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Car Gestures – Advisory Warning Using Additional Steering Wheel Angles

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Abstract

Advisory warning systems (AWS) notify the driver about upcoming hazards. This is in contrast to the majority of currently deployed advanced driver assistance systems (ADAS) that manage emergency situations. The target of this study is to investigate the effectiveness, acceptance, and controllability of a specific kind of AWS that uses the haptic information channel for warning the driver. This could be beneficial, as alternatives for using the visual modality can help to reduce the risk of visual overload. The driving simulator study (N=24) compared an AWS based on additional steering wheel angle control (Car Gestures) with a visual warning presented in a simulated head-up display (HUD). Both types of warning were activated 3.5 s before the hazard object was reached. An additional condition of unassisted driving completed the experimental design. The subjects encountered potential hazards in a variety of urban situations (e.g. a pedestrian standing on the curbs). For the investigated situations, subjective ratings show that a majority of drivers prefer visual warnings over haptic information via gestures. An analysis of driving behavior indicates that both warning approaches guide the vehicle away from the potential hazard. Whereas gestures lead to a faster lateral driving reaction (compared to HUD warnings), the visual warnings result in a greater safety benefit (measured by the minimum distance to the hazard object). A controllability study with gestures in the wrong direction (i.e. leading towards the hazard object) shows that drivers are able to cope with wrong haptic warnings and safety is not reduced compared to unassisted driving as well as compared to (correct) haptic gestures and visual warnings.

1 Introduction

Traffic psychology has revealed some evidence that drivers profit from AWS that rise drivers' attention and direct it towards the potentially risky objects in the scene. Especially novice drivers, when driving in complex urban environments, could profit from such assistance. This

helps drivers to identify potential hazards or critical situations in the near future and react accordingly (Underwood, 2007). In this context, an AWS could be seen as a technical co-pilot that accompanies the driver and gives additional and early information if an object is likely to become a risk for traffic safety.

As an example, Naujoks et al. (accepted for publication) studied the effect of an AWS on drivers' behavior in different situations. The driving situations varied in (1) the visibility when approaching the conflict point (the conflicting road user is visible vs. not visible) and (2) the possibility to anticipate the conflict (depending on the right-of-way condition). The AWS was realized by a simulated HUD and a notifying tone indicating the type of conflict as well as the direction of the hazard 2s before the latest possible warning moment (see below for a detailed explanation). The results of the study conducted in a driving simulator show that driving safety profits especially in conflict situations that appear suddenly and are not foreseeable (e.g. because the conflicting partner ignores the driver's right-of-way).

Due to the substantial safety potential of AWS, Naujoks (2015) discussed concepts of collision mitigation and imminent warnings (e.g. forward collision warning systems) and suggests that such systems should be supplemented by advisory warnings.

This leads to the following categorization of ADAS based on the point in time when the warning is presented to the driver (Neukum, 2011; Naujoks, 2014):

- Collison mitigation: The latest point in time for warning the driver can be estimated using the drivers' reaction time and maximum deceleration of the vehicle (ISO 15623:2013(E)). Later warnings are too late for collision avoidance but could help to reduce the impact of a collision by triggering appropriate actions (e.g. emergency brake assist).

- Imminent warning: Established concepts of imminent warnings become active prior to the latest possible warning moment. The main objective of imminent warnings is to

trigger an immediate driver action, such as braking or steering in order to avoid a collision (Lenné and Triggs, 2009).

- Advisory warning: By applying AWS, the time frame prior to the imminent crash warning (> 1500 ms) is used to inform the driver about potentially dangerous driving situations. The AWS should alert the driver and direct his attention to a potential conflict in order to increase his preparation time before response (Neukum, 2011).

1.1 Human machine interface (HMI) for an AWS

AWS pose high demands for the design of the information/warning towards the driver (Naujoks et al., accepted for publication). Especially the fact that the prediction of a situation can be wrong and thus might lead to unreliable warnings (e.g. false alarms or missing warnings), makes it challenging to develop an HMI which is accepted by the drivers (Bliss and Acton, 2003; Sorkin, 1988).

Regarding timing, advisory warnings should be presented as late as possible, in order to ensure maximum reliability – but as early as necessary for triggering an appropriate driver reaction. Naujoks et al. (2012) showed that visual-auditory information presented 1-2s before the latest possible warning moment leads to a significant reduction of traffic conflicts (compared to non-assisted driving). Using a fixed-base driving simulator Naujoks and Neukum (2014) investigated the effect of early warnings presented via HUD on driver behavior and acceptance. The timing of the warning was varied in five steps (between the latest possible warning moment and up to four seconds prior to the latest possible warning moment in steps of 1s). The results show that upcoming conflicts should be indicated 1-2s prior to the latest possible warning moment in order to trigger appropriate driver reactions and reduce situation criticality. Although earlier warnings did not contribute to a further reduction of the risk for a collision, drivers preferred to receive the warning even 2-3s prior to the latest possible warning moment.

Warnings could also notify the driver of the type (type specificity) and direction (directional specificity) of the potential conflict partner as well as its distance (location specificity) and likelihood (risk specificity; Naujoks and Neukum, 2014). Concerning the effectiveness of all these parameters, scientific evidence shows mixed results (for directional-specificity see e.g. Bliss and Acton, 2003, Cummings et al., 2007, Spence and Ho, 2008; for type specificity see e.g. Cummings et al., 2007, Thoma et al., 2009; for location specificity see e.g. Popiv et al. 2010, Totzke et al., 2012; for risk specificity see e.g. Cacciabue and Martinetto, 2006, Gupta et al., 2002, Lee et al., 2004).

In general, more specific content could lead to a higher probability for providing wrong information to the driver. Nevertheless, research shows that AWS could be efficient although the content of the information delivered to the driver is wrong. Using a driving simulator, Naujoks (2015) studied the behavior of drivers that experience early warnings that indicate the wrong direction of a conflicting road user. He showed that the wrong warnings did not reduce the effectiveness of driver warnings and drivers react equally fast and brake similarly compared to drivers receiving an unspecific warning.

Regarding the warning modality, scientific work has shown that visual displays should be preferred over voice messages or intrusive audio sounds (COMSIS Corporation, 1996; Dingus et al., 1998; Green et al., 1993; International Harmonized Research Activities working group on Intelligent Transport Systems, 2008; Rhede et al., 2011). Acoustic signals are to be avoided and should be reserved only for urgent warnings. Nevertheless, a non-intrusive sound could make the information/warning more effective, because the drivers' perception of a visual warning largely depends on the viewing direction of the driver (e.g. a driver might not recognize a warning displayed in the instrument cluster, if he focusses all his visual attention on an object in the traffic scene). In general, scientific literature supports the opinion that redundant display concepts using different modalities are more efficient than unimodal information (Kramer et al., 2007; Ho et al., 2007; Scott and Gray, 2008). Despite this advantage of multi-modal warnings, purely visual displays are preferred for AWS, because

AWS could be activated frequently and with some likelihood of false alarms. Therefore, intrusive warnings should be avoided, as they could lead to reduced efficiency and acceptance (Bliss and Acton, 2003; Dingus et al., 1998). Furthermore, the differences in reaction times between visual and visual-auditory warnings are less relevant for early warnings (Naujoks, 2015).

