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Complementing Haptic Shared Control With Visual Feedback for Obstacle Avoidance

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Abstract: For automated vehicles (SAE Level 2-3) part of the challenge lies in communicating to the driver what control actions the automation is taking and will take, and what its capabilities are. A promising approach is haptic shared control (HSC), which uses continuous torques on the steering wheel to communicate the automation's current control actions. However, torques on the steering wheel cannot communicate future spatiotemporal constraints, that might be required to judge appropriate overtaking or obstacle avoidance. A visualisation of predicted vehicle trajectory, along with velocity-dependent constraints with respect to achievable trajectories is proposed. The goal of this paper is to experimentally compare obstacle avoidance behaviour while driving with the designed visualisation against driving with a previously designed HSC, as well as the two support systems combined. It is expected that adding visual feedback improves obstacle avoidance and user acceptance, and reduces control effort with respect to HSC only. In a driving simulator experiment, 26 participants drove three trials with each feedback condition (visual, HSC, and combination) and had to avoid obstacles that appeared with a Time to collision of either 1.85 s (critical) or 4.7 s (non-criticall). Results showed that, compared to HSC only, the HSC and visual combination yielded slightly smaller safety margins to the obstacle, a significant reduction of control activity on straights, and increased subjective acceptance rating. Visual and HSC offered a beneficial synergy, as it seemed the visual feedback allowed drivers to anticipate the effect of their steering actions on the car's trajectory more accurately, and the HSC reduced the intra-subject variability. Future research should investigate the effects of added visual feedback in more detail, specifically in terms of the effectiveness to communicate automation capabilities and driver gaze behavior.

Keywords: Haptic Shared Control, Visual Feedback, Ecological Interface Design, Obstacle avoidance.

1. INTRODUCTION

Automated driving systems can support drivers, but currently not always and everywhere (Litman, 2017). SAE level 2 or 3 automated driving systems (SAE, 2016) require drivers to be able to take over at unexpected moments, which comes with many known issues (Carsten and Martens, 2019).

Haptic Shared Control (HSC) is a cooperative form of automation aimed at keeping the driver in-the-loop (Abbink et al., 2008; Flemisch et al., 2008), which attempts to avoid the pitfalls of automation by providing sharing control torques between the automation and driver instead of

trading control. HSC has proven to yield improvements in vehicle locomotion, such as reduced human variability for different control tasks (Griffiths and Gillespie, 2005; Tsoi et al., 2010), and reduced control activity (Mulder et al., 2008). However, these improvements can come at a cost of increased physical workload (Boink et al., 2014), caused by conflicts in intent between the driver and HSC. Such conflicts occur partly due to the limited amount of information shared control torques can provide (Martens and van den Beukel, 2013; Lee et al., 2006). In that, forces on a steering wheel can only communicate an instantaneous steering action, but not what the automation is planning to do in a few seconds. This paper explores the potential benefits of complementing HSC with visual feedback.

1.1 Visuals to complement haptic feedback

Studies have found promising results of combining feed-back modalities, such as visual and auditory, together with haptic feedback (Beeftink et al., 2018), showing improved primary task performance and reduced control activity, visual and cognitive demand. Visual feedback is often used for longer time scales where interpretation of the information is more prevalent (Hoc et al., 2009). Current applications of visual-haptic feedback are often designed to reflect the automation constraints imposed by the under-lying controller, and thereby do not consider constraints beyond this envelope, (Beeftink et al., 2018). In other words, the current visual feedback is focused mostly on informing the operator about the operational domain of the haptic feedback, but not on the actual performance of the vehicle with respect to its surroundings. This means that visual-haptic feedback is generally well-accepted for routine tasks where the haptic feedback is reliable, yet the visual feedback becomes obsolete for non-routine tasks in which the haptics may fail, often imposing control conflicts. To increase the robustness of HSC during un-expected situations and to prevent for control conflicts, a new approach is required which reflects more than just the automation constraints.

