Designing cooperative interaction of automated vehicles with other road users in mixed traffic environments

interACT D.6.2. Evaluation report on on-board user and road users interaction with AVs equipped with the interACT technologies

Work package	WP6: Evaluation & Impact Assessment of Human-Vehicle Interaction
Task(s)	Task 6.2. Evaluating the effect of the new human-vehicle interaction strategies and means on on-board user behaviour and interaction with other road users
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Revision and history chart

Version	Date	Main author	Summary of changes
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0.2	01/04/2020	Portouli, Evangelia, Nathanel, Dimitris	ICCS study description
0.3	05/05/2020	Tango, Fabio	Demonstrator description
0.4	13/05/2020	Weber, Florian	BMW study description
0.5	20/05/2020	Boos, Annika	TUM study description (real world)
0.6	29/05/2020	Utesch, Fabian, Avsar Hüseyin	DLR study descriptions
0.7	29/05/2020	Lee, Yee Mun, Madigan, Ruth	ITS study descriptions
0.8	24/06/2020	Dietrich, André	TUM study description (test track). Concatenation of all Inputs, Key Findings and Recommendations.
0.9	09/09/2020	Dietrich, André	Introduction, Objectives and Summary. Formating and Final Touch. Ready for Review. Implementation of Hella internal review, rewriting of Exec Summary and parts of the key facts Implementation of the internal reviews and the final Leeds Simulator Study
1.0	30/09/2020	Dietrich, André	Final version

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Glossary of terms

Term	Description
Automated Vehicle (AV)	Vehicle that provides automation of longitudinal and lateral vehicle control and can free the driver from the driving task – at least in some driving situations
eHMI / external HMI	External Human-Machine Interface positioned on the vehicle's exterior to communicate with surrounding traffic participants
iHMI / internal HMI	Internal Human-Machine Interface positioned in the vehicle's interior to communicate with the on-board user (or driver, when not driven automated)
On-board user	Person within the AV controlling the vehicle when not automated or who can regain control of the automation (SAE3-4)
Other road user(s)	All possible road users from the perspective of the ego vehicle, i.e. pedestrians, bicyclists, motorists and vehicles. Note – In this deliverable, other AVs are not considered as other road users, as digital communication between automated systems is not regarded.
Use-case	Functional description of the behavior of the AV in a traffic situation
Mixed Traffic	Usually referred to traffic consisting of different types of road users, including AVs
Wizard of Oz (WoZ) vehicle	Manually driven vehicle hiding the driver to mimic an AV

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List of abbreviations and acronyms

Abbreviation	Meaning
AV	Automated Vehicle
WP	Work Package
HMI	Human-Machine Interface
eHMI	External Human-Machine Interface
iHMI	Internal Human-Machine Interface
TP	Traffic Participant
CCPU / CCP Unit	Cooperation and Communication Planning Unit
D	Deliverable
HMD	Head-Mounted Display
AOI	Area of Interest
HIKER	Highly Immersive Kinematic Experimental Research
FH	Flashing Headlights
LED	Light-Emitting Diode
ATI	Affinity for Technology Interaction Scale
SUS	System Usability Scale
SURT	Surrogate Reference Task
SAM	Self-Assessment Manikin Scale
FOTS	Facets of Trustworthiness Scale
SAE	Society of Automotive Engineers
WoZ	Wizard of Oz
CIT	Crossing Initiation Time

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IRT	Intention Recognition Time

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Executive Summary

Introducing Automated Vehicles (AVs) to urban traffic comes along with a variety of challenges, especially when encountering other, unequipped road users. In these mixed traffic conditions, interaction is key to keep traffic moving and minimise misunderstandings and potentially critical situations. The interACT project aims to enable AVs to interact with other traffic participants in mixed traffic situations by introducing among others novel lighting elements – so called external Human Machine Interfaces (eHMI) and using the vehicles motion to communicate.

This deliverable presents the evaluation of the interACT interaction strategies developed in Work Package (WP) 4 (see D4.1, Wilbrink et al., 2018 and D4.2, Weber et al., 2019). Multiple participant studies using the methodologies described in Deliverable D6.1 (Lee et al., 2019) were conducted giving an in-depth view on how implicit and explicit communication strategies influence other road users and how the internal Human Machine Interface (iHMI) influences passengers on board.

AV communication was evaluated in 10 participant studies with different research focuses and methodologies including virtual reality simulators, test track experiments and a real-world evaluation. eHMIs were shown to be beneficial in regards to the subjective perception of the vehicle's intent and automated vehicles themselves. Most studies found that eHMIs decrease the time other road users need to initiate their maneuver (e.g. crossing for pedestrians, turning for drivers), thus leading to quicker interactions, which could enhance traffic flow (see also D6.3, Lee et al., 2020). In conditions where the eHMI was not present encounters with the AV were still resolved, but generally slower when compared to conditions with eHMIs. Different eHMI designs did not result in different objective results, however participants almost unanimously preferred to have AVs equipped with one of the presented eHMIs.

The variety of experimental designs and methodologies used enabled to ascertain potential negative effects that could be introduced by the novel lighting elements. Miscommunication and communication failures were found to potentially create dangerous situations in simulator studies. Furthermore, participants who experienced many encounters with a yielding AV communicating its yielding intention using an eHMI, found to overly rely on that information, inducing traffic conflicts, in situations where the AV was addressing a different road user. To avoid these situations, we conclude this report with recommendations for future work on the safe, efficient and accepted introduction of AVs with eHMI and iHMI onto urban roads.

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1. Introduction

1.1 Background, purpose and scope

1.1.1 Background

One of the main challenges in the introduction of automated vehicles (AVs) is that they will have to interact with other road users, such as other manually driven cars and pedestrians (as illustrated in Figure 1). It is, therefore, important to have a good understanding of the interactions arising between AVs, their on-board users, and other traffic participants (TPs) in order to achieve and enable the integration of AVs in complex and mixed traffic situations.

As the human driver is not available in higher levels of automation, the AV needs to interact with other road users and keep the on-board users informed. A Cooperation and Communication Planning Unit (CCPU) was developed in **WP3** (see D3.1, Drakoulis et al., 2018 and D3.2, Markowski et al., 2019) enabling to identify interaction-demanding situations and behave in an expectation-conforming way. External and internal Human Machine Interfaces were developed within **WP4** (see D4.1, Wilbrink et al., 2018 and D4.2, Weber et al., 2019) to enable the interaction between the AV, on-board users and other TPs. In **WP5** (see D6.1 Lee et al., 2019) these were implemented in two demonstrator vehicles to enable communication between the AV, on-board users and other traffic participants.

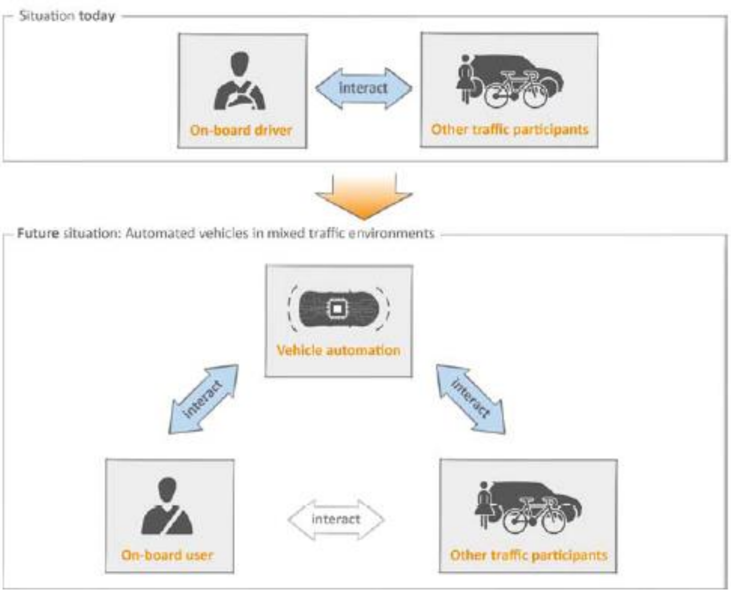

Figure 1: Illustrating the current interaction between on-board driver and other TPs (top). Illustrating the future interaction between AVs in mixed traffic environments (bottom).

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1.1.2 Purpose and scope

The main objective of this deliverable is to evaluate the effects of the final interACT interaction strategies on other traffic participants and on-board users. Building on the evaluation methodologies defined in D6.1 (Lee et al., 2019, chapter 5) and findings from the user studies conducted in WP4 (see D4.2, Weber et al., 2019), a set of final evaluation studies is conducted to assess the effects of the interACT solutions on acceptance, usability, traffic efficiency and perceived safety of other road users and passengers.

Chapter 3 gives a brief description of the interaction strategies and their implementation into the two interACT demonstrators. Furthermore, the various methods used to evaluate the interACT solutions are presented, ranging from Head-Mounted Display (HMD) simulators to test track studies with the interACT demonstrators.

