Testing external HMI designs for automated vehicles – An overview on user study results from the EU project interACT

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***Abstract*— This paper gives an overview on the design and research work conducted in the EU interACT project. The objective of the project is to ensure the safe integration of Automated Vehicles (AVs) into mixed traffic environments. Based on psychological models of current interaction between humans in traffic, interaction design strategies were defined for the implicit and explicit communication of an AV with other road users. Those strategies were tested with users in eight simulator studies. The main objectives, methods and results of these studies are summarized in this paper. The outcomes of the studies reveal a need for a well-adjusted communication of the AV by implicit and explicit (external HMI) signals in urban environments.**

Keywords—Automated vehicles, interaction design, simulator studies, external HMI

I. INTRODUCTION

It is very likely that Automated Vehicles (AVs) will be deployed in mixed traffic including none automated vehicles, cyclists and pedestrians. Thus, they need to interact safely and efficiently with other traffic participants [1]. The EU H2020 project interACT works towards the safe integration of AVs into mixed traffic environments (https://www.interactroadautomation.eu/). Across three European countries (Germany, Greece, & the UK), data was collected on how human traffic participants currently interact in real traffic conditions [2]. This data was used by the interACT project team to develop, implement and evaluate novel external Human-Machine Interface (eHMI) and internal HMI (iHMI) elements to enable AVs to communicate both with surrounding road users and on-board users (Fig. 1).

Fig. 1. Change of interaction needs for AV in mixed traffic environments

This paper focusses on the development of the interACT implicit and explicit (eHMI) communication strategies for other road users (right half of Fig.1). First, we give an insight into the design process of the interaction strategies (see section II), starting with a catalogue of implicit and eHMI design considerations that were applied to the interACT scenarios (urban intersections and parking spaces). Thereafter, the different interaction strategies derived from the design work will be presented. The paper also summarizes the results of eight participants studies conducted in Virtual Reality simulators and driving simulators at BMW, TU Munich, ITS Leeds and DLR (see section III). Finally, we recapitulate the main results of the studies and come up with conclusions on implicit and eHMI designs for AVs (see section IV).

II. THE DESIGN PROCESS

In the interACT project we followed an iterative, user-centered design process [3]. The design process itself was split into three main steps: 1. The definition of relevant messages and the development of general interaction strategies; 2. The selection of appropriate technologies to cover the eHMI requirements; 3. The selection of specific implicit and eHMI designs based on the interaction strategies.

All steps were significantly influenced by the insights of the observational studies on human-human interaction in current traffic situations [2]. The main outcomes taken into account were the following:

- Implicit communication, that means a behaviour which is at the same time both achieving and signaling movement and/or perception such as increasing the gap size or reducing the vehicle speed, is the most often used, essential form of communication;
- Explicit communication, defined as behaviour signaling perception and/or movement without at the same time achieving either of these such as a hand gesture; takes place in ambiguous interaction scenarios with low velocities of the traffic participants;
- Explicit communication can support the cooperation among traffic participants, especially in cases when a potential conflict exists or might occur.

A. *Definition of Interaction Design Strategies for eHMI*

Taking the observational results and previous work on design considerations [4] into account, the design team defined the following messages as relevant for other traffic participants:

Table 1: Relevant messages for the AV interaction design

Category	**Next manoeuvre**
Message	AV will start moving
Message	AV starts moving
Category	**Environmental perception**
Message	AV has detected (one or more) other/specific TP(s)
Category	**Cooperation capability (CC)**
Message	AV gives way

Based on these messages the following two interaction design strategies were developed: The intention-based and the perception-based interaction strategy. Furthermore a combination of those two strategies was considered. The intention-based strategy is characterized by the AV conveying information about its next manoeuvres and its cooperation capability. Compared to this, the perception-based strategy is mainly characterized by giving explicit information to other traffic participants that they have been detected as relevant interaction partners by the AV and that the AV will react to them. Both strategies will be supported by the implicit communication of the AV such as deceleration and gap size, vehicle speed and/or the adjustment of lateral distance to other traffic participants. The project partners agreed to use eHMI based communication only in interaction demanding situations.

