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

Melman, Timo; de Winter, Joost; Abbink, David

DOI
10.1016/j.aap.2016.10.016

Publication date
2017

Document Version
Final published version

Published in
Accident Analysis & Prevention

Citation (APA)
Melman, T., de Winter, J., & Abbink, D. (2017). Does haptic steering guidance instigate speeding? A driving simulator study into causes and remedies. *Accident Analysis & Prevention*, *98*, 372–387. https://doi.org/10.1016/j.aap.2016.10.016

Accident Analysis and Prevention 98 (2017) 372–387

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

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

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

Department of BioMechanical Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, the Netherlands

ARTICLE INFO

Article history:
Received 22 May 2016
Received in revised form
17 September 2016
Accepted 13 October 2016

Keywords:
Behavioral adaptation
Haptic steering guidance
Human-automation interaction
Driving simulator

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, experiments on haptic steering guidance have measured driver performance while the vehicle speed was kept constant. 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 lateral bandwidth (Band). Participants were familiarized with each condition prior to the experimental runs and were instructed to drive as they normally would 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.

1. Introduction

Advanced Driver Assistance Systems (ADAS) support drivers in tasks 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 have indeed shown such benefits (Bengler et al., 2014; Piao and McDonald, 2008). In reality, however, the anticipated safety benefits are often diminished because drivers show behavioral adaptation (BA), such as driving with a higher speed, driving closer to a lead vehicle, performing distractive non-driving tasks, or driving longer trips as compared to driving without ADAS (Elvik, 2013; Hiraoka et al., 2010; Martens and Jenssen, 2012; Mehler et al., 2014; OECD, 1990; Saad, 2006).

The ability to adapt is intrinsic to humans, and although adaptation can have positive effects in certain circumstances (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 taxis equipped with an Anti-lock Braking System (ABS), compared to taxis without ABS. Their results suggest that the taxi drivers exploited the fact that ABS reduces the braking distance by driving closer to the vehicle in front. Such BA with negative consequences has been implicated in many types of ADAS including not only ABS, but also adaptive cruise control (Panou et al., 2007), lane departure warning systems (Rudin-Brown and Noy, 2002), and collision avoidance systems (Janssen and 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

* Corresponding author.
E-mail address: j.c.f.dewinter@tudelft.nl (J.C.F. de Winter).

http://dx.doi.org/10.1016/j.aap.2016.10.016
0001-4575/

and Summala, 1974; Wilde, 2013, 1998), task difficulty (Fuller, 2005), or time/safety margins (Gibson and Crooks, 1938; Van Winsum et al., 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., when adding road lighting; Assum et al., 1999) or increased assistance in the car driving task (e.g., when using adaptive cruise control; Dragutinovic et al., 2005).

The magnitude of the BA effect is thought to depend on 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 et al., 2012; Saad et al., 2004; Sullivan et al., 2016). One supposedly important predictor of BA is the 'noticeability' of the ADAS: 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 et al., 2004a,b). That is, if drivers are more aware that ADAS interferes with their driving task, 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 for 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 that 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 interface as a medium of cooperation between the driver and an intelligent vehicle, with the aim to keep the driver informed and involved in the driving task, and to prevent 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, see Petermeijer et al., 2015b for a review). Concretely, haptic steering guidance continuously assists drivers in the steering task by providing torques on the steering wheel based on the target steering behavior of an automated controller. The driver may 'relax' his muscles and conform to the applied torque, or may steer against it. Thus, the human and the machine are jointly steering the car, and the degree of support can vary along a continuous scale from driver-in-control (i.e., the driver has a firm grip on the steering wheel and overrides the applied torques) to machine-in-control (i.e., the driver has a very light grip on the steering wheel). Previous research has shown beneficial effects in terms of improved lane-keeping performance, increased safety margins, and reduced self-reported workload for driving with steering guidance as compared to unsupported driving (Mars et al., 2014b; Mulder et al., 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. A driving simulator study by Petermeijer et al. (2015a) found that drivers showed dangerous steering oscillations, also called 'aftereffects', after the steering guidance failed prior to entering a curve. 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 when the guidance system is active and functioning normally. The only study on this topic found no BA with continuous haptic steering guidance compared to manual driving (Mars et al., 2014b). The authors compared two groups of participants in a driving simulator; 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, this particular study may have lacked the statistical power to detect a difference in mean driving speed.

The aim of the present research was twofold. As indicated above, haptic steering guidance is a noticeable type of ADAS and may therefore be highly susceptible to BA. Our first aim was to test the hypothesis that haptic steering guidance causes BA operationalized as driving speed. Driving speed is a prime measure of BA with strong implications for road safety (Elvik, 2013): An increase of speed reduces a driver's time to respond in an emergency scenario, increases the probability of being involved in a crash, increases the driver's severity of injury if a crash occurs, and increases the severity of injury of (vulnerable) road users that are hit by the driver (Aarts and Van Schagen, 2006; Elvik et al., 2004a,b; 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 system 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. These fundamentally different systems were both 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 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 appear only after a learning period that allows drivers to develop a mental model of the system (Beggiato et al., 2015; Bianchi Piccinini et al., 2014; Martens and Jenssen, 2012; Saad, 2006; 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 cone hits. 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 dots) 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 (see Zhai et al., 2004 for a speed-accuracy trade-off in lane keeping). 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.

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 manually without support. Furthermore, a lateral and longitudinal alternative steering guidance were tested. Both designs were

Fig. 1. Simulator environment including the car front and cone hit warning (i.e., red dot). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 of 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). In an attempt to measure participants' familiarity with automated driving systems, we asked them whether they had ever heard of the Google Driverless Car. The majority of participants (21 of 24, or 88%) indicated 'yes' to this question, which is higher than a previously measured global average of 52% obtained via an international Internet survey (Kyriakidis et al., 2015).

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 ECol8000S 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, which 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 and Mulder, 2009; Mulder et al., 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 Eq. 1.

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

The feedback gains were identical to Mulder et al. (2008), with the force feedback gain (K_f) = 2.0, the proportional gain (P) = 0.08, and the derivative gain (D) = 0.9.

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 Eq. 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.

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

2.3.3. Bandwidth guidance (Band)

The bandwidth guidance was 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 Eqs. 3 and 4.

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

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

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

	Manual (1)	ContRF (2)	Band (3)	Cont (4)		Pairwise comparisons					
						1–2	1–3	1–4	2–3	2–4	3–4
	M (SD)	M (SD)	M (SD)	M (SD)	p value $F(3,69)$	p (d_z)	p (d_z)	p (d_z)	p (d_z)	p (d_z)	p (d_z)
Speed											
Mean speed (km/h)	105.7 (12.7)	106.4 (9.0)	108.3 (11.3)	113.3 (13.1)	$p = 0.001$ $F = 5.96$	(0.22)	(0.31)	xx (0.74)	(0.19)	x (0.71)	(0.43)
Percentage of time above 125 km/h (%)	9.8 (22.2)	5.3 (10.6)	13.4 (24.2)	23.8 (31.6)	$p = 6.57 \times 10^{-4}$ $F = 6.44$	(0.20)	(0.28)	x (0.72)	(0.43)	xx (0.76)	(0.38)
Lane-keeping performance											
Percentage time off-road (%)	7.21 (4.36)	3.32 (2.24)	3.92 (2.49)	3.40 (2.67)	$p = 2.51 \times 10^{-10}$ $F = 22.68$	xxx (1.58)	xxx (1.07)	xxx (1.36)	(0.37)	(0.00)	(0.32)
Mean absolute lateral error (m)	0.087 (0.014)	0.074 (0.010)	0.086 (0.011)	0.074 (0.012)	$p = 1.08 \times 10^{-11}$ $F = 27.10$	xxx (1.47)	(0.01)	xxx (1.13)	xxx (1.33)	(0.06)	xxx (1.31)
Maximum absolute lateral error (m)	0.47 (0.15)	0.33 (0.06)	0.37 (0.14)	0.38 (0.24)	$p = 2.17 \times 10^{-7}$ $F = 14.42$	xxx (1.32)	xx (0.75)	xxx (1.22)	(0.35)	(0.04)	(0.24)
Mean lane return time (s)	3.19 (1.64)	2.03 (1.16)	2.00 (1.07)	1.72 (0.73)	$p = 4.41 \times 10^{-6}$ $F = 11.22$	xx (0.85)	x (0.70)	xxx (1.35)	(0.02)	(0.28)	(0.22)
Workload											
Mean absolute feedback torque (Nm)		0.19 (0.03)	0.06 (0.03)	0.21 (0.04)	$p = 1.95 \times 10^{-22}$ $F = 179.15$				xxx (3.38)	x (0.60)	xxx (3.90)
Steering reversal rate (Hz)	0.73 (0.23)	0.49 (0.17)	0.64 (0.17)	0.51 (0.17)	$p = 6.04 \times 10^{-14}$ $F = 35.31$	xxx (2.09)	(0.57)	xxx (1.58)	xxx (1.45)	(0.17)	xx (0.83)
NASA-TLX (%)	47.78 (12.12)	33.26 (11.70)	42.19 (16.07)	32.81 (13.19)	$p = 2.64 \times 10^{-6}$ $F = 11.74$	xxx (1.22)	(0.42)	xx (0.86)	(0.58)	(0.00)	(0.50)
Mean absolute driver torque (Nm)	0.75 (0.07)	0.72 (0.06)	0.75 (0.06)	0.76 (0.08)	$p = 0.047$ $F = 2.78$	(0.37)	(0.06)	(0.16)	(0.37)	x (0.61)	(0.20)
System acceptance											
Satisfaction scale (−2,2)		0.88 (0.52)	0.52 (0.69)	0.79 (0.73)	$p = 0.076$ $F = 2.72$				(0.45)	(0.10)	(0.31)
Usefulness scale (−2,2)		0.98 (0.35)	0.83 (0.44)	0.92 (0.50)	$p = 0.410$ $F = 0.92$				(0.23)	(0.12)	(0.17)