Chapter 4 lists all experiments conducted within Work Package 6 and gives insights into the different experimental approaches, research questions and main findings of each individual study. The results are merged and presented as key findings in chapter 5, which in turn are used to derive recommendations for future work on AVs and their interaction strategies when encountering unequipped road users.

1.2 Intended readership

This deliverable provides insight into the evaluation studies of the interACT solutions and the developed demonstrator vehicles conducted in WP6. It serves as a documentation on the final evaluation of the interACT technologies for all project partners, our Project Officer, the reviewers and the European Commission. This deliverable is publicly available and intended to provide valuable insights for our stakeholders, other researchers, industrial partners and the general public about results from interACT and evaluation of AVs interaction strategies in general.

1.3 Relationship with other Work Packages

As shown in Figure 2, WP 6 is closely related with WP 1, 2 and 5 but also relies on the findings and developments from WP 3 and 4. The must-have use cases defined within **WP1** "*Scenarios, Requirements and interACT System Architecture*" (see D1.1 Wilbrink, et al., 2017) served as a basis for the studied traffic encounters in the evaluation. Findings from **WP2** "*Psychological Models on Human Interaction and Intention Recognition Algorithms*" (see D2.1 and D2.2, Dietrich et al., 2018; 2019) were utilized to refine the experimental designs and underlying research question. Finally, the two prototypes – a BMW i3s and a Jeep Renegade (see section 3.2 for details) – that were integrated within **WP5** "*Integration, Testing and Demonstration*" are evaluated within WP6 with the results of the studies described in this deliverable.

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The CCPU incorporated within the Jeep Renegade demonstrator vehicle was developed within **WP3** "*Cooperation and Communication Planning Unit*" (see D3.1, Drakoulis et al., 2018; and see D3.2, Markowski et al., 2019). Both vehicles were equipped with HMI elements developed within **WP4** "*Suitable HMI for Successful Human-Vehicle Interaction*" (see D4.3, Kaup et al., 2019 and D4.2, Weber et al., 2019).

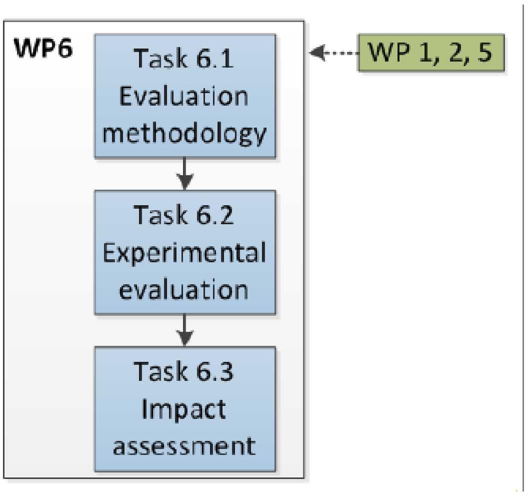

Figure 2. Relationship with other interACT Work Packages

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2. Objectives in WP6

WP6 "*Evaluation and Impact Assessment of Human-Vehicle Interaction*" has the main objectives to define the methodologies used to evaluate the effect of introducing interaction strategies and communication means for AVs on human behaviour and road safety and to conduct these evaluations for the interACT prototypes. As automated vehicles are likely to be introduced onto roads used by other human road users, the vehicle automation will need to replace the driver's interaction capabilities. As Figure 3 shows, evaluating developed interaction strategies from WP4 "*Suitable HMI for Successful Human-Vehicle Interaction*" means to study the AVs effects on the on-board users as well as other traffic participants and measuring their impact on traffic flow, safety and overall societal acceptance, ultimately assessing the success of the interACT system.

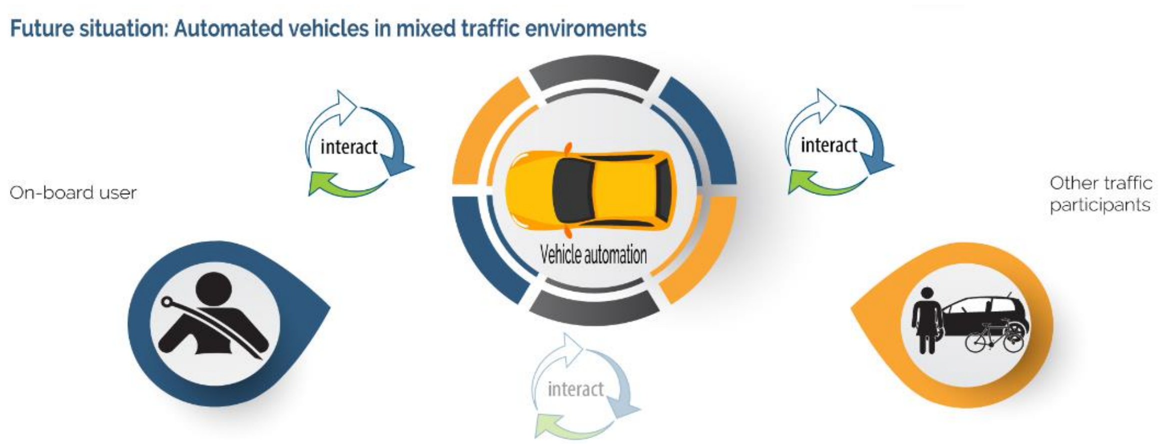

Figure 3: Automated vehicle interacting in future mixed traffic environments

Task 6.2 "*Evaluating the effect of the new human-vehicle interaction strategies and means on on-board user behaviour and interaction with other road users*" utilizes the evaluation methodologies defined within D6.1 (Lee et al. 2019) to assess the interACT solutions and prototypes using pedestrian simulators, driving simulators as well as test track and real world studies. The evaluation is aimed to assess the traffic situations depicted in Figure 3 evaluating the must have use-cases defined in D1.1 (Wilbrink et al.):

- React to crossing non-motorized TP at crossing without traffic lights
- React to an ambiguous situation at an unsignalized intersection
- React to non-motorized TP at a parking space
- React to vehicles at a parking space

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3. Description of final interaction strategies and evaluation methodologies within interACT

This chapter summarizes the interACT interaction strategies described in D4.2 (Weber et al., 2019) and the methodologies chosen to evaluate them (for more details see D6.1, Lee et al., 2019). Furthermore, the implementation of the demonstrators that are evaluated in section 3.2 are briefly described.

3.1 Final interaction strategies

External HMI

The user studies of WP 4 revealed that more than one design showed promising user ratings and objective results. This is why one main eHMI interaction design and two secondary designs were selected as interACT designs.,. The intention-based design – a slowly pulsing cyan LED band – design described in D4.2 (Weber et al., 2019) was found to be a very fruitful approach and therefore implemented as main design.

For the perception-based interaction strategy, where a smaller part of the LED emits light in the direction of the interaction partner, a specific signal on the light-band was included. For the combined strategy a sequence of the intention-based slow-pulsing light-band, as well as the illumination of the Directed Signal Lamp – a lamp behind the windshield only visible by the addressee of the communicated message – (secondary design 2), was implemented. Details can be seen in the detailed signal flows in chapter 5 of D4.2 (Weber et al., 2019). These additional design variants were considered to be the secondary designs which will not be thoroughly evaluated in WP 6, but can serve as an additional design if the interACT researchers discover shortcomings of the selected intention-based design in the WP 6 evaluation.

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WP 4 decided not to pursue a specific signal for displaying the AV's automation status permanently. The interACT AV only signals that it is driving in automated mode in situations where interaction is necessary, by communicating with specific signals (such as slow pulsing for communicating the intention to yield).

Figure 4: intention-based (left) and perception based light-band (middle) and combined (right) eHMI

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Table 1: interACT message catalogue and the respective signal design for eHMI

Intention communication: Next manoeuvre		**Signal design chosen**	**Design abbreviation for this deliverable**
NM_13 & NM_14	AV will turn	Turn indicator	**TI** (turn indicator)
NM_4 & NM_5	AV turns	Turn indicator	**TI**
NM_9	AV will start moving	Fast pulsing light-band	**IBF** (intention based – fast)
-	AV starts moving	Fast pulsing light-band	**IBF**
Intention communication: Cooperation Capability			
CC_1	AV gives way *(Message was changed from "AV gives right of way" compared to D4.1)*	Slowly pulsing light-band	**IBS** (intention based – slow)
Secondary design			
Environmental perception			
EP_1 & EP_2	AV has detected (one or more) other/specific TP	Lit up light-segment on light-band	**PB** (perception based)
Combined design: cooperation capability + perception of TP			
	AV gives way AV has detected (one or more) other/specific TP	Slowly pulsing light-band and signal lamp lights up shortly afterwards	**IBS_SL** (Intention based – slow with signal lamp)
Dropped messages for further implementation			
Other messages of lower priority			
VDM_1	AV drives in automated mode		

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-	Temporal indication (e.g. searching for a parking slot)		
CC_9	AV says “thank you”		
CC_10	AV indicates “irritation”		
CC_11	AV has technical problems		

3.2 Demonstrator implementation

CRF Demonstrator

The following figure shows the eHMI implemented on the CRF demonstrator:

Figure 5: external HMI (eHMI) built by HELLA on the demonstrator vehicle of CRF.