B. *Selection of eHMI Technology*

After rating several technical solutions according to their suitability to meet the project requirements, the project partners decided to take the following eHMI technologies into account [5]. A 360° light-band around the AV and a Directed Signal lamp. While the light-band is meant to send information to all traffic participants and is visible for all, signals of the Directed Signal lamp are only visible for specific traffic participants and thus, they are especially applicable for the perception-based design. For the light-band as well as for the Directed Signal lamp cyan was chosen as main color.

C. *Selection of eHMI Designs*

Other researchers have tested different design variants of external HMI signals to let other traffic participants know about the intention of the AVs ([6] [7] [8] [9]) . However, up to now there is no agreement on one design. Thus, the interACT partners developed the project solutions based on the existing research results, technical considerations and the interaction design strategies described under II. A. and B.

The interACT eHMI designs [10] developed for the intention-based design consists of the light-band pulsing in different frequencies to communicate that the AV will start moving or that it gives way. There is no intention-based design for the Directed Signal lamp as this technology is not meant to communicate intentions of the AV. The perception-based design for the light-band looks as follows: Specific position(s) of the light band are illuminated that indicate the position of the other detected traffic participant(s). For the Directed Signal lamp, a detection light is sent in the direction of the other traffic participant that is only visible for the relevant interaction partner. A combination of the light-band and the Directed Signal lamp uses the light-band for all intention-based communication and the Directed Signal lamp for all perception-based communication.

III. OVERVIEW ON USER STUDIES

To test the effectiveness of the implicit and explicit interaction design strategies developed within the project, a series of participant studies were conducted at different partner sites. The following section gives a brief overview on those research studies. Further details on all studies reported can be found in the interACT Deliverables D2.2 [11] and D4.2 [10].

A: Studies testing implicit communication strategies

Study A.1: Investigating pedestrians' crossing behaviour during car decelerations [12]

Research question / Objective

A VR Head-Mounted-Display (HMD) study was conducted by ITS Leeds to investigate pedestrians’ crossing behaviour during vehicle deceleration [12]. This study was designed to also understand the effect of different speeds of approaching vehicles and the time gaps of approaching vehicles and any learning effect on pedestrians’ crossing behaviour. It is important to understand pedestrians’ crossing behaviour in VR HMD, in order to develop a framework for evaluating eHMI that can be used for future studies.

Method

Fourteen participants (9 male) took part in the study (M = 27.64 years old, S.D. = 10.57). The virtual environment consisted of a 3.5 meter width, single lane road during daytime. Participants were standing at the edge of the road, where a row of trees was located (Fig. 2). They were asked to press a button on the hand-held controller to trigger the trial. During each trial, two saloon vehicles approached from the right hand side of the road. Participants’ task was to cross naturally between the approaching vehicles if they felt safe to do so. After crossing the road, they were asked to cross back and return to their initial position and trigger the next trial again.

Fig. 2. An example of the stimuli and the virtual environment for study A.1

This study used a within-subject design, and 48 stimuli were created. The approaching vehicles were travelling at 25, 30 or 35mph, whereas the time gaps between the vehicles were manipulated between 1-8 seconds with 1 second increments. In addition, the second approaching vehicle decelerated and stopped at 50% of the trials, where the rest remain to travel at a constant speed. A total of three blocks (3 x 48 trials) was administered, with a short break between blocks.

The dependent variables in this study included pedestrians' crossing decision and behaviour, such as the initiation time, crossing time and safety margin.

Main results

This study found a 'bimodal crossing' pattern which is in line with previous studies, such as the simulation models by [13] or test track studies conducted by [14]. 51% of crossing were made before the deceleration of the vehicle, 31% of crossing were made only after the vehicle had stopped and only 18% crossing were made while the car was still decelerating. Therefore, it will be interesting to see if the presence of eHMI is likely to increase crossings during deceleration as compared to without eHMI. This study also found that the highest speed of approaching vehicle produced the smallest safety margin, in line with [15]. A learning effect across blocks was also observed, whereby more crossings were made during the decelerations and less after the car had stopped was found across blocks. This study provided the application of studying the evaluation of eHMI, such that a better eHMI should show a lower initiation time while making a crossing decision and also providing a higher safety margin.