Apart from Beeftink et al. (2018), little research has been done investigating the potential benefits of applying continuous visual-haptic feedback to vehicle locomotion and car driving in particular. A promising design strategy to support operators in complex work domains where unexpected events may occur, is the principle of Ecological Interface Design (EID; Rasmussen and Vicente, 1989). The main goal of EID is to transform a cognitive task into a perceptual task by providing meaningful information about the work domain constraints that humans can directly perceive and act on accordingly. By visualizing the constraints directly, EID interfaces assist users in the development of their mental model of the domain. Driver support system interfaces resulting from this analysis may not only help drivers form better situation awareness, but also an improved mental model of the vehicle, which consequently calibrates trust and reliance (Seppelt and Lee, 2007; Lee et al., 2006). In the driving domain EID has already successfully been applied to reflect the operational envelope of Adaptive Cruise Control with respect to other work domain constraints. However, it has not yet been combined with haptic feedback systems.

1.2 Research Objective

The aim of this simulator study was to quantify the bene-fits and drawbacks of haptic shared control complemented with a visualisation of the current vehicle trajectory and the velocity dependent constraints, compared to unas-sisted driving, or driving with either haptic shared control or the vehicle trajectory visualisation. Driving behavior was assessed for obstacle avoidance by using a previously developed continuous haptic feedback system (Scholtens et al., 2018) in combination with a novel EID-inspired visual feedback system, displaying the future trajectory with respect to the physical limitations of the vehicle and the intentional constraints imposed by the road.

Kuiper et al. (2016) compared predictive visual and haptic feedback in a needle steering task in easy and difficult conditions. They found that any feedback (i.e., visual or haptic) improved task performance compared to no feedback, especially when the task was difficult.

Haptic shared control is effective in unexpected events on a short time scale, but less satisfactory for non-critical tasks, where the performance improvement is marginal and usually accompanied by torque conflicts (Della Penna et al., 2010; Tsoi et al., 2010). The opposite holds for visual feedback, which tends to be most useful for non-critical events, but can become confusing or distracting in task of a short time scale.

To investigate the effect of visual feedback in combination with HSC, it was hypothesized that combining HSC with EID-inspired visual feedback, compared with HSC-only, would result in: (1) improved task execution, (2) reduced control activity, and (3) reduced control effort. It was expected that these effects would be more distinct for critical scenarios.

2. VISUAL FEEDBACK

An overview of the EID-inspired visual feedback design is depicted in Fig. 1, where the road, vehicle and performance envelope are shown.

2.1 Visualizing the physical constraints

The physical constraints weres visualized with:

- *Yaw-limits*: Two arcs are shown, which define the maximum yaw limits (i.e. outer lines) and two arcs for the intermediate yaw limit (i.e., inner lines). For the outer arcs the maximum physically possible yaw rate was assumed constant, making their curvature only dependent on the ego-car velocity. The intermediate yaw limit was chosen such that it would match a common road curve with a radius of approximately 300 m at a speed of 24 m/s.
- *Trend vector*: Visualized the predicted path of the ego-vehicle, based on the instantaneous yaw rate of the car, which is updated real-time.
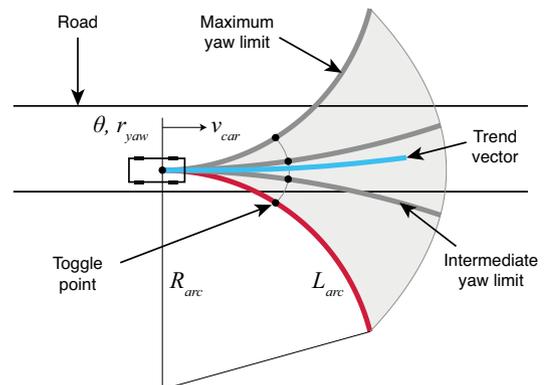

Fig. 1. Overview of visual feedback design showing the physical constraints, with future trajectory curves forming the performance envelope (grey). In the simu-lation only the curves are visualized, the grey envelope is presented here for clarity.