x: $p < 0.05$, xx: $p < 0.01$, xxx: $p < 0.001$.
Note: $F(2,46)$ for the mean absolute feedback torque, satisfaction scale, and usefulness scale.

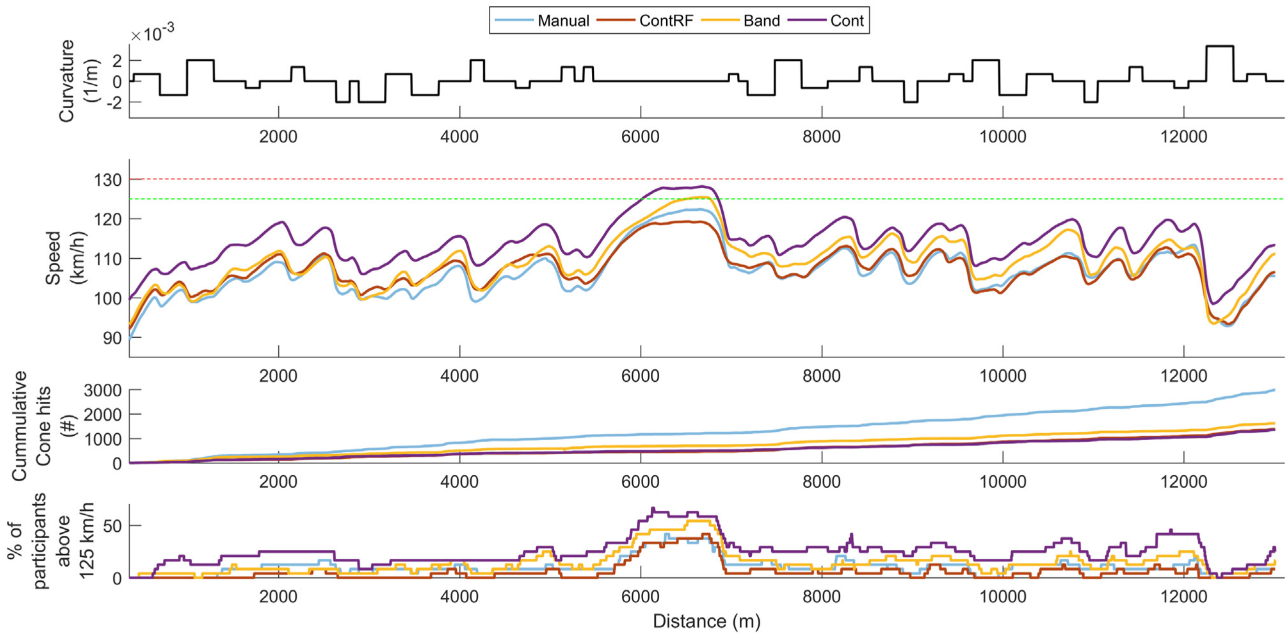

Fig. 2. From top to bottom: First: curvature (1/curve radius) of the trajectory. Second: mean speed across all participants per condition. The horizontal dashed lines indicate the speed thresholds of the ContRF condition. Third: cumulative number of cone hits for all participants combined per condition. Cones were 8 m apart. The cone hit results for the Cont and ContRF conditions are overlapping. Fourth: the percentage of participants who drove faster than 125 km/h per condition.

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), driving in one of the four conditions (Manual, ContRF, Band, or Cont). The road width of 2.2 m and car width of 1.8 m allowed 0.2 m 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 1500 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 (10.5 km) of the road in the subsequent experimental trials. Speed perception was enhanced by means of trees alongside the road. Cones were placed along the entire road with a distance of 8 m between cones. A cone hit was visualized with a red dot on the side where the car hit a cone (Fig. 1). No on-road obstacles and no traffic were simulated.

2.5. Experimental design

The four conditions were presented in a counterbalanced within-subjects design. Prior to the experiment participants read and signed an informed consent form, explaining the purpose, instructions, and procedures of the study. 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 completed a questionnaire regarding their driving experience as well as a Driver Behaviour Questionnaire (DBQ) containing seven violation items (De Winter and Dodou, 2016). A previous meta-analysis indicated that the DBQ violations scale has a moderately strong relationship ($r = 0.24$) with recorded measures of speed and speeding (De Winter et al., 2015).

Prior to each trial, a training run of approximately six minutes was performed (i.e., fixed distance of 10.5 km). Six minutes was considered sufficient to become familiar with a guidance system (McGehee et al., 2004). To enhance the familiarization process, two actions were taken. First, the experimenter explained the working mechanism of each guidance system, 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, and for Band drivers were asked to let go of the steering wheel to observe that the guidance turns on just before hitting the cones.

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 and Staveland, 1988) to assess workload, an acceptance questionnaire (Van der Laan et al., 1997) to assess satisfaction and usefulness of the guidance, and a simulator sickness item. In the latter, participants needed to indicate whether they were feeling simulator sickness on a scale from 1 to 6 (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 nauseous, retching, 6 = vomiting). A response of 4 or higher would stop the experiment. The total

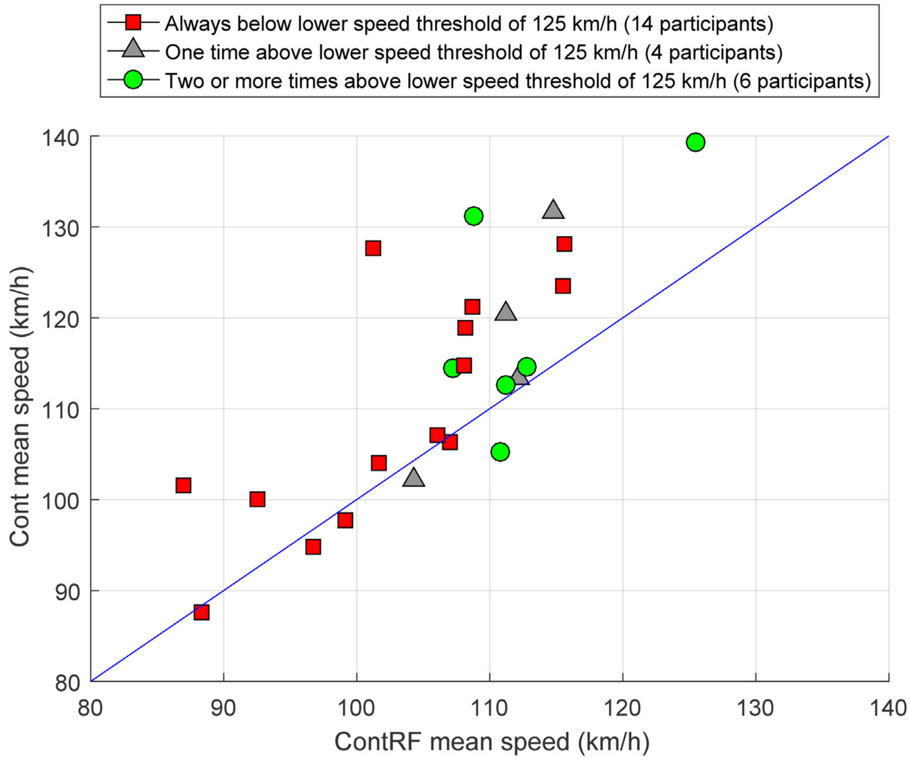

Fig. 3. The participants' mean driving speeds (km/h) for the ContRF condition compared to Cont condition. The blue line indicates equal speed for both conditions. The different markers designate the number of times a participant exceeded the 125 km/h speed threshold when driving with ContRF. 18 out of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

experiment, including filling out all questionnaires, took approximately 1.5 h 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.

