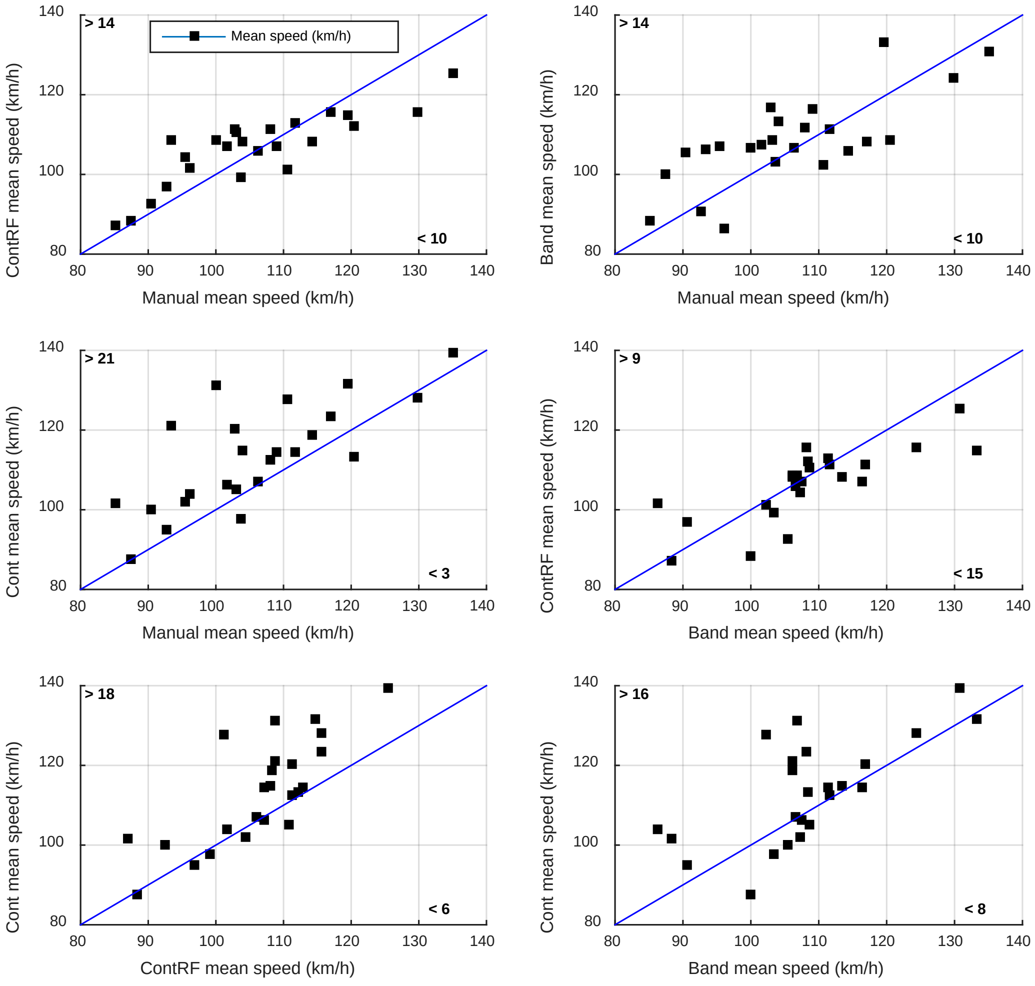


Figure 2: Scatter plot of the mean speed per participant (black square) for all conditions. The blue line indicate equal speeds for both conditions.

Average driving behavior raw and mean

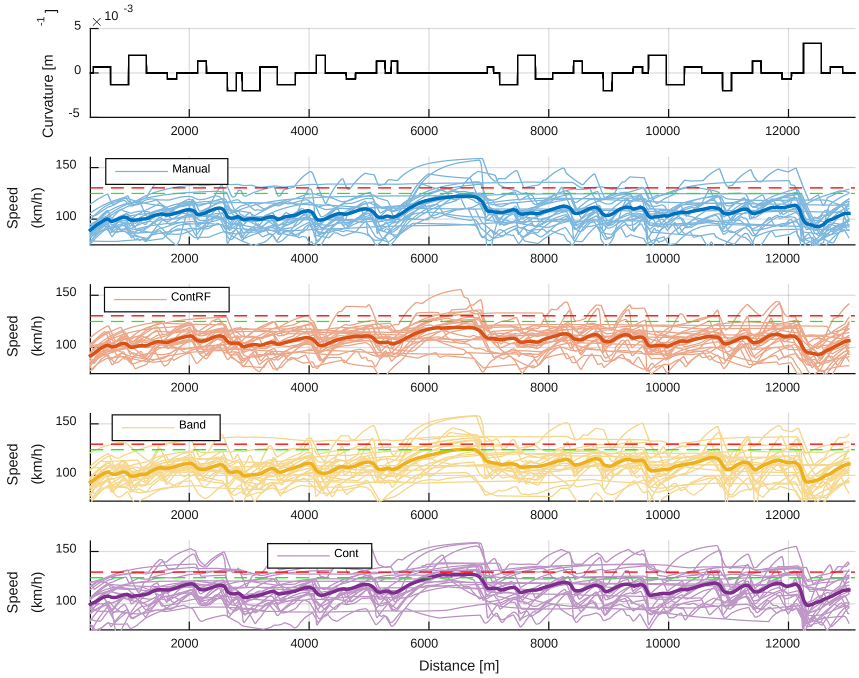


Figure 3: Speed of all participants, and the mean of all participants per distance for all conditions. From top to bottom: road curvature, Manual, ContRF, Band, Cont. The dotted green and red line indicate the ContRF speed threshold.

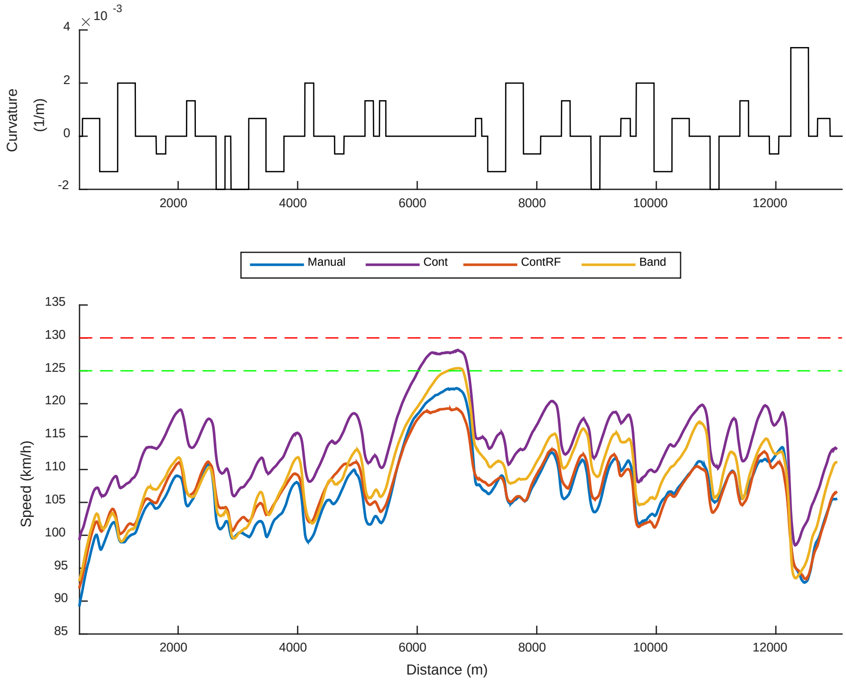


Figure 4: Mean speed distance traces across all participants (same as thick lines in figure 3) per condition. The dotted green line is the moment the ContRF guidance reduces the feedback force. The dotted red line is the moment the ContRF guidance is turned off and the controller is similar to the manual condition.

Speed distribution of average driver

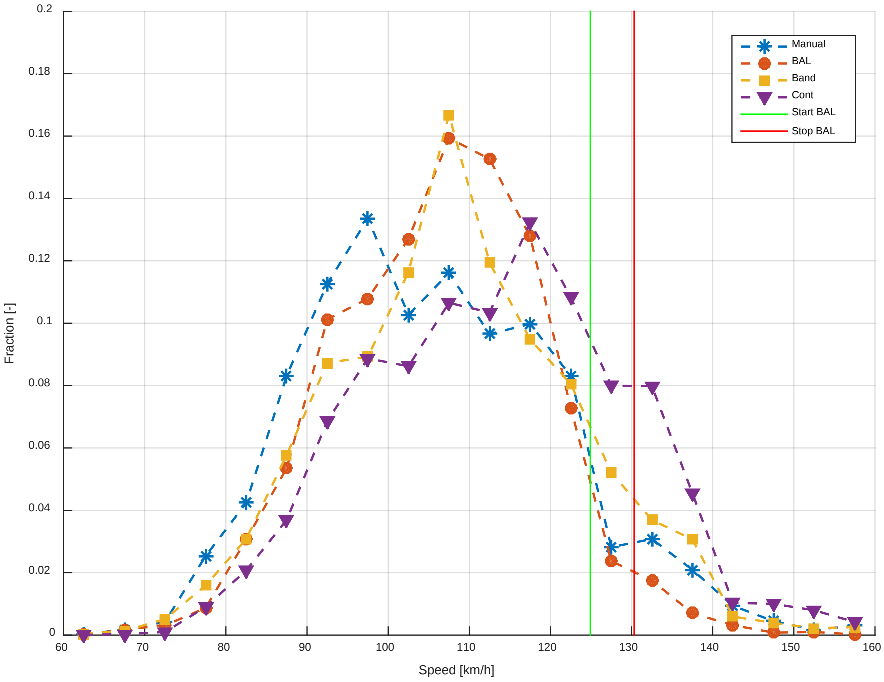


Figure 5: Average speed distribution over the entire trajectory of all participants per condition. Bin width 5 km/h. Fraction output is plotted in the middle of the bins. The red and green line show the ContRF guidance thresholds

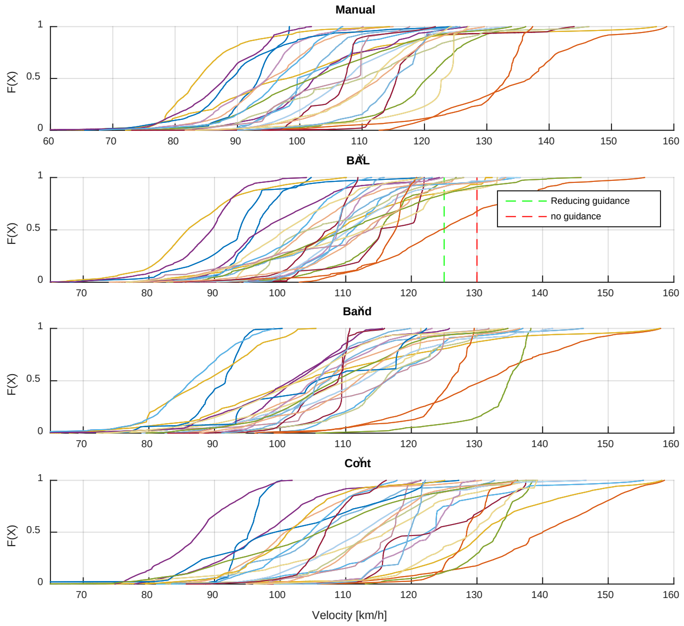


Figure 6: Cumulative distribution function of the velocity for all participants per condition. The dotted green and red line show the ContRF guidance thresholds.

Extensive performance results

Number of cone hits and percentage time off-road

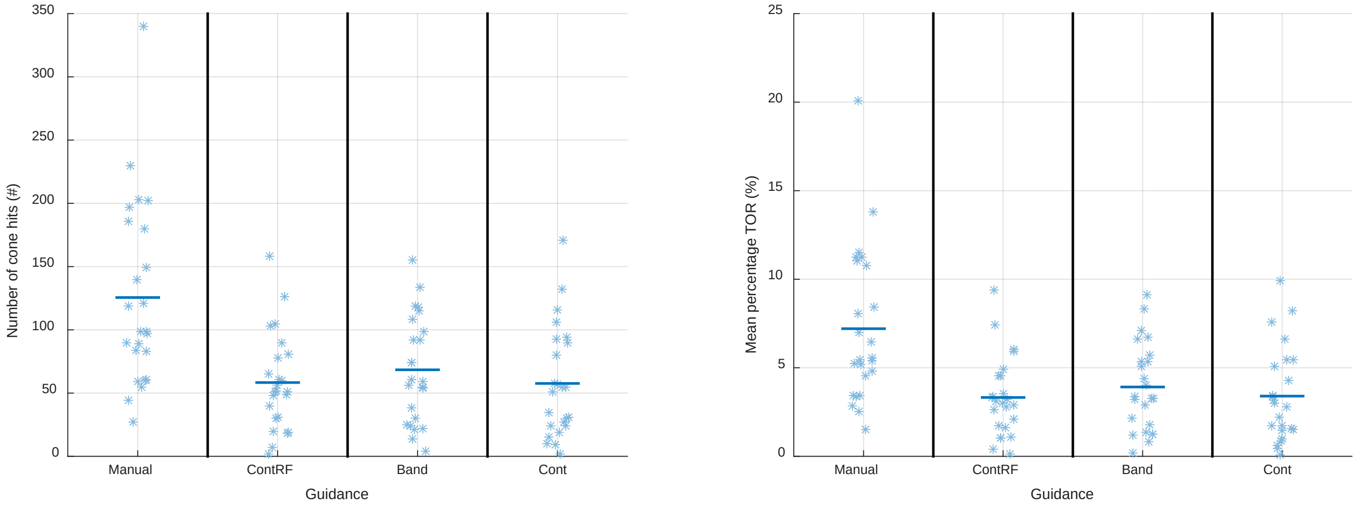


Figure 7: Left figure: Number of cone hit of individual participants (stars) and mean number of cone hits across all participants (horizontal line) per condition. Right figure: time off-road of individual participants (stars) and mean time-off-road across all participants (horizontal line) per condition

Absolute Lateral error

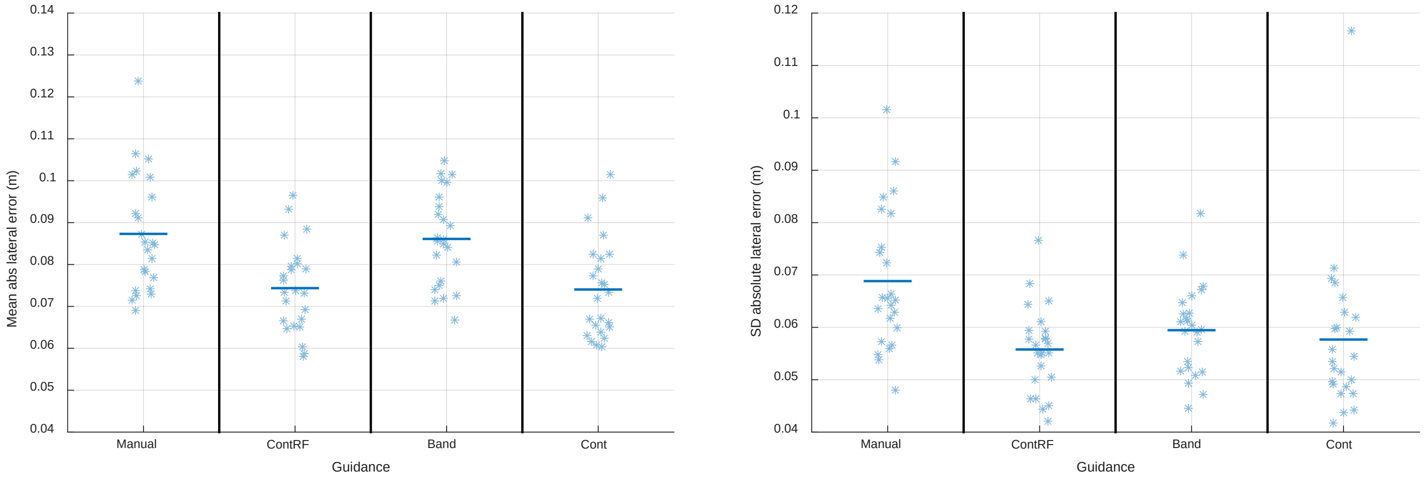


Figure 8: Left figure: Mean absolute lateral error of individual participants (stars) and mean absolute lateral error across all participants (horizontal line) per condition. Right figure: STD absolute lateral error of individual participants (stars) and mean STD absolute lateral error across all participants (horizontal line) per condition.