The arcs were shown in the simulator by attaching them to the vehicle's center of gravity and accounting for the current heading. As such, the physical constraints show the physical performance of the dynamic vehicle model. The performance envelope, indicated in grey (see Fig. 1) provides an estimation of the future trajectory given a constant steering wheel input, thereby representing the domain for which the vehicle remains stable (i.e. space of possibilities). The outermost curves indicate the predicted trajectory for which the vehicle reaches the maximum yaw rate at the current speed. The inner lines show an intermediate yaw rate that can be used for heading estimation. The radius of the arcs is based on the current velocity and yaw rate, meaning that the higher the speed, the greater the radius of the curves. A comparable design was researched previously in the aviation domain (Rijndorp et al., 2017), visualizing the flight envelope of an aircraft.

2.2 Visualizing the intentional constraints

The implementation of the intentional constraints (rules and laws) was done through the detection of the road boundaries (see 'road' in Fig. 1). Each arc had imaginary toggle points, placed 0.9 (s) ahead in time. An algorithm was constantly updated to determine whether these toggle points were outside road boundaries. If so, the corresponding arc would turn from grey to red, as can be seen in Fig. 1. The lane boundary detection informs the driver about their interaction with the intentional constraints and what the field of safe travel is during a certain driving manoeuvre.

3. METHOD

3.1 Participants

Twenty-six participants (4 women and 22 men) between 24 and 58 years old (M = 28, SD = 6.6), holding a driving license for at least 1 year (M = 9.0, SD = 6.9) conducted the experiment. All participants had normal to corrected eyesight and took part on a voluntary basis without a financial compensation for their effort. The study was approved by the Human Research Ethics Committee of the Delft University of Technology.

3.2 Apparatus

The experiment was conducted using a fixed-base driving simulator, equipped with an actuated steering wheel, an adjustable driver seat, an LCD dashboard and three projectors visualizing the driving scene. The steering wheel was actuated by a Moog-FCS S-motor and controlled through a control-loading computer at a rate of 2500 Hz. The total scene projection on the front and side walls yielded a size 10.1 m x 2.1 m, which corresponds to a 180° x 40° field of view. The simulation was updated and logged at a rate of 100 Hz. The vehicle dynamics were identical to those used in previous studies (Mulder et al., 2008).

3.3 Experiment Design

A within-subjects repeated-measures design was used with four feedback conditions, namely, (1) No feedback (Manual), (2) visual feedback only (Visual), (3) haptic feedback only (HSC) and (4) a combination of both (Combi). In the training session, the conditions were introduced in a generic order, being: (1) Manual, (2) Visual, (3) HSC and (4) Combi. During the four main trails the driving conditions were randomized across the participants.

Participants drove on a a two-lane road having a total width and length of 7.2 m (2 x 3.6 m) and 9.3 km, respectively. The driving speed was fixed at 24 m/s ($\approx$ 85 km/h), resulting in a completion time of 390 s per trail. The outer-lane boundaries were marked by continuous white lines, the center line by a dashed white line. The trajectory was identical for all trails and consisted of 14 straight sections of 300 m, each alternated by two left or right curves with a center radius of 375 m. No other vehicles shared the road.

Obstacles would randomly appear in the middle of the right lane on straight sections, with a time-critical TTC of 1.85 (s) or non-critical TTC of 4.7 (s). Fig. 2 shows the straight road sections with the two obstacle conditions. The cubic obstacles had a width (length and height) of w_{obs} = 2.0 m. Five critical and five non-critical obstacles were distributed over 14 straight sections, resulting in 4 empty sections. Anticipatory behavior in obstacle avoidance was prevented by applying two different obstacle orders among the four feedback conditions.
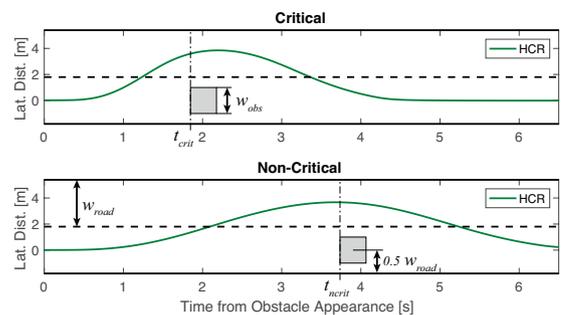