Advisory warnings based on haptic signals are a promising approach to direct the driver's attention, because they trigger fast responses and can be specific to direction as well as location without putting additional load to the visual information channel or delivering annoying acoustic signals (Neukum, 2011). Haptic information can also be delivered to the driver without annoying or alarming other passengers. Examples for using haptic information in the vehicle include lane keep assistance, heading control, active accelerator pedals for efficient driving, and collision mitigation using tightening of the seat belt (for an overview see Fecher and Hoffmann, 2015). The major drawback of haptic warnings is the fact that this modality does not allow to deliver complex information to the driver.

1.2 Objective of the present study

The approach taken in the present study uses an additional steering motion (called Car Gesture) that results in an additional steering wheel angle and torque to inform the driver about potential hazards or conflict partners. The gesture communicates to the driver in which direction the vehicle should be steered in order to increase the safety distance to a potential hazard. The basic idea is that the gesture nudges the driver to drive a safer trajectory rather than autonomously carrying out this trajectory.

An advantage of haptic warning signals is that the haptic information channel is used to a much smaller extent compared to the visual channel. The latter is the main information channel during driving and additional stimuli could lead to distraction. Another advantage is that additional steering is directional and therefore recommends in which direction (and when) the driver should move the vehicle to reduce the risk. Another benefit of using

additional steering to communicate information to the driver lies in the fast reaction on haptic stimuli (Neukum and Krüger, 2003; Neukum et al., 2008; Switkes et al., 2007).

As Car Gestures directly intervene with the vehicle control, the acceptance as well as safety implications have to be analyzed before the concept can be further developed. Therefore, the objective of the following driving simulator study was to investigate the effect of the gestures on the drivers' understanding, acceptance, driving behavior (e.g. speed, deceleration, steering), and safety. Furthermore, controllability was analyzed by adding wrong alarms (additional steering angle towards a potential hazard) to the experimental conditions.

The driving simulator study compared the gestures with visual warnings presented in a HUD and a baseline condition without any assistance. The analysis was done using different urban driving situations including potential hazards.

In the following sections, we detail the methods used in our study. Following this, the results are presented and discussed. Finally, the approach of using additional steering wheel angles for an early warning of the driver is evaluated and recommendations for its future usage are provided.

2 Material and Methods

2.1 Participants

24 participants (14 female) took part in the study and were paid for their participation. Their mean age was 39.2 (sd = 13.8) years (Figure left). The mean self-reported annual driving experience was 15979 (sd = 12119) km (Figure right), with 34.0% (sd = 19.2) experienced in urban environments.

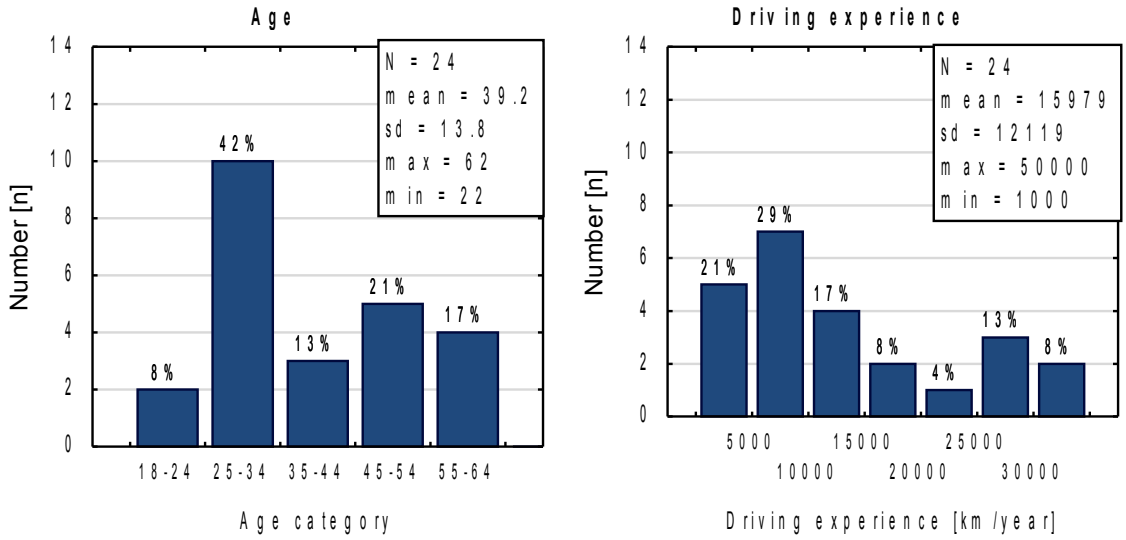

Figure . Age distribution (left) and yearly driving experience (right) in the study sample.

Participants were recruited from the test driver panel of WIVW GmbH (Würzburg Institute for Traffic Sciences). Having received a 5 hours training on general driving, all subjects are well trained for driving in the dynamic driving simulator. This amount of training also prevents problems of simulator sickness.

2.2 Apparatus

The study took place in the dynamic driving simulator of WIVW GmbH. The simulator consists of a dome that is mounted on a FCS Moog motion system with six degrees of freedom. The mock-up is made up of a real BMW 520i that is cut off behind the B-pillar. The steering system consists of a SENSO-Wheel capable to set steering torques up to 7.5 Nm.

The simulator has a 180° horizontal and 47° vertical field of view with three image channels. The images are presented on a spherical projection screen with a diameter of 6 m. For presenting the driving scenario, 14 computers connected by a 100 MBit/s Ethernet network were used. The update frequency of the projection system is 60 Hz at minimum. There are three LCDs representing the rear view mirror as well as the left and right outside mirrors. Auditory output includes eight sound channels including subwoofer and bodyshaker.

The driving simulation software SILAB 4.0 developed by WIVW GmbH was used. During simulation, a graphical user interface allowed the observation and logging of all data. The measurement frequency was 100 Hz. An experimenter observed all driver views on separate display screens and communicated with the participants via intercom.

For the subjective evaluations participants answered questions containing scales of six verbal categories for evaluating the predictive warning (item: “How helpful was the system in the situation just experienced?”; answer categories from “not helpful at all” to “very helpful”), and 13 numeric categories for measuring the design of the warning (item: “The moment of intervention was…”; answer categories from -6 “too early” to 6 “too late” with 0 indicating an absolutely appropriate moment of intervention). Qualitative questions were asked in order to get some more details about user acceptance and preferences.

During the controllability run with gestures to the wrong direction a scale with eleven categories was used to assess the criticality of the situation (from “not noticed” to “uncontrollable”; Neukum et al., 2008).