Mean time needed to get back in the lane

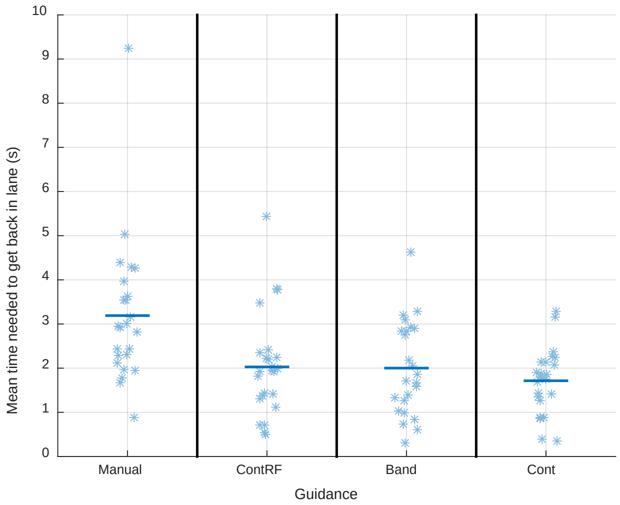


Figure 9: Mean time needed to get car back in lane (e.g. absolute lateral error of car center < 0.2 m) and stay in the lane for at least 5 seconds per participant (stars) and mean across all participants per condition.

Lateral Error distribution of average driver

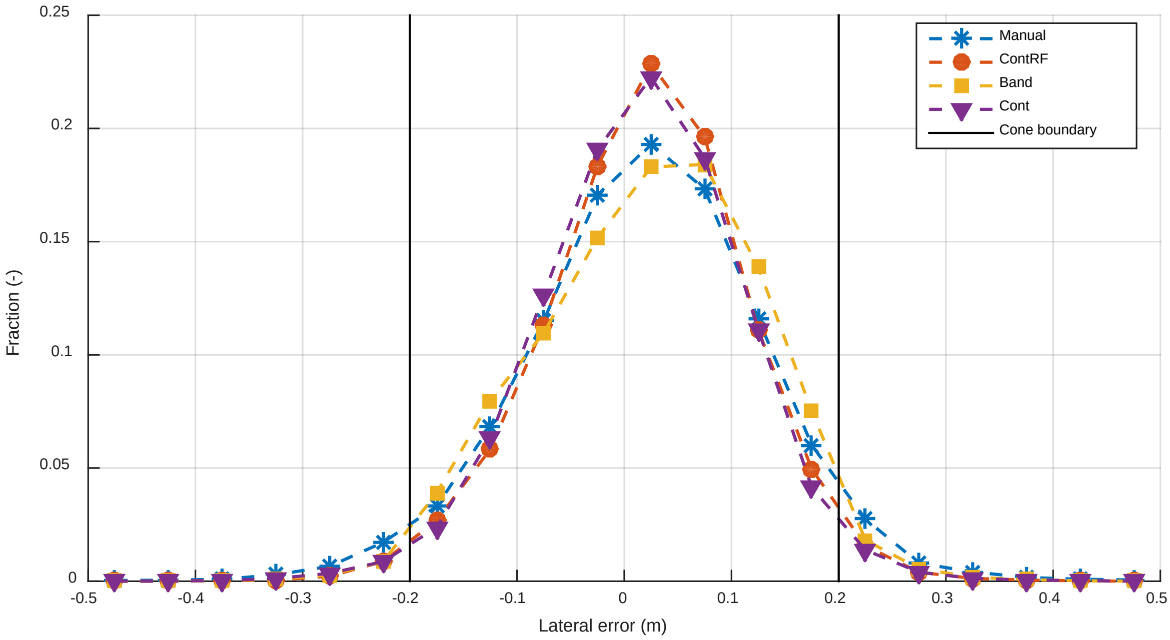


Figure 10: Average lateral error distribution over the whole trajectory of all participants per condition. Bin width 0.05 m, fraction output plotted in the middle of the bins. Dotted black lines show the cone locations (the moment the side of the car would hit a cone)

Scatter plot of the total time off-road per participant

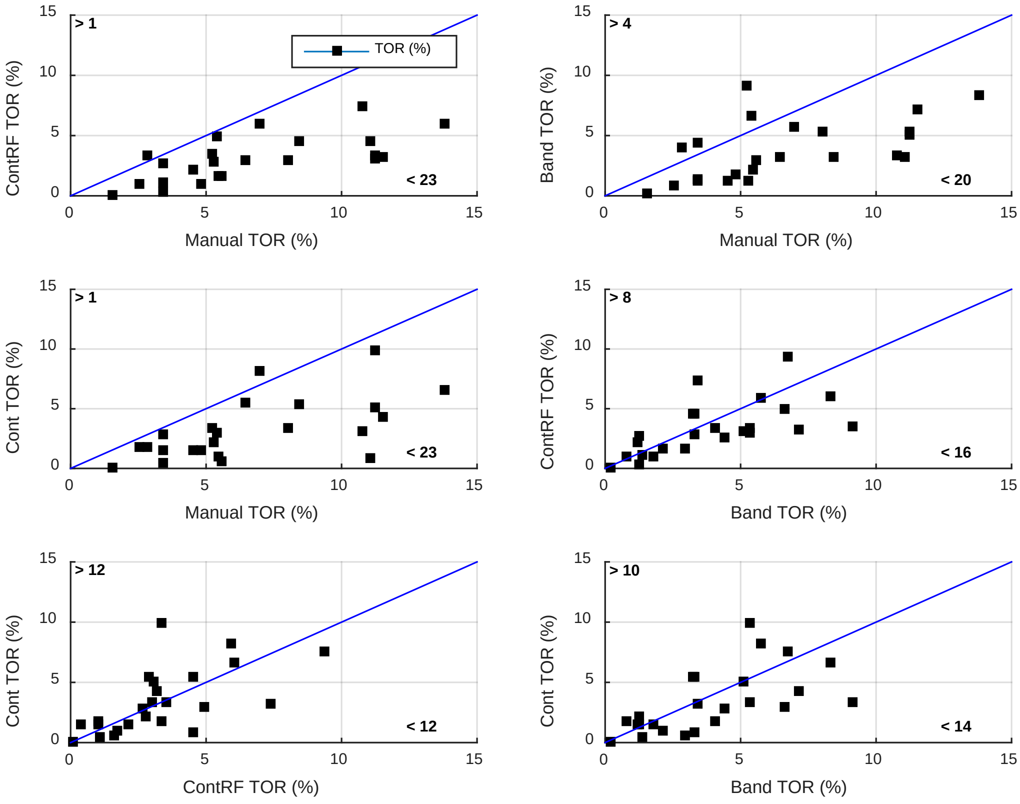


Figure 11: Within subject percentage time off-road (TOR) comparison per participant (black square) for all conditions. The blue line indicate equal speeds for both conditions.

Scatter plot of the absolute lateral error per participant

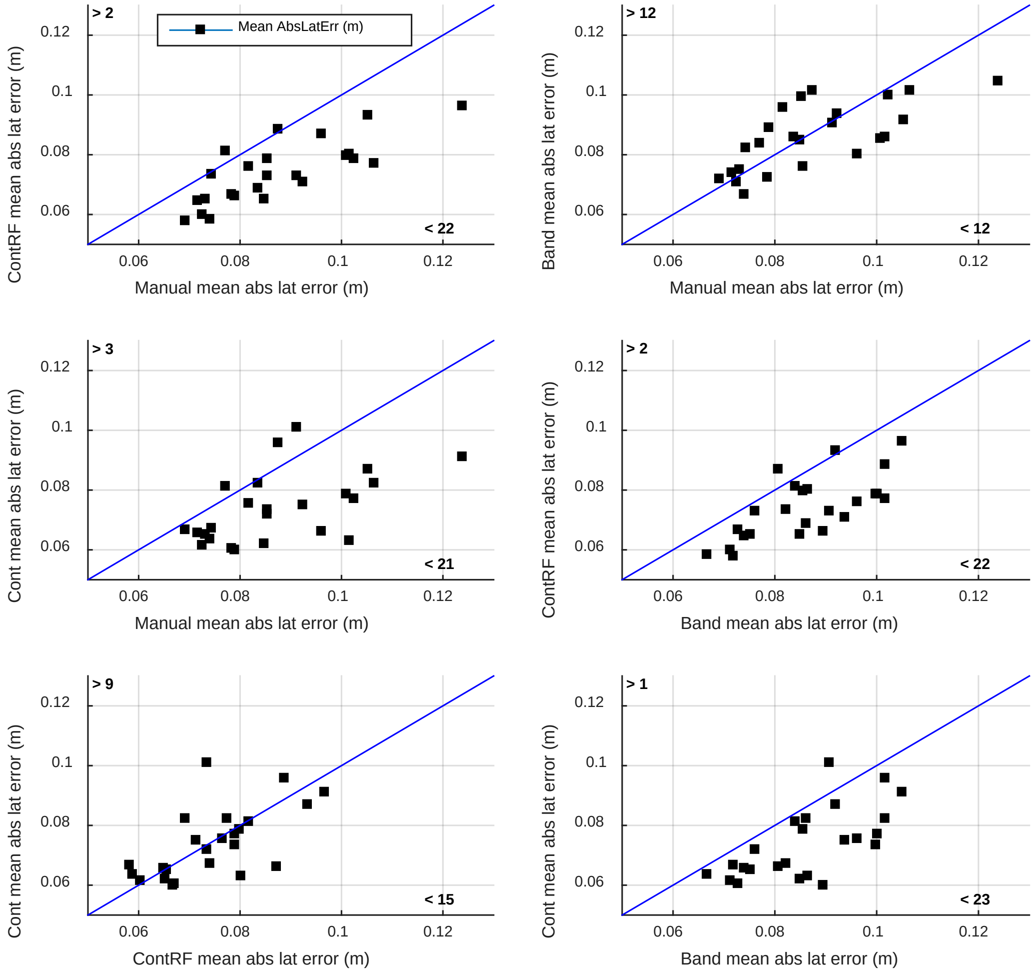


Figure 12: Within subject mean absolute lateral error (m) comparison per participant (black square) for all conditions. The blue line indicate equal speeds for both conditions.

Cone hit location

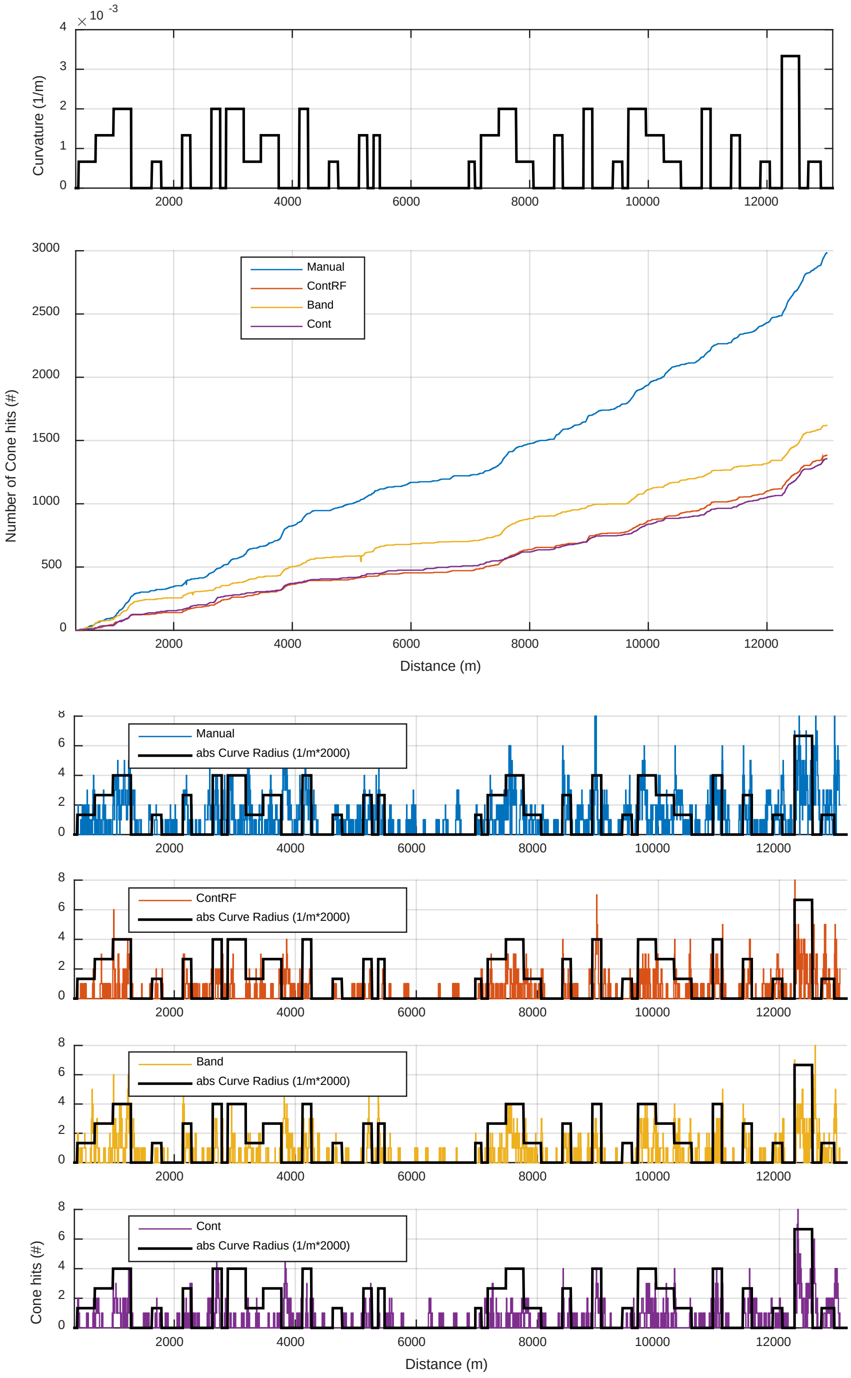


Figure 13: The sum of cone hits of all subjects together. The top figure shows the cumulative sum of cone hits for all subjects per distance per condition. The bottom figure shows the amount of cone hits in bins of 5m of all subjects together per distance per condition.