The dark cover presents in Figure 5 is used to enhance the contrast of the blue-green light of the eHMI and to reduce reflections on the bonnet.

There are two types of eHMI designs implemented on the CRF vehicle using the light band:

- Intention based design, where the full light band (FLB) pulses slowly
- Perception based design, where the a smaller part of the light band is glowing in the direction of the addressee

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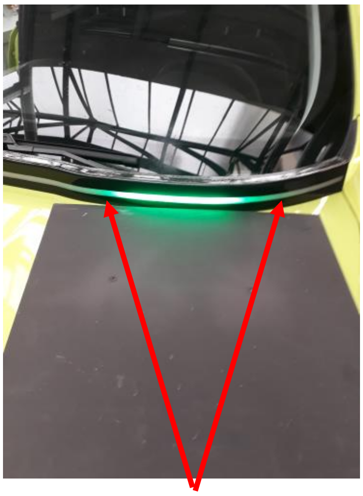
They are shown in the following figure:

FLB (Intention based eHMI)



PLB (Perception based eHMI)

Figure 6: the two different eHMI types implemented in the CRF vehicle. FLB means Full Light Band, while PLB means Partial Light Band.

For what concerning the capabilities of the CRF vehicle, they are listed hereafter. The AOI (Area of Interest) is a square of 2m side. The pedestrian is detected by the perception system from the starting point of the test, that is at least 30m, but the deceleration action starts only when the pedestrian enters the AOI. The CRF demonstrator always yields when there is a participant inside. The maximum deceleration rate of the vehicle is -3.5 m/s^2, while the deceleration profile is not fixed, but it depends on when the pedestrian enters in the AOI.

BMW Demonstrator

The BMW demonstrator aims to evaluate the eHMI designs developed in D4.2 (Weber et al., 2019). It is equipped with a 360° light-band and a directed signal lamp both of which are controlled by a person on board via tablet. The vehicles action is recorded using a PC, which receives a live video stream from two cameras, positional data using DGPS and inertial measurement units as well as information of the lighting elements and tablet inputs. A complete description of the demonstrator is available in D6.1 (Lee et al., 2019).

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Figure 7: The BMW Wizard of Oz demonstrator with Implemented eHMIs. The LED band displays the perception-based (PB) (l.) and intention-based signalling (IBS and IBF) (c.). The signal lamp (r.) was utilized as a part of the combined signalling (IBS:SL).

The implemented communication strategies are shown in Figure 7. The Perception-based signalling consisted of 35 consecutive LEDs emitting light constantly. The luminous part is moved by the person on board to match the relative position of a traffic participant, the vehicle is communicating with, mimicking the sensory perception of the AV. The intention-based signalling utilizes the full light band to communicate the vehicle's intention. The full light band is "pulsing" with a frequency of 0.4 Hz when the AV is signalling a yielding intention, or 2 Hz when indicating that it will start driving soon. The signal lamp transmits a light signal in a small angle, aimed towards the addressee. In the combined design, both signal lamp and light band are used to communicate.

3.3 Evaluation methodologies

Within Deliverable 6.1, we conducted an extensive literature review to establish appropriate criteria for the measurement of road users' interactions, investigating the use of different research environments, methods, and tools (Lee et al., 2019). It was found that the appropriateness of a particular research environment (e.g. simulator, real world, questionnaire etc.), depends on the particular research question being addressed. Therefore, a number of complementary methods were chosen by the WP6 partners to test our prototypes and solutions in a comprehensive manner. A series of test-track, real world (on-campus), and simulator studies (pedestrian and driving simulator) were conducted to evaluate the interACT solutions.

The CRF demonstrator vehicle is fully automated, and operated by the CCPU. To maximise safety and adherence to legal restrictions, it has been evaluated in a test-track environment with a safety driver on-board.

The use of the test-track allowed more stringent safety controls than a real-world environment, while also facilitating more controlled experimental research, making it easier to draw conclusions on specific

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research questions around pedestrian and drivers' evaluations of the usability of the AV communication tools.

The BMW demonstrator vehicle is controlled by a driver, reducing the safety risks. Therefore, a Wizard of Oz approach was used to evaluate this vehicle in both test-track and real world (on-campus) environments. This approach facilitated an understanding of the how pedestrians' perceive and react to our eHMI solutions in a natural context.

To complement the demonstrator vehicle studies, and provide additional information on pedestrian and driver reactions to the eHMI solutions developed within interACT, a series of simulator studies were conducted using a Head-Mounted Display, a Pedestrian Simulator (HIKER: https://uolds.leeds.ac.uk/facility/hikerlab/) and a driving simulator. Simulator studies provide a safe and controlled environment for testing. They also allowed more flexibility in setting up a different virtual environment for testing different research questions, such as the capability in testing the effects of eHMI variations and any potential negative effects of AV interactions.

Finally, there are some evaluation criteria which are prioritised in our interACT evaluations, based on the expected impact of the interACT solutions and the findings of D6.1. These include subjective measures such as perceived safety, ease-of-use, and user acceptance; as well as objective measures such as percentage of crossings, crossing initiation time, crossing duration, and traffic lag time. Some of these subjective and objective measures are further implemented in the models provided in Deliverable 6.3 (Lee et al., 2020) to investigate and project the societal impact of the interACT solutions.

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4. Evaluation of the interACT solutions in participant studies

For the final evaluation of the interaction strategies developed in WP4, eleven participant studies have been conducted in simulators, test tracks and real world settings. Overall 350 participants took part in the studies. The variety of test environments allowed us to study the effects of implicit and explicit communication in several less and more critical scenarios (real vehicle vs. simulator studies) and to countercheck the potential impact of the interACT solutions in each of the individual studies.

This chapter briefly introduces each study, giving an overview of the underlying research questions, methodologies used and main results. A summary of all studies conducted in WP6 is listed in Table 2.

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Table 2: Overview of conducted studies within the interACT evaluation

Study no. / Chapter	Study identifier	eHMI effects on pedestrian crossings	Communication through motion	eHMI effects on other drivers	Multiple interaction Partners	eHMI failure / miscommunication	iHMI and on-board user	Tested scenarios	Number of participants	Test environment	Responsible Partner
1 Ch. 4.1.1	ITS Pedestrian Simulator Study 1	x	x					React to crossing non-motorised TP at crossings without traffic lights	60	HIKER	ITS Leeds
2 Ch. 4.1.1	ITS Pedestrian Simulator Study 2	x			x			React to crossing non-motorised TP at crossings without traffic lights	30	VR pedestrian simulator	ITS Leeds
3 Ch. 4.1.1	ITS Pedestrian Simulator Study 3	x	x			x		React to crossing non-motorised TP at crossings without traffic lights	30	HIKER	ITS Leeds

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Study no. / Chapter	Study identifier	eHMI effects on pedestrian crossings	Communication through motion	eHMI effects on other drivers	Multiple interaction Partners	eHMI failure / miscommunication	iHMI and on-board user	Tested scenarios	Number of participants	Test environment	Responsible Partner
4 Ch. 4.1.1	ITS Pedestrian Simulator Study 4	x						React to crossing non-motorised TP at crossings without traffic lights	20	HIKER	ITS Leeds
5 Ch. 4.1.2	BMW Pedestrian Simulator Study	x			x	x		React to crossing non-motorised TP at crossings without traffic lights	60	VR pedestrian simulator	BMW
6 Ch. 4.1.3	DLR Vehicle-Vehicle-Interaction Simulator Study			x	x	x		React to an ambiguous situation at an unregulated 4-way intersection	28	Driving simulator	DLR

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Study no. / Chapter	Study identifier	eHMI effects on pedestrian crossings	Communication through motion	eHMI effects on other drivers	Multiple interaction Partners	eHMI failure / miscommunication	iHMI and on-board user	Tested scenarios	Number of participants	Test environment	Responsible Partner
7 Ch. 4.1.4	DLR Internal HMI Driving Simulator Study						x	React to an ambiguous situation at an unregulated 4-way intersection	10	Driving simulator	DLR
8 Ch. 4.2.1	TUM BMW Wizard of Oz: Test Track Experiment	x	x					React to crossing non-motorised TP at crossings without traffic lights	38	BMW i3 WoZ demonstrator on a test track	TUM
9 Ch. 4.2.2	TUM BMW Wizard of Oz: Instructed Walking	x						React to crossing non-motorised TP at crossings without traffic lights	30	BMW i3 WoZ demonstrator in real world conditions	TUM