2.3 Driving scenario

The driving scenario had a length of 19 km and consisted of different urban sections with one or two lanes per driving direction. The scenario included several intersections and was surrounded by pavements, rows of houses, parks, and parked vehicles. The scenario included 20 test situations that varied regarding the movement of the hazard (moving vs. not moving), the lateral position of the hazard (extending into the driving lane of the ego-vehicle vs. possible to pass without the need to steer), the hazard object type (vehicle, pedestrian, bicycle), and the direction of the hazard (left vs. right side of the current driving lane). The same situations (but in different order) were used for all experimental conditions. The driving time in each condition was about 25 minutes.

Error: Reference source not found provides some examples of the driving situations used. Depending on the above mentioned characteristics, the criticality of the situations varies from very low (e.g. a pedestrian standing on the curbs) to high (e.g. a pedestrian walking on the street requiring an evasion maneuver by the driver).



Figure . Exemplary test situations with varying movement characteristic, lateral position, hazard object, and direction (the hazard object is highlighted).

Subjects were instructed to drive with a speed of 50 km/h and to always drive straight through all intersections. On roads with more than one lane per direction, subjects should drive on the most right hand lane but were allowed to pass slower vehicles. Furthermore, subjects were instructed to hold the steering wheel loosely with both hands.

An additional driving scenario including three test situations was used to make the subjects experience gestures that direct the vehicle into the wrong direction (i.e. into the direction of the hazard) in order to measure controllability and acceptance of such a malfunction. The driving time for this additional scenario was about 4 minutes.

2.4 Design

The study had a full within-subject design and compared behaviors in the BASELINE (no assistance), CAR GESTURE (haptic warning at steering wheel), and HUD (visual warning) conditions.

The Car Gesture concept was originally researched and developed on a prototype vehicle with real actuation in simplified situations driven by expert drivers. The specifications were subject to safety considerations, limitations of real vehicle controllers, and the messages communicated to the driver as well as potential observers outside the vehicle. The dynamics introduced by the gesture should be in the order of a lane keeping assistant with respect to steering wheel angle velocity and steering wheel torque. The maximum offset in the lateral direction should be in the order of the tire width of the vehicle. This turned out to be well noticeable by the driver but is almost not noticeable to outside observers. The steering wheel pattern was tuned for maximum acceptability by the driver by balancing the perceptibility versus the potential to induce active counter steering due to threatening steering movements. The longitudinal timing of the maneuver was derived from the length of the required pattern and the timing requirements for a predictive warning system as pointed out above. This concept was to be evaluated in more realistic scenarios with non-expert drivers. Hence, the study was designed with the goal to transfer the concept from the real vehicle into the simulator while maintaining the character of the function within the described design space. This leads to the framework for the specifications as described below.

When driving in the CAR GESTURE condition in the simulator, an additional steering angle movement informed the driver of a potential hazard object at a time to arrival of 3.5 s (TTA). This steering angle “nudged” the vehicle into the opposite direction of the hazard. The gesture itself (i.e. without additional effort by the driver) is not designed to safely avoid an obstacle (e.g. bicycle driving on the own lane) automatically. A maximum steering wheel angle of 8 degrees was reached 0.75 s after the onset of the gesture. Afterwards, the

additional steering wheel angle was reduced and turned negative after approximately 1.5 s. This was done in order to roughly align the vehicle into a straight direction again. The maximum negative steering wheel angle was -2 degrees. After 3.5 s the gesture is complete.

In an open loop condition with the hands off the steering wheel (Figure left), the gesture resulted in a lateral movement of approx. 0.45 m away from the hazard. In the closed loop condition with hands loosely on the steering wheel (Figure right), the gesture had a reduced effect, because the driver intuitively reacted with some hardening of the grip before he followed the additional steering wheel torque. Therefore, the lateral displacement was reduced to approx. 0.35 m away from the hazard.

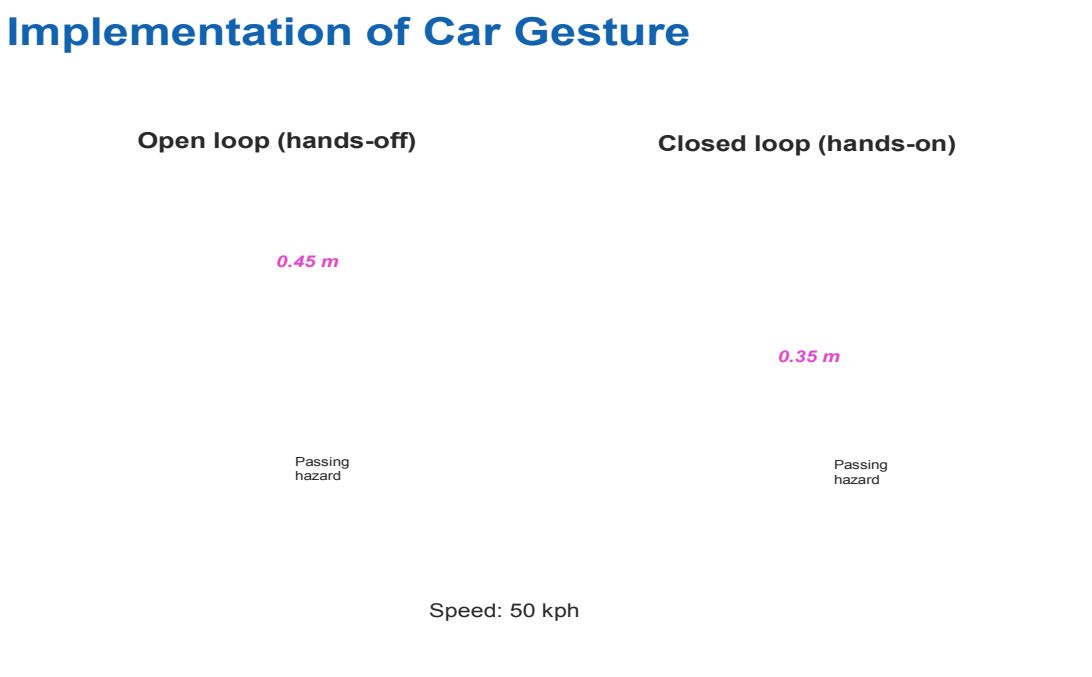

Figure . Effects of a gesture in open (left) and closed (right) loop condition.

The visual warning in the HUD condition was done using the projection of an icon into the driving scene (i.e. on the road just in front of the ego-vehicle) if the system detects a potentially hazardous object (Figure). The icon depicts a street with two lanes and a steering wheel. Two arrows illustrate in which direction the steering wheel should be turned and thus

the resulting trajectory of the vehicle. Identical to the CAR GESTURE condition, the warning was activated 3.5 s before the hazard was reached and remained active for 3.5 s.