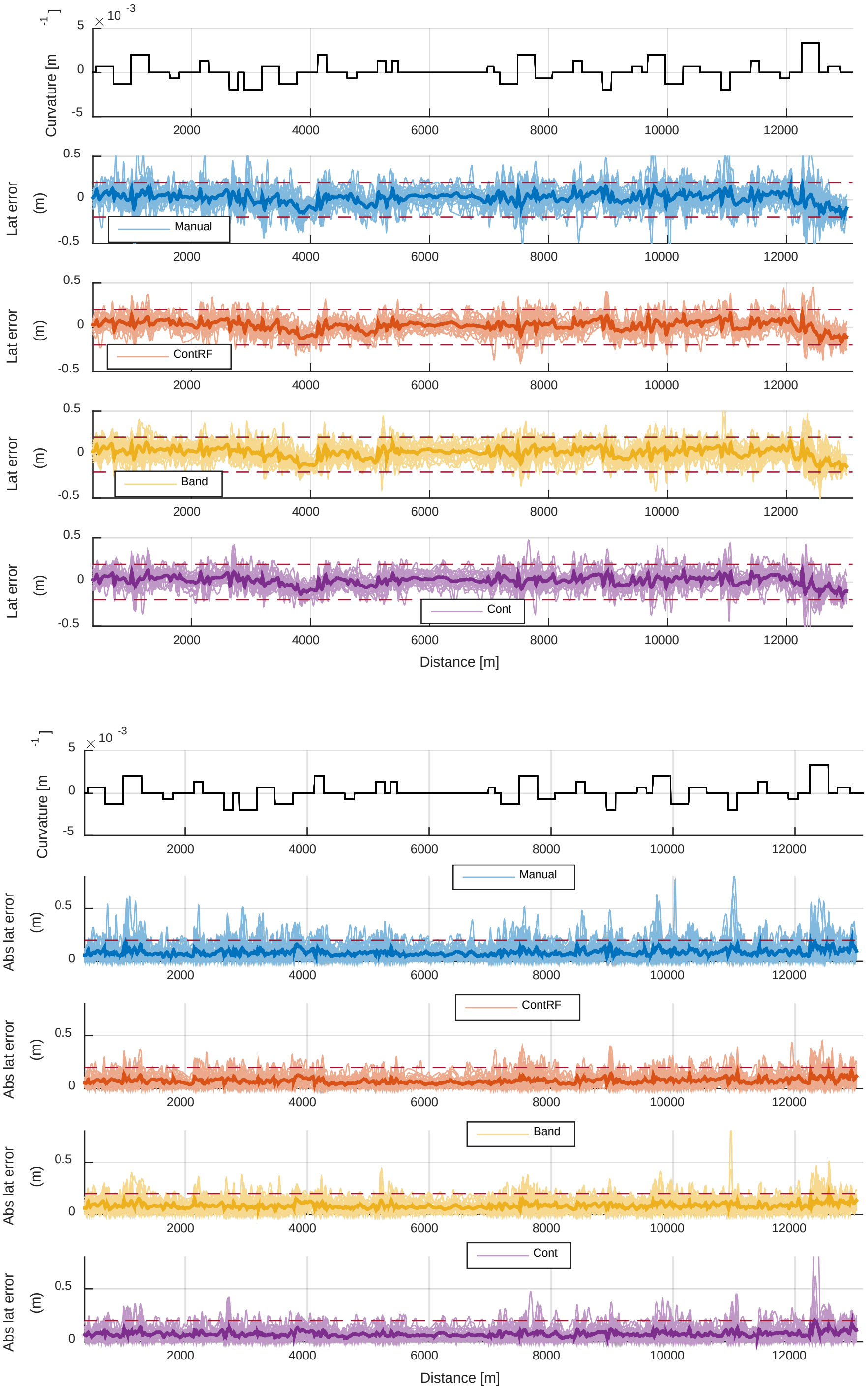


Figure 14: mean lateral error (top) and mean absolute lateral error (bottom) of all participants (light colored), and mean across all participants (thick dark line) per distance for all conditions. From top to bottom: road curvature, Manual, ContRF, Band, Cont.

Extensive Safety Margins results (TLC)

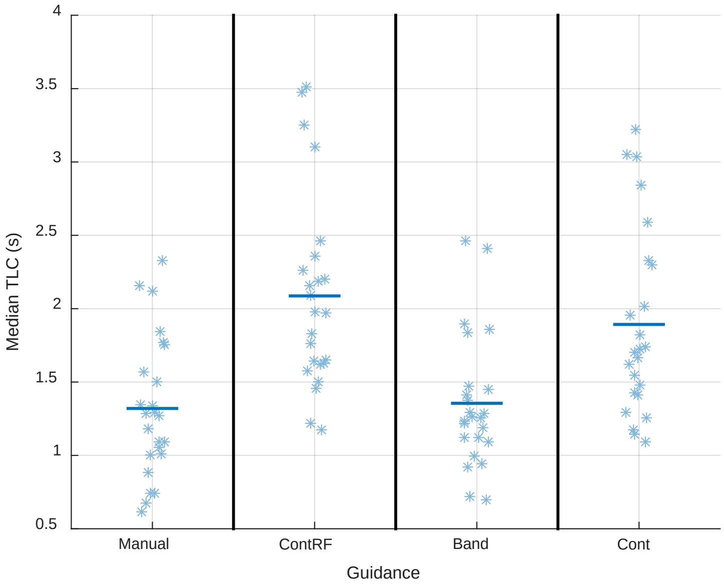


Figure 16. Median TLC (s) of individual participants (stars) and mean TLC (s) across all participants (horizontal line) per condition.

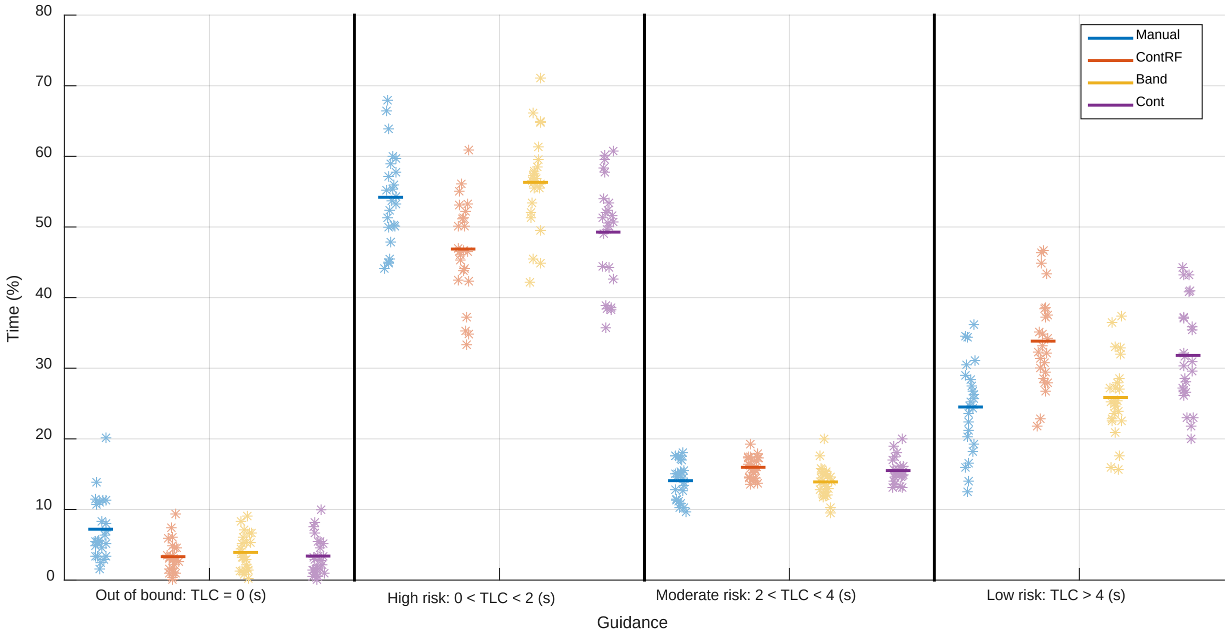


Figure 15. Percentage of time driving in a risk group. The TLC values are categorized in four groups: Out of bound (TLC = 0), High risk (0<TLC<=2), moderate risk (2 < TLC < 4), Low risk (TLC>4).

Table 2: Means (M), standard deviations (SD), and effect size of the repeated measures ANOVA (F,p) for the time to line crossing (TLC). x means p ≤ 0.05, xx means p ≤ 0.01, XXX means p ≤ 0.001.

	Manual (1)	ContRF (2)	Band (3)	Cont (4)		Pairwise comparison					
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*p*-value *F*(3,69)	1-2	1-3	1-4	2-3	2-4	3-4
Median TLC (s)	1.32 (0.48)	2.09 (0.67)	1.36 (0.46)	1.89 (0.65)	$p = 4.73 \cdot 10^{-17}$ F=48.86	xxx		xxx	xxx		xxx
Percentage low safety margin (0 s < TLC ≤ 2 s) (%)	54.20 (6.59)	46.87 (7.01)	56.32 (6.78)	49.27 (7.57)	$p = 1.61 \cdot 10^{-13}$ F=33.67	xxx		xx	xxx	x	xxx
Percentage moderate safety margin (2 s < TLC ≤ 4 s) (%)	14.08 (2.68)	15.97 (1.47)	13.90 (2.26)	15.51 (1.75)	$p = 2.48 \cdot 10^{-7}$ F=14.24	xx		x	xxx		xxx
Percentage high safety margin (TLC > 4 s) (%)	24.51 (6.46)	33.84 (6.84)	25.86 (5.68)	31.82 (7.22)	$p = 2.07 \cdot 10^{-16}$ F=45.83	xxx		xxx	xxx		xxx

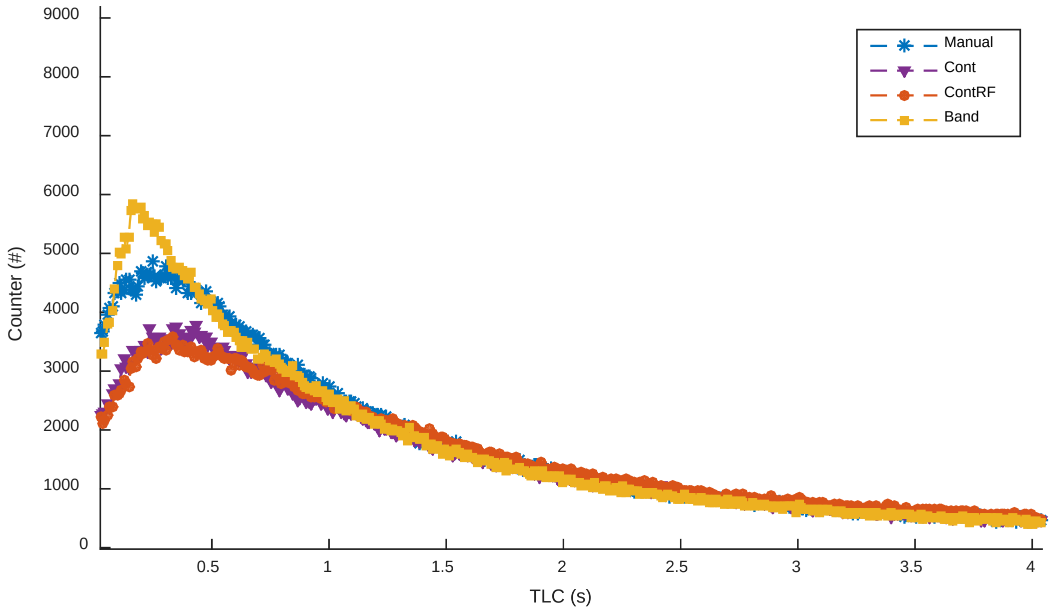
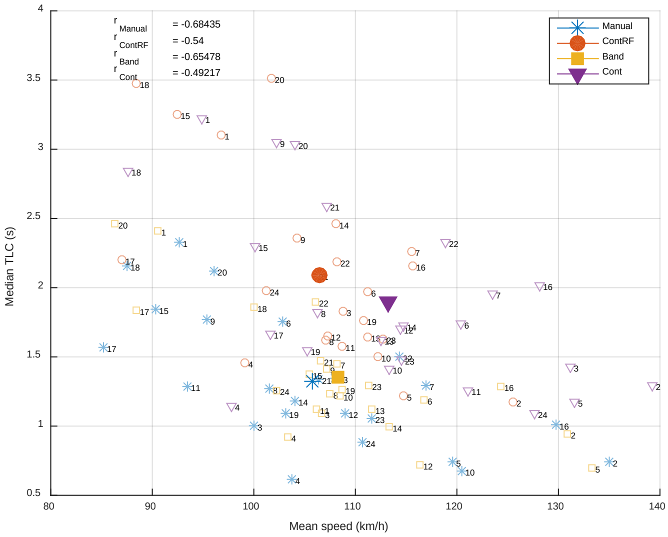
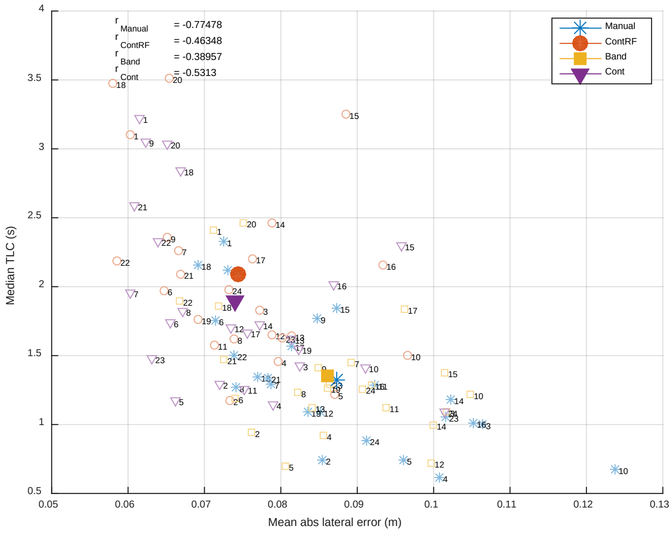
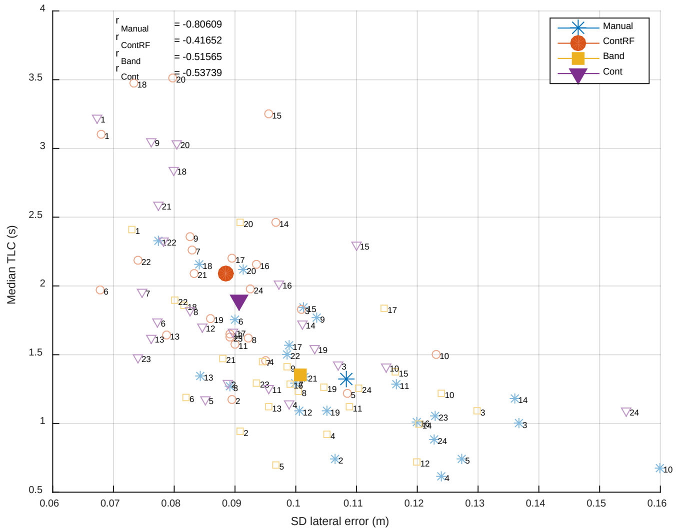


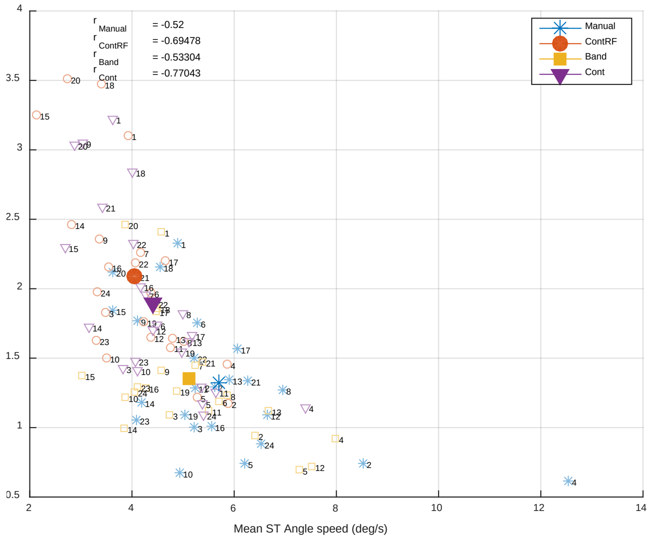
Figure 17. Time to lane crossing distribution. The number of TLC values driven in bins of 0.01 for all 24 participants combined per condition.