Percentage of Time Above 125 km/h (%). The 125 km/h threshold corresponds to the lower speed threshold of the ContRF guidance.

2.6.2. Performance

Percentage Time Off-Road (%), 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 time off-road are measures of lane-keeping accuracy.

Mean Lane Return Time (s). This measure represents the time 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 moment of returning the car 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 and Staveland, 1988).

Steering Reversal Rate (reversals/s). The steering reversal rate was defined as the number of times that the steering wheel was reversed by a magnitude greater than 2 deg (McLean and Hoffmann, 1975). It 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. This measure can be considered an objective indicator of workload (Johansson et al., 2004).

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. Because TLC varies much during lane keeping, an additional fine-grained analysis was performed 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). These TLC bins were roughly based on previous studies which have assessed

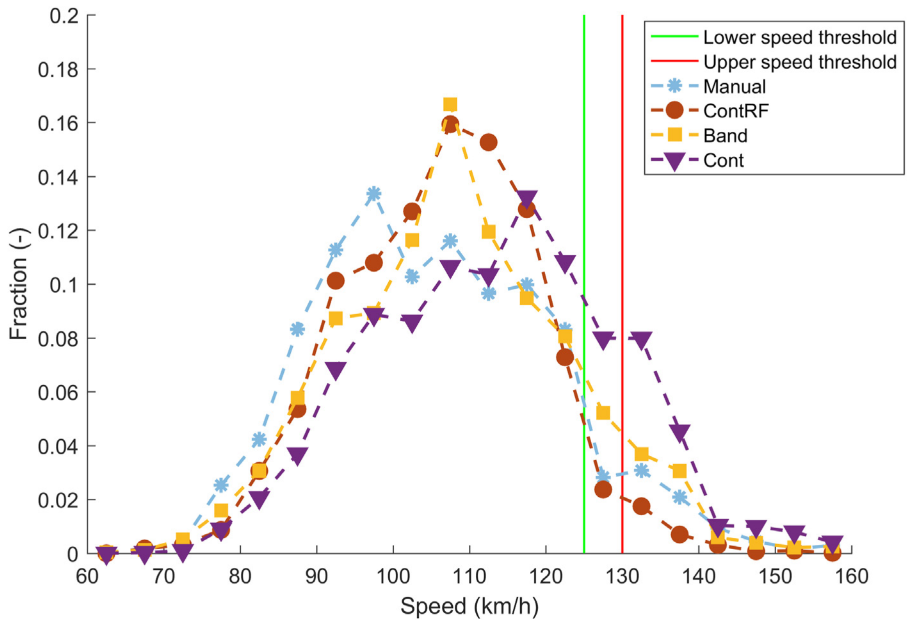

Fig. 4. Speed distribution (km/h) of all participants combined. The bin width is 5 km/h. The fraction is plotted in the middle of each bin. The red and green lines indicate the speed thresholds of ContRF. The sum of all fractions equals 1 for each condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

TLC or time-to-collision (TTC) in terms of subjective risk (Kondoh et al., 2006), criteria for driver impairment (Brookhuis et al., 2003), and self-chosen occlusion times (Godthelp et al., 1984).

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* was 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 × 4 numbers was obtained (24 participants and 4 conditions). This matrix was rank-transformed according to Conover and Iman (1981) to account for possible violations of the assumption of normality associated with parametric tests. 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. The d_z effect sizes for pairwise comparisons were calculated using Eq. 5 (Faul et al., 2007), where μ_{x-y} is the mean of the difference and σ_{x-y} is the standard deviation of the difference. Redundancies/associations between dependent measures were assessed by means of Spearman rank-order correlation coefficients.

$$d_z = \frac{|\mu_{x-y}|}{\sigma_{x-y}} \quad (5)$$

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. Participants' mean speeds were significantly different between the four conditions, $F(3,69) = 5.96$, $p = 0.001$. When supported by Cont, participants drove significantly faster (on average by 7 km/h, with medium effect sizes) compared to ContRF and Manual. 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). Fig. 2 shows the mean speed, cumulative number of cone hits, and percentage of participants exceeding the 125 km/h threshold as a function of travelled distance. It can be seen that participants in all four conditions drove faster on the long straight than on the other parts of the route. The difference in mean speeds between Cont and the three other conditions occurred both on straights and in curves (Fig. 2).

The average (*SD*) completion times of the 13.1 km trajectory were 440 s (52), 435 s (39), 428 s (45), and 411 s (48), for Manual, ContRF, Band, and Cont, respectively. Note that the mean speed and completion times show a perfect negative Spearman correlation ($\rho = -1$), and so the completion times were not subjected to statistical tests.

Participants in the ContRF condition drove slower than the 125 km/h threshold for on average 94.7% of the time, 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 (Fig. 3). Even though ContRF and Cont effectively were identical conditions for most of the driving time, the speed distribution between these two conditions was notably different (Fig. 4). Fig. 4 shows a drop for the ContRF just before the lower speed threshold, whereas for

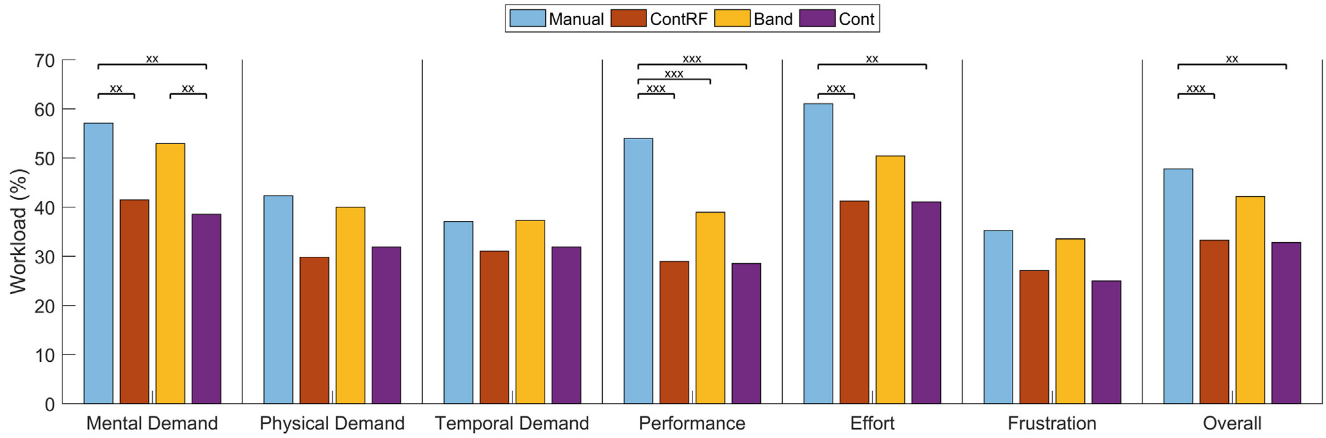

Fig. 5. Mean scores on the NASA-TLX. x: $p < 0.05$, xx: $p < 0.01$, xxx: $p < 0.001$.

the Cont condition, no such drop can be seen. Fig. 4 further shows that 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, an effect that is statistically significant with respect to the Manual and ContRF conditions (Table 1).

3.2. Performance

All three steering guidance conditions yielded strongly improved lane-keeping performance compared to the Manual condition, in terms of a lower time off-road, lower maximum absolute lateral error, and lower lane return time (Table 1; Fig. 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.

3.3. Workload

Table 1 shows that the self-reported workload (NASA-TLX score) and objective workload (steering reversal rate) were significantly higher for Manual than for Cont and ContRF. For each of the six NASA-TLX items, the Manual condition yielded higher workload scores than the Cont and ContRF conditions, with statistically significant effects for the Mental Demand, Performance, and Effort items (Fig. 5). Furthermore, the Band condition yielded significantly higher Mental Demand than the Cont condition.

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

Substantially 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 ($p = 0.071$). 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 conditions. 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

Table 1 shows a lower satisfaction score for Band than for ContRF and Cont, 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 curve of 135 km/h (rank 1/96) and 117 km/h (rank 12/96), respectively. Fig. 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) conditions compared to the ContRF (0.16 m) and Band (0.16 m) conditions.