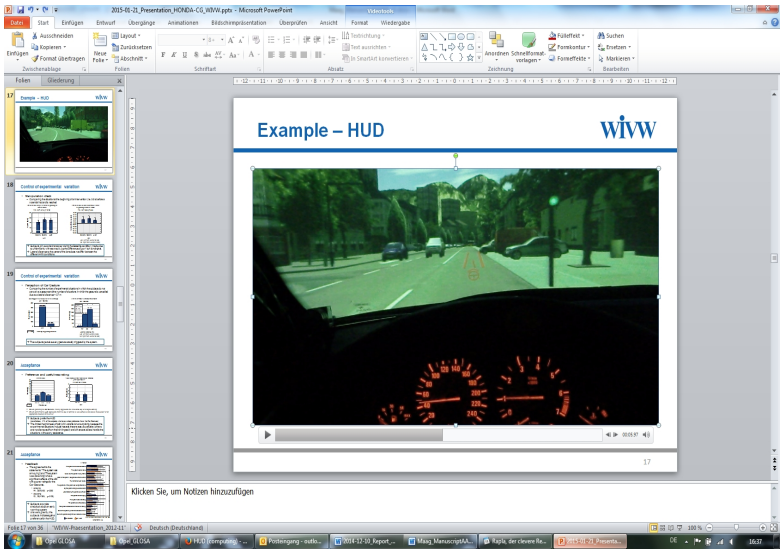

Figure : Warning in the HUD (left) and icon (right) indicating a potential hazard from the right side of the lane.

For the analysis of driving behaviors in the different experimental conditions, the driving simulator software recorded dynamic driving data. In particular, the following driving variables were extracted from the raw data: (1) maximum deceleration between the point of time of the early warning (3.5 s TTA) and a TTA of 1.0 s [m/s^2], (2) speed difference between 3.5 s and 1.0 s TTA [km/h] (negative values: driver reduces speed; positive values: driver increases speed), (3) difference in lateral distance to the center of the lane between 3.5 s and 1.0 s TTA [m] (negative values: vehicle moves into the direction of the hazard; positive values: vehicle moves away from the hazard), (4) difference in steering wheel positions between 3.5 s and 1.0 s TTA [rad] (negative values: driver steers into the direction of the hazard; positive values: drivers steers away from the hazard), and (5) minimum distance between the ego-vehicle and the hazard [m] (Euclidean distance between the edge of the vehicle and the edge of the hazard).

2.5 Procedure

Drivers were instructed about the objectives of the study and completed a data privacy statement. They were familiarized with the driving scenario by driving a short practice session including some potential hazard objects. Subsequently, participants drove the BASELINE condition.

Afterwards participants drove the CAR GESTURE condition and the HUD condition. The order of these two conditions was counterbalanced between participants. Before both runs started, the drivers were familiarized with the assistance systems on a short practice course. Subjects were instructed that the gestures as well as the visual warnings in the HUD indicate a direction into that the vehicle should be guided, in order to safely pass a potential hazard. Drivers were also instructed that they were free to follow the suggestions or not. During both experimental conditions and after each experienced warning, the subjects had to press a button at the steering wheel to indicate that they had recognized a warning. After each press of the button they had to state how helpful the system intervention was. After participants had driven both conditions, the preferred condition (CAR GESTURE vs. HUD) had to be reported.

Subsequently, the subjects drove another short scenario including three hazard situations. The gestures during that drive directed the vehicle in the wrong direction (i.e. in the direction of the hazard). If a driver reported surprise or astonishment, the experimenter asked to rate the criticality and controllability of the situation. Overall, the experiment took about two hours for each participant.

3 Results

For the analyses the five driving parameters (maximum deceleration, speed difference, difference in lateral distance, difference in steering wheel position and minimum distance) were calculated for each of the 20 test situations (i.e. for each potential hazard object

passed) separately for each participant and each treatment factor (BASELINE vs. CAR GESTURE vs. HUD). According to the repeated measurement design, analyses of variance (ANOVAs) were executed with HMI as within-subjects factor. In order to get a deeper understanding of the driving behavior after receiving an advisory warning, the influence of situation characteristics is examined by conducting two-way ANOVAs with HMI and situation characteristic as within-subjects factors. The studied situation characteristics are (1) static vs. dynamic hazard, (2) explicit vs. implicit hazard, and (3) vehicle vs. non-vehicle hazard. The α-level for all statistical analyses is set to 0.05.

In the following, the effect of the two early warning concepts (CAR GESTURE vs. HUD) on the drivers' acceptance is reported. Secondly, the effects of the gestures vs. the two other experimental conditions on driving behavior and safety (measured by objective parameters) are presented. And lastly, the controllability of false warnings (i.e. guiding to the wrong direction) is described.

3.1 Acceptance and preference

After the subjects experienced the Car Gestures as well as the warnings in the HUD, they were asked to indicate their preferred type of HMI. 42% preferred the HUD, 29% the Car Gestures, and 29% had no preference (Figure left).

In addition to this overall feedback, the subjects rated the usefulness of the system after every hazard they had experienced. This online feedback resulted in comparable ratings for the Car Gestures and the HUD (Figure right). With regard to the test situations used, both HMI conditions were rated as not very helpful.

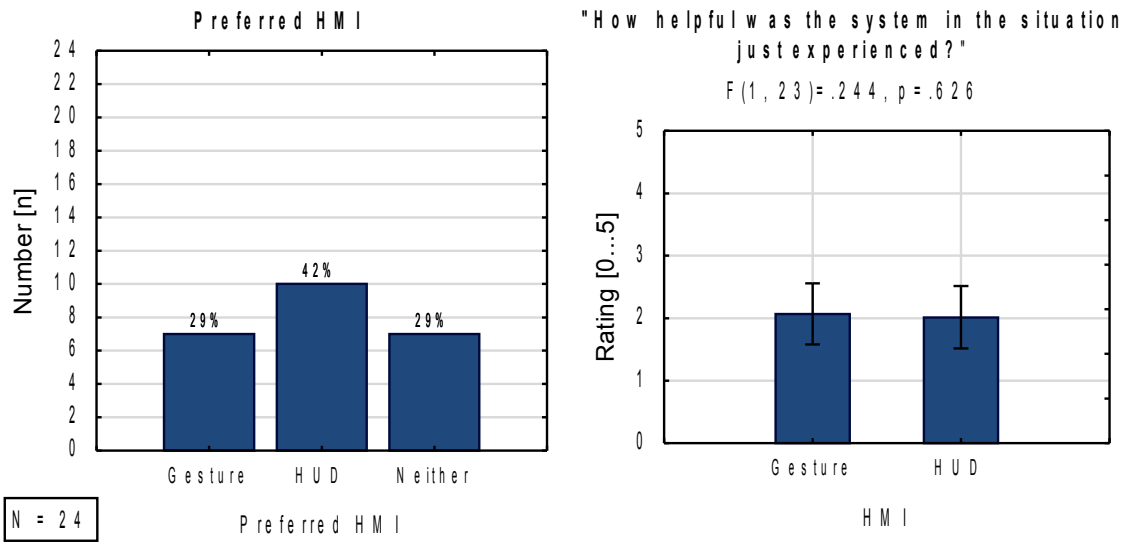

Figure . Preference of Car Gesture vs. HUD (left) and rating of usefulness of system (right).