TLC Spearman correlation vs. speed, absolute lateral error, SDLP, Steering angle speed









Speed-accuracy trade-off

Speed-accuracy trade-off between subjects

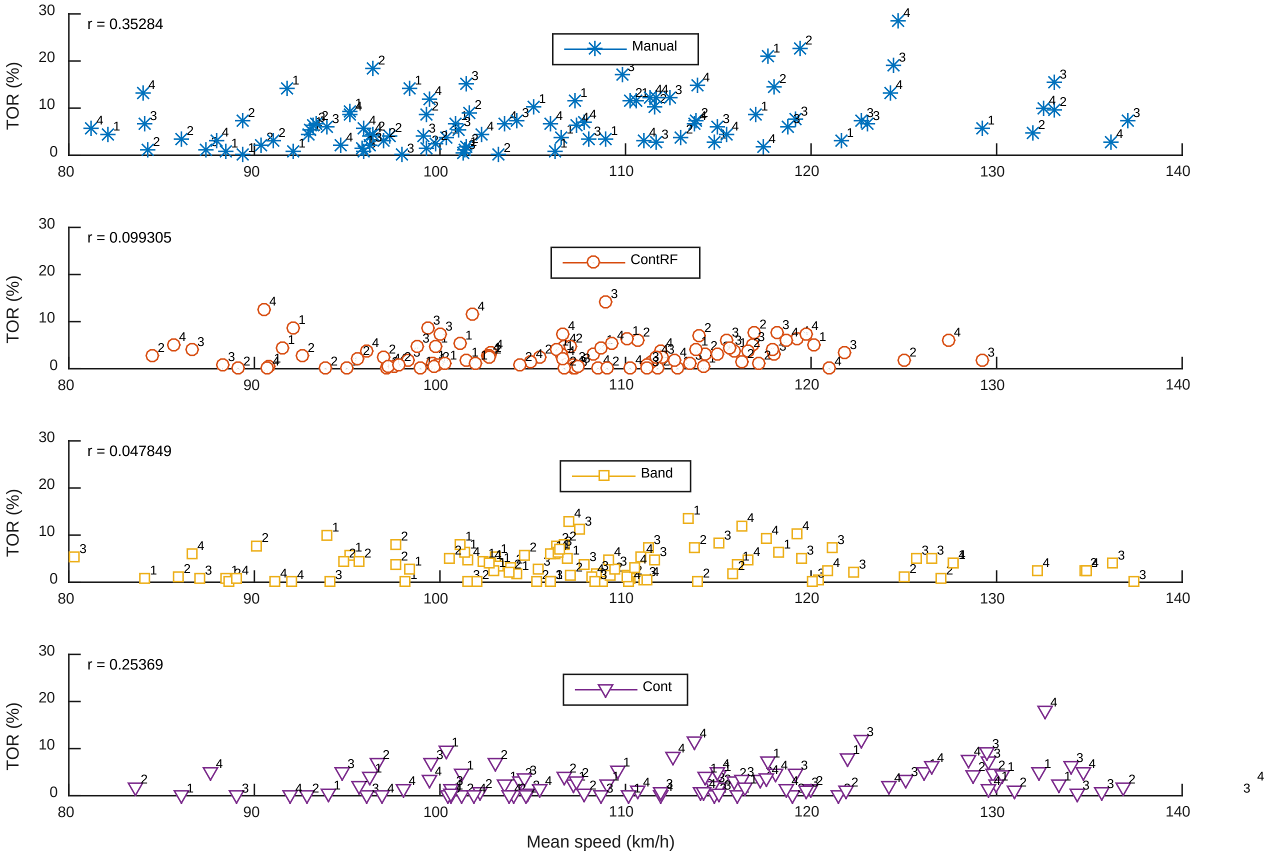


Figure 18: Mean speed and percentage time off-road at four similar segments for all participants per condition. The numbers next to the marker indicate the used segment (e.g. 1. first segment, 2. Second segment, 3. Third segment, 4. Fourth segment). Segment have the same length (± 3 km) and consist of 2 curves with radius 500 m, 2 curves with radius 750 m and 2 curves with radius 1500 m. The Pearson correlation (r) is shown in the left top of each subplot.

Speed-accuracy trade-off within subjects

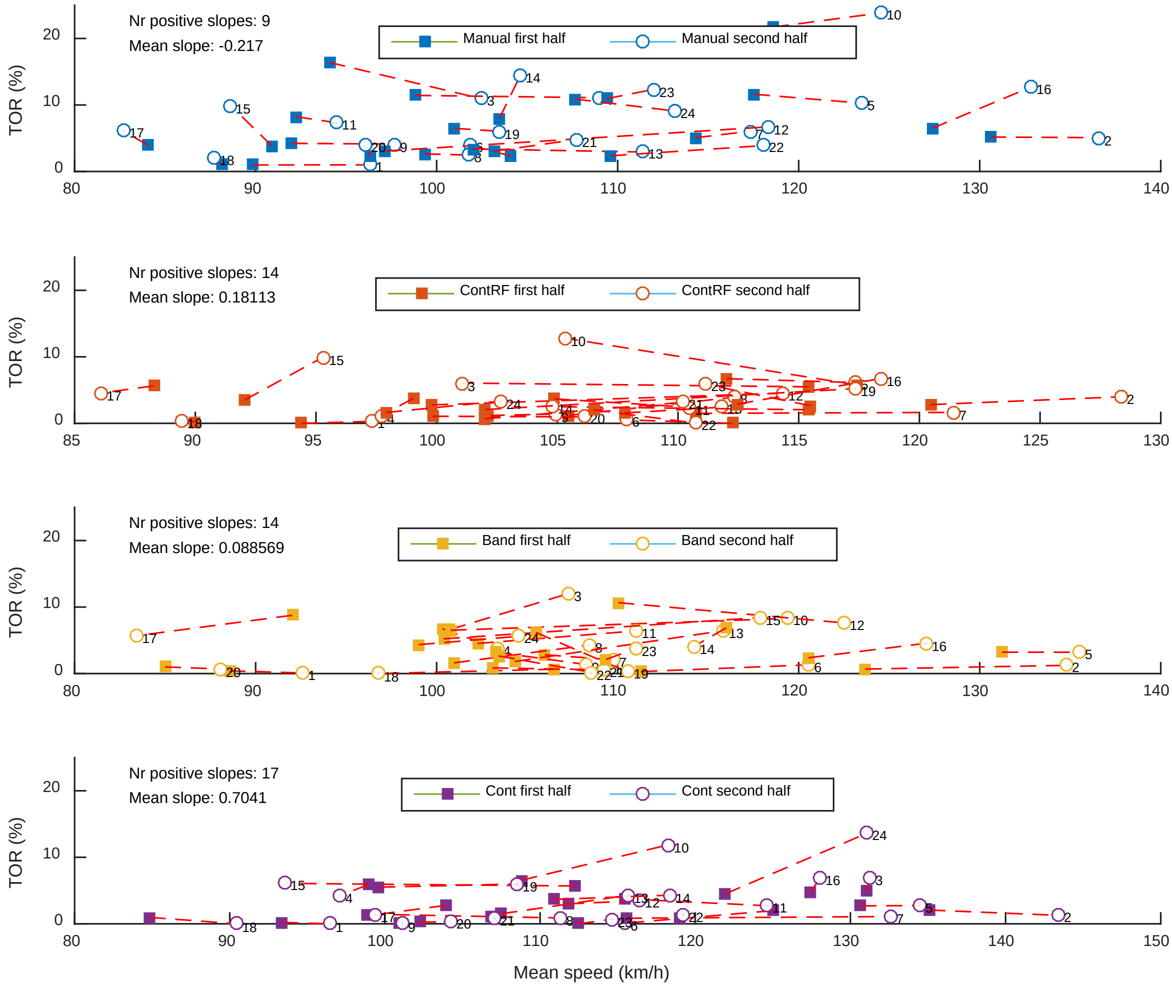


Figure 19: Mean speed and percentage time off-road at for the first half (squares), and second half (circles) of the entire road for all participants per condition. The numbers next to the marker indicate the subject number. Each segment has the same length (±6 km) and consist of 4 curves with radius 500 m, 4 curves with radius 750 m and 4 curves with radius 1500 m. Amount of positive slopes and mean slope across all participates is shown in the left corner of each condition plot.

Questionnaire results

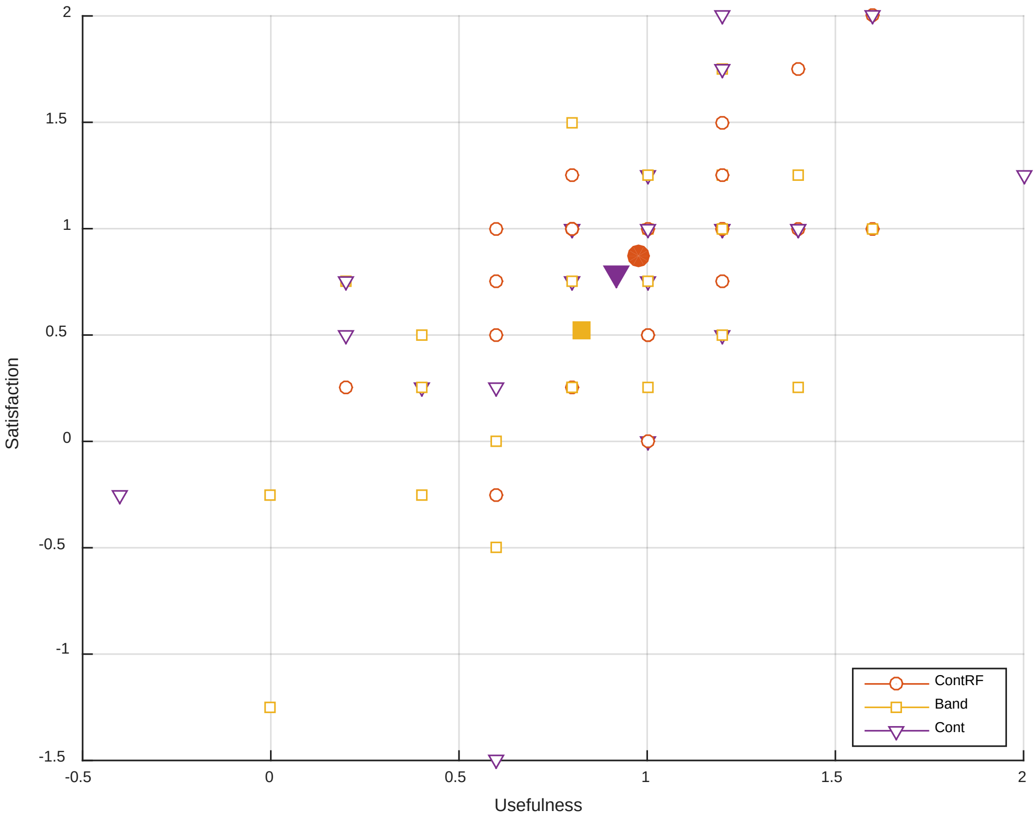


Figure 20: Van der Laan questionnaire results for all participants per condition. The x-axis shows the subjective usefulness (+2,-2) and the y-axis show the subjective satisfaction (+2,-2). Condition are respectively ContRF (circles), Band (squares), and Cont (triangles). The large markers show the mean across all participants for each condition.

Workload

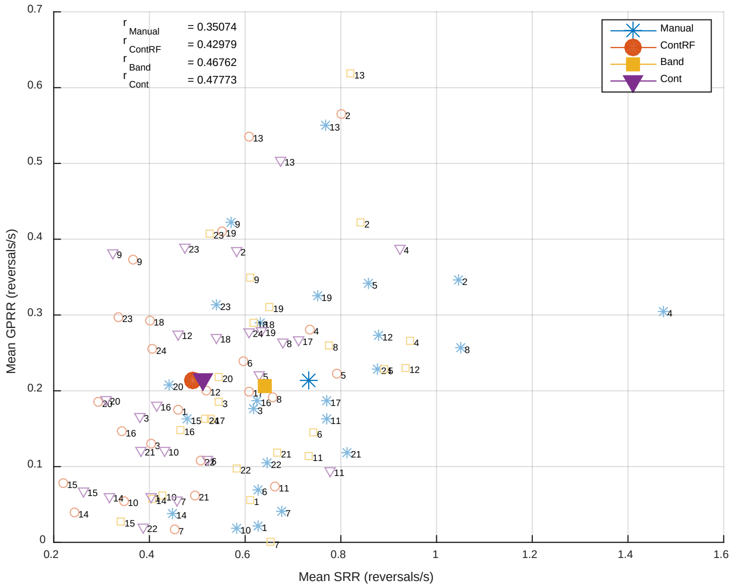


Figure 21. Mean steering reversal rate and mean gas pedal reversal rate of individual participants per conditions. The mean across participants is indicated with the large marker.

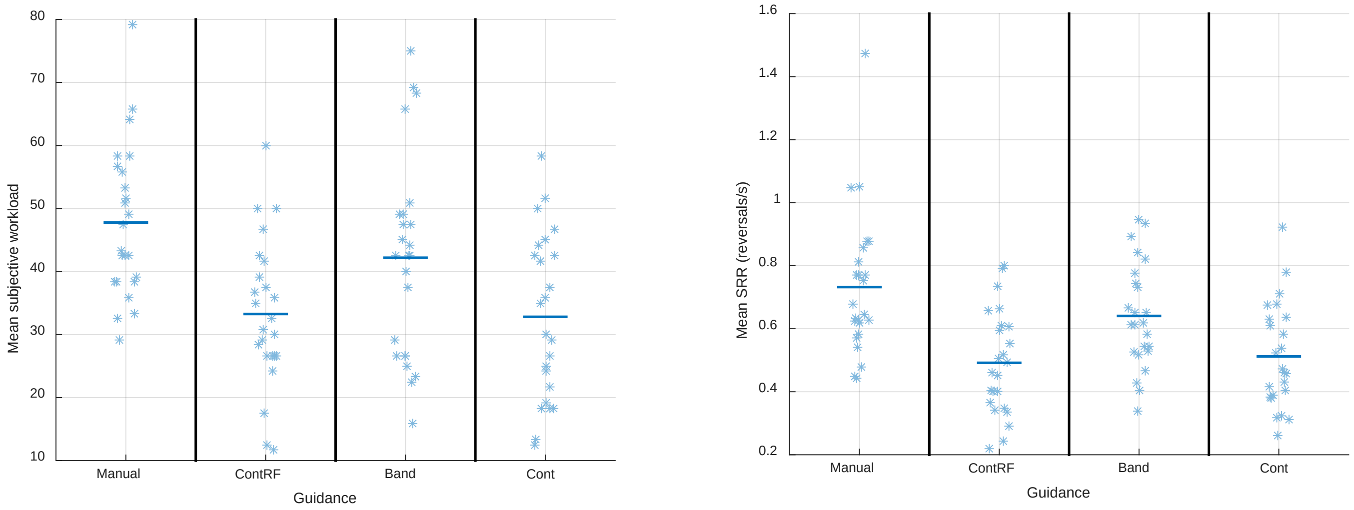


Figure 22: Left figure: Mean NASA TLX workload of individual participants (stars) and mean NASA TLX workload across all participants (horizontal line) per condition. Right figure: mean SRR of individual participants (stars) and mean SRR across all participants (horizontal line) per condition. Local minima/maxima steering angles larger than 3 degrees difference were considered as a reversal.