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Study no. / Chapter	Study identifier	eHMI effects on pedestrian crossings	Communication through motion	eHMI effects on other drivers	Multiple interaction Partners	eHMI failure / miscommunication	iHMI and on-board user	Tested scenarios	Number of participants	Test environment	Responsible Partner
10 Ch. 4.2.3	ITS CRF Demonstrator Test Track Study	x	x					React to non-motorised TP at a parking space	24	Jeep Renegade demonstrator vehicle on a test track	ITS Leeds
11 Ch. 4.2.4	ICCS Parking Lot Experiment		x					React to vehicles at a parking space	40	ICCS test vehicle on a parking lot	ICCS

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4.1 Results of Simulator Studies

4.1.1 ITS Pedestrian Simulator Studies

Research Question and Objective

A cyan coloured slow pulsing light band (representing the Intention Based Signalling or IBS) at 0.4Hz located 360° around the vehicle was identified as the interACT solution for communicating 'I am giving way' (Weber et al., 2019; Lee et al., 2019, see Figure 8). It is important to evaluate the effect of this eHMI solution on pedestrians' crossing behaviour and subjective evaluation. Four studies were conducted, to enable an exploration of different research questions and objectives, and each one built upon the previous study. In Study 1, we investigated the effect of eHMI on pedestrians crossing behaviour, comparing the IBS group to a group who were exposed to conventional flashing headlights (FH), and a group with no eHMI exposure at all. For both eHMI designs, a within-subjects comparison was incorporated between trials where eHMI was on and off. In addition, we also compared the IBS eHMI solution to FH across a number of subjective measures. In Study 2, we were interested in the situation where the vehicles were always decelerating, but participants had to judge whether the decelerating vehicles were decelerating for them or just merely decelerating for the traffic. In Study 3, we investigated what happens when eHMI fails and how this affects pedestrians' crossing behaviours. In Study 4, we investigated the effect of eHMI and right-of-way on pedestrians' crossing behaviours in a cross-road scenario.

Figure 8: Cyan coloured pulsing light band around the vehicle

Method

Study 1, 3 and 4 were conducted in a Highly Immersive Kinematic Experimental Research (HIKER) pedestrian lab, which is a cave-based pedestrian simulator at the University of Leeds (see Figure 9). Study 2 was conducted by using a Head-Mounted Display.

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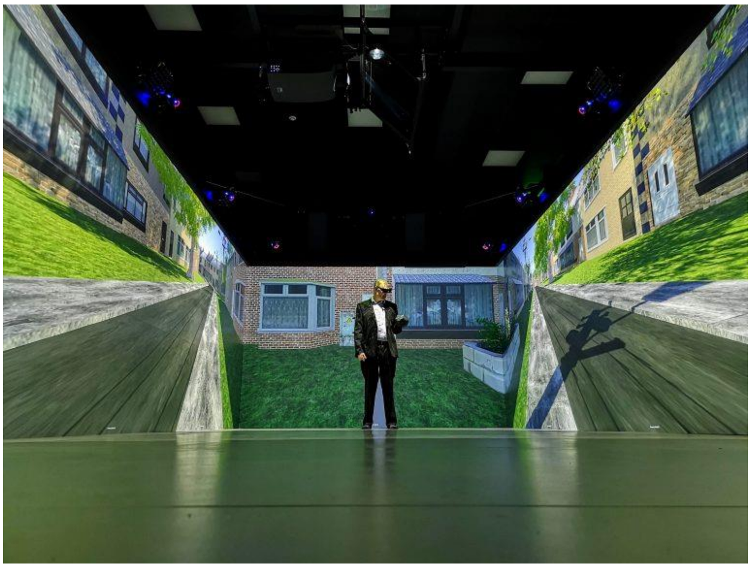

Figure 9. Highly Immersive Kinematic Experimental Research (HIKER) pedestrian lab at the University of Leeds

Three studies (1, 2, 3) were conducted in a similar virtual environment, consisting of a single lane residential area in the UK, where the vehicles were approaching from the right-hand side of the road (see Figure 10). Study 4 was conducted in a cross-road environment (see Figure 13).

Figure 10: The virtual environment used in all three studies

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In all four studies, participants were asked to physically cross the road if they felt comfortable to do so. In Study 1 and 2, participants began each trial by standing at the edge of the road ready to cross. During each trial, a pair of vehicles approached from the pedestrian's right-hand side (as illustrated in Figure 10), and the participants task was to cross (or not) between the approaching vehicles. Different independent variables/parameters of the vehicles were manipulated in different studies (see Table 3). In Study 2, we changed the scenario slightly by adding a traffic light and queueing traffic on the participants' left-hand side (see Figure 11). This allowed us to investigate the situation, such that the approaching vehicles were always decelerating, but the additional traffic light on the left provided an additional reason for why the vehicles were decelerating. Therefore, participants had to take that into account and judge whether the approaching vehicles were decelerating for them or for the traffic.

Figure 11. Traffic light and the queuing vehicles on the left-hand side of the road in Study 2

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We used the same virtual environment in Study 3. However, in Study 3, there was only one approaching vehicle instead of two. Participants were asked to walk forward a few steps to arrive at the edge of the road prior to each trial commencing. In this study, we also manipulated the eHMI onset and deceleration onset (see Table 3 for design and Figure 12 for illustration), and the 37th trial and 50th trial were misleading trials. Misleading trials were trials where the eHMI was on, but the vehicle was not decelerating. In this study, the visibility of the eHMI was increased by increasing the illuminance, colour and surface area of the light band cover on the vehicle (see Figure 12). Note that the reason for this was purely to increase the visibility of the eHMI in the experiment.

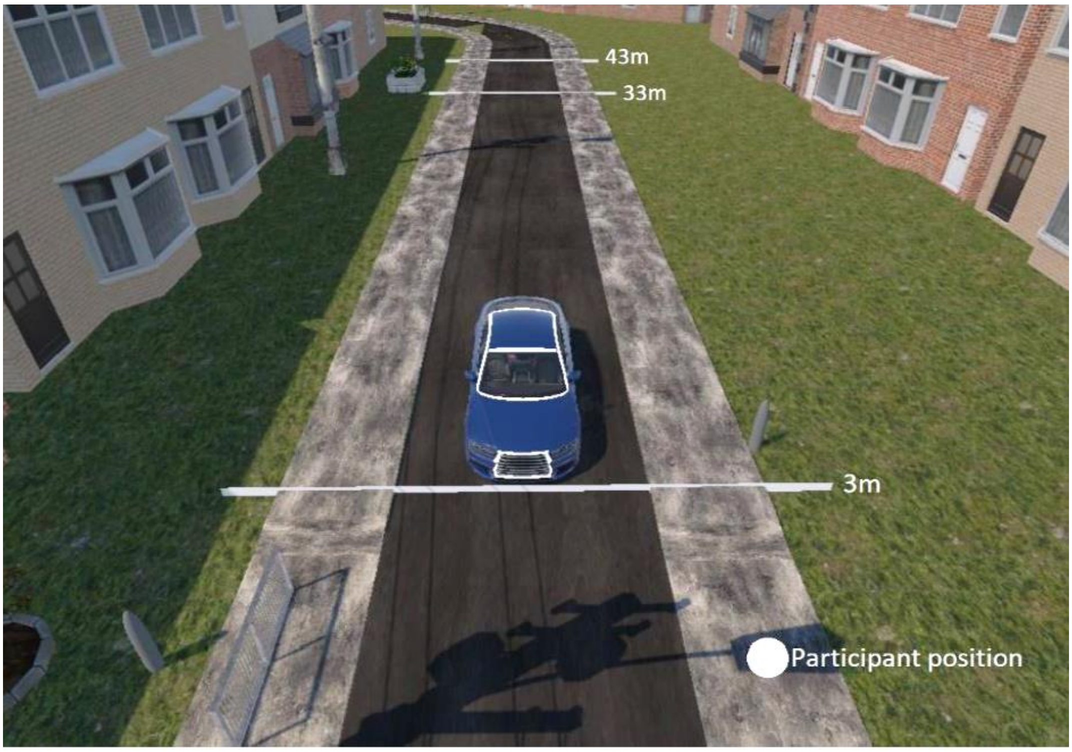

Figure 12: Deceleration onsets were manipulated in Study 3

In Study 4, participants were asked to cross the road close to a crossroad junction. They encountered one approaching vehicle in each trial, which was either about to turn right onto the road they were crossing, or was approaching from the right on the road they were crossing. Participants were asked to cross the road when they felt comfortable to do so (the intended pathway is indicated with red arrows in Figure 13). In this study, we also manipulated the presence/absence of eHMI, and the presence/absence of a zebra crossing (to manipulate their right-of-way). The approaching vehicles either yielded for pedestrians while displaying eHMI, yielded for pedestrians without displaying eHMI, did not yield, or did not cross the pedestrians' path.