Study A.2: Effects of deceleration strategy and jerk on pedestrian crossing behaviour [16]

Research question/Objective

In this study at TU Munich, the effects of different deceleration strategies and artificial pitches were evaluated to explore the effects on pedestrian crossing behaviour. Three possible deceleration strategies were identified, with an equal maximum deceleration value and braking distance, but different jerks progression:

- *Defensive*: The vehicle initially braked hard to implicitly communicate its yielding intent, followed by a slow approach with softer deceleration to the full stop position.
- *Baseline*: In this condition, the vehicle decelerated as constant as possible, by raising the deceleration to the maximum value within a second in the beginning and lowering it within a second towards the full standstill.
- *Aggressive*: In the least time consuming strategy, the vehicle decelerated slowly in the beginning and strongly close to the full stop position. This strategy is somewhat reverse to the defensive strategy, but takes less time to execute.

Furthermore, four vehicle pitch behaviours were introduced and tested:

- *Normal pitch* – realistic vehicle pitching behaviour
- *No pitch* – the vehicle decelerated without pitching forward
- *Boosted pitch* – an artificially amplified pitch
- *Premature pitch* – the vehicle started pitching prior to decelerating

Method

30 (9 Female) participants participated in a VR pedestrian simulator study (M = 23.90 years old, S.D. = 3.17). Virtual convoys of vehicles were passing the study participant with 30 km/h. One vehicle within the convoy started to decelerate using one of the three strategies and one of the four pitch conditions.

Results

With regards to the deceleration strategy, the defensive strategy lead to a sooner crossing compared to the baseline and aggressive strategy. Furthermore, participants reported to dislike discrepancies between pitching and vehicle behaviour. Overall, pedestrians seem to differentiate between deceleration strategies but mostly through the kinematic movement of the vehicle rather than its dynamics. Therefore, active artificial pitching does not seem to be an appropriate communication method for transmitting yielding intentions in side road velocities.

Study A.3: *Effects of deceleration distance and presence of an eHMI on pedestrian crossing behaviour and perception* [17]

Research question/Objective

This research study at TU Munich explored how the deceleration distance influences a pedestrian's crossing decision. Additionally, the effects of an eHMI on the crossing initiation of pedestrians and potential interaction effects with the deceleration distance were under research. Further, the effect of the eHMI on the acceptance of pedestrians was assessed. The study tested six different braking distances ranging from 18 to 45 meters.

Method

32 participants (14 female; M = 23.97 years old, S.D. = 3.15) were asked to cross a virtual road whenever they felt safe to do so. A convoy of virtual traffic was presented, with one car decelerating and either displaying the yielding intent with an eHMI resembling the interACT main design (see [10]) or not.

Main results

The presence of an eHMI seems to expedite the decision making process of pedestrians, so that the crossing process is initiated sooner and thus, the interaction is progressing quicker. Also, decelerating at higher distances leads to pedestrians initiating their crossing way before the vehicle comes to a full stop. However, as the vehicle is progressing more slowly, the actual time gain is diminished. Further studies should explore, whether the combination of defensive deceleration in combination with an early braking onset leads to even faster crossing initiations. The pedestrian also might be outside of the encroachment zone before the vehicle comes to a full stop, thus, further increasing the potential of enhancing traffic flow.

B: Studies testing explicit communication strategies

Study B.1: Exploring the interpretation of different eHMI messages [18]

Research question / Objective

A VR Head-Mounted Display (HMD) study was conducted at ITS Leeds to investigate the understanding of the messages conveyed by automated vehicles [18]. This study tested 10 different eHMI signal designs on conveying three different messages, such as ‘I am giving way’, ‘I am in automated mode’ and ‘I will start moving’. The aim of the study focused on which of these eHMI signal designs convey best, and to what extend these designs conveyed these three messages.