Curves Versus straight segments

Overall comparison

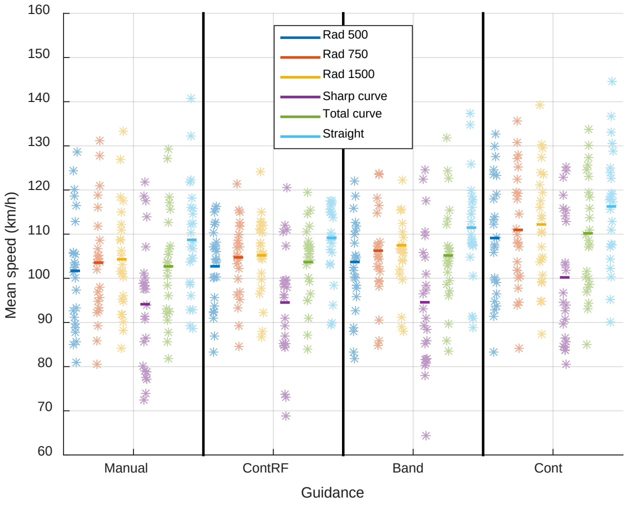


Figure 23: Mean velocity per curve radius and straight segments for all participants per condition.

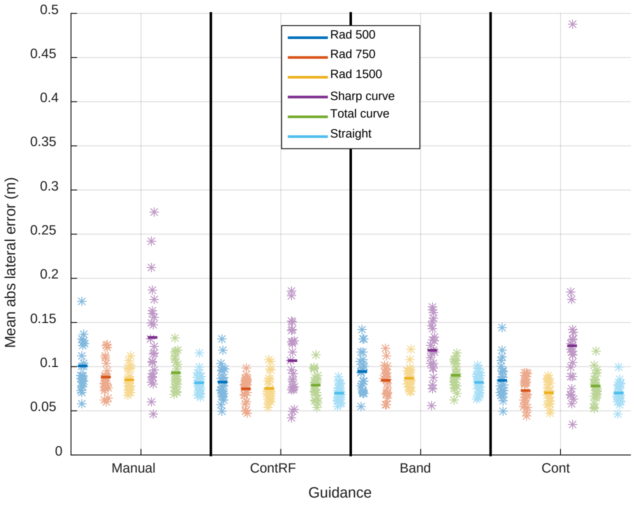


Figure 24: Mean absolute lateral error per curve radius and straight segments for all participants per condition.

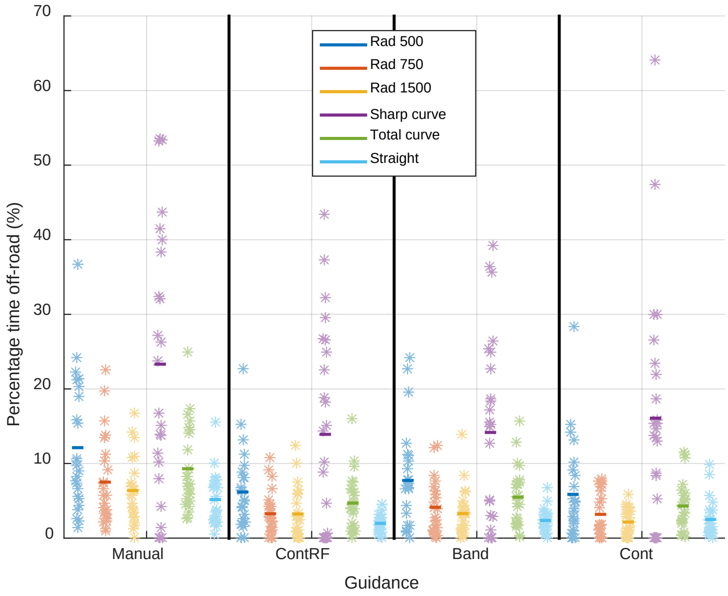


Figure 25: Mean time off-road per curve radius and straight segments per subject (stars) and mean across all participants (horizontal line) per condition.

Scatter plot of the mean speed per participant: straight and curve speed

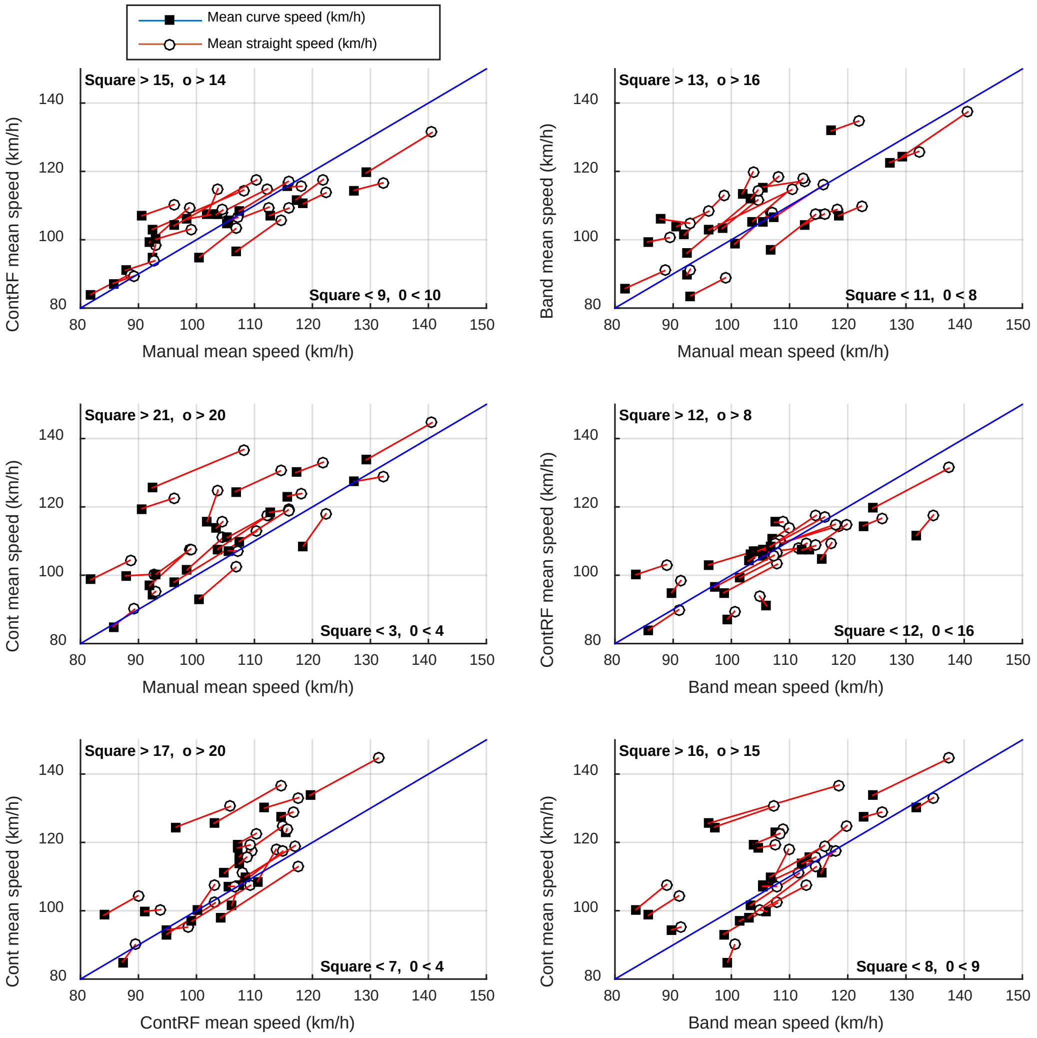


Figure 26: Within subject mean speed (km/h) comparison per participant in curves (black square) and straight segments (white circles) for all conditions. The blue line indicate equal speeds in both conditions. The numbers in the left top and right bottom show respectively the amount of participants above or below the blue line. Numbers next to a black square indicate the subject number.

Average straight behavior per condition

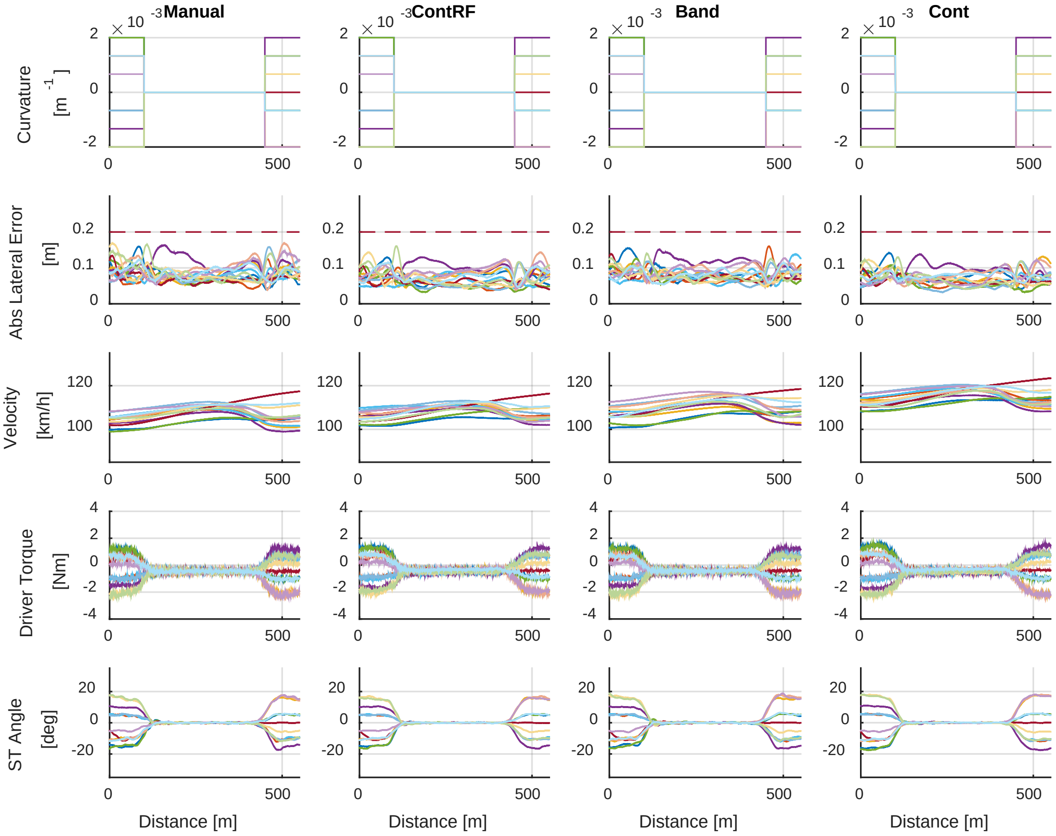


Figure 27: All subjects average driving behavior on the straight section per condition. First row contains the curvature; All straight segments are plotted on top of each other indicated with different colors. The other rows contain respectively from top to bottom: absolute lateral error, velocity, driver torque, and steering angle.

Average curve radius 1500 behavior per condition

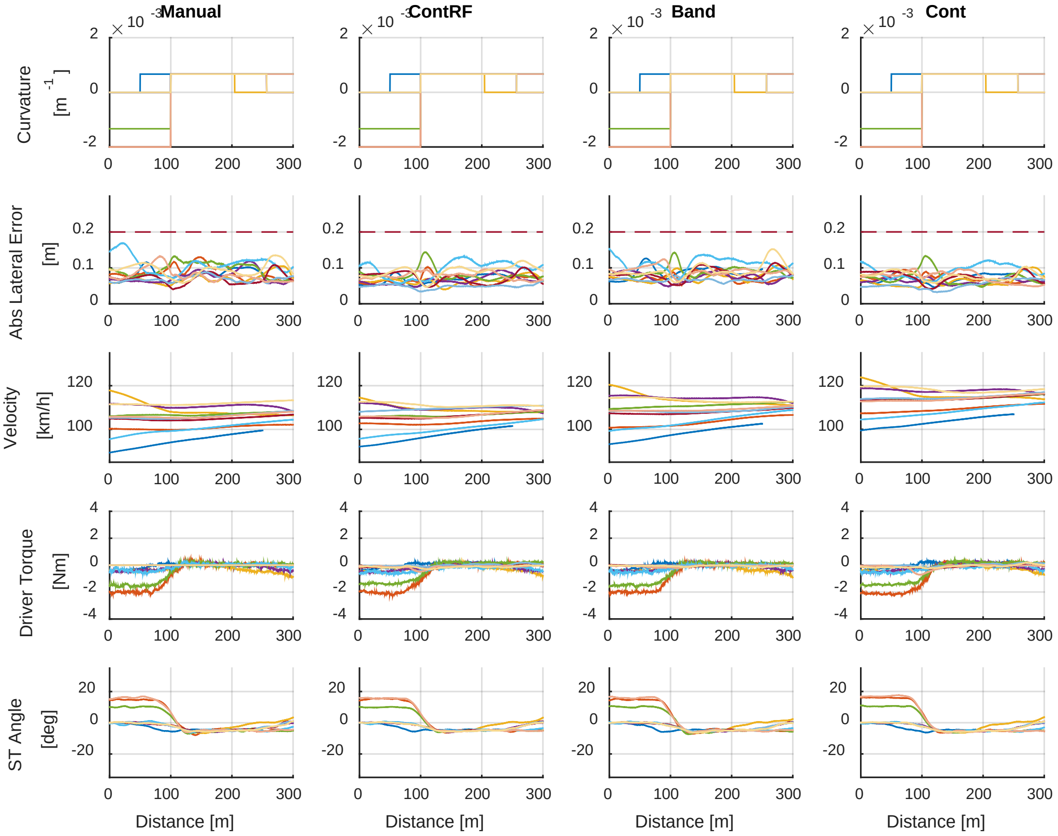


Figure 28: All subjects average driving behavior per condition at curve segments with inner radius of 1500m. First row contains the curvature; All curve segments with inner radius of 1500 m are plotted on top of each other and are indicated with different colors. The other rows contain respectively from top to bottom: absolute lateral error, velocity, driver torque, and steering angle.