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Figure 13: Right-of-way was manipulated in the cross-road study in the Study 4

Table 3: Overview of the pedestrian simulator studies conducted by ITS Leeds

Studies	Independent Variables	Objective Measures	Subjective Measures
Study 1: HIKER Effect of eHMI on pedestrians' crossing behaviour and the subjective evaluation of eHMI • 144 trials • 1.5 hours	(1) Speeds: 25, 30, 35 mph (within-subject) (2) Time gaps: 2-5 seconds, with 1 second interval (within-subject) (3) Yielding behaviour and presence of eHMI: Not yielding without eHMI, Yielding with eHMI and Yielding without eHMI (within-subject) (4) eHMI groups: no eHMI, Slow Pulsing Light Band, Conventional Flashing Headlights (between-subject)	(1) Percentage of crossing (2) Crossing Initiation Time (3) Crossing Duration (4) Traffic Lag Time	Post-trial question: 'I felt safe during this road crossing situation, both while standing and walking', where 1 = 'Disagree', and 4 = 'Agree'. Post-experimental question: Van der Laan et al. (1997)'s usability and satisfaction questionnaire; Jander, Borgvall and Ramberg (2012)'s learnability scale and System Usability Scale (Brooke, 1986)

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Study 2: HMD Can pedestrians identified whether the approaching vehicles were decelerating for them or for the traffic? And how eHMI play a role in crossing decision? • 90 trials • 1.5 hour	(1) Deceleration: Decelerated for pedestrian (80% of the experimental trials) and decelerated for traffic (20%) (within-subject) (2) eHMI designs: no eHMI, slow pulsing light band, conventional flashing headlights (within-subject)	(1) Percentage of crossing (2) Crossing Initiation Time (3) Crossing Duration (4) Traffic Lag Time	NA
Study 3: HIKER What happens when eHMI failed? Will pedestrians still cross the road? • 50 trials • 1 hour	(1) eHMI onsets: 1 second before deceleration started, 1 second after deceleration started (between-subject) (2) Deceleration onset: started at 43m away from participants or 33m (within-subject) (3) Failure trial: Happened at the 37th trial and 50th trial	Participants' position	Post-trial questions: (1) 'I experienced the situation as risky' (2) 'I could comprehend the behaviour and appearance of the approaching vehicle' (3) 'I trust the behaviour and appearance of the automated vehicle' Where 1 = strongly disagree; 10 = strongly agree
Study 4: HIKER The effect of eHMI, vehicle approach direction, and right-of-way on pedestrians' crossing behaviour • 52 trials • 40 minutes	(1) Right-of-way: Zebra crossing or no zebra crossing (within-subject) (2) Vehicle's behaviour: Yielding, Not yielding, did not cross pedestrians' path (within-subject design) (3) Vehicle's approaching direction: turning vs driving straight (within-subject) Presence of eHMI when yielding: eHMI or no eHMI (within-subject)	(1) Percentage of crossings Crossing Initiation Time	Post-trial interview about eHMI, crossing experiences and decision making processes

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Main results

Study 1 revealed that there was no difference between the IBS and FH in percentages of crossings. The visibility of FH was significantly higher than the IBS, whereby the distance at which the FH was perceived was further than the IBS. After controlling for visibility, there was still a significant difference between FH and IBS on Crossing Initiation Time, whereby Crossing Initiation Time was shorter for FH. This suggests that although the visibility of eHMI is important, it may be that the familiarity of the signal also plays a role. Crossing initiation time was significantly shorter when eHMI was turned on than off (for both IBS and FH) at the lower speed and time gaps. Overall ratings of user-acceptance (Van der Laan, J.D., Heino, & De Waard, 1997) were positive. However, there were different benefits for IBS and FH. Stopping distance for IBS was rated as safer and more comfortable than FH, whereas FH was rated higher for raising alertness, visibility, consistency and ease of understanding. Finally, the no eHMI group provided an overall higher rating for crossing experience (comfort, safe, natural) and safer stopping distance as compared to IBS group and FH group.

In Study 2, the eHMI designs (both IBS and FH) did not affect crossing decisions or crossing durations. However, participants did initiate their crossing earlier in response to the FH. Study 3 revealed that failure trial caused approximately 30% of the participants to have collisions, regardless of eHMI onsets and deceleration distance onsets. Risk, comprehension and trust ratings decreased during failure trials but quickly went up again when AV behaviour was consistent. Study 4 revealed that Crossing Initiation Time was significantly shorter when eHMI was on than off, but only when there were no zebra crossings. When there was a zebra crossing, eHMI did not have an impact on Crossing Initiation Time.

Conclusions

(1) If we decide to have eHMI, ensuring high visibility is important, as it might have the potential to encourage early crossings. (Supported by Study 1 and Study 2)
(2) Different eHMI designs have different pros. Overall ratings showed towards the positive side for both IBS and FH (supported by Study 1)
(3) Ensuring the consistency between eHMI message and vehicle behaviour is important (supported by Study 2 and Study 3)
(4) eHMI failure could potentially cause collisions (supported by Study 3)

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Recommendations based on the study findings

eHMI can potentially change crossing decisions and some behaviours if visibility and consistency are ensured. The consequences of eHMI failure are severe, and therefore public guidance around eHMI capability will be required.

Implications and Practicalities

(1) Increase the visibility of IBS
(2) Ensure consistency between the yielding behaviour and eHMI
(3) The public should be educated about the risk of eHMI failures

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4.1.2 BMW Pedestrian Simulator Study

A study was conducted to assess the influence of the eHMI interaction strategies on pedestrians' crossing behaviour. In a WP4 simulator study on vehicle-vehicle interaction it was found that drivers find traffic scenarios where interaction is needed clearer and rate AVs better when the AV is equipped with an eHMI. Driver behaviour, however, was not affected by eHMI; Time to enter the road crossings was not influenced by eHMI, but remained constant. Furthermore no difference between the different eHMI strategies (intention based, detection based, perceivable by only the detected TP) was found. In addition, the traffic scenario and the position of the ego driver, the AV, and the simulated manually driven vehicle did not have an influence on driver behaviour. In the present study, the three eHMI solutions studied in WP4 were evaluated in a pedestrian setting.

Methods

The pedestrian simulator of the BMW research department was used to run this study. The scenarios from the driving simulator study (see D4.2, Weber et al. 2019) were replicated, however with a focus on AV-pedestrian interaction instead of AV-driver interaction (for scenarios see Figure 14).

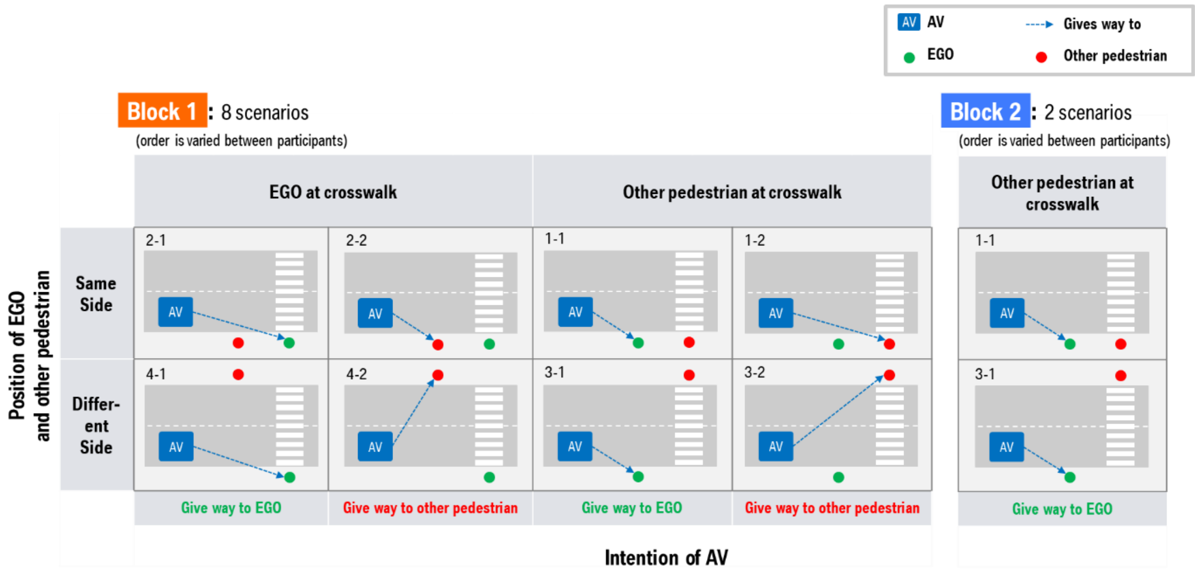

Figure 14: Scenarios presented including participant (EGO) and virtual pedestrian

Participants were placed as pedestrians in virtual reality at the curb of a street and had to decide if and when they would want to cross and consecutively actually cross the street. Participants encountered various vehicles including an AV equipped with one of the 3 different eHMIs or no eHMI see Figure 15. eHMI conditions were presented between participants resulting in 4 experimental groups. A further – simulated – pedestrian was present in all trials. The pedestrian either stood on the same side as the

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participant, or on the opposite side of the street, in closer proximity to the arriving AV or in further distance than the participant. The simulated pedestrian was introduced to identify multi-actor scenarios in which one of the eHMIs might perform different from the other one due to the features of the eHMI solutions. The directional light-band for instance is able to point in the direction of the pedestrian that is addressed and thus to differentiate between the participant and the simulated pedestrian. However, the directional light-band cannot be well distinguished if showing detection of one interaction partner who is standing on the same street side in proximity to another interaction partner. The signal lamp on the other hand can restrict visibility in exactly this scenario. The restricted visibility is, however a feature, which is not directly perceivable to the pedestrian that sees the signal. The full light-band on the other hand – communicating solely intentions – appears the same in all experimental conditions and the participant has to deduct from driving behaviour if the AV will stop for him or the virtual pedestrian. For further descriptions of the eHMI designs please refer to D4.2. The experiment was split into two experimental blocks. In Block 1, participants were not instructed on the eHMI solutions. After Block 1, participants were briefed on the driving behaviour and the actual meaning of the eHMI solutions as well as the driving behaviour and then placed again in 2 test scenarios. Participants in the no eHMi group were briefed on the driving behaviour only.