An analysis of the effect of implicit vs. explicit situations on drivers' usefulness rating shows that advisory warnings in the HUD as well as Car Gestures are more helpful in situations with an explicit hazard ($F(1,23)=20.52$, $p=.001$). The advisory warning is rated as significantly more helpful in situations with an explicit hazard (protruding into the ego-vehicle's lane; $m=2.32$) compared to situations with an implicit hazard (non-protruding into the ego-vehicle's lane; $m=1.71$). An analysis of the other situation characteristics (static vs. dynamic hazards; vehicle vs. non-vehicle hazards; hazard from the left vs. hazard from the right) on the usefulness ratings shows no further significant effects.

The drivers were also asked to give a more detailed reason for their preference. A categorization of the answers reveals that drivers preferring the gestures mainly appreciate the innovative mode of warning and the use of the haptic information channel (n=4). Drivers preferring the visual warning appreciate that this way of warning is less obtrusive (n=6) and leaves the decision for an appropriate reaction to the driver (n=4). The drivers who prefer none of both HMI variants mention that they reacted earlier than the systems and that the warnings are triggered too late. Another point mentioned by three drivers is that both systems distract the driver from the driving task.

Concerning the point of time of the system intervention (from too early to too late), no significant differences between both HMI variants can be seen (Figure). The answers for both variants confirm that a warning at 3.5 s before the potential hazard is reached is considered as appropriate.

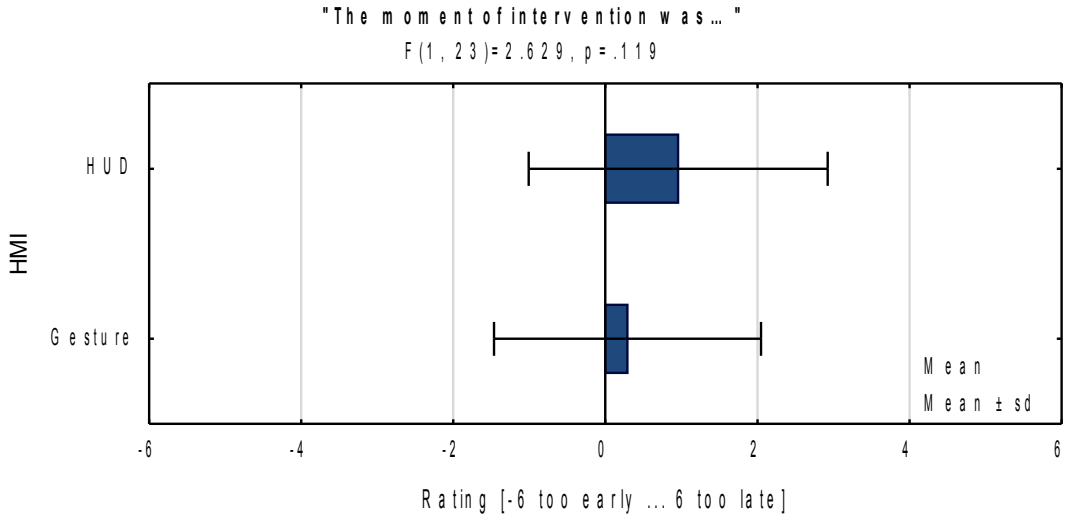

Figure . Rating of moment of system intervention.

3.2 Driving behavior and safety

The results concerning lateral driving behavior show that the Car Gestures as well as the visual warnings via the HUD influenced the drivers to steer the vehicle further away from the potential hazard compared to the baseline condition without any warning (Figure left). The lateral distance between the hazard and the vehicle increased by approximately 0.38 m in the BASELINE, by 0.53 m in the CAR GESTURE, and 0.48 m in the HUD condition. The maximum deceleration was highest for the BASELINE (-0.67 m/s2) and significantly lower for the CAR GESTURE (-0.37 m/s2) and the HUD condition (-0.39 m/s2; Figure right). Effects on speed difference and difference in steering wheel position are not significant (speed: $F(2, 46)=.0789$, $p=.924$; steering behavior: $F(2, 46)=1.387$, $p=.260$).

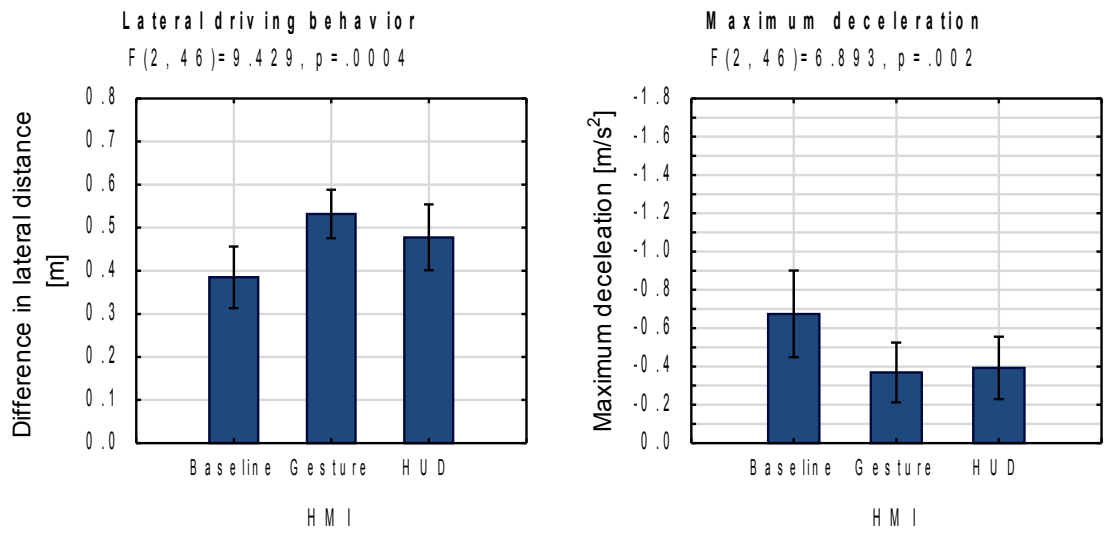

Figure . Effect of warning condition on lateral driving behavior (left; >0: vehicle moves away from hazard) and maximum deceleration (right).

The results support the hypothesis that an early warning could help the drivers to react earlier by increasing the lateral distance to the hazard. In the CAR GESTURE condition the effect on lateral driving behavior is a result of shared control with a driver interacting with the haptic “nudge” from the gesture. By that, a longitudinal reaction in terms of a deceleration becomes unnecessary.

The analysis of a static vs. moving hazard shows that dynamic hazards lead to a more pronounced lateral adjustment (0.52m vs. 0.43m; Figure left). The interaction effect HMI x static vs. dynamic becomes not significant (F(2, 46)=.068, p=.935).

As explicit hazards protrude into the trajectory of the ego-vehicle, it is expected that the lateral distance away from the hazard is greater for explicit than for implicit objects. The significant two-way interaction shows that this effect is visible in all three HMI conditions, although most prominent in the baseline drives (Figure right). The reason for that is that without any warning the lateral adjustment due to the potential hazard is very small compared to the conditions with haptic or visual warning.