Fig. 2. Straight road sections with critical and non-critical obstacle conditions. The origin indicates the moment at which the obstacle appears on the road. Human Compatible Reference for the manoeuvre is represented by the green trajectory. Note, that the lateral axis and the obstacle length are not to scale.

3.4 Haptic shared control algorithm

The haptic shared control torques were generated by means of the Four Design Controller Algorithm (FDCA) controller, as proposed by Van Paassen et al. (2017). This FDCA controller provides torques that guide the vehicle along a predetermined human-compatible reference trajectory. The torques can be tuned by three parameters: a gain on a feed-forward torque component (Level of Haptic Support), a gain on feedback torque component (Strength of Haptic Feedback), and a gain on the stiffness feedback (Level of Haptic Authority). The human compatible reference was implemented a priori by recording several manual trails, which were averaged to generate a generic reference which included the avoidance of the obstacles. All other control parameters of the HSC were chosen similar to a previous study by Scholtens et al. (2018).

3.5 Procedure and instructions

Prior to the experiment, the participants were asked to read and sign a consent form, explaining the procedure, purpose and risks of the experiment. It was stated that the participant's primary goal was to stay in the middle of the right lane on a curvy two-lane road, while avoiding objects that randomly appeared on the road. After the obstacle was avoided, the participants should turn back to the right lane at their own pace. Participants were not informed about the obstacle location on the road nor the evasive direction to be taken.

Before taking place in the simulator the participants were asked to fill out a questionnaire about their demographics, driving experience and their affinity with video games. Subsequently, the participants were invited to be seated in the simulator and to adjust the driver seat to their comfort, while maintaining a ten-to-two position on the steering wheel. Next, a training session of 15 minutes was held to familiarize the participant to the different forms of vehicle feedback. After the training session, the participants performed the four main trials of 7 minutes each. Each trial was completed by a 5-minute break, where the participants were asked to leave the simulator to fill out a NASA Controller Acceptance Rating Scale (NASA-CARS; Lee et al., 2001). The completion time of the experiment was approximately 1.5 hours per participant.

3.6 Dependent Measures

The following metrics were used to quantify driving behaviour, and used in the statistics as dependent measures:

- *Mean lateral obstacle margin*, defined as the lateral distance between the car's right side and the obstacle's left side at the moment when the car's CoG passed the obstacle's front face (see Fig. 3).
- *Standard deviation lateral obstacle margin*, as a measure of intra-subject variability.
- *Mean lateral road margin*, defined as the lateral distance between the car's left side and the left lane boundary at the same moment of passing the obstacle.
- *Mean response time*, defined as the time from obstacle onset to the moment when the car's right side exceeds the minimum lateral distance required to avoid the obstacle, equal to half the obstacle width $(0.5 \times w_{obs} = 1.0 \text{ m})$.
- *mean Steering wheel Reversal Rate* (SRR) was measured to analyze the control activity related to lane keeping on the straight road sections without obstacles. The SRR is defined as the number of steering

direction reversals having a magnitude greater than 2° (McLean and Hoffmann, 1975).

3.7 Statistical Analyses

Eight conditions, with two within-subject factors (four driving x two criticality conditions) were categorized as ADAS factor Time factor. In case of any sphericity violations, values were corrected by the Greenhouse-Geisser correction. Subsequently, a two-way repeated measures ANOVA was used to verify the overall significance of the test conditions between the participants. Pair-wise comparisons were performed using a post-hoc test with bonferroni correction.