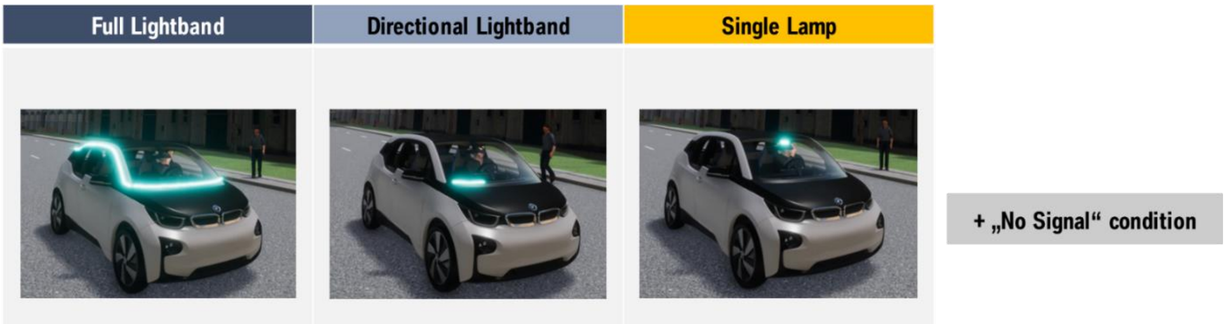

Figure 15: eHMI conditions

Results

Without instruction on the eHMI, no effects on crossing initiation times were found. No wrong decisions or accidents took place in this study, even in scenarios that were chosen to provoke misinterpretations. In the full light-band condition, a decreased certainty of choice was found in scenario 1-2 (see Figure 15). The other eHMI conditions did not differ from the no eHMI condition also in this scenario. No effect of eHMI on perceived safety was found between the conditions. Perceived safety levels were at an average level of 4.4 on a 5-point Likert scale (see Figure 16). After experiencing the eHMI in Block1 and being instructed on the eHMI in Block 2, there was a trend towards lowered crossing initiation times were for the full light-band group compared to other eHMI groups or the no eHMI group.

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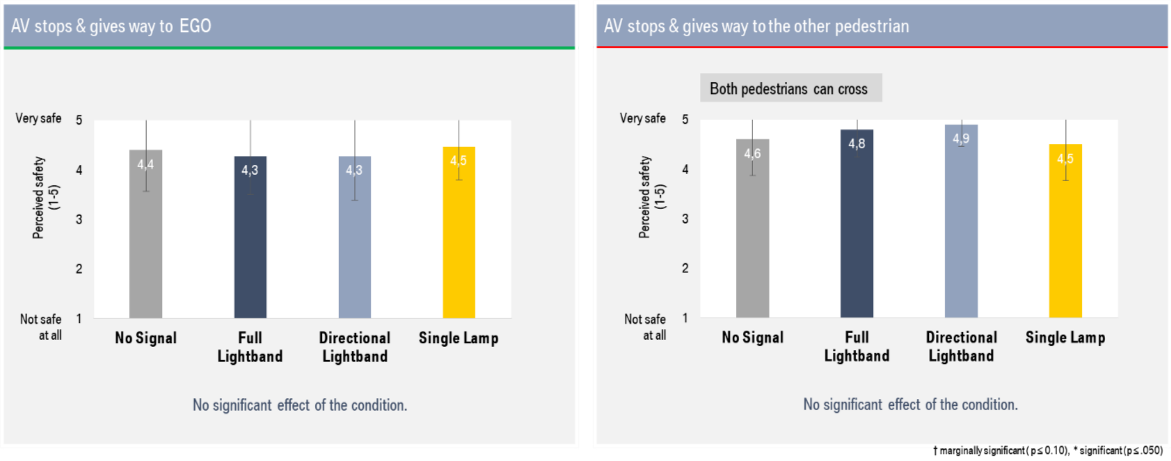

Figure 16: perceived safety when AV gives way to participant or virtual pedestrian

Conclusions

This study found no differences of eHMI groups on efficiency parameters such as reduced crossing initiation times without previous exposure or explanations to eHMI. No decision errors or accidents took place. A trend towards improved crossing initiation times was found when the participants were instructed on the eHMI functionality for the full light-band, which was the most salient eHMI in this study. The only difference found between eHMI variants was perceived clarity being reduced for the full light-band in a scenario where the AV yielded to the other pedestrian. Perceived safety was at a high level in all groups including the no eHMI group (Figure 16). The lack of gains in crossing initiation time might, however, be due to the study setting in which participants did not have any pressure to cross the crossing as well as the overall clarity of the scenarios. On a subjective level, participants in the no eHMI condition experienced the overall interaction as being very clear and safe. From this study, it can be concluded that eHMI has very limited effects and the lack of eHMI did not negatively affect interaction with the AV in any way.

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4.1.3 DLR Vehicle-Vehicle-Interaction Simulator Study

Research Question and Objective

This study investigated the communication of an automated vehicle (AV) with another vehicle. A slow pulsing 360° LED light band (0.4 Hz) in turquoise colour should convey the message "I give way" to AV's interaction partner (IP). The LED light band was mounted outside of the vehicle (see Figure 17). An important question is how well this external HMI (eHMI) can be integrated into existing traffic. The aim of the simulator study was to evaluate the learning and negative effects of this display.

Since the eHMI signal is a novel way of interaction, it is likely that other road users do not understand its meaning immediately. Thus, the first research question was to find out how long it takes to understand the message of the eHMI. It was expected that drivers gain more experience and confidence with increasing number of interactions with the AV.

Drivers are likely to develop a certain understanding of the eHMI meaning and become better in predicting the driving behaviour of the AV. This prediction could lead to confusion if the traffic situation is ambiguous. Drivers may think that they are the intended interaction partner even if they are not. Thus, another research question was whether drivers build an "overtrust" in the eHMIs message over time.

Figure 17: Cyan coloured external HMI on the AV.

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Method

The study was conducted in the Virtual Reality Lab (Figure 18) of the German Aerospace Centre in Braunschweig. This Lab is a highly dynamic and scalable simulation environment. It is able to show a 360° representation of the virtual world created by 12 projectors mounted in the middle of a simulation cave. Each projector has a resolution of 2560x1600 pixels and a contrast ratio of 8000:1. Test drivers sat in a VW Golf 5 that was adapted for simulator use. It was operated like a normal car with throttle, brake pedal, steering wheel and an indicator lever. An active force-feedback system was utilized to simulate realistic steering force.

Figure 18: Test vehicle inside the virtual reality lab

Test drivers repeatedly encountered T-junctions where they had to yield to incoming traffic (Figure 19). As test drivers were closing in on the T-junction, an incoming traffic participant (TP) was triggered just so that the driver had to let it pass before being able to turn. After the TP, an AV equipped with the eHMI was following. The test driver could either turn and take the gap between the TP and AV or wait and let them pass.

The independent variables in this study were gap size, signal and scenario.

Three levels of signal were varied. The first signal type was basically a baseline (no signal) where the AV continued with constant speed (30 km/h) and did not send any signals. In the second level, the AV was

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signalling implicitly that it is yielding by breaking and increasing the gap. In the last level, the braking manoeuvre was combined with the explicit message from the eHMI.

The gap size was varied in three levels. A small gap, which should be rejected by the majority of drivers, a medium gap, large enough that approximately half of the test drivers should accept it and a large gap, which should be accepted by the majority of drivers. The gap sizes were derived from the research conducted by Fitzpatrick (1991). However, test trials inside the simulator showed that they were perceived as smaller than in reality and did not yield the desired effect. Thus, the gap sizes were reduced for data collection inside this simulator.