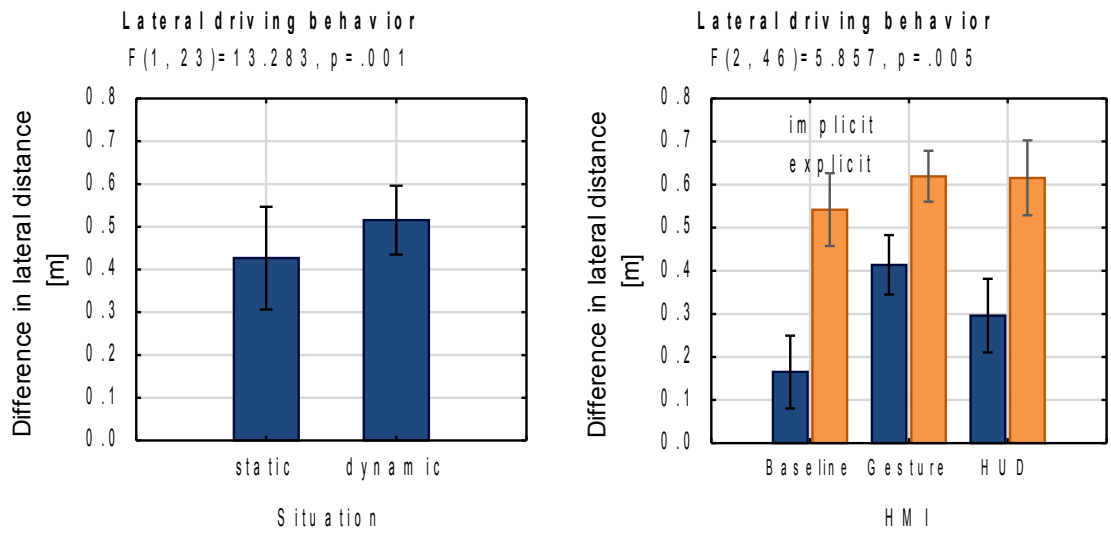

Figure . Effect of static vs. dynamic hazard (left) and warning condition and implicit vs. explicit hazard (right) on lateral driving behavior (>0: vehicle moves away from hazard).

Subjects are warned when they approach vehicle and non-vehicle (e.g. bicycle, pedestrian) hazards. The gathered data show that lateral driving behavior is stronger influenced by vehicles (Figure). The drivers steer on average 0.49 m away from a vehicle hazard compared to 0.41 m for non-vehicle hazards. Due to the larger dimensions of vehicle objects, this behavior is comprehensible – especially as in most test situations vehicle hazards protrude into the lane in a larger extent than non-vehicle objects. The interaction effect HMI x hazard object becomes not significant ($F(2, 46)=1.427$, $p=.250$).

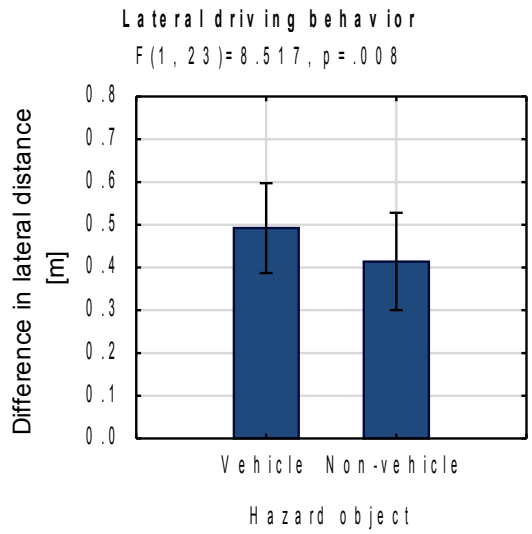

Figure . Effect of vehicle vs. non-vehicle hazard on lateral driving behavior (>0: vehicle moves away from hazard).

An analysis for the hazard direction is not feasible, as the situations with hazards from the right were three times more frequent than hazards from the left.

The effect of the early warnings on driving behavior can be further examined by taking into account the timing of the driver behavior. The results show that the CAR GESTURE condition leads to a faster lateral reaction compared to BASELINE and HUD (Figure left). Whereas there is no difference in lateral driving behavior for the period 3.50 - 2.67 s TTA for the different treatments, the period 2.67 - 1.83 s TTA shows a stronger reaction for the CAR GESTURE than for the BASELINE and HUD condition. In the latest period (1.83 - 1.00 s TTA) the difference between CAR GESTURE and HUD is no longer visible.

Therefore, Car Gestures and – to a lesser extent – visual warnings lead to a faster reaction in terms of lateral driving behavior compared to driving without any warning system. As a consequence, the need for lowering the speed in the latest period before reaching the hazard (1.83 - 1.00 s TTA) is reduced (Figure right).

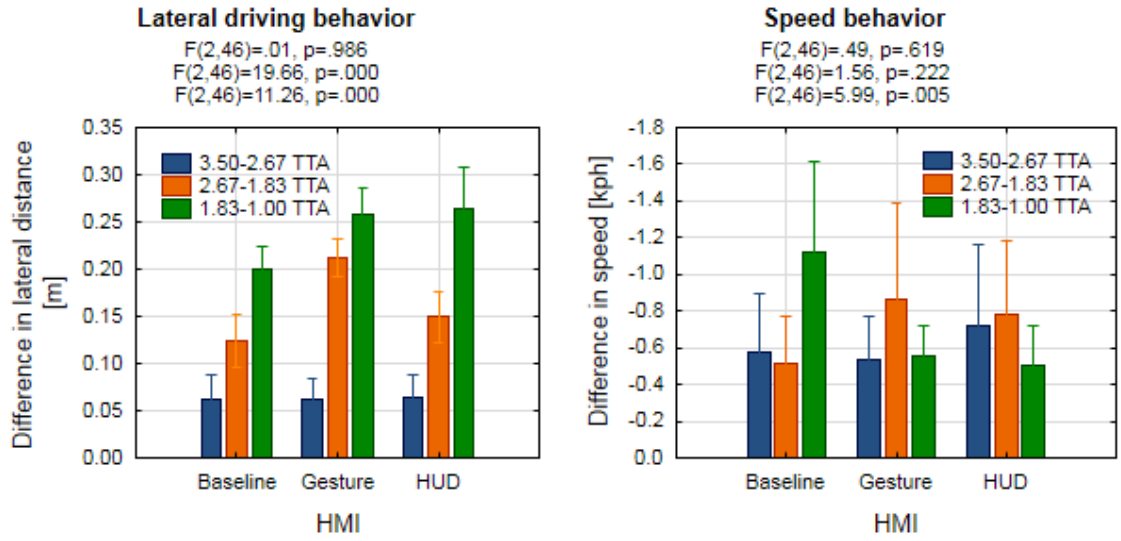

Figure . Effect of warning condition and reaction time on lateral driving behavior (left; >0: vehicle moves away from hazard) and speed behavior (right; <0: vehicle becomes slower).