Average curve radius 750 behavior per condition

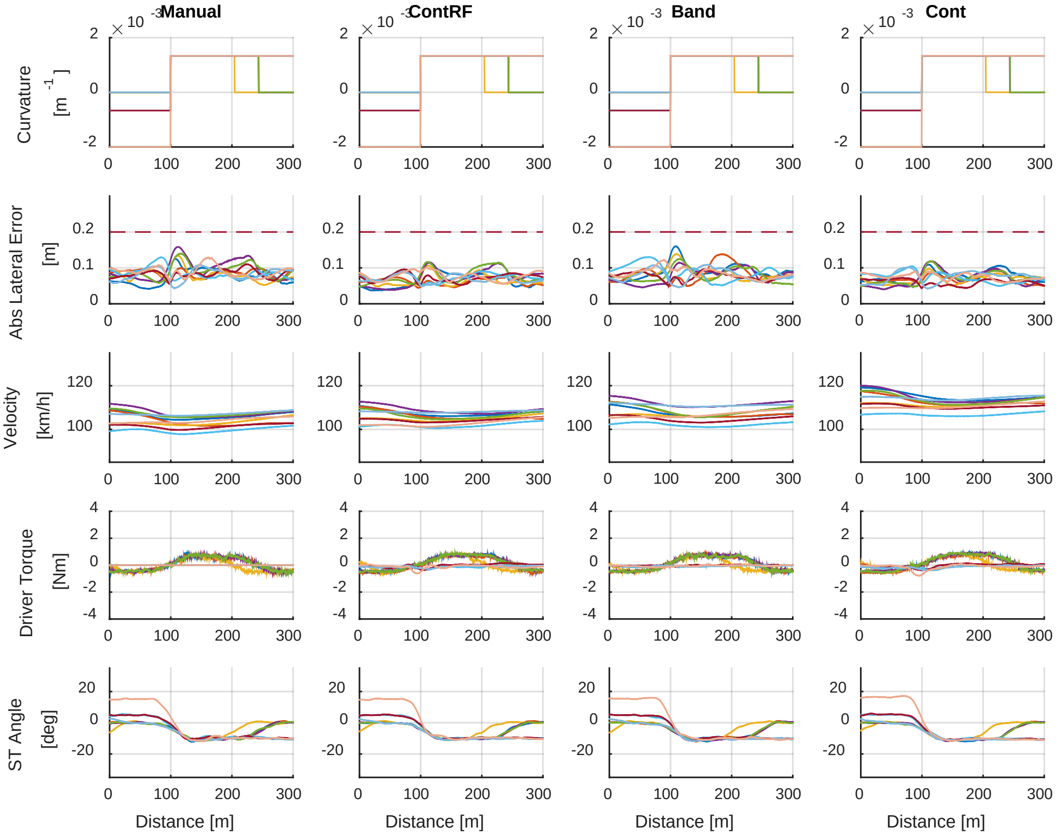


Figure 29: All subjects average driving behavior per condition at curve segments with inner radius of 750m. First row contains the curvature; All curve segments with inner radius of 750 m are plotted on top of each other and are indicated with different colors. The other rows contain respectively from top to bottom: absolute lateral error, velocity, driver torque, and steering angle.

Average curve radius 500 behavior per condition

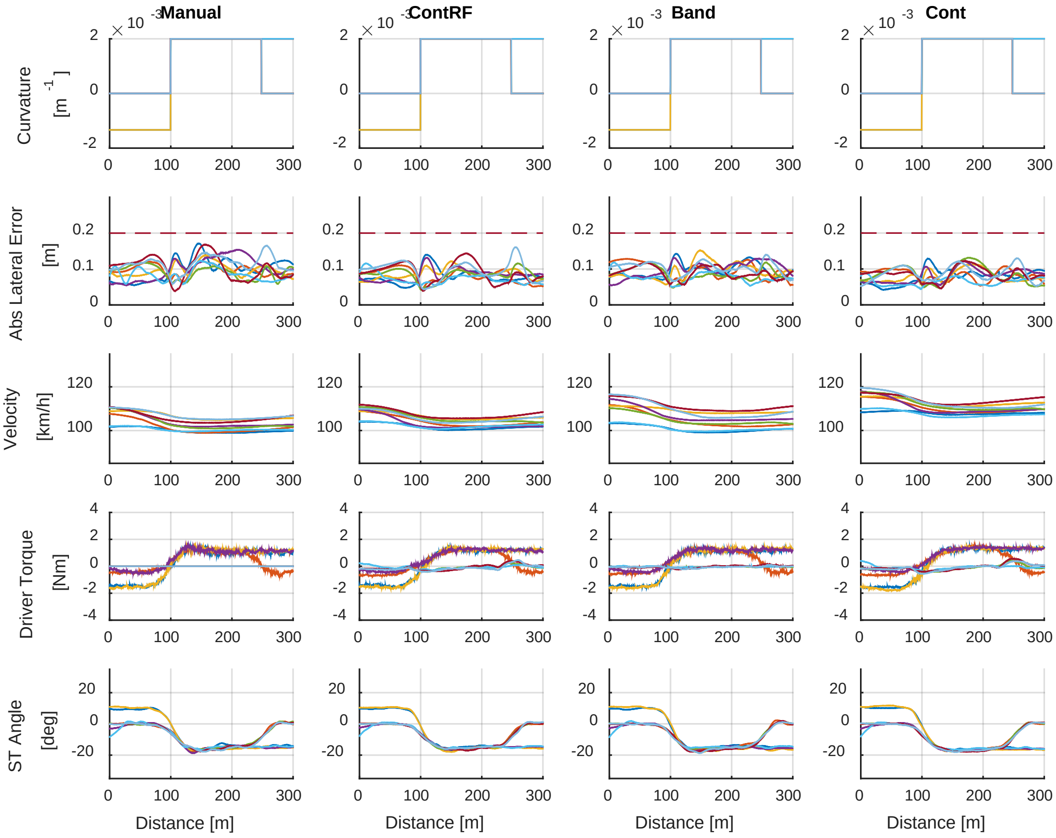


Figure 30: All subjects average driving behavior per condition at curve segments with inner radius of 500 m. First row contains the curvature; All curve segments with inner radius of 500 m are plotted on top of each other and are indicated with different colors. The other rows contain respectively from top to bottom: absolute lateral error, velocity, driver torque, and steering angle.

ContRF guidance analysis

ContRF guidance overall metrics

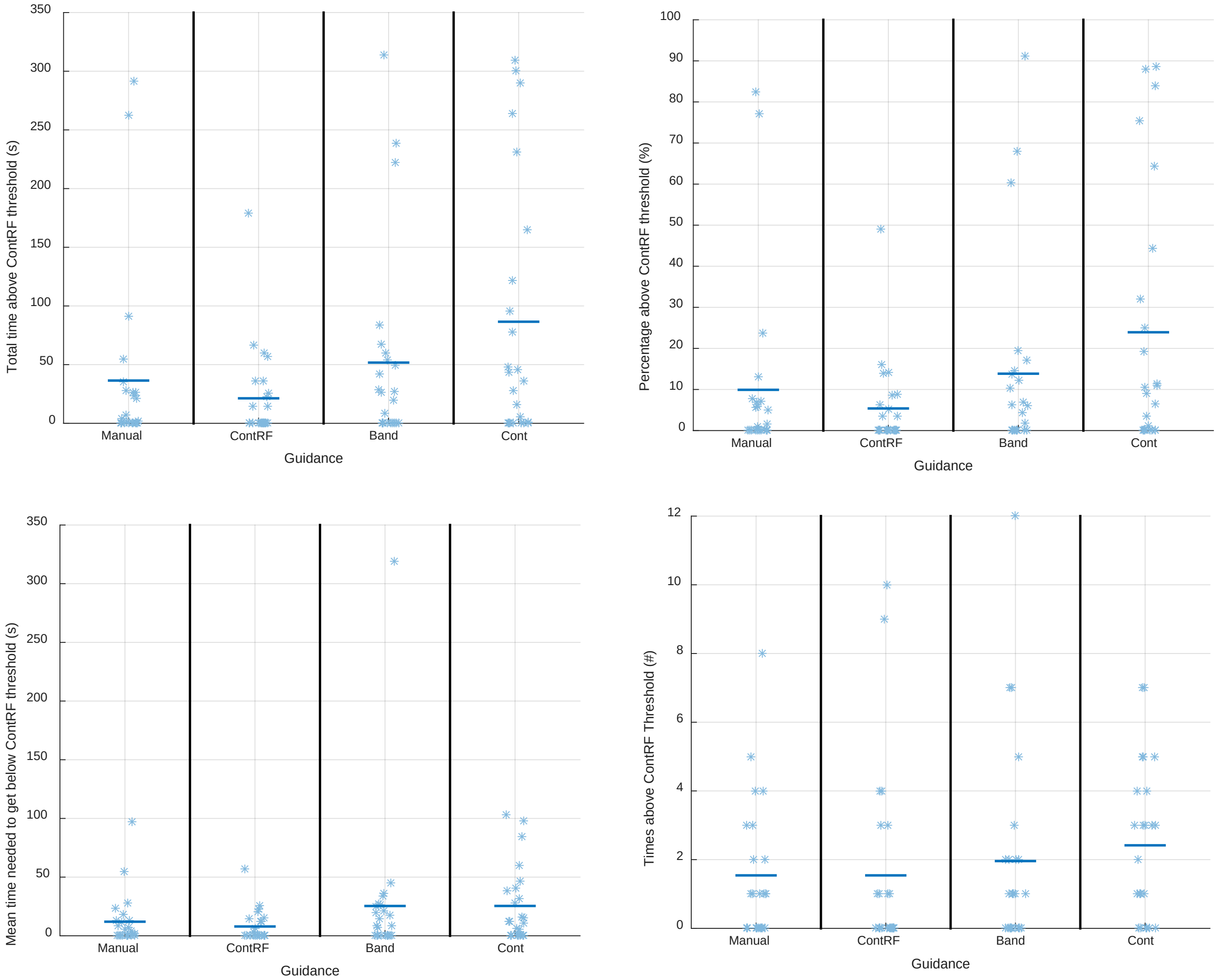


Figure 31: Metrics related to the ContRF guidance threshold of 125 km/h. Top left: Total time driven above ContRF speed threshold per subject per condition. Top right: Percentage of time above ContRF threshold per subject per condition. Bottom left: Mean time needed to get below ContRF threshold per subject per condition. Bottom right: the number of times above ContRF threshold

Comparison between people who did and didn’t encounter ContRF

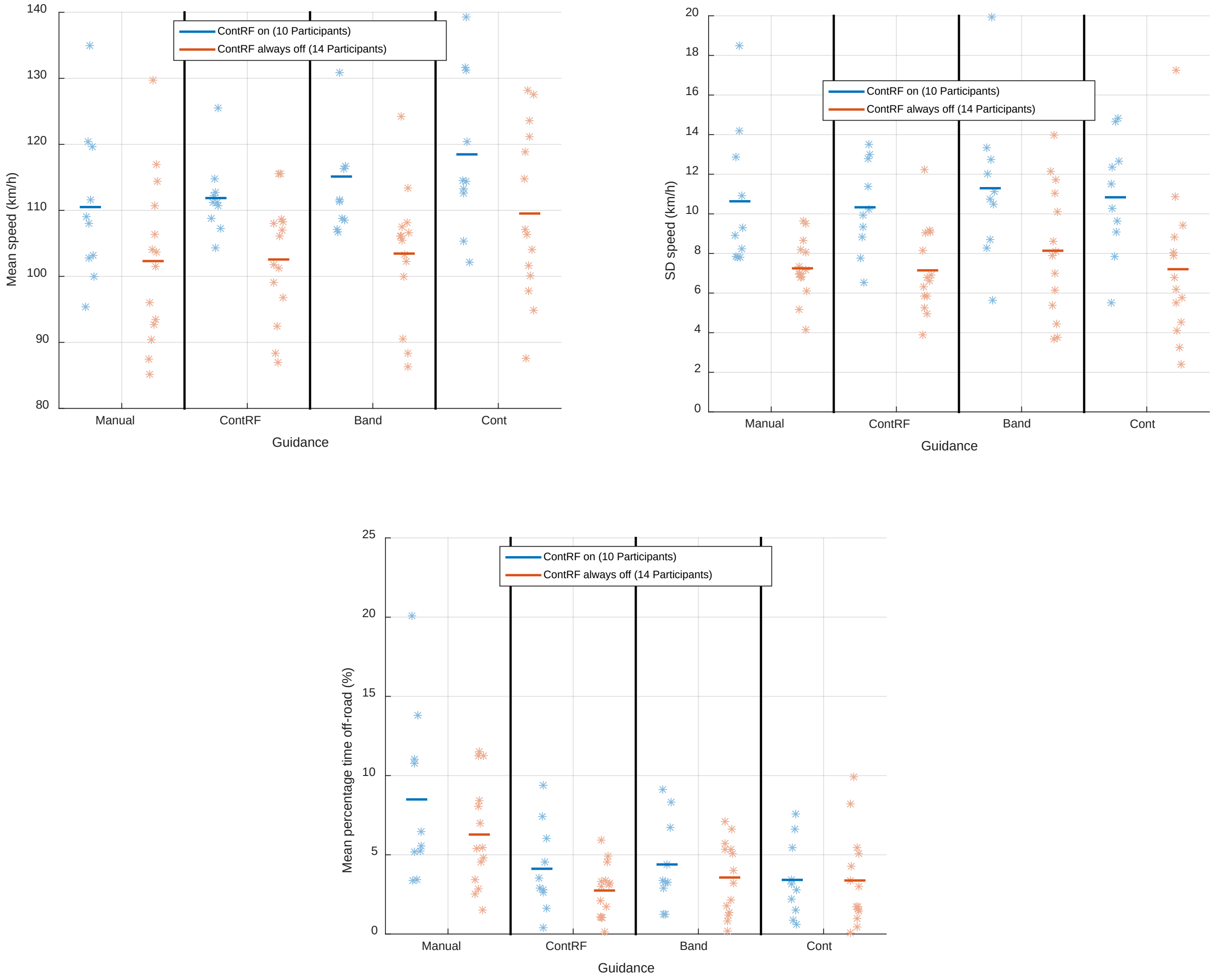


Figure 32: Comparison between individual participants who encountered the ContRF workings principle (e.g. drove faster than the speed 1 threshold (125 km/h) during the ContRF condition at any time) (blue stars) or always drove below the threshold (red stars). Left top: mean speed of individual participants (stars) and mean speed across all participants (horizontal line) per condition. Right top: mean percentage time off-road (TOR) of individual participants (stars) and mean TOR across all participants (horizontal line) per condition. Bottom: mean std speed of individual participants (stars) and mean std speed across all participants (horizontal line) per condition.