Table 4: Adaptation of gap sizes from real world observations for driving simulator use. For the simulator the base duration is shown. The actual gap was larger for the brake and brake & eHMI condition due to the deceleration of the braking AV.

Gap size	Based on traffic observations by Fitzpatrick (1991)	Adapted gap size optimized for driving simulator
Small	6.5 s	~4.0 s
Medium	7.9 s	~5.0 s
Large	8.9 s	~6.0 s

The scenario was varied in three levels. In two scenarios, the test drivers were approaching from a side street and turning either left or right into a main road. In the third scenario, they turned from the main road into a side street (Figure 19).

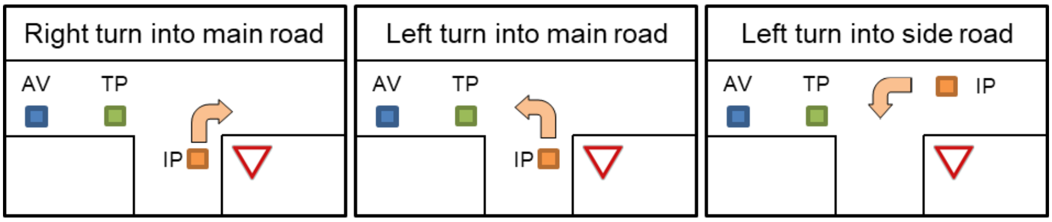

Figure 19: Overview of the scenarios. The test driver was operating the IP. The AV was instrumented with the external HMI. The TP was included to create a gap together with the AV that the IP could turn into.

To increase validity, we aimed to provide a naturalistic driving feeling in the simulator. With this in mind, it was decided to create one closed test track, where participants drive from one junction to the next one without leaving the simulator environment (Figure 20).

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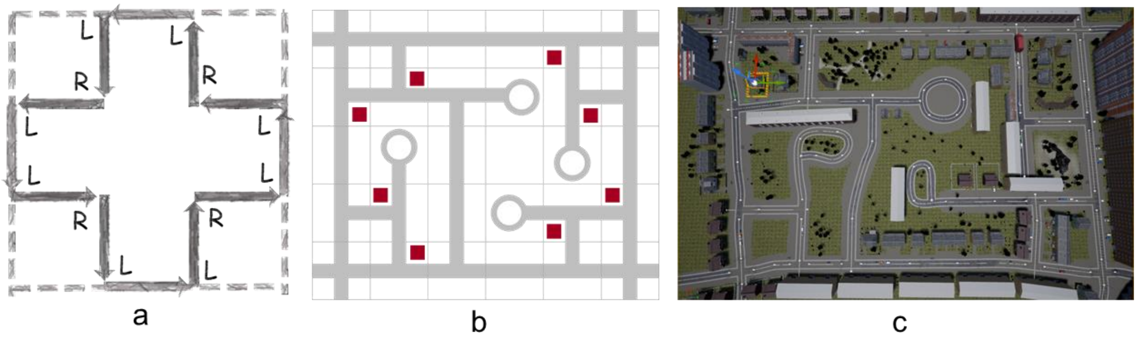

Figure 20: Development of the test track in three steps. First, a closed track was derived from the desired T-junctions (a). A more natural track layout was created (b) which was converted to the final track with buildings and trees (c).

To avoid that test drivers adjust their speed to avoid stopping at the intersection or speed up to turn in front of the TP, objects were placed to block the sight at the intersection (red dots in Figure 20b).

Turn direction and give way signs were placed at each T-junction to indicate the turn direction and that the AV had always the right of way. To minimize simulator sickness the study was split into three maps where participants had to make 9 turns before they had a break. The order of the experimental condition was randomly selected per map within the limits of the intersection type. A total of three maps with 27 scenarios were created to investigate the learning effects. In addition, a fourth map was created where potential negative effects of eHMI were evaluated at one intersection. In order to eliminate carry over effects between maps, the sequence of the three maps was counterbalanced using the Latin square method. The map with the negative effect scenario was always driven at the end of the study.

Test drivers were informed that they would drive in an urban scenario with only T-junctions. They were instructed to drive naturally and follow the instructions of the traffic signs. They stopped after each turn to answer a brief questionnaire about the last interaction. Before the data collection test, drivers completed one map without any road users to become familiar with the simulation environment. After completing all test tracks, test drivers filled out the post experiment questionnaires.

An additional scenario was created to investigate the negative effects of eHMI signals further. In this use case the AV was giving way to another vehicle (TP2) approaching from the right side (Figure 21), instead of addressing the IP. This scenario was similar to the “left turn into side road”-scenario. It was supposed to make the test drivers believe that they are the intended interaction partner.

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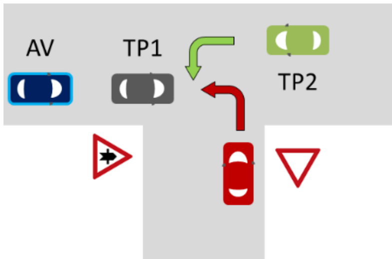

Figure 21: The final critical scenario featured an additional traffic participant (TP2) as intended receiver for the eHMI message.

The learning effect of the eHMI message was measured by counting the number of encounters with the eHMI until drivers correctly reported its function. If the number was small, test drivers understood the signal intuitively. If it was high, they had difficulty grasping its message. Gap acceptance was measured by counting the number of accepted gaps for each gap size.

Table 5: Overview of questions asked, translated from the original version in German.

Question(naire)	When given?
Demographic questionnaire	Before experiment
Affinity for technology interaction scale (Franke, Attig, & Wessel, 2018)	Before experiment
System usability scale (Brooke, 1996)	After each turn
What size did the gap have? (5 point scale 1 = small to 5 = large)	After each turn
Did the AV support you in the turning manoeuvre? (yes/no)	After each turn
How did the AV support you? (open question)	If previous question was answered with “yes”
How safe did you feel turning? (5 point scale 1 = very unsafe to 5 = very safe)	After each turn (if applicable)
What influenced your decision to turn? (open question)	After each turn (if applicable)

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How did you understand the signal? (open question)	After each turn with eHMI
Would you feel safer if the eHMI signal was activated? (yes/no)	After each turn without eHMI
Systems acceptance scale (Van der Laan et al., 1997)	After the simulator runs

Before the experiment, a questionnaire was deployed to collect demographical information of participants (Table 5). This included age, gender, education, licenses, driving frequency and annual mileage information. After this the “affinity for technology interaction scale” (ATI) (Franke, Attig & Wessel, 2018) was given. This scale is designed to assess a person’s tendency to actively engage in intensive technology interaction.

During the experiment, questionnaires were given after each use case. Thus, participants were asked to stop after each turn to respond to these questions. The experimenter confirmed whether participants turned in front or after the AV and asked what factor influenced their decision. If participants stated more than one factor, it was requested (if possible) to prioritize these factors. A question regarding perceived safety was only asked if participants turned in front of the AV. The next question checked whether the selected gaps are also perceived as small, medium or large by participants. In the following question, the experimenter asked whether participants thought that the AV supported them during the turn manoeuvre. If participants thought that the AV supported them, an open question was asked to describe how they felt the AV supported them and whether it played a significant role for their decision. The last question depended on the signal level of the AV. For scenarios, where the eHMI was activated, the investigator asked the meaning of the eHMI signal. This question was not repeated if participants stated the same interpretation twice. The other two questions were only asked if participants had an understanding of the eHMI signal. For the scenarios where the eHMI was not activated but participants turned in front of the AV, the investigator asked whether they would feel safer if the eHMI was activated. In cases where the gap was rejected the investigator asked whether participants would turn if the eHMI was activated.

The usability and acceptance of the eHMI solution was assessed with the system usability scale (SUS) and the systems acceptance scale (Van der Laan) after the simulator runs (Brooke, 1996, Van der Laan et al., 1997).

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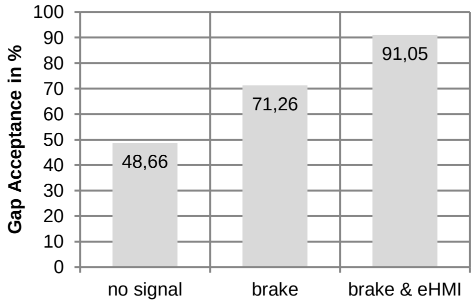
28 participants completed the simulator study (39% female). On average participants were 38 years old, ranging from 19 to 69 years. Every participant had a car-driving license. Most of the participants drove their car daily, with an average of 12.750 km per year.

Main Results

A total of 649 turns were recorded during the data collection phase. Data sets with technical difficulties were excluded from the analysis. The final data set included 25 test drivers who completed 572 turns.