Method

Twenty participants (9 female, M = 26.85 years old; S.D. = 4.74) took part in the study .Two approaches were used. During Task 1 (see Fig. 3), a paired-comparison forced choice task was conducted, where the eHMI signal design was presented in 45 pairs for each message, and participants were asked to choose which of the two eHMI signals presented is the one which best conveys the message within each pair. Data was analyzed by using the log-linear Bradley-Terry method.

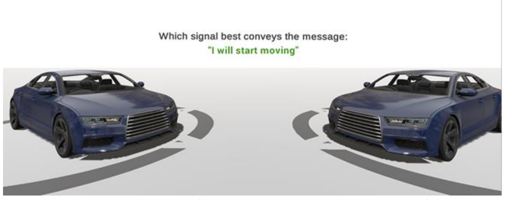

Fig. 3. The experimental setup for the paired-comparison forced choice task (Task 1)

During Task 2 (see Fig. 4), a 6-point rating task was conducted to assess to which extent each of these eHMIs conveys each messages.

Fig. 4. The experimental setup for the 6-point rating task (Task 2)

Main results

Task 1 showed that the ‘I am giving way’ flashing headlights were the best for conveying the message. For ‘I am in automated mode’, results suggest that the best eHMI design to convey this message was a slow-pulsing lightband. Multi-modality (fast pulsing light-band + fast auditory beeping) was found to be the best to convey ‘I will start moving’.

For Task 2 linear mixed-effect models were used for analysis, which suggested no significant differences between the ten eHMI signal designs in conveying ‘I am giving way’; but according to the rating score, the most preferred options for this message were a fast pulsing light-band, flashing headlights and multi-modality. For ‘I am in - automated mode’, a linear mixed-effect model showed a significant difference, and the top 3 eHMI signal designs were slow pulsing light-band, slow pulsing single lamp and fast pulsing light-band. For the message ‘I will start moving’, there was also a significant difference between signal designs, and the top 3 designs were multi-modality, fast auditory cue, and fast pulsing light-band. In general, results demonstrated that the same eHMI design could convey different messages equally well. It is therefore important to avoid using a misleading eHMI, which could potentially lead to miscommunication and unsafe situations.

Study B.2: To yield vs. not to yield [10]

Research question / Objective

A study on the effects of two eHMIs (both intention-based) vs. a baseline was conducted at BMW. The main research question addressed in this study was the need to communicate both intentions (yield vs. proceed) and the dependency on traffic scenarios.

Method

A VR pedestrian simulator study was conducted. N=30 (16 females, (m = 43 years old; S.D. = 13) took part in this study. Two eHMIs were included. The eHMIs consisted of a light-band, showing signals in white colour and a display, showing icons in the windscreen in white colour (Fig. 5). Two types of AV intentions (give-way, pass) were included. Three different traffic scenarios (zebra crossing, two lane streets, and parking space) were included. The pedestrian had to wait on the edge of the curb and decide when he recognized the intention of the AV and press a button at this moment in time. Intention recognition time and correctness of the decision was measured

Fig. 5. Different eHMI concepts in BMW study B.2

Main results

When the AV was communicating the intention to give way, eHMI (slow pulsing light-band) improves intention recognition rates compared to a baseline without eHMI. eHMI (fast pulsing light-band) deteriorates intention recognition when the AV’s intention is to pass the pedestrian and go first. Intention recognition times remain constant across scenarios. The light-band seems to be a more fruitful approach than a display showing icons.

Study B.3: Examining effects of perception- vs. intention-based design strategies in different scenarios [19]

Research question / Objective

Different eHMI concepts, based on perception-based and intention-based interaction strategies, were tested at DLR in different urban scenarios. The main research questions addressed in this study were a) if there is a preference of pedestrians for one of the interaction strategies and b) if there is a difference in the preferences of the interaction strategies across different urban driving scenarios.