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 driving speed moderately yet consistently influenced task performance, presumably due to a speed-accuracy trade-off (cf. Zhai et al., 2004). In the simulator sickness item, none of the participants responded 4 (*nauseous*) or higher, and thus everyone finished the experiment. Specifically, the number of responses being 1 (*not experiencing any nausea*), 2

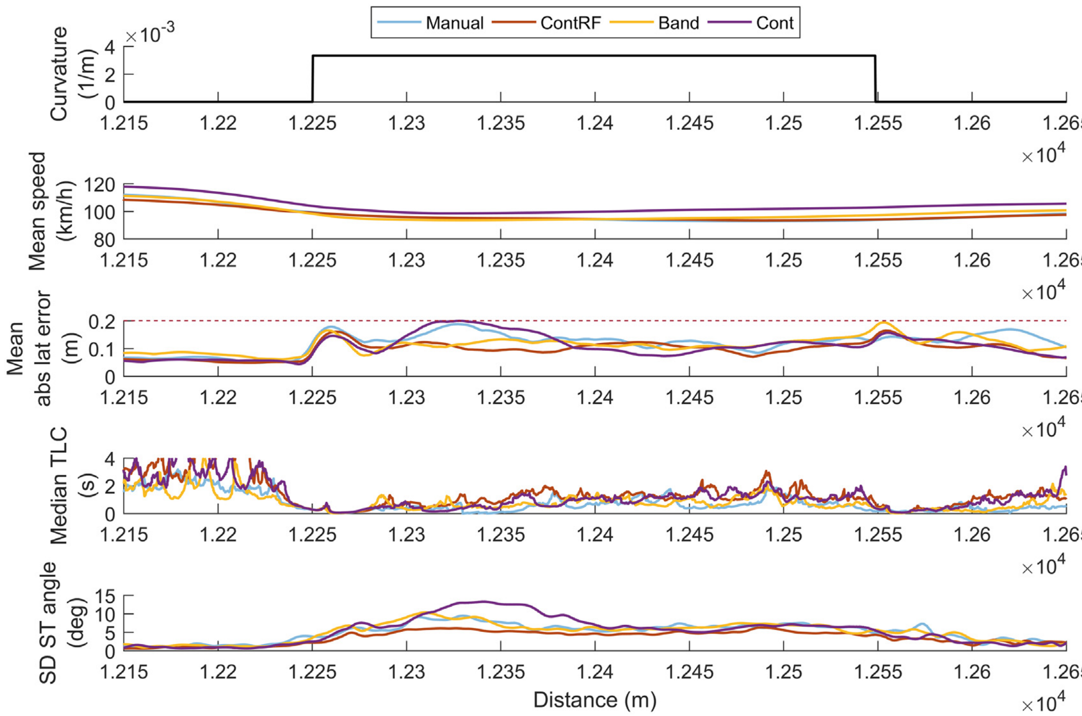

Fig. 6. Mean speed (km/h), mean absolute lateral error (m), median TLC (s), and standard deviation of the steering wheel angle (deg) among the participants as a function of traveled distance in the sharp curve. The top figure shows the curvature (i.e., 1/radius in meters).

(*arising symptoms*), and 3 (*slightly nauseous*) were 61, 27, and 8, respectively. 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). When averaging the speed across the four conditions, the DBQ-speed correlation was 0.24, which is in line with a previously published meta-analysis (De Winter et al., 2015) but not significantly different from zero (p = 0.262). 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 variations of haptic driver support that were designed to mitigate such speeding. To understand driving behavior better, we also assessed 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 drive faster, which diminishes the safety benefits of this assistive technology as compared to fixed-speed simulator studies. The results are in accordance with 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 and Nilsson, 1993).

The laterally adjusted (Band) and longitudinally adjusted (ContRF) guidance conditions that were designed to mitigate speeding were both successful in achieving this objective, 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 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, possibly 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 driving speed of 108.4 km/h, and 14 of the 24 participants never experienced the reduction of guidance during their trials (i.e., their speed was always below 125 km/h). The effectiveness 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 reduction in subjective risk because they had been instructed and trained that the benefits of this assistive system would disappear when driving fast.

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

Table 2
Means (M), standard deviations (SD), effect sizes (d_z), and results of the repeated measures ANOVA (F, p) for time to line crossing (TLC).

	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 p (d_z)	1–3 p (d_z)	1–4 p (d_z)	2–3 p (d_z)	2–4 p (d_z)	3–4 p (d_z)
Median TLC (s)	1.32 (0.48)	2.09 (0.67)	1.36 (0.46)	1.89 (0.65)	$p = 4.73 \times 10^{-17}$ $F = 48.86$	xxx (1.97)	(0.07)	xxx (1.56)	xxx (1.90)	(0.56)	xxx (1.33)
Percentage low safety margin ($0\,s < TLC \le 2\,s$) (%)	54.20 (6.59)	46.87 (7.01)	56.32 (6.78)	49.27 (7.57)	$p = 1.61 \times 10^{-13}$ $F = 33.67$	xxx (1.79)	(0.45)	xx (0.75)	xxx (2.06)	x (0.63)	xxx (1.10)
Percentage moderate safety margin ($2\,s < TLC \le 4\,s$) (%)	14.08 (2.68)	15.97 (1.47)	13.90 (2.26)	15.51 (1.75)	$p = 2.48 \times 10^{-7}$ $F = 14.24$	xx (0.83)	(0.23)	x (0.62)	xxx (1.20)	(0.31)	xxx (1.10)
Percentage high safety margin ($TLC > 4\,s$) (%)	24.51 (6.46)	33.84 (6.84)	25.86 (5.68)	31.82 (7.22)	$p = 2.07 \times 10^{-16}$ $F = 45.83$	xxx (2.46)	(0.23)	xxx (1.66)	xxx (1.80)	(0.52)	xxx (1.03)

x: $p < 0.05$, xx: $p < 0.01$, xxx: $p < 0.001$.
Note: The results for TLC = 0 are identical to the time off-road results in Table 1.

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.

At present, it is difficult to establish whether the effectiveness of ContRF is caused by conscious ('explicit') mechanisms or by unconscious ('implicit') mechanisms (cf. Evans, 2008). Regarding implicit mechanisms, it may be argued that the ContRF system gives physical feedback about the objective level of risk (speed) at a subcortical neuromuscular level (cf. Abbink et al., 2011). Loosely speaking, because participants received the haptic feedback directly on their hands, they may have reflexively and habitually responded to this feedback, without being consciously aware of this. Alternatively, participants may have been explicitly aware of the fact that the haptic feedback disappears when driving fast, either through the training they had received or through the fact that the disappearance of feedback is emotionally arousing and leaves a consciously accessible trace in memory. Future research should investigate which implicit or explicit mechanisms are underlying factors in BA prevention technologies. For example, to gain more insight into the explicit factors behind a behavioral change, a verbal protocol method could be used (Banks et al., 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 high (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 that reduces the guidance 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 both the continuous guidance and the bandwidth guidance was found to improve drivers' lane-keeping performance compared to manual driving (Flemisch et al., 2008; Kienle et al., 2012; Marchal-Crespo et al., 2010; Petermeijer et al., 2015a). More specifically, in our study, the Band condition yielded substantially improved time off-road compared to the Manual condition, but it did not improve the mean absolute lateral error. Furthermore, no statistically significant difference in overall self-reported workload was found between Manual and Band. These effects can be explained by the fact that 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 working principle of the Band system corresponds to marketed lane-keeping assistance systems (e.g., Daimler, 2013; Volvo Car Corporation, 2015), which also guide the driver away from lane boundaries rather than towards the lane center as the Cont system.

The fact that the Band system closely resembles manual driving for the majority of the driving time may be the reason that it prevents BA in the form of speeding and aftereffects when the system fails or disengages. The latter statement is in line with a previous field study conducted by Breyer et al. (2010), which did not find evidence of adverse aftereffects for a corrective steering system that was deactivated after a prolonged exposure to the system. Our bandwidth condition functioned similarly to Breyer et al.'s corrective steering system by supporting the driver when crossing a lane boundary, yet allowing the driver to sway within the lane boundaries. In summary, the satisficing approach (i.e., keeping the driver fully in charge when driving in the lane; see also Goodrich et al., 2000; Summala, 2007), as opposed to the 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 (Breyer et al., 2010; Petermeijer et al., 2015a). However, this occurs at the cost of an elevated workload and worse lane-centering performance compared to continuous guidance.