The main objective of an early warning system is to reduce the risk of a potential collision. For the situations tested, safety can be measured by the minimum distance to the hazard. An analysis of this safety variable shows a statistically significant effect of the warning condition on the minimum distance to the hazard object (Figure). A post-hoc analysis reveals that only the difference between the BASELINE (1.19 m) and the HUD condition (1.33 m) is significant. The minimum distance in the CAR GESTURE condition is 1.27 m, i.e. located between the other two treatment conditions.

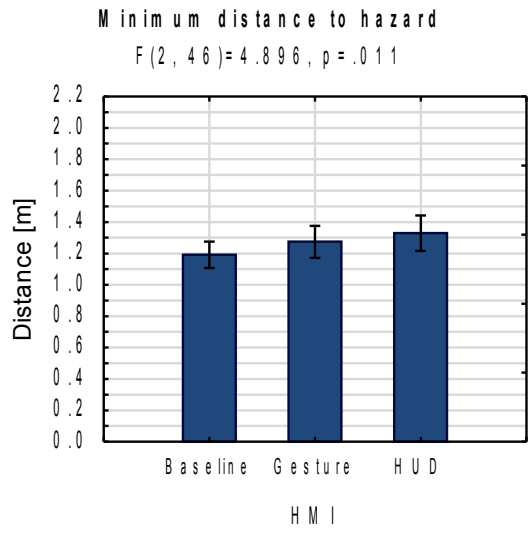

Figure . Effect of warning condition on the minimum distance to hazard.

3.3 Controllability

As an AWS based on gestures actively intervenes with the driving task by applying an additional torque to the steering wheel, it is very important to check how drivers cope with wrong warnings and whether they are able to control them. This was tested by presenting the subjects gestures that direct the vehicle into the wrong direction, i.e. towards the potentially hazardous object. Afterwards the subjects were asked about the criticality of the situation.

The mean ratings of criticality for the three situations range between 3.8 and 4.3 on a scale from 0 to 10 (Figure left). This means that on average drivers perceived the situation as unpleasant but not as dangerous. Three subjects did not recognize that the gestures directed them into the wrong direction (Figure right; average rating ≤ 0.5). Nevertheless, two subjects (8%) rated gestures to the wrong direction as “dangerous” (average rating > 6.5). “Uncontrollable” was never used as an answer category.

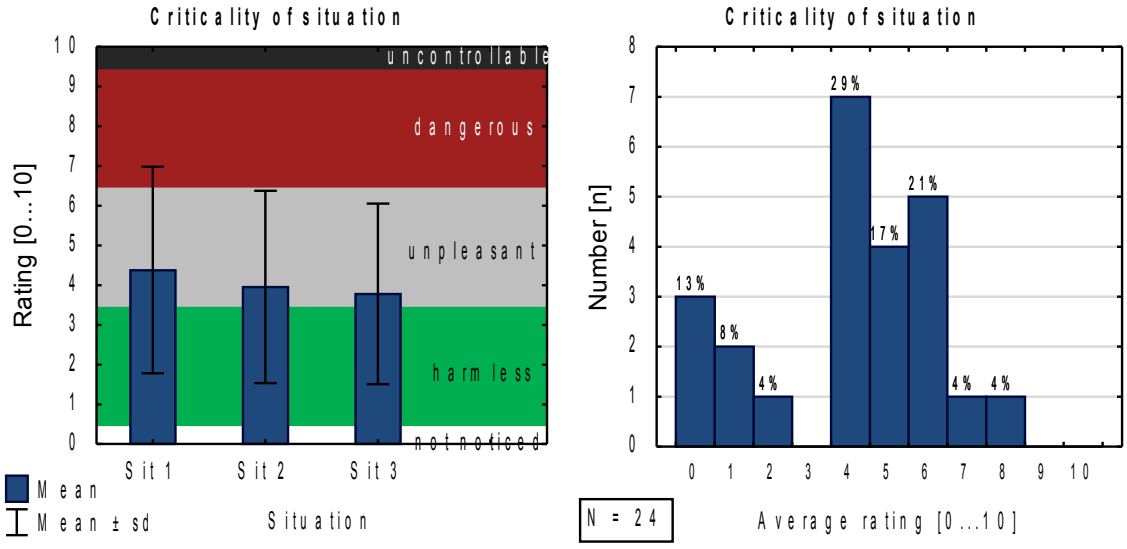

Figure . Mean ratings of criticality for the three situations (left; Sit 1 and Sit 3 are situations with a vehicle as hazard, Sit 2 is a situation with a pedestrian as hazard) and average criticality rating per subject (right) for gestures to the wrong direction.

The following analyses are based on a selection of three similar driving situations of the conditions BASELINE, CAR GESTURE, HUD, and WRONG CAR GESTURE. The lateral driving behavior shows no significant effect for the conditions BASELINE, CAR GESTURE, and HUD. In the distance of 3.5 s to 1.0 s TTA, the gesture to the wrong direction (WRONG CAR GESTURE) leads to a lateral displacement of about 0.14 m towards the potentially hazardous object (Figure left). Nevertheless, the amount of counter-steering does not exceed any steering movements found for the correct Gar Gestures. This supports the feedback given by the subjects who rate the wrong Car Gestures as unpleasant but not as dangerous.

The comparison of the objective safety parameters when passing the hazard object shows that gestures to the wrong direction do not reduce safety, because they do not lead to smaller minimum distances (Figure right) to the hazard. Drivers are able to cope with the malfunctioning of the AWS based on additional steering wheel angles. As a consequence, the lateral effect of wrong gestures is controlled by drivers and safety is not compromised.

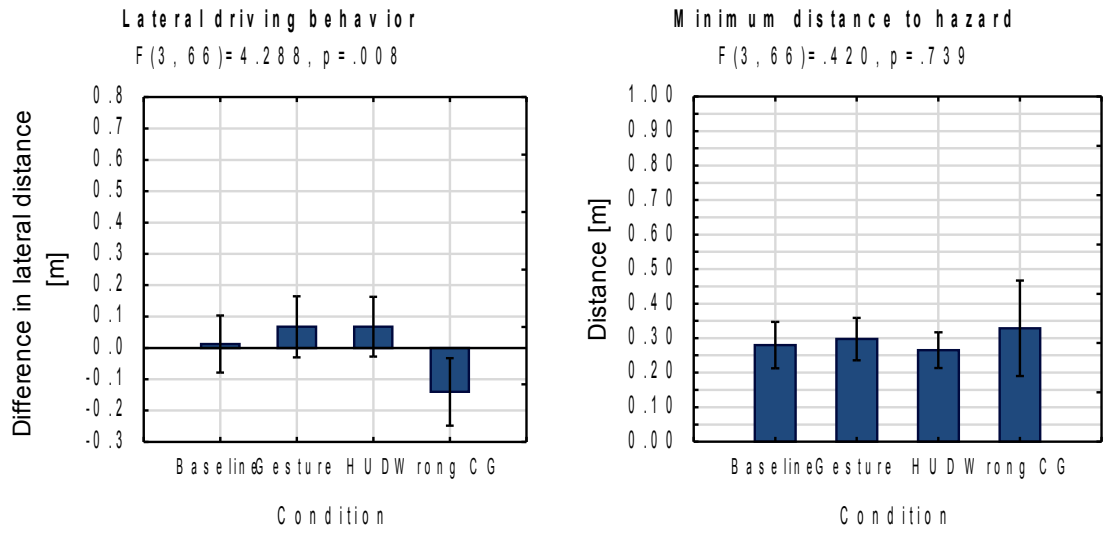

Figure . Lateral driving behavior (left; >0: vehicle moves away from hazard) and minimum distance to the hazard (right) during wrong alarms (gesture in wrong direction) compared to other warning conditions.