Method

To investigate the interaction of an automated vehicle with a pedestrian, a VR pedestrian simulator was used. 27 participants (13 females; M= 34 years old, S.D.=13) took part in the study. Six different light-based designs for eHMI were tested. The different eHMIs were used to present information for a perception-based, an intention-based and a combination of these two interaction strategies (Fig. 6). All designs were tested in three different urban scenarios (crossing scenario, intersection scenario and parking scenario). The participant had to wait at the edge of the pavement and had to make a decision to cross the road if they felt safe to cross. Afterwards participants were asked to rate the eHMI design in terms of preference and intuitiveness.

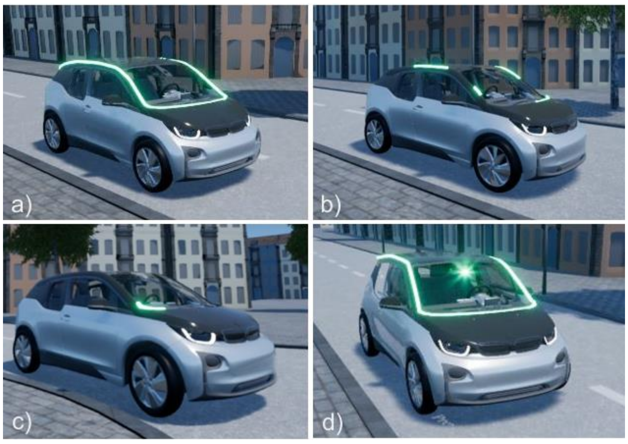

Fig. 6. Different eHMI design strategies (a) intention1, b) intention2, c) perception1 und d) perception2 in study B.3

Main results

No influence could be found in the user preferences of the design strategies across the driving scenarios. Therefore, it can be assumed that one eHMI design strategy can be used in different urban scenarios. The perception-based eHMI strategies were ranked higher compared to the intention-based strategies in terms of preference. The combination of the intention- and perception-based design strategies were most preferred. Furthermore, the intuitiveness was rated high for the perception-based variant (perception1) and for one combination of perception- and intention-based designs.

Study B.4: Addressing messages to drivers in multi-actor scenarios [10]

Research question / Objective

Whether to use intention or perception-based eHMI designs and if using perception-based design which technology should be used is a major question throughout the interACT project. As differences are mostly to be expected in a multi-actor environments, BMW ran a driving simulator study with other – simulated – traffic participants besides the actual study participant. The intention-based interaction strategy using the 360° light-band as well as the perception-based light-band as well as the aforementioned Directed Signal lamp was included in this study.

Method

N=60 (7 female) took part in this study (M = 31.6 years old; S.D. = 10.9). The three eHMI variants as well as a baseline were compared in a between-group design. All four groups were controlled for driving style. Eight traffic scenarios with differing priorities and different viewing angles between the respective participants were included. The participant and the other AV were positioned either in opposite or in similar viewing angles. The legal priority could be on the participants', the AV's, or the other manually driven cars' side.

Main results

No effects of eHMI on crossing times were found. Subjective clarity was not significantly improved using eHMI. However, if only the second half of all trials were analyzed, to account for learning effects occurring in the first half of the trials, eHMI improved subjective clarity significantly for the intention-based light-band as well as the Directed Signal lamp. Furthermore, participants judged the AV equipped with the full light-band as well as the AV equipped with the signal lamp to be more efficient and more reliable than the baseline AV without any eHMI. No benefit of a technically more demanding perception-based interaction strategy over an intention-based strategy was found in this study. Given limited results potentially caused by large interaction distances existing in vehicle-vehicle interaction in comparison to vehicle-pedestrian interaction it remains questionable what benefits eHMI will bring in the interaction between AVs and manually driven vehicles.