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 speed difference between a group of 12 participants driving with haptic steering guidance and another group of 12 participants driving manually. First, the focus of the Mars et al. study is different from ours: whereas Mars et al. measured how driving speed evolves with practice across twelve 4.3 km laps over two days, the present study investigated more immediate speed adaptations in 24.4 km of driving per condition (10.5 km training plus an experimental drive of 13.9 km). Second, although a between-subjects design is methodologically strong because it prevents carry-over effects between conditions, large individual differences in speed make it less likely to observe statistically significant effects in a between-subjects design as compared to a within-subject design. Third, 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 h 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 time off-road, 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 (Fig. 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. 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. This is in accordance with results by Navarro et al. (2010) and De Winter et al. (2008), who found that participants gave relatively low ratings of acceptance to a discontinuous haptic intervention on the steering wheel or gas pedal, respectively. Discontinuous haptic feedback may cause unwanted reflexes/overshoots, excessive wear of hardware, or timing problems associated with the balance between false alarms and missed detections (De Winter et al., 2008; Navarro et al., 2010). 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 13 min, 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 and Jenssen, 2012; Panou et al., 2007; see also Mars et al., 2014b who found that driving speed increased with the amount of experience). Considering 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 present participants, many of whom were recruited from the technical university community, may be more familiar with intelligent vehicle technology, and more likely to understand the working mechanisms of such technology, than the general public. This was exemplified by the fact that only 3 of 24 participants had not heard of the Google Driverless Car before, which is considerably lower than Kyriakidis et al. (2015) who reported that 48% of 4845 respondents in an international crowdsourced sample had not heard of the Google Driverless car. Thus, it remains to be investigated how our BA findings generalize to the general population, who may need a longer period to grow accustomed to haptic guidance technology. The correlations between the driving experience variables and the mean speed were 0.25 at maximum and so explained up to 6% of the variance, suggesting that the degree of BA of a driver is not easily predictable from a person's level of driving experience. At present, the relation between short- and long-term BA effects is unknown (De Winter and Dodou, 2011), and it is recommended to obtain a better understanding of this topic by means of longitudinal studies.

In our study, BA was operationalized as increased driving speed, and driving performance was quantified in terms of lane-keeping performance and safety margins, which are measures that are causally related to safety. We also measured workload, and found that Cont yielded lower scores on the Mental Demand item of NASA-TLX than Manual and Band. This may be because the latter two conditions required the driver to keep visually attentive, whereas the former provided continuous assistance on the steering wheel. Researchers have pointed out that reduced attentiveness itself should also be regarded as a manifestation of BA (e.g., Elvik, 2013). Indeed, it is possible that low mental workload associates with low attentiveness and complacency, poor performance in reclaiming manual control, and an inclination towards performing non-driving tasks behind the wheel (De Winter and Dodou, 2011; Young and Stanton, 2002). Future research, conducted across multiple days or months, should establish the optimal range of workload (see also De Waard, 1996). That is, on the one hand, it can be argued that a reduction of workload leaves mental spare capacity for scanning objects in the environment and for enhancing situation awareness (e.g., McDowell et al., 2008), whereas on the other hand the aforementioned mental underload is a risk factor too (Young and Stanton, 2002).

4.9. Driving simulators versus on-road driving

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 fact that our study featured a narrow road and real-time feedback on performance.

Participants in our study adopted high mean speeds of 110 km/h despite the fact that the road was narrow and contained various curves. The relatively high speed in a driving simulator may be explained by the fact there were no road users sharing the road with the participant, as well as by incorrect speed perception and low perceived risk when driving in a simulator (De Winter et al., 2012; Wallis et al., 2007). Drivers in a simulator do not experience a real risk of crashing, which is a downside of using a driving simulator as opposed to a real car, especially because subjective risk is considered to be an important determinant of BA (Näätänen and Summala, 1974; Wilde, 1998).

Nevertheless, simulators offer important advantages compared to tests in real cars. For example, it would be technically, legally, and ethically challenging to expose participants to a sharp curve on a real road in a controlled manner. Regarding ethical and legal implications, it may be debated whether the ContRF system, which removes haptic guidance when driving faster than 125 km/h so that drivers are ‘on their own’, is an acceptable type of driver support in real traffic. Here, valuable lessons may be learned from existing lane-keeping assistance systems, which all have various functional limitations. For example, current lane-keeping systems do not function above 200 km/h, when lane markers are absent, in sharp curves, or on narrow roads (e.g. Daimler, 2013; Volvo Car Corporation, 2015).

Although simulators have various limitations, their *relative* validity (i.e., the effect sizes between the pairwise comparisons) may still be high, 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 fixed 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 with similar lane-keeping performance and self-reported acceptance as continuous guidance. Participants in our experiment drove 13 min in each of the four conditions; future research should address real-world and long-term effects, and establish which cognitive mechanisms are at play regarding the causes and remedies of BA.

Acknowledgements

The authors would like to thank Sjors Oudshoorn, Dimitra Dodou, and Bastiaan Petermeijer for their useful support and well-founded comments.

Appendix A. – Correlation Matrices

For each condition, the Spearman correlation was calculated between dependent measures (with an additional measure, the mean absolute steering speed [deg/s]). The correlation matrices are shown in the tables below.

Table A1
Spearman rank-order correlation matrix for the Manual condition ($N = 24$).

	Mean speed	Percentage time above 125 km/h	Percentage time off-road	Mean absolute lateral error	Max absolute lateral error	Mean lane return time	Median TLC	NASA-TLX	Mean steering reversal rate	Mean absolute driver torque	Mean absolute steering speed	DBQ violations	Mileage
Mean speed	1.00												
Percentage time above 125 km/h	0.68	1.00											
Percentage time off-road	0.33	0.29	1.00										
Mean absolute lateral error	0.40	0.44	0.93	1.00									
Max absolute lateral error	0.55	0.29	0.66	0.72	1.00								
Mean lane return time	0.21	0.13	0.67	0.64	0.42	1.00							
Median TLC	−0.68	−0.68	−0.72	−0.77	−0.71	−0.47	1.00						
NASA-TLX	0.03	0.00	0.23	0.37	0.37	0.27	−0.27	1.00					
Mean steering reversal rate	0.20	0.24	−0.16	−0.10	0.10	−0.21	−0.39	0.21	1.00				
Mean absolute driver torque	0.92	0.67	0.30	0.37	0.51	0.23	−0.75	0.10	0.45	1.00			
Mean absolute steering speed	0.37	0.40	−0.04	0.05	0.23	−0.14	−0.52	0.20	0.93	0.62	1.00		
DBQ violations	0.08	0.16	−0.07	−0.10	−0.02	−0.14	−0.03	0.09	0.06	0.19	0.12	1.00	
Mileage	0.25	0.04	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	−0.02	0.07	0.08	0.10	0.17	−0.11	0.26	−0.06	0.26	0.05	0.22	0.81

Note: $p < 0.05$ for $|\rho| \geq 0.41$, $p < 0.01$ for $|\rho| \geq 0.52$ and $p < 0.001$ for $|\rho| \geq 0.63$.

Table A2
Spearman rank-order correlation matrix for the ContRF condition ($N = 24$).

	Mean speed	Percentage time above 125 km/h	Percentage time off-road	Mean absolute lateral error	Max absolute lateral error	Mean lane return time	Median TLC	NASA-TLX	Mean steering reversal rate	Mean absolute feedback torque	Mean absolute driver torque	Mean steering speed	Usefulness scale	Satisfaction scale
Mean speed	1.00													
Percentage time above 125 km/h	0.57	1.00												
Percentage time off-road	0.19	0.20	1.00											
Mean absolute lateral error	0.31	0.23	0.86	1.00										
Max absolute lateral error	0.00	0.13	0.83	0.59	1.00									
Mean lane return time	0.26	0.16	0.66	0.44	0.50	1.00								
Median TLC	−0.54	−0.53	−0.42	−0.46	−0.50	−0.28	1.00							
NASA-TLX	0.11	0.21	0.33	0.40	0.15	0.22	−0.13	1.00						
Mean steering reversal rate	0.15	0.16	−0.07	−0.08	0.09	0.05	−0.66	−0.17	1.00					
Mean absolute feedback torque	0.19	−0.13	0.73	0.76	0.59	0.33	−0.51	0.24	0.23	1.00				
Mean absolute driver torque	0.77	0.47	0.06	0.14	0.05	0.20	−0.57	0.28	0.31	0.10	1.00			
Mean absolute steering speed	0.29	0.18	−0.01	0.06	0.06	0.09	−0.69	−0.14	0.96	0.34	0.37	1.00		
Usefulness scale	−0.11	−0.19	−0.06	−0.20	0.15	−0.02	0.11	−0.24	−0.10	−0.03	0.13	−0.11	1.00	
Satisfaction scale	0.19	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 violations	0.25	0.23	−0.22	−0.17	−0.05	−0.20	−0.30	−0.03	0.27	0.04	0.31	0.32	0.32	0.35
Mileage	0.01	0.25	−0.11	0.08	−0.10	−0.06	−0.03	0.39	−0.08	−0.28	0.05	−0.09	−0.32	0.04
Weekly driving	−0.04	0.07	−0.02	0.27	−0.05	−0.14	−0.08	0.30	−0.12	0.03	−0.06	−0.07	−0.37	−0.07

Note: $p < 0.05$ for $|\rho| \geq 0.41$, $p < 0.01$ for $|\rho| \geq 0.52$ and $p < 0.001$ for $|\rho| \geq 0.63$.

Table A3
Spearman rank-order correlation matrix for the Band condition ($N = 24$).