4. RESULTS

Results are summarized in Table 1, for the time-critical event (i.e., obstacle TTC = 1.85 s). Future analyses should be performed in order to reveal any effects for the non-critical events.

Lateral obstacle and road margin Fig. 4, shows the obstacle margin and reveals that the visual feedback (i.e., Visual and Combi) reduces the lateral obstacle margin (while increasing the mean road margin) compared to the Manual or HSC condition. The ANOVA revealed a significant effect between the feedback conditions for the mean lateral obstacle margin ($F(2.34, 58.56) = 19.57$, $p < .05$). Pairwise comparison revealed that all conditions were significantly different ($p < .05$), except between Manual and Combi.

The lateral obstacle and road margin are geometrically related, so statistical results for the lateral road margin are similar to those above (ANOVA: $F(2.35, 58.73) = 19.84$, $p < .05$).

Response Time The response time showed similar trends to the obstacle margins (see Table 1). The ANOVA revealed a significant effect ($F(3, 75) = 20.23$, $p < 0.05$). Pairwise comparisons revealed significant results between all conditions, except between Manual-Visual and HSC-Combi.
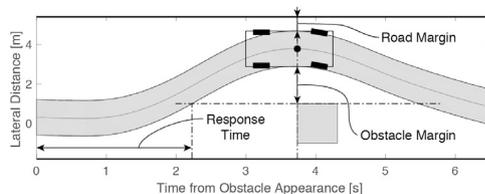
Fig. 3. Schematic overview of obstacle avoidance trajectory and the related dependent measures. Grey trajectory represents the car width around the CoG (black dot).
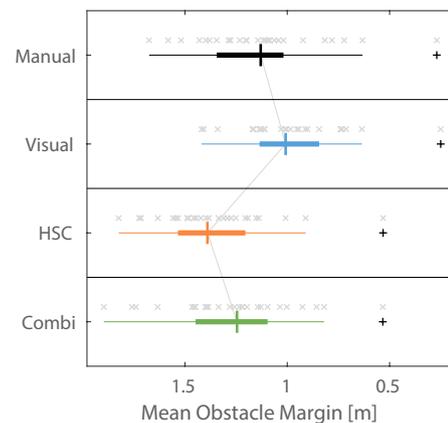
Fig. 4. Boxplots of the mean lateral obstacle margin across participants for the critical obstacles. Individual means and outliers are indicated by an x and +, respectively. Note, the x-axis is reversed to match with the driver perspective.

Table 1. Means and standard deviations of the dependent measures, including pairwise comparisons.

Measure		Manual (1) critical	Visual (2) critical	HSC (3) critical	Combi (4) critical	Pairwise comparison					
						1-2	1-3	1-4	2-3	2-4	3-4
Mean lateral	M	1.128	0.988	1.354	1.264	X	X	-	X	X	X
obstacle margin [m]	SD	0.312	0.257	0.275	0.308						
SD lateral obstacle	M	0.223	0.309	0.165	0.169	-	-	-	X	X	-
margin [m]	SD	0.101	0.116	0.060	0.080						
Mean lateral road	M	1.482	1.624	1.256	1.344	X	X	-	X	X	-
margin [m]	SD	0.313	0.257	0.274	0.308						
Mean response time	M	1.518	1.561	1.473	1.471	-	X	X	X	X	-
[s]	SD	0.087	0.079	0.065	0.071						
Mean SRR straight	M	0.486	0.212	0.340	0.179	X	X	X	X	-	X
[s^{-1}]	SD	0.260	0.185	0.250	0.186						

Significance for pairwise comparisons among driving conditions was rejected for p > 0.05.

SD obstacle margin   The standard deviation lateral obstacle margin (see Table 1) revealed a significant effect for the feedback conditions (F(3, 75) = 12.46, $p < .05$). Pairwise comparisons revealed significance between Visual-HSC and Visual-Combi. In short, haptic feedback significantly reduces intra-subject variability, compared to Visual only.