Finally the correlations of objective parameters that indicate a safe driving behavior with subjective ratings of criticality are analyzed. The results show that no correlation turns significant (Table):

Table . Correlations between the driving behavior / safety parameters and the subjective criticality of the situation with Car Gestures in the wrong direction.

Correlations (N=67)	Maximum deceleration [m/s^2]	Speed adjustment [kph]	Lateral driving behavior [m]	Steering behavior [rad]	Minimum distance to hazard [m]	Minimum TTC to hazard [s]
Criticality [0…10]	.116 (p=.351)	.019 (p=.881)	.029 (p=.819)	.014 (p=.913)	.148 (p=.234)	.088 (p=.480)

4 Discussion

The report at hand compares an AWS based on an additional steering wheel angle (i.e. Car Gestures) with informing the driver via visual warnings that are presented in the driving scenery (i.e. via HUD). Both experimental conditions are compared to a baseline condition with no warning at all. The comparison is made in terms of subjective acceptance and preference, driving behavior following an early warning, and safety.

The effects have been measured in a variety of urban situations with varying hazard objects that are characterized by different movement characteristics, lateral position, and direction. The study took place in a driving simulator with motion system and included 24 subjects who experienced the three experimental conditions (within-subjects design).

Regarding the subjective acceptance and preference, the results show that drivers clearly prefer the visual warning presented in a HUD compared to the gestures in the steering wheel (42% vs. 29%). Drivers preferring the HUD especially appreciate that this way of warning is less obtrusive and leaves the decision for an appropriate action at the driver. Moreover, HUDs are seen as state-of-the-art HMI solutions in the vehicle by many drivers. This might also contribute to the drivers' preference of that warning modality.

Nevertheless, both variants of an AWS are rated as not very helpful. Presumably, this is due to the non-criticality of the hazards that – in most cases – are easy to notice by drivers who are not distracted from their primary task of driving. Thus, the baseline condition without any assistance showed that drivers were able to handle all situations without any risk of a (near-) accident.

Concerning the design and timing of the tested AWS, subjects reported that a warning given 3.5 s before a potential hazard is reached is appropriate for an urban setting.

Besides the subjective feedback given by the drivers, it is important to analyze how drivers react when they have recognized an early warning. The results show that the Car Gestures

as well as the visual warnings guide the driver and his vehicle further away from the potential hazard compared to unassisted driving. The maximum deceleration is highest for the baseline condition and significantly lower for the situations in which the driver is supported by Car Gestures or visual warnings in the HUD. Both results support the hypothesis that warnings presented by an AWS help the driver to react earlier by increasing the lateral distance to the hazard. By that, an adjustment of speed and acceleration becomes unnecessary.

As the driver interacts with the steering torque triggered by the Car Gesture, the resulting lateral driving behavior represents a combined effect of driver and system. But as the driver is able to easy override the gesture, it is the driver who decides if the driving direction indicated by the gesture is appropriate. Therefore, it remains the driver – supported by the Car Gesture – who reacts to the potential hazard.

When looking at safety it becomes apparent that visual warnings as well as Car Gestures increase safety. Whereas post-hoc analysis reveals that only in the HUD condition the minimum distance to the hazard object is greater than without assistance (the difference between driving assisted by haptic warnings at the steering wheel and the baseline condition is not significant), the timing of lateral driving behavior supports also a benefit of the Car Gestures. Haptic warnings lead to a significant faster lateral driving reaction than visual warnings presented in the HUD.

In addition, the advantage of Car Gestures is to warn the driver without using the visual information channel. As visual distraction and overloading of the driver is discussed since many years (Matthews et al., 1996; Wickens, 2002), using another way of informing the driver about upcoming hazards could be beneficial in many situations. Therefore, it seems possible that the safety benefit of Car Gestures becomes even more apparent if the visual load for the driver is increased (e.g. by introducing secondary tasks).

Regarding the ability to cope with Car Gestures to the wrong direction, the results show that most drivers perceive the situation as unpleasant, but not as dangerous. No subject rated the situation as uncontrollable, although two subjects rated an additional steering wheel angle that guided the vehicle towards the hazard object as dangerous. The controllability of wrong gestures can also be seen by the fact that the minimum distance to the hazard is not adversely affected compared to all other experimental conditions (i.e. baseline driving without assistance, correct Car Gestures, and visual warnings in the HUD). Drivers are able to compensate the Car Gesture in the wrong direction without reducing safety.

All in all, the Car Gestures have revealed a positive effect on the drivers' behavior when approaching a potentially hazardous object. They lead – similar to a visual warning in a HUD – to a more pronounced avoidance behavior compared to the baseline condition. This can be shown by an increased lateral distance to the hazard object, meaning that the minimum distance to the hazard is increased. Although the overall safety benefit of Car Gestures seems to be somewhat lower than that of visual warnings, the analyses have shown that the vehicle is guided away from the hazard faster when using gestures at the steering wheel. Especially in situations where the potential hazard develops into an actual hazard this faster reaction could be very valuable.

5 Conclusions

Car Gestures are an innovative approach to inform and warn the driver about upcoming potential hazards by actively intervening with the trajectory of the vehicle and smoothly steering to the opposite direction (away from the potential hazard). As a consequence, the driver's attention is increased, leading to a faster and more appropriate reaction than during unassisted driving. Further studies should analyze if novice and experienced drivers react differently when warned by Car Gestures and if haptic warnings have an even greater effect on driving behavior and safety when the driver is distracted by a secondary task.

Furthermore, future studies should analyze drivers' visual attention. If drivers understand the meaning of the early warnings correctly, they should allocate their attention earlier towards the hazard object and keep attention until the hazard is safely passed. Moreover, further research should use hazards that are more difficult to detect by drivers.

Although alternative approaches (e.g. HUD) are available and appreciated by many drivers, Car Gestures remain an approach for driver warnings that is worth to be considered further. The reasons are that Car Gestures recommend an appropriate steering action to the driver and are effective by increasing safety distance already at a point in time when drivers are still analyzing the situation. Moreover, the visual channel is already used for presenting much information to the driver. Finally, haptic HMI concepts become worth considering when further steps towards automated driving are taken. More and more advanced assistance systems allow the driver to shift his attention away from the road and the driving task for an increasing amount of time, rendering him unaware to most existing visual warning concepts. In contrast, as long as a driver has to keep his hands on the steering wheel a haptic signal will still alert him efficiently, and can, as was done with the Car Gestures, already suggest a necessary response before the driving scene is fully analyzed by the driver.

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