	Mean speed	Percentage time above 125 km/h	Percentage time off-road	Mean absolute lateral error	Max absolute lateral error	Mean lane return time	Median TLC	NASA-TLX	Mean steering reversal rate	Mean absolute feedback torque	Mean absolute driver torque	Mean steering speed	Usefulness scale	Satisfaction scale
Mean speed	1.00													
Percentage time above 125 km/h	0.77	1.00												
Percentage time off-road	0.10	0.15	1.00											
Mean absolute lateral error	0.14	0.09	0.87	1.00										
Max absolute lateral error	0.32	0.41	0.77	0.63	1.00									
Mean lane return time	0.10	0.08	0.89	0.71	0.67	1.00								
Median TLC	−0.65	−0.68	−0.55	−0.39	−0.73	−0.55	1.00							
NASA-TLX	0.33	0.16	0.41	0.39	0.52	0.31	−0.37	1.00						
Mean steering reversal rate	0.27	0.32	−0.22	−0.44	0.13	−0.05	−0.44	0.04	1.00					
Mean absolute feedback torque	0.36	0.35	0.89	0.81	0.73	0.83	−0.77	0.35	−0.04	1.00				
Mean absolute driver torque	0.83	0.58	−0.04	−0.09	0.16	0.03	−0.63	0.28	0.54	0.28	1.00			
Mean absolute steering speed	0.35	0.43	−0.10	−0.30	0.25	0.05	−0.53	0.08	0.97	0.09	0.56	1.00		
Usefulness scale	0.04	0.16	−0.11	−0.09	−0.08	−0.16	−0.01	−0.32	−0.07	−0.07	−0.13	−0.04	1.00	
Satisfaction scale	−0.24	−0.07	−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 violations	0.07	−0.06	−0.03	−0.09	0.06	−0.03	−0.15	0.04	0.36	−0.07	0.10	0.37	−0.04	−0.04
Mileage	0.20	0.26	0.16	0.02	0.25	−0.05	−0.35	0.37	0.02	0.19	0.23	0.01	0.02	−0.25
Weekly driving	0.20	0.12	0.17	0.04	0.11	0.07	−0.35	0.11	−0.03	0.21	0.26	−0.05	0.11	−0.13

Note: $p < 0.05$ for $|\rho| \geq 0.41$, $p < 0.01$ for $|\rho| \geq 0.52$ and $p < 0.001$ for $|\rho| \geq 0.63$.

Table A4
Spearman rank-order correlation matrix for the Cont condition ($N = 24$).

	Mean speed	Percentage time above 125 km/h	Percentage time off-road	Mean absolute lateral error	Max absolute lateral error	Mean lane return time	Median TLC	NASA-TLX	Mean steering reversal rate	Mean absolute feedback torque	Mean absolute driver torque	Mean steering speed	Usefulness scale	Satisfaction scale
Mean speed	1.00													
Percentage time above 125 km/h	0.80	1.00												
Percentage time off-road	0.22	0.38	1.00											
Mean absolute lateral error	0.11	0.31	0.93	1.00										
Max absolute lateral error	0.41	0.36	0.79	0.67	1.00									
Mean lane return time	0.16	0.17	0.73	0.65	0.70	1.00								
Median TLC	−0.49	−0.57	−0.60	−0.53	−0.56	−0.51	1.00							
NASA-TLX	−0.08	−0.13	0.28	0.26	0.24	0.16	−0.02	1.00						
Mean steering reversal rate	0.03	0.26	0.16	0.18	0.04	0.29	−0.62	−0.15	1.00					
Mean absolute feedback torque	0.45	0.60	0.84	0.79	0.66	0.60	−0.86	0.04	0.40	1.00				
Mean absolute driver torque	0.90	0.71	0.32	0.19	0.42	0.35	−0.64	−0.05	0.21	0.59	1.00			
Mean absolute steering speed	0.33	0.49	0.30	0.27	0.22	0.36	−0.77	−0.21	0.92	0.60	0.51	1.00		
Usefulness scale	0.21	0.09	−0.44	−0.47	−0.31	−0.30	0.10	−0.50	−0.23	−0.20	0.22	−0.13	1.00	
Satisfaction scale	0.29	0.20	−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	0.09	−0.14	−0.15	−0.12	−0.19	−0.01	−0.19	0.00	−0.03	0.17	0.06	0.37	0.37
Mileage	0.12	0.00	0.21	0.28	0.19	0.10	−0.09	0.44	−0.23	0.18	0.18	−0.08	−0.20	−0.41
Weekly driving	−0.06	−0.13	0.27	0.35	0.15	0.20	−0.06	0.35	−0.15	0.18	0.06	−0.06	−0.24	−0.44

Note: $p < 0.05$ for $|\rho| \geq 0.41$, $p < 0.01$ for $|\rho| \geq 0.52$ and $p < 0.001$ for $|\rho| \geq 0.63$.

References

Aarts, L., Van Schagen, I., 2006. Driving speed and the risk of road crashes: a review. Accid. Anal. Prev. 38, 215–224, http://dx.doi.org/10.1016/j.aap.2005.07.004.

Abbink, D.A., Mulder, M., 2009. Exploring the dimensions of haptic feedback support in manual control. J. Comput. Inf. Sci. Eng. 9, 011006, http://dx.doi.org/10.1115/1.3072902.

Abbink, D.A., Mulder, M., Van der Helm, F.C.T., Mulder, M., Boer, E.R., 2011. Measuring neuromuscular control dynamics during car following with continuous haptic feedback. IEEE Trans. Syst. Man Cybern. Part B: Cybern. 41, 1239–1249, http://dx.doi.org/10.1109/TSMCB.2011.2120606.

Abbink, D.A., Mulder, M., Boer, E.R., 2012. Haptic shared control: smoothly shifting control authority? Cogn. Technol. Work 14, 19–28, http://dx.doi.org/10.1007/s10111-011-0192-5.

Assum, T., Bjørnskau, T., Fosser, S., Sagberg, F., 1999. Risk compensation—the case of road lighting. Accid. Anal. Prev. 31, 545–553, http://dx.doi.org/10.1016/S0001-4575(99)00011-1.

Banks, V.A., Stanton, N.A., Harvey, C., 2014. What the drivers do and do not tell you: using verbal protocol analysis to investigate driver behaviour in