Study B.5: Examining possible negative effects of an AV's eHMI on pedestrians' crossing decisions

Research question / Objective

This study conducted by DLR focused on possible negative effects of an AV's eHMI that might occur in the interaction with pedestrians crossing a road, e.g., the pedestrian might feel being invited by the AV's eHMI to cross the street without checking for oncoming traffic. The crossing decision time and certainty of a pedestrian's decision when crossing a road as well as negative effects on the frequency of gaze checks for oncoming traffic where explored. A comparison was made with non-automated vehicles and AVs without eHMI.

Method

N = 62 (47% females) volunteered as participants in this pedestrian VR-simulated study. Their ages ranged from 19 to 61 years with a mean age of M = 33.19 years (S.D. = 11.67). The study followed a mixed 3x3-factorial design with the first between-factor 'eHMI interaction design' (intention-based vs. perception-based vs. both combined; see Fig. 6) and the second within factor 'interacting vehicle' (AV vs. AV with eHMI vs. manually driven vehicle). The AV's automation status was shown by a static 360° light-band. For manually driven vehicles the light-band was not visible. The three different eHMI interaction strategies were realized for intention-based with a dynamic 360° light-band, for detection-based with the Directed Signal lamp, and for the combination with both. The pedestrian had to wait at the curb of an urban street and to decide when he or she felt save to cross the street in front of the interacting vehicle respectively. In total, 11 trials simulating mixed traffic with different vehicle types (AVs with eHMI vs. non automated vehicles) and vehicle behaviour (stopping vs. not stopping) per participant were presented in a randomized order. During all trialsthe dependent variables “decision time” (measured by a button press) and “certainty” (5-point Likert scale) as well as the gaze direction, i.e., checking for oncoming traffic, were recorded.

Main results

Results of the study showed that participants felt significantly more certain in their decision to cross the road in front of the interacting vehicle when it was an AV with eHMI. Additionally, pedestrians decided earlier to cross the street in front of these vehicles. The frequency of gaze checks for oncoming traffic did not differ significantly between interacting vehicle types; No negative effect of eHMI was detected in this study as the frequency of gaze checks for oncoming traffic did not differ significantly between vehicle types. In addition, no differences between the three eHMI interaction strategies were observed. These findings should be validated in more natural and complex traffic situations.

IV. SUMMARY AND CONCLUSIONS

This paper describes the design process followed in the interACT project to come up with implicit and explicit communication strategies for an AV in mixed traffic situations. Based on the observational studies and the simulator studies reported in this paper, a two-fold approach enabling the AV to safely interact with other road users seems to be promising: Firstly, the vehicle behaviour is an important design factor for other traffic participants to understand the intentions of the AV. The study results summarized in this paper show that a defensive deceleration strategy led to sooner pedestrian crossing decisions while artificial pitching had no effect. Furthermore, early braking of the AV led to sooner crossing decisions. Secondly, other traffic participants benefit from explicit communication via eHMI technology. The studies conducted show a clear effect of eHMI compared to a baseline without eHMI for the decision making process of other traffic participants. In the project, a 360° light-band as well as a Direct Signal lamp was chosen as eHMI elements. The studies revealed that both elements seem to work fine and that no main benefit could be shown for an intention-based vs. perception-based design in the different studies. We also could not find any negative effects on gaze behaviour for both design strategies. Further, no need was found to work with different interaction strategies in different urban scenarios or for different road users (pedestrians and drivers). Thus, one and the same messages could be used in the tested scenarios.

In this paper, we reported only studies conducted in Virtual Reality or driving simulator studies. Based on the outcomes of the research work on the interaction strategies, the interACT partners are working on the full integration of the implicit interaction strategy and the eHMI components in two demonstrator vehicles from BMW and CRF. In the further course of the project, both vehicles will under-go an extensive user evaluation phase (see [20] for further details on the evaluation plan). Main objective is to test the demonstrators under real life conditions and to validate the current simulator study results for more complex scenarios. This data will be accomplished by results of controlled evaluation studies in simulators and of quantitative models on other road user behaviour generated by software simulations.

By this, we hope to contribute with important results to the safe, cooperative, and expectation-conforming interaction between the AV and other road users in mixed traffic environment by the end of the interACT project in 2020.

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