Steering wheel reversal rate   To investigate the effect of visual feedback during nominal driving, the mean SRR for straight sections was evaluated over the straight sections without obstacles. The ANOVA indicated a significant effect imposed by the driving condition, F(3, 75) = 25.77, $p < .05$. Compared to Manual, control activity was reduced by a factor 2.5 for both Visual and Combi, while HSC yielded a reduction factor of 1.4 for HSC. Pairwise comparisons showed significant effects between all conditions, except for Visual-Combi.

5. DISCUSSION

5.1 Driving trajectories and safety margins

Contrary to hypotheses, driving with additional visual feedback yielded a significant reduction in the mean obstacle margin and increase in road margin in the time critical events. In short, drivers with visuals feedback skirted closer around the obstacle than without. This phenomenon could be explained by two factors: (1) the visualization of the physical constraints provided the drivers with more direct insight in their future trajectory in relation to the obstacle, which corroborated by the decreased SRR on the straights. Similar findings were done in the aviation domain, where aircraft pilots showed a tendency of moving towards system limitations (Borst et al., 2015). Conversely, (2) the visualization of intentional constraints warned the participants of potential lane departure during the obstacle avoidance (by means of red yaw limits), promoting greater road margins compared to having no visualization.

The reduced obstacle margins as imposed by the visual feedback may raise concerns about the likelihood of accidents and the added benefit in terms of driving safety. However, throughout the experiment no accidents in terms of obstacle collisions occurred, which does not allow for proper 'safety' comparisons between the conditions. Hence, it is believed that the visual feedback

confirmed driver assumptions, leading to a higher certainty of their actions. Consequently, it can be said that the visuals improve adherence to the intentional constrains, while respecting the physical constraints. In addition, prior research has shown that the tendency of pushing the envelope does not necessarily imply a higher likelihood of accidents (Borst et al., 2015).

5.2 Visual feedback design

The implemented visuals provided the driver with predictive information based on the instantaneous state of the vehicle. Separately visualizing the automation intentions, would give the driver a better understanding of the underlying controller. One way to visualize the automation intent could be through presenting a future trajectory (curve) based on the desired yaw rate imposed by the controller, together with the existing trend line that is based on the current yaw rate of the vehicle. This visualization should give drivers more direct insight in the difference between the automation and their intent. However, care should be taken not to clutter the display with visual information in order to prevent overloading the driver.

Already during this experiment, participants reported that the implemented visual feedback considerably reduced their field of view from far sight to near sight, which could result in decreased awareness with respect to the surroundings. The phenomenon of visual interference between the driving scene and overlaying visual feedback is also known as cognitive tunnelling (Thomas and Wickens, 2001), which could be prevented by improving the design of the visual feedback. A possible solution would be to adapt the visual feedback to the driving situation. For example, by applying a yaw-threshold to the trend vector, such that the curve remains stable for straight sections, while the curve starts to bend when the threshold is exceeded (e.g. curve negotiation).

6. CONCLUSION

This paper presented novel visual feedback, which visualized the predicted trajectory, the vehicle's yaw limits, and the spatio-temporal constraints to the lane boundary, in order to complement an existing haptic shared control system. A driving simulator experiment (n = 26) revealed that with visual feedback drivers adopted a lower

safety margins with respect to an obstacle (i.e., larger road margins) and a decreased control activity, compared to manual and haptic shared control only. The reduced control activity in combination with the lower obstacle margin suggests that adding visuals allows drivers to anticipate the effect of their steering actions on the car's trajectory more accurately. The combination of haptic shared control and visual feedback yields benefits from the constituent parts, as was shown by a decreased the intra-subject variability and reduced steering activity. Future research should investigate the effects of visual feedback in more detail, specifically with respect to their ability to communicate automation boundaries and intentions, and their effect on the driver's gaze behaviour.

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