emergency situations. Ergonomics 57, 332–342, http://dx.doi.org/10.1080/00140139.2014.884245.
Beggiato, M., Pereira, M., Petzoldt, T., Krems, J., 2015. Learning and development of trust, acceptance and the mental model of ACC. A longitudinal on-road study. Transp. Res. Part F: Traffic Psychol. Behav. 35, 75–84, http://dx.doi.org/10.1016/j.trf.2015.10.005.
Bengler, K., Dietmayer, K., Farber, B., Maurer, M., Stiller, C., Winner, H., 2014. Three decades of driver assistance systems: review and future perspectives. Intell. Transp. Syst. Mag. IEEE 6, 6–22, http://dx.doi.org/10.1109/MITS.2014.2336271.
Bianchi Piccinini, G.F., Rodrigues, C.M., Leitao, M., Simoes, A., 2014. Driver's behavioral adaptation to Adaptive Cruise Control (ACC): the case of speed and time headway. J. Saf. Res. 49, 77–84, http://dx.doi.org/10.1016/j.jsr.2014.02.010.
Breyer, F., Blaschke, C., Farber, B., Freyer, J., Limbacher, R., Färber, B., 2010. Negative behavioral adaption to lane-keeping assistance systems. Intell. Transp. Syst. Mag. IEEE 2, 21–32, http://dx.doi.org/10.1109/MITS.2010.938533.
Brookhuis, K.A., De Waard, D., Fairclough, S.H., 2003. Criteria for driver impairment. Ergonomics 46, 433–445, http://dx.doi.org/10.1080/0014013021000039556.
Cain, B., 2007. A review of the mental workload literature. Defence Research and Development Toronto (Canada), Retrieved from http://www.dtic.mil/get-tr-doc/pdf?AD=ADA474193.
Carsten, O., Lai, F.C.H., Barnard, Y., Jamson, A.H., Merat, N., 2012. Control task substitution in semiautomated driving: does it matter what aspects are automated? Hum. Factors 54, 747–761, http://dx.doi.org/10.1177/0018720812460246.
Conover, W.J., Iman, R.L., 1981. Rank transformations as a bridge between parametric and nonparametric statistics. Am. Stat. 35, 124–129, http://dx.doi.org/10.1080/00031305.1981.10479327.
Daimler, A.G., 2013. Driver Assistance Systems. Technology Guide, Retrieved from http://oem1stop.com/sites/default/files/2013-12_Fahrerassistenzsysteme_EN.PDF.
De Waard, D., 1996. The Measurement of Drivers' Mental Workload (Doctoral Dissertation). University of Groningen, The Netherlands.
De Winter, J.C.F., Dodou, D., 2011. Preparing drivers for dangerous Preparing drivers for dangerous situations: a critical reflection on continuous shared control. Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, 1050–1056 http://dx.doi.org/10.1109/ICSMC.2011.6083813.
De Winter, J.C.F., Dodou, D., 2016. National correlates of self-reported traffic violations across 41 countries. Personal. Individ. Differ. 98, 145–147, http://dx.doi.org/10.1016/j.paid.2016.03.091.
De Winter, J.C.F., Mulder, M., Van Paassen, M.M., Abbink, D.A., Wieringa, P.A., 2008. A two-dimensional weighting function for a driver assistance system. IEEE Trans. Syst. Man Cybern. Part B Cybern. 38, 189–195, http://dx.doi.org/10.1109/TSMCB.2007.908860.
De Winter, J.C.F., Van Leeuwen, P.M., Happee, R., 2012. Advantages and disadvantages of driving simulators: a discussion. Proc. Meas. Behav., 75–78, http://dx.doi.org/10.1016/j.beproc.2013.02.010.
De Winter, J.C.F., Dodou, D., Stanton, N.A., 2015. A quarter of a century of the DBQ: some supplementary notes on its validity with regard to accidents. Ergonomics 58, 1745–1769, http://dx.doi.org/10.1080/00140139.2015.1030460.
Dixon, J.C., 1988. Linear and non-linear steady state vehicle handling. Proc. Inst. Mech. Eng. Part D: J. Autom. Eng. 202, 173–186, http://dx.doi.org/10.1243/PIME_PROC_1988_202_171_02.
Dragutinovic, N., Brookhuis, K.A., Hagenzieker, M.P., 2005. Behavioural effects of advanced cruise control use: a meta-analytic approach. Eur. J. Transp. Infrastruct. Res. 5, 267–280, Retrieved from http://www.ejtir.tbm.tudelft.nl/issues/2005_04/pdf/2005_04_03.pdf.
Eichelberger, A.H., McCartt, A.T., 2016. Toyota drivers' experiences with dynamic radar cruise control, pre-collision system, and lane-keeping assist. J. Saf. Res. 56, 67–73, http://dx.doi.org/10.1016/j.jsr.2015.12.002.
Elvik, R., Christensen, P., Amundsen, A., 2004a. Speed and road accidents: An evaluation of the Power Model (TOI report 740/2004). Retrieved from http://www.trg.dk/elvik/740-2004.pdf.
Elvik, R., Vaa, T., Hoye, A., Sorensen, M., 2004b. The Handbook of Road Safety Measures. Emerald Group Publishing, Bingley.
Elvik, R., 2013. Impact of behavioural ecology. In: Rudin-Brown, C., Jamson, S. (Eds.), Behavioural Adaptation and Road Safety, 374. CRC Press, Boca Raton, pp. 371–384.
Evans, J.S.B.T., 2008. Dual-processing accounts of reasoning, judgment: and social cognition. Annu. Rev. Psychol. 59, 255–278.
Faul, F., Erdfelder, E., Lang, A.G., Buchner, A., 2007. G* power 3: a flexible statistical power analysis program for the social, behavioral: and biomedical sciences. Behav. Res. Methods 39, 175–191.
Ferguson, D., Darms, M., Urmson, C., Kolski, S., 2008. Detection, prediction, and avoidance of dynamic obstacles in urban environments. IEEE Intell. Veh. Symp. Proc., 1149–1154, http://dx.doi.org/10.1109/IVS.2008.4621214.
Flemisch, F.O., Kelsch, J., Loper, C., Schieben, A., Schindler, J., Matthias, H., 2008. Cooperative control and active interfaces for vehicle assistance and automation. FISITA World Autom. Congr., 301–310.
Fuller, R., 2005. Towards a general theory of driver behaviour. Accid. Anal. Prev. 37, 461–472, http://dx.doi.org/10.1016/j.aap.2004.11.003.
Gibson, J., Crooks, L., 1938. A theoretical field-analysis of automobile-driving. Am. J. Psychol. 51, 453–471.
Godthelp, H., Milgram, P., Blaauw, G.J., 1984. The development of a time-related measure to describe driving strategy. Hum. Factors 26, 257–268.
Goodrich, M.A., Stirling, W.C., Boer, E.R., 2000. Satisficing revisited. Minds Mach. 10, 79–110, http://dx.doi.org/10.1023/A:1008325423033.
Griffiths, P.G., Gillespie, R.B.1, 2005. Sharing control between humans and automation using haptic interface: primary and secondary task performance benefits. Hum. Factors 47, 574–590, http://dx.doi.org/10.1518/001872005774859944.
Hart, S.G., Staveland, L.E., 1988. Development of NASA-TLX (Task load index): results of emperical and theoretical research. In: Meshkati, P.A.H.N. (Ed.), Human Mental Workload, vol. 1. North Holland Press, Amsterdam, pp. 139–183, http://dx.doi.org/10.1017/CBO9781107415324.004.
Hedlund, J., 2000. Risky business: safety regulations, risks compensation, and individual behavior. Inj. Prev. J. Int. Soc. Child Adolesc. Inj. Prev. 6, 82–89, http://dx.doi.org/10.1136/ip.6.2.82.
Hiraoka, T., Masui, J., Nishikawa, S., 2010. Behavioral adaptation to advanced driver-assistance systems. Proc. SICE Annu. Conf., 930–935.
Janssen, W., Nilsson, L., 1993. Behavioural effects of driver support. In: Parkes, A.M., Franzen, S. (Eds.), Driving Future Vehicles. Taylor & Francis, London – Washington DC, pp. 147–155.
Jiménez, F., Aparicio, F., Paíez, J., 2008. Evaluation of in-vehicle dynamic speed assistance in Spain: algorithm and driver behaviour. IET Intel. Transport Syst. 2, 132, http://dx.doi.org/10.1049/iet-its.
Johansson, E., Engström, J., Cherri, C., Nodari, E., Toffetti, A., Schindhelm, R., Gelau, C., 2004. Review of existing techniques and metrics for IVIS and ADAS assessment (AIDE IST-1-507674-IP). Retrieved from www.aide-eu.org/pdf/sp2_deliv_new/aide_d2_2_1.pdf.
Johns, M., Mok, B., Sirkin, D.M., Gowda, N.M., Smith, C.A., Talamonti Jr., W.J., Ju, W., 2016. Exploring shared control in automated driving. Proceedings of the 11th ACM/IEEE International Conference on Human-Robot Interaction, 91–98, New Zealand.
Kienle, M., Dambock, D., Bubb, H., Bengler, K., 2012. The ergonomic value of a bidirectional haptic interface when driving a highly automated vehicle. Cogn. Technol. Work 15, 475–482, http://dx.doi.org/10.1007/s10111-012-0243-6.
Klüver, M., Herrigel, C., Heinrich, C., Schöner, H.-P., Hecht, H., 2016. The behavioral validity of dual-task driving performance in fixed and moving base driving simulators. Transp. Res. Part F: Traffic Psychol. Behav. 37, 78–96, http://dx.doi.org/10.1016/j.trf.2015.12.005.
Kondoh, T., Yamamura, T., Kitazaki, S., Kuge, N., Boer, E.R., 2006. Identification of visual cues and quantification of drivers' perception of proximity risk to the lead vehicle in car-following situations. J. Mech. Syst. Transp. Logist. 1, 170–180, http://dx.doi.org/10.1299/jmtl.1.170.
Kyriakidis, M., Happee, R., De Winter, J.C.F., 2015. Public opinion on automated driving: results of an international questionnaire among 5, 000 respondents. Transp. Res. Part F: Traffic Psychol. Behav. 32, 127–140, http://dx.doi.org/10.1016/j.trf.2015.04.014.
Marchal-Crespo, L., McHughen, S., Cramer, S.C., Reinkensmeyer, D.J., 2010. The effect of haptic guidance, aging, and initial skill level on motor learning of a steering task. Exp. Brain Res. 201, 209–220, http://dx.doi.org/10.1007/s00221-009-2026-8.
Mars, F., Deroo, M., Hoc, J.M., 2014a. Analysis of human-machine cooperation when driving with different degrees of haptic shared control. IEEE Trans. Haptics 7, 324–333, http://dx.doi.org/10.1109/TOH.2013.2295095.
Mars, F., Deroo, M., Charron, C., 2014b. Driver adaptation to haptic shared control of the steering wheel. 2014 IEEE International Conference on Systems, Man, and Cybernetics (SMC), 3585–3592, http://dx.doi.org/10.1109/SMC.2014.6974486, San Diego.
Martens, M.H., Jenssen, G.D., 2012. Behavioral adaptation and acceptance. In: Eskandarian, A. (Ed.), Handbook of Intelligent Vehicles. Springer-Verslag, London, pp. 117–138, http://dx.doi.org/10.1007/978-0-85729-085-4.
McDowell, K., Nunez, P., Hutchins, S., Metcalfe, J.S., 2008. Secure mobility and the autonomous driver. IEEE Trans. Robot. 24, 688–697, http://dx.doi.org/10.1109/TRO.2008.924261.
McGehee, D., Lee, J., Rizzo, M., Dawson, J., Bateman, K., 2004. Quantitative analysis of steering adaptation on a high performance fixed-base driving simulator. Transp. Res. Part F: Traffic Psychol. Behav. 7, 181–196, http://dx.doi.org/10.1016/j.trf.2004.08.001.
McLean, J.R., Hoffmann, E.R., 1975. Steering reversals as a measure of driver performance and steering task difficulty. Hum. Factors 17, 248–256, http://dx.doi.org/10.1177/001872087501700304.
Mehler, B., Reimer, B., Lavallière, M., Dobres, J., Coughlin, J.F., 2014. Evaluating technologies relevant to the enhancement of driver safety Washington. AAA Foundation for Traffic Safety, DC, Retrieved from https://www.aaafoundation.org/sites/default/files/Evaluating%20Vehicle%20Safety%20Techs%20FINAL%20FTS.pdf.
Mohellebi, H., Kheddar, A., Espie, S., 2009. Adaptive haptic feedback steering wheel for driving simulators. IEEE Trans. Veh. Technol. 58, 1654–1666, http://dx.doi.org/10.1109/TVT.2008.2004493.
Mulder, M., Abbink, D.A., Boer, E.R., 2008. The effect of haptic guidance on curve negotiation behavior of young, experienced drivers. Conference Proceedings – IEEE International Conference on Systems, Man and Cybernetics, 804–809, http://dx.doi.org/10.1109/ICSMC.2008.4811377.
Mulder, M., Abbink, D.A., Boer, E.R., 2012. Sharing control with haptics: seamless driver support from manual to automatic control. Hum. Factors: J. Hum. Factors Ergonom. Soc. 54, 786–798, http://dx.doi.org/10.1177/0018720812443984.
Näätänen, R., Summala, H., 1974. A model for the role of motivational factors in drivers' decision-making. Accid. Anal. Prev. 6 (3–4), 243–261, http://dx.doi.org/10.1016/0001-4575(74)90003-7.