Sharp curve analysis

Average driving behavior curve and long straight segment

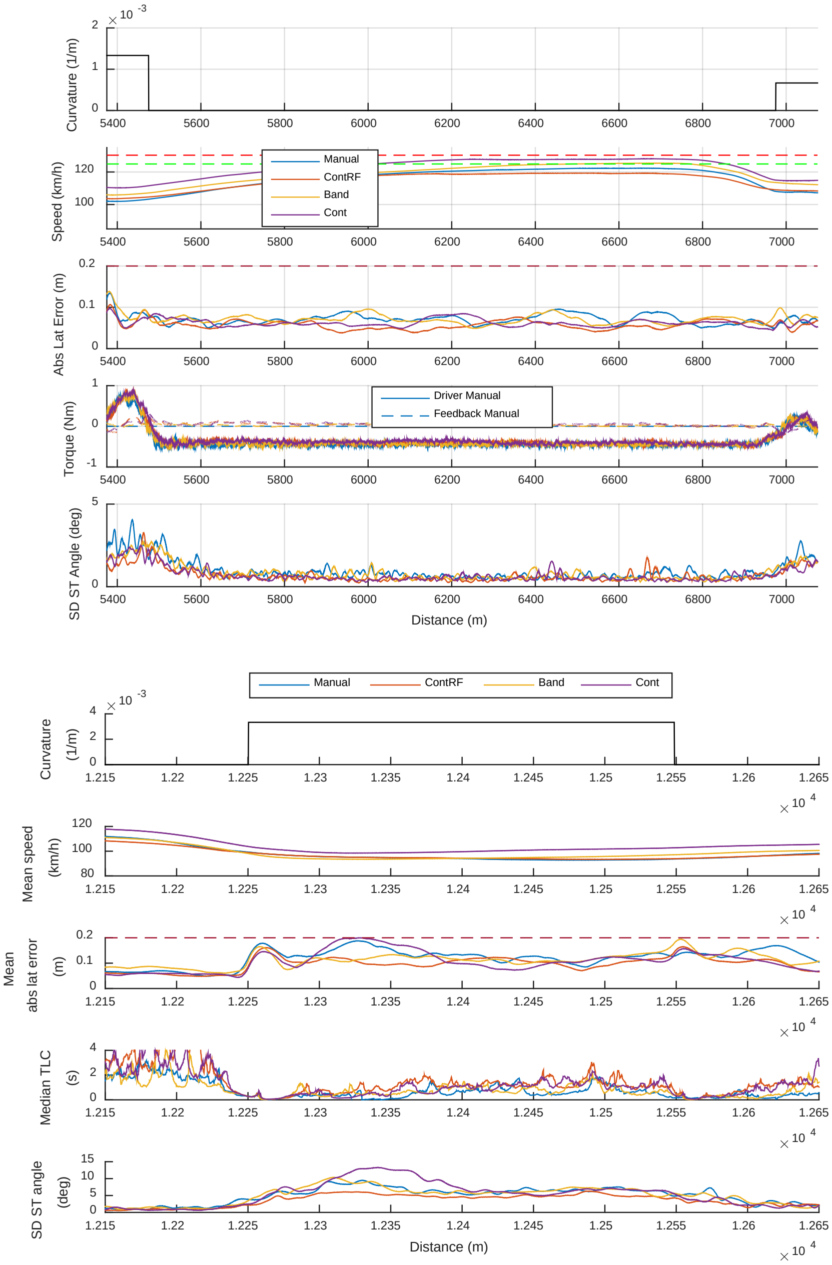


Figure 33: Average driving behavior in the sharp curve (left) and at the long straight section (right). The figures show respectively from top to bottom: Curvature, Speed, absolute lateral error, Torque, SD steering angle.

Raw speed and absolute lateral error in sharp curve

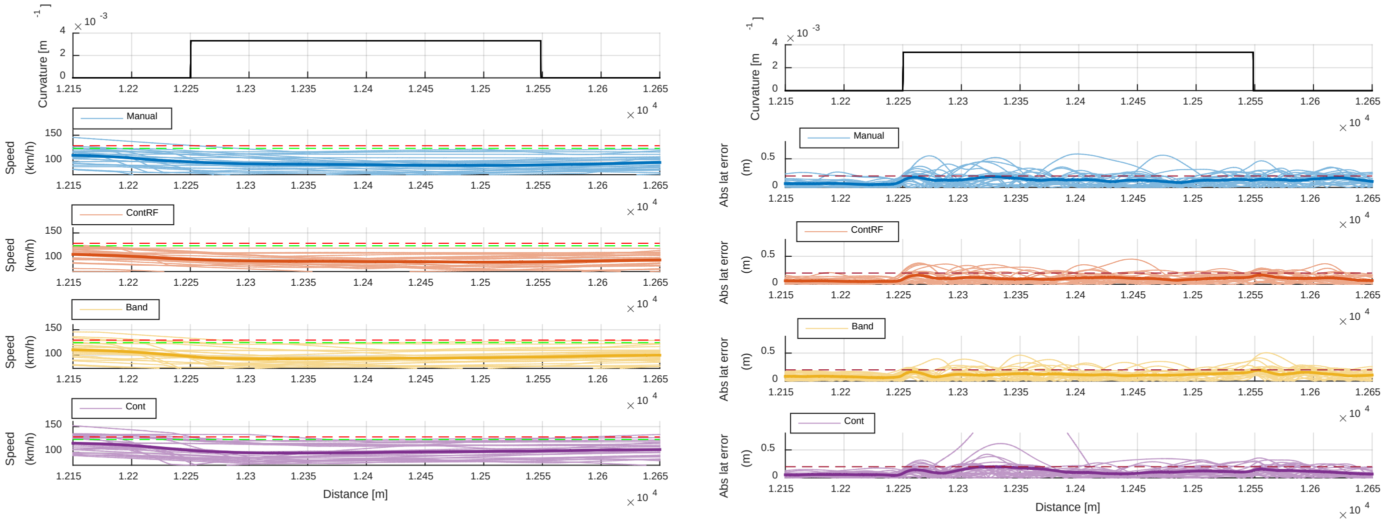


Figure 34: Raw data (light colored lines) and mean absolute lateral error (right) and speed (left) for all participants per condition. Figure contain from top to bottom: curvature, manual, ContRF, Band, Cont.

Raw speed and absolute lateral error at long straight section

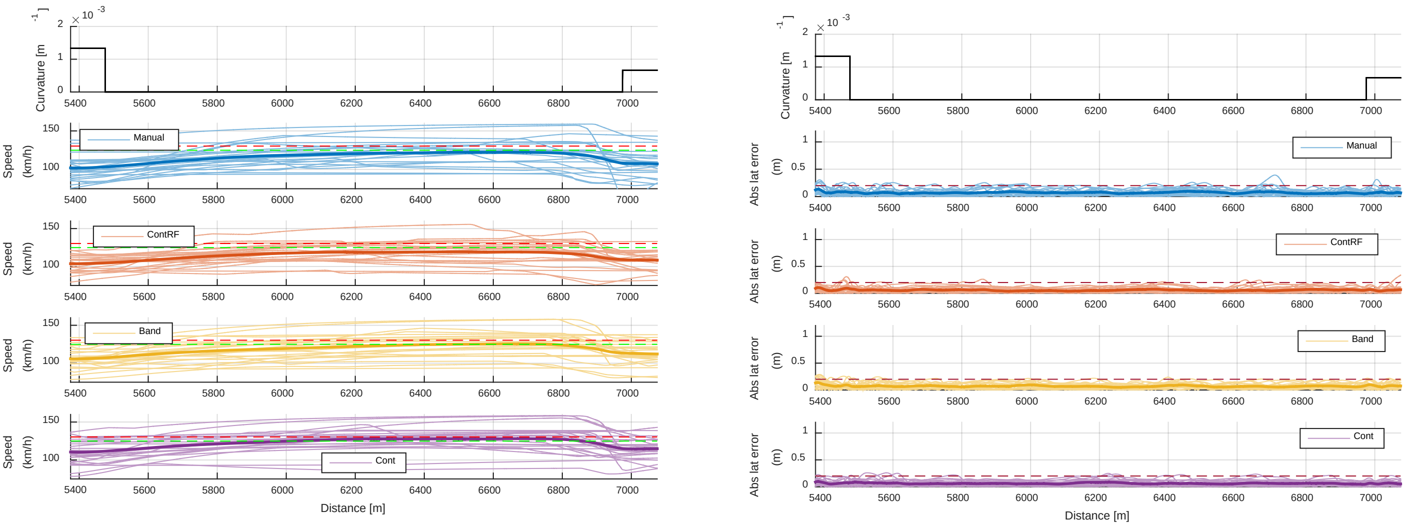


Figure 35: Raw data (light colored lines) and mean absolute lateral error (left) and velocity (right) for all participants per condition. Figure contain from top to bottom: curvature, manual, ContRF, Band, Cont.

Mean and standard deviation plots for the sharp curve

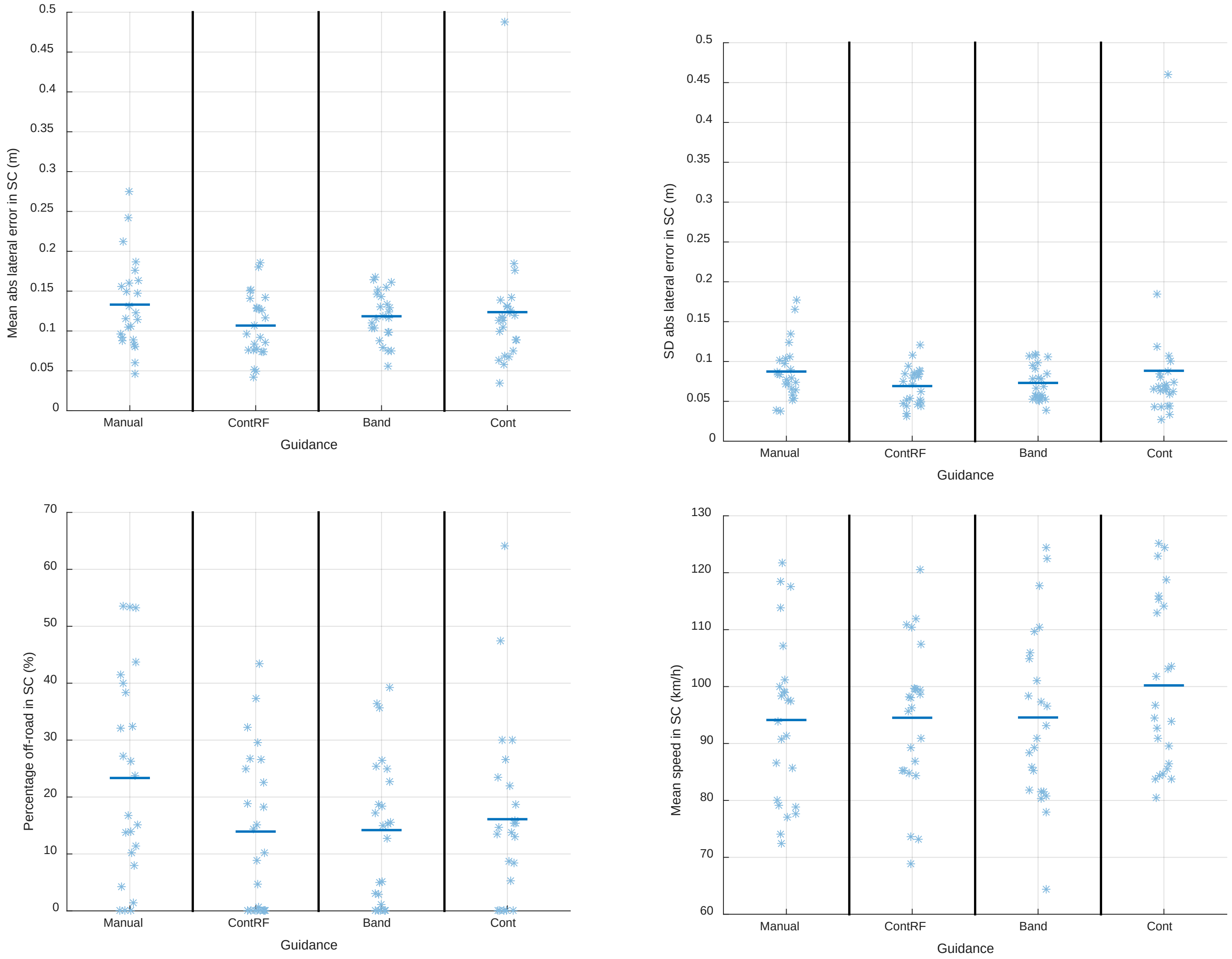
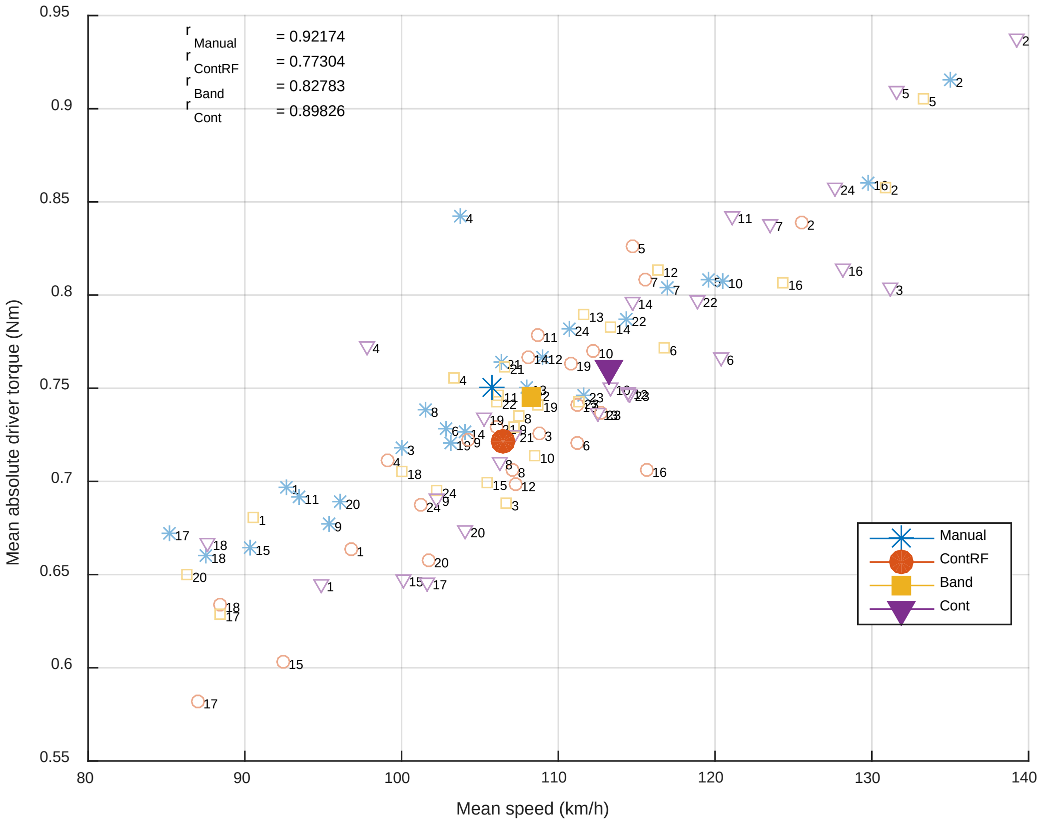


Figure 36: Left top: Mean absolute lateral error of individual participants (stars) and mean absolute lateral error across all participants (horizontal line) per condition. Right top: STD absolute lateral error of individual participants (stars) and mean STD absolute lateral error across all participants (horizontal line) per condition. Left bottom: Mean percentage off-road of individual participants (stars) and mean across all participants (horizontal line) per condition. Right top: mean speed of individual participants (stars) and mean speed across all participants (horizontal line) per condition.

Speed dependency plots

Drivers adapt different velocities during the experiment. Some metrics are highly speed dependent and need to be verified in order to allow intra participant comparison. For instance, applied driver torque (figure below) is very strong correlated to the velocity. Therefore it is hard to proof whether differences in driver torque are caused by the guidance conditions or by the adopted velocity. The Spearman correlation matrices can be found in one of the appendices.



Learning effect

Slight speeding effect could be found for the condition order. For the time off-road no performance benefits are observed for the conditions performed at higher orders (See table 1).

Table 3: Mean speed and percentage time off-road of all participants per condition order. All orders contain 6 trials of each condition.

	Order 1	**Order 2**	**Order 3**	**Order 4**
Mean speed (km/h)	107.8338	107.5694	108.9197	109.4458
STD speed (km/h)	10.96577	11.77986	11.76284	13.25812
Mean Time Off-Road (%)	4.251364	4.640858	4.128883	4.824589
STD Time Off-Road (%)	3.086738	2.789	3.093162	4.563814

Lateral accelerations

The peak lateral acceleration need to stay below 3.5m/s^2 such that the bicycle model, used in the simulator, is valid.