The study revealed positive effects of the eHMI. A three way log linear model revealed that the gap acceptance increased with the level of signal (Table 6). The increase from one level to another was between 20% - 22%. There was a significant effect between the signal and gap acceptance $\chi^2(2) = 80.84$, $p < .001$. Odds ratio indicated that the odds of gap acceptance in scenarios where the AV was sending implicit signals (brake) were 1.46 times, and at scenarios where the AV was sending additionally explicit signals (brake and eHMI) were 1.87 times higher than in scenarios where the AV was driving with constant speed (no signal).

Table 6: Overview of gap acceptance by signal with frequencies for each condition.



Signal	N	Accepted
no signal	187	91
brake	174	124
brake & eHMI	190	173

The gap acceptance also increased with gap size (Table 7). The increase from one level to another was approximately 8%. There was a significant effect between the gap size and gap acceptance $\chi^2(2) = 12.20$, $p = .004$. Odds ratios indicated that the odds of gap acceptance in scenarios with medium gaps were 1.14 times, and in scenarios with large gaps were 1.26 times higher than in scenarios with small gaps.

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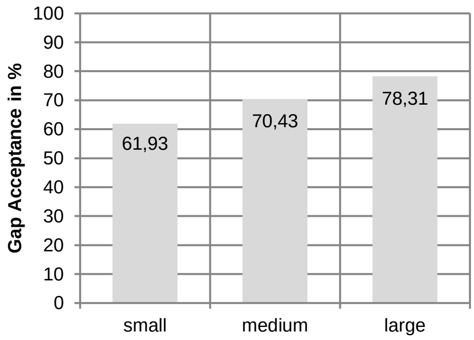
Table 7: Overview of gap acceptance by gap size with frequencies for each condition.



Gap	N	Accepted
small	176	109
medium	186	131
large	189	148

The score of the ATI questionnaire was negatively correlated with overall the acceptance of the gap (r = - .135, p = .001). In other words, participants with a high affinity for technology are likely to accept the gap more often. The gap acceptance did account for 1.82 % of the variability in the ATI Score. The ATI score was even higher correlated to gap acceptance in scenarios where the eHMI was activated (r = -.213, p = .002). This supports the hypothesis that people, who are more interested in technology, understand or trust the eHMI of the AV better and therefore accept the gap more often. The acceptance of the gap did account for 4.54% of the variability in the ATI Score.

When asked what influenced their decision to accept a gap, the majority of test drivers (52%) stated gap size as primary reason. Braking was mentioned second (25%) and the eHMI third (24%).

Table 8: Primary reasons affecting Gap Acceptance Decision

Reason	N	Primary	Secondary
Gap	330	321	9
Brake	169	153	16
eHMI	165	147	18

The eHMI signal was easy to learn and perceived as beneficial once it was understood. The analysis of the reported function of the eHMI message revealed that almost half of test drivers (68%) understood the message of the eHMI after two interactions. When the eHMI was understood, practically all gaps signalled by it were accepted (98%). In trials without eHMI signal, practically all test drivers indicated that they would feel safer with the eHMI (98%). In trials without eHMI, where test drivers rejected the gap, half of them indicated they would have taken it with the eHMI present (52%).

However, a tendency to overtrust in the system could be observed. In an ambiguous scenario where the signal was intended for another vehicle accidents occurred when test drivers did not check the rest of the traffic situation. Out of 22 test drivers who completed the critical scenario four (18%), crashes

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were observed. Test drivers who checked the traffic situation before turning were involved in near miss situations (27%) or handled the scenario safely (55%).

4.1.4 DLR Internal HMI Driving Simulator Study

Research Question and Objective

The aim of this study was to investigate driver's reactions travelling inside an automated vehicle (AV) that is interacting with external road users. We wanted to know if the drivers' ratings in regard to usability of the iHMI change, if they are engaged with the secondary task.

The drivers might prefer if the current intention of the automated vehicle is communicated with an internal HMI (iHMI). If not the driver might be surprised or even concerned about what is happening. It is also possible that the drivers might feel unsafe when they do not know if another road user was detected correctly.

Method

To investigate the effects of a perfect functioning system, the iHMI in this study was accurate and did not give any false alarms. Since the vehicle is self-driving, the driver could engage in other activities. This was simulated by requiring the drivers to execute the surrogate reference task (SURT) while driving (Figure 22). The SURT is a standardized secondary task in which a target stimulus has to be found between several distractors (Wynn & Richardson, 2008). The iHMI was displayed on a tablet (Galaxy Tab A, 1920x1200 pixel resolution) mounted next to the steering wheel (Figure 22). The SURT was shown on a touch screen next to the iHMI (Figure 22).

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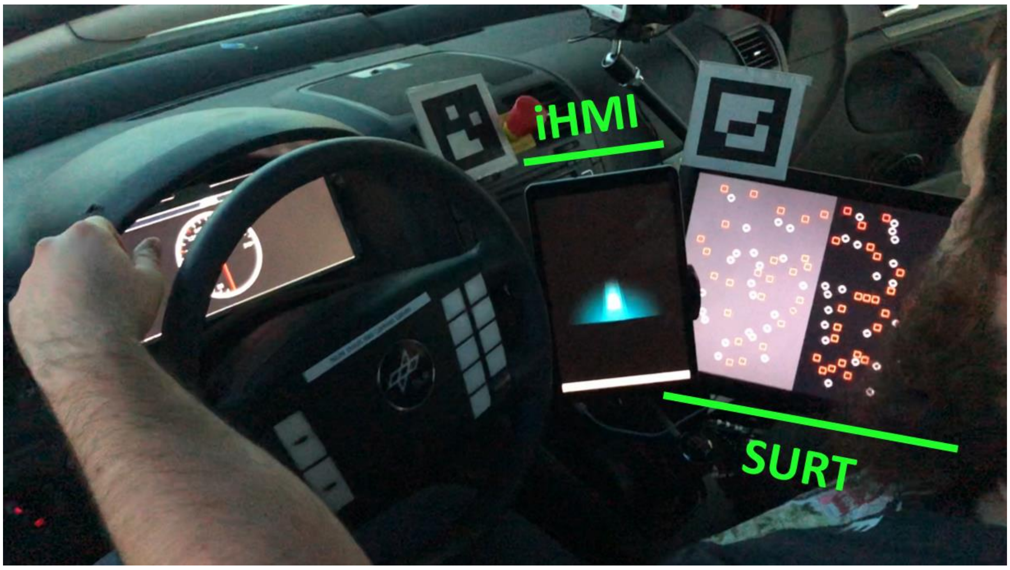

Figure 22: Simulator setup inside the vehicle. The iHMI and SURT were mounted next to the steering wheel on the right.

A 2x2 within subject design was realised. The independent variables were iHMI (with/without) and secondary task (with/without). The AV was driving a rectangle shaped track inside an urban environment. There were no other road users present, except two encounters with vehicles and pedestrians each (Figure 23). There were two encounters with pedestrian and vehicle each per condition to give the test drivers a good impression of the iHMI. The track was identical to the one used as in interACT D6.2 eHMI Study (see section 4.1.3).

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Figure 23: The map featured a rectangular shaped track driven by the AV. There were two encounters with pedestrians crossing the street and a vehicle turning each. The same map was driven four times to test all combinations with the HMI and SURT on and off.

Test drivers rated the usability, emotional reaction, trust, safety and understanding of the iHMI. The usability was assessed with the acceptance scale (Van der Laan et al., 1997). The Self-Assessment Manikin scale (SAM) was utilized to measure the emotional reaction (Bradley & Lang, 1994). The information displayed in a HMI will only be of use if it is deemed trustworthy. Hence, the trustworthiness was measured with the facets of trustworthiness (FOST) scale (Franke et al., 2015). Finally the test drivers were asked to rate if they feel safe, if they understood the actions of the autonomous vehicle and if they found the actions of the vehicle predictable on a scale from 1 (not at all) to 5 (very).

Ratings of electronic devices may vary with the experience with technology. Thus, the Affinity for Technology Interaction scale (ATI) was applied to measure technological affinity (Franke, Attig, & Wessel, 2018).

The same driving simulator was used as in interACT D6.2 eHMI Study (see section 4.1.3). The Unreal Engine was utilized to create a high quality simulation (Figure 24).

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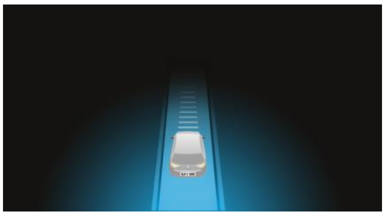
Figure 24: The Unreal Engine was used to create a high quality urban environment for the study.

Table 9: Overview of internal HMI signals

Idle	Pedestrian crossing	Vehicle Turning
		
This screen was shown as default when no event is detected.	This screen was shown, when a pedestrian was detected right to the AV. It was shown 7 s before the vehicle reached the crossing point.	This screen was shown, when a vehicle was detected in front of the AV. It was shown 7 s before the vehicle reached the crossing point.

Test drivers were informed that they will drive in an AV in an urban scenario. The investigator gave safety instructions how to operate the simulator vehicle and explained how the rest of the study will be conducted. The test