Navarro, J., Mars, F., Forzy, J.F., El-Jaafari, M., Hoc, J.M., 2010. Objective and subjective evaluation of motor priming and warning systems applied to lateral control assistance. Accid. Anal. Prev. 42, 904–912, http://dx.doi.org/10.1016/j.aap.2009.07.008.
O'Malley, M.K., Gupta, A., Gen, M., Li, Y., 2006. Shared control in haptic systems for performance enhancement and training. J. Dyn. Syst. Meas. Control 128, 75–85, http://dx.doi.org/10.1115/1.2168160.
OECD, 1990. Behaviour adaptations to changes in the road transport system. Paris: OECD.
Panou, M., Bekiaris, E., Papakostopoulos, V., 2007. Modelling driver behaviour in european union and international projects. In: Cacciabue, P.C. (Ed.), Modelling Driver Behaviour in Automotive Environments. Springer, London, pp. 3–25, http://dx.doi.org/10.1007/978-1-84628-618-6_1.
Petermeijer, S.M., Abbink, D.A., De Winter, J.C.F., 2015a. Should drivers be operating within an automation-free bandwidth? Evaluating haptic steering support systems with different levels of authority. Hum. Factors: J. Hum. Factors Ergonom. Soc. 57, 5–20, http://dx.doi.org/10.1177/0018720814563602.
Petermeijer, S.M., Abbink, D.A., Mulder, M., De Winter, J.C.F., 2015b. The effect of haptic support systems on driver performance and behavior: a literature review. IEEE Trans. Haptics 8, 467–479, http://dx.doi.org/10.1109/TOH.2015.2437871.
Piao, J., McDonald, M., 2008. Advanced driver assistance systems from autonomous to cooperative approach. Transport Rev. 18, 659–684, http://dx.doi.org/10.1080/01441640801987825.
Rudin-Brown, C.M., Noy, Y.I., 2002. Investigation of behavioral adaptation to lane departure warnings. Transp. Res. Rec. 1803, 30–37, http://dx.doi.org/10.3141/1803-05.
Saad, F., Hjälmdahl, M., Cañas, J., Alonso, M., 2004. Literature review of behavioural effects, Retrieved from http://www.aide-eu.org/pdf/sp1_deliv_new/aide_d1_2_1.pdf.
Saad, F., 2006. Some critical issues when studying behavioural adaptations to new driver support systems. Cogn. Technol. Work 8, 175–181, http://dx.doi.org/10.1007/s10111-006-0035-y.
Sagberg, F., Fosser, S., Sætermo, I.A.F., 1996. An investigation of behavioural adaptation to airbags and antilock brakes among taxi drivers. Accid. Anal. Prev. 29, 293–302, http://dx.doi.org/10.1016/S0001-4575(96)00083-8.
Soualmi, B., Sentouh, C., Popieul, J.C., Debernard, S., 2014. Automation-driver cooperative driving in presence of undetected obstacles. Control Eng. Pract. 24, 106–119, http://dx.doi.org/10.1016/j.conengprac.2013.11.015.
Sullivan, J.M., Flannagan, M.J., Pradhan, A.K., Bao, S., 2016. Literature review of behavioral adaptations to advanced driver assistance systems Washington, D.C., Retrieved from https://www.aaafoundation.org/sites/default/files/BehavioralAdaptationADAS.pdf.
Summala, H., 2007. Towards understanding motivational and emotional factors in driver behaviour: comfort through satisficing. In: Cacciabue, P.C. (Ed.), Modelling Driver Behaviour in Automotive Environments. Springer Verslag, pp. 189–207, http://dx.doi.org/10.1007/978-1-84628-618-6.
Van Winsum, W., De Waard, D., Brookhuis, K., 1999. Lane change manoeuvres and safety margins. Transp. Res. Part F: Traffic Psychol. Behav. 2, 139–149, http://dx.doi.org/10.1016/S1369-8478(99)00011-X.
Van Winsum, W., Brookhuis, K., De Waard, D., 2000. A comparison of different ways to approximate time-to-line crossing (TLC) during car driving. Accid. Anal. Prev. 32, 47–56, http://dx.doi.org/10.1016/S0001-4575(99)00048-2.
Van der Laan, J.D., Heino, A., De Waard, D., 1997. A simple procedure for the assessment of acceptance of advanced transport telematics. Transp. Res. Part C: Emerg. Technol. 5, 1–10, http://dx.doi.org/10.1016/S0968-090X(96)00025-3.
Veldstra, J.L., Bosker, W.M., De Waard, D., Ramaekers, J.G., Brookhuis, K.A., 2015. Comparing treatment effects of oral THC on simulated and on-the-road driving performance: testing the validity of driving simulator drug research. Psychopharmacology 232, 2911–2919, http://dx.doi.org/10.1007/s00213-015-3927-9.
Verster, J.C., Roth, T., 2011. Standard operation procedures for conducting the on-the-road driving test, and measurement of the standard deviation of lateral position (SDLP). Int. J. Gen. Med. 4, 359–371, http://dx.doi.org/10.2147/IJGM.S19639.
Volvo Car Corporation, 2015. S60 Owner's Manual, web edition. Retrieved from https://carmanuals2.com/get/volvo-s60-2016-owner-s-manual-61805.
Wallis, G., Tichon, J., Mildred, T., 2007. Speed perception as an objective measure of presence in virtual environments. Proceedings of SemTecT 2007. Retrieved from http://hms.health.uq.edu.au/vislab/publications/reprints/simtect07.pdf.
Wilde, G.J.S., 1998. Risk homeostasis theory: an overview. Inj. Prev. J. Int. Soc. Child Adolesc. Inj. Prev. 4, 89–91, http://dx.doi.org/10.1136/ip.4.2.89.
Wilde, G.J.S., 2013. Applying the risk homeostatic dynamic to improvement of safety and lifestyle-dependent health. In: Rudin-Brown, C., Jamson, S. (Eds.), Behavioural Adaptation and Road Safety. CRC Press, Boca Raton, pp. 385–400.
Young, M.S., Stanton, N.A., 2002. Attention and automation: new perspectives on mental underload and performance. Theor. Issues Ergon. Sci. 3, 178–194, http://dx.doi.org/10.1080/14639220210123789.
Zhai, S., Accot, J., Woltjer, R., 2004. Human action laws in electronic virtual worlds: an empirical study of path steering performance in VR. Presence: Teleoperators Virtual Environ. 13, 113–127, http://dx.doi.org/10.1162/1054746041382393.