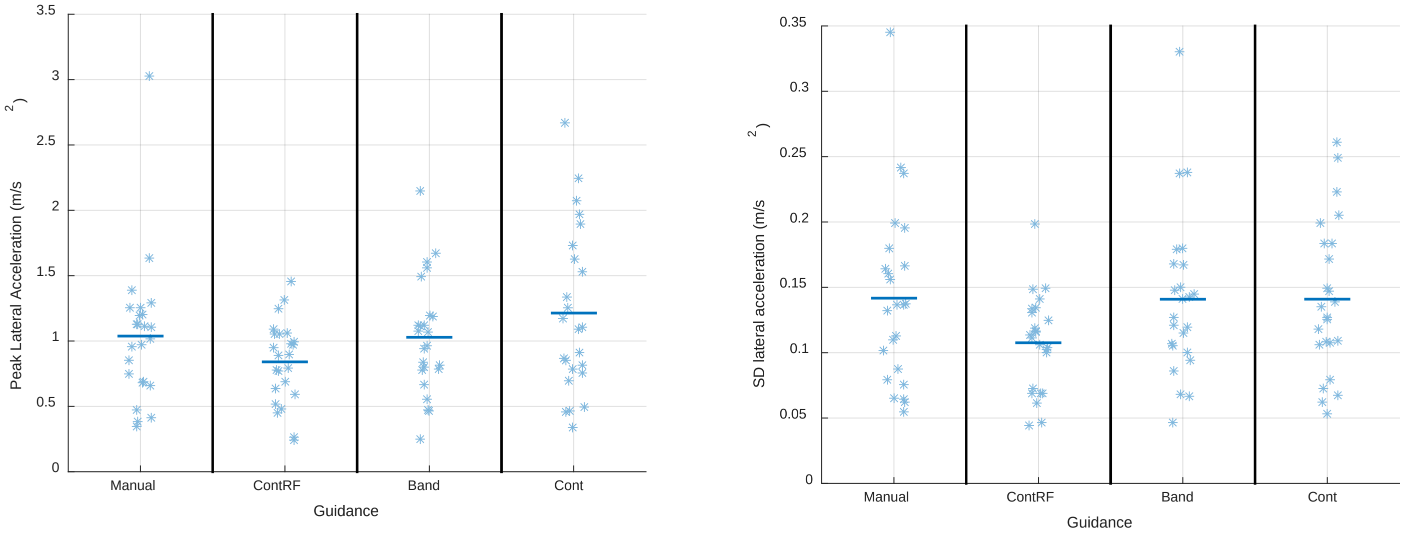


Figure 37: Left figure: Peak lateral acceleration of individual participants (stars) and mean peak acceleration across all participants (horizontal line) per condition. The peak lateral acceleration should be less than 4.5 m/s² such that the car model used in this experiment is valid. Right figure: STD lateral acceleration of individual participants (stars) and mean STD lateral acceleration of all participants (horizontal line) per condition.

G

Behavioral Adaptation Pilot

Prior to the real experiment, three pilots were conducted with 2 participants in each pilot (so 6 participants for the 3 pilots). The first pilot was used to investigate whether participants driving with continuous guidance were able to drive faster if this was explicitly instructed. The second pilot probes whether drivers will adopt a different speed when driving with continuous guidance even if this was not explicitly instructed. The last pilot was used to determine the ContRF speed threshold value.

Pilot 1: drive as fast as possible.

The aim of this pilot was to investigated whether people driving with continuous guidance were able to drive faster if this was explicitly instructed.

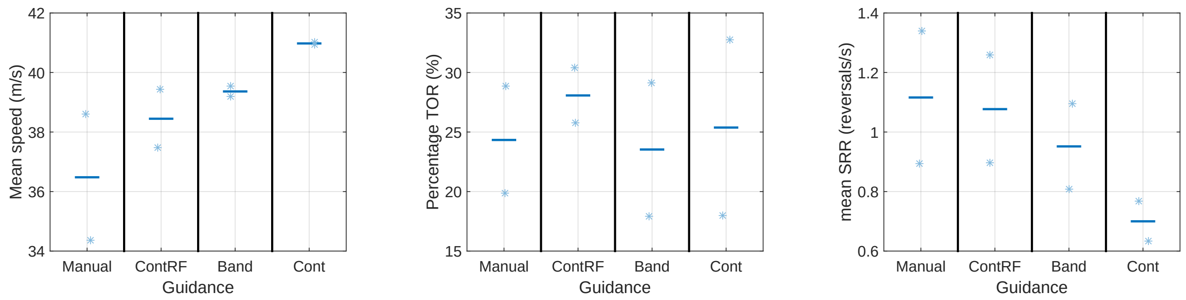
Participants and apparatus. Two participants (both male) age 23 and 24 with normal or corrected-to-normal vision, and at least 5 years licensed volunteered to drive for a driving simulator experiment. The same driving simulator and set-up was used as described in the apparatus section of the paper.

Environmental design. All participants drove each trial on the same narrow single-lane-road (2.2 m wide and 13.9 km long), assisted by one of the four controllers. The Manual, Band, and Cont are identical to the systems described in the method section of the paper, ContRF speed threshold was set at 36.1 m/s (130 km/h), and the guidance is fully off above 37.4 m/s (135 km/h). The entire trajectory contained three curves with an inner radius of 1100 m, 600 m, 350 m. Please note that in the real experiment slightly milder curves were used.

Experimental design. Prior to the experiment participants read and signed an informed consent form, explaining the purpose, instructions and procedure of the study (same consent form as shown in appendix B, but with a different task instruction). Participants were informed about the availability of each steering guidance and to keep both hands on the steering wheel in a ten-to-two position at all time. Participants were instructed: '*during the entire track you are requested to drive as fast as possible but try to avoid hitting cones*'. Prior to each trial, a training run of approximately six minutes was performed to become familiar with the guidance system.

Results, discussion, and conclusion. Figure G.1 shows the pilot results in terms of the mean speed (m/s), percentage Time Off-Road (TOR) (%), and Steering Reversal Rate (SRR) (reversals/s) (i.e., to indicate workload). Due to the low sample size (n=2) no statistical test was conducted. The results suggest that compared to manual, participants driving with Cont *can* drive faster while having similar lane-keeping performance, and a lower workload (i.e., lower SRR). For ContRF these lane-keeping benefits are diminished since drivers were driving faster than the ContRF threshold (36.1 m/s), and thus effectively driving manual but with a higher speed. When driving with Band, it seems that participants can drive slightly faster compared to manual while not compromising the TOR, and a lower workload.

These results suggest that drivers driving with continuous guidance *can* drive faster, without compromising the lane-keeping performance. With ContRF drivers cannot drive faster than manual, unless giving in on the lane-keeping performance, and thus no speeding effect is expected for ContRF. Whether participants will also speed up when this is not explicitly instructed is still unknown, and was investigated in pilot 2.



(a) Mean speed (m/s) of individual participants (asterisks) and mean across both participants (horizontal line) per condition.

(b) Mean TOR (m/s) of individual participants (asterisks) and mean across both participants (horizontal line) per condition.

(c) Mean SRR (reversals/s) of individual participants (asterisks) and mean across both participants (horizontal line) per condition.

Figure G.1: Results of the pilot with the instructions: *during the entire track you are requested to drive as fast as possible but try to avoid hitting cones*

Pilot 2: drive as you normally would without hitting cones

The aim of this pilot was to investigated how drivers would behave if they were *not* explicitly instructed to drive fast.

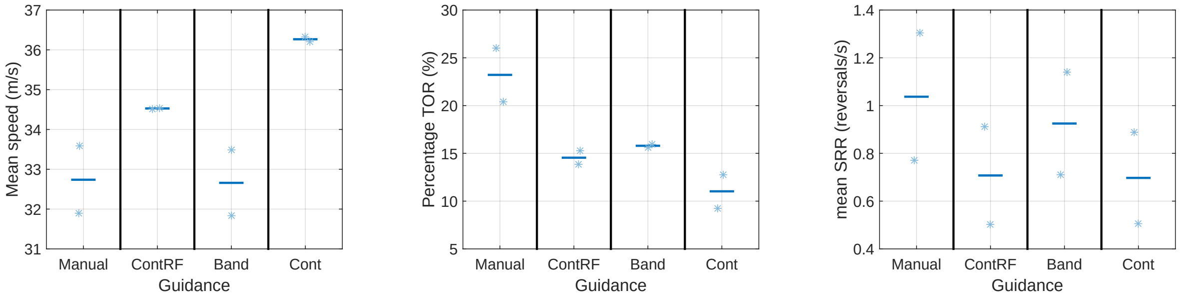
Participants and apparatus. Two participants (both male) age 23 and 20 with normal or corrected-to-normal vision, volunteered to drive for a driving simulator experiment. The same driving simulator and set-up was used as described in the apparatus section of the paper.

Environmental design. All participants drove each trial on the same narrow single-lane-road (2.2 m wide and 13.9 km long), assisted by one of the four controllers. The Manual, Band, and Cont are identical to the systems described in the method section of the paper, ContRF speed threshold was set at 36.1 m/s (130 km/h), and the guidance is fully off above 37.4 m/s (135 km/h). The entire trajectory contained three curves with an inner radius of 1100 m, 600 m, 350 m. Please note that in the real experiment slightly milder curves were used.

Experimental design. Prior to the experiment participants read and signed an informed consent form, explaining the purpose, instructions and procedure of the study (same consent form as shown in appendix B). Participants were informed about the availability of each steering guidance and to keep both hands on the steering wheel in a ten-to-two position at all time. Participants were instructed: '*During the entire track you are requested to drive as you normally would do, and try to minimize the number of cone hits*'. Prior to each trial, a training run of approximately six minutes was performed to familiarize the driver with the guidance system.

Results, discussion, and conclusion. Figure G.2 shows the pilot results in terms of the mean speed (m/s), percentage Time Off-Road (TOR) (%), and Steering Reversal Rate (SRR) (reversals/s) (i.e., to indicate workload). Due to the low sample size (n=2) no statistical test was conducted. The results suggest that all guidance systems have beneficial effect on the lane keeping performance (i.e., lower TOR) compared to the manual condition. When driving with Cont and ContRF drivers adopt a higher speed while having a lower workload than Manual and Band.

These results suggest that speeding effects can be expected for driving with continuous even without explicit speed instructions. In addition, Band seems successfully prevented speed adaptations, while having a lower TOR. ContRF seems to suffer from a minor speed adaptation, which is probably caused by a too high chosen speed threshold (i.e., 36.1 m/s far above the average manual speed of 33.3 m/s). To determine a more suited ContRF speed threshold, a third pilot was conducted.



(a) Mean speed (m/s) of individual participants (asterisks) and mean across both participants (horizontal line) per condition.

(b) Mean TOR (m/s) of individual participants (asterisks) and mean across both participants (horizontal line) per condition.

(c) Mean SRR (reversals/s) of individual participants (asterisks) and mean across both participants (horizontal line) per condition.

Figure G.2: Results of the pilot with the instructions: *during the entire track you are requested to drive as you normally would do, and try to minimize the number of cone hits*

ContRF speed threshold

The aim of this pilot is to determine the ContRF speed threshold. In order to obtain many haptic interactions with the guidance and the driver it was decided to place the ContRF threshold on the mean manual speed driven in this pilot.

Participants and apparatus. Two participants (both male, and age 23) with normal or corrected-to-normal vision, and at least 5 years licensed to driver volunteered in a driving simulator experiment. The same driving simulator and set-up was used as described in the apparatus section of the paper.

Environmental design. All participants drove each trial on the same narrow single-lane-road (2.2 m wide and 13.9 km long), assisted by the continuous guidance (Cont) or Manual. The training and real trial trajectory was identical to the one described in the paper.

Experimental design. Prior to the experiment participants read and signed an informed consent form, explaining the purpose, instructions and procedure of the study (same consent form as shown in appendix B). Participants were informed about the availability of each steering guidance and to keep both hands on the steering wheel in a ten-to-two position at all time. Participants were instructed: '*During the entire track you are requested to drive as you normally would do, and try to minimize the number of cone hits*'. Prior to condition, a training run of approximately six minutes was performed to familiarize with each condition.

Results, discussion, and conclusion. Figure G.3 shows the cumulative speed distribution function for both Manual and Cont. The average speed for Manual was approximately 125 km/h and for continuous guidance approximately 135 km/h. Based on these results it was decided to use a the average manual speed (125 km/h) for the lower ContRF threshold.

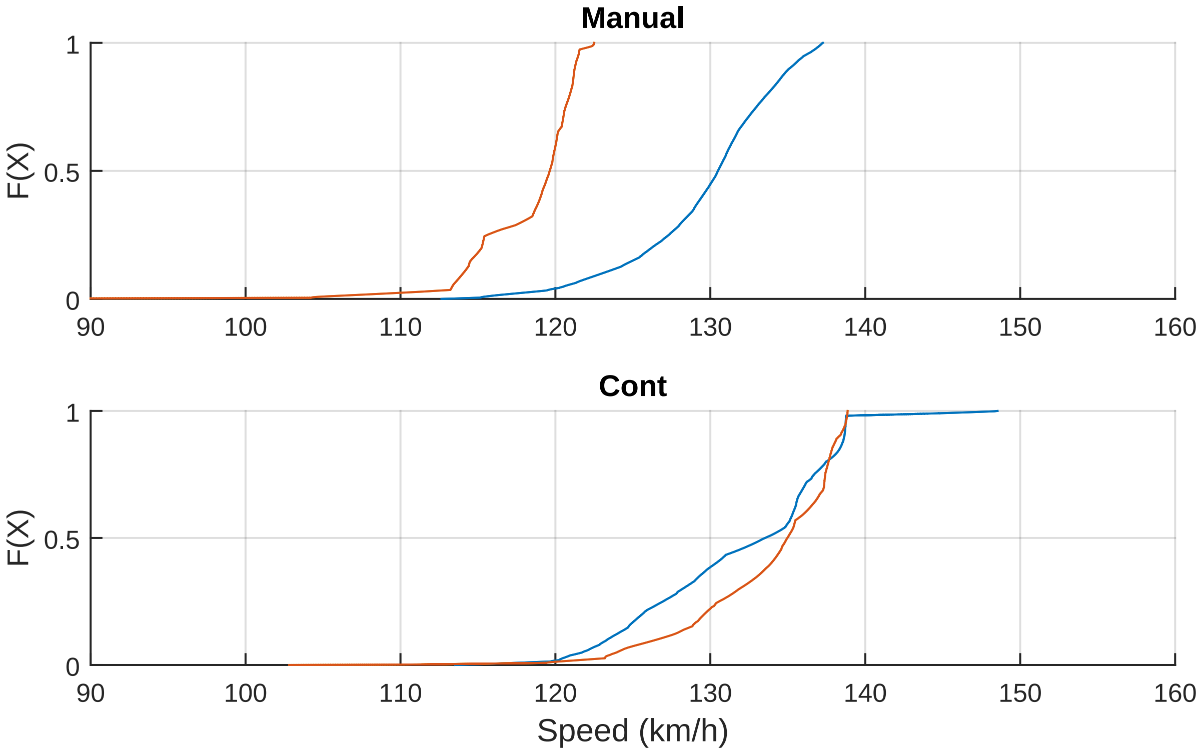


Figure G.3: Cumulative speed distribution function for two participants driving with Cont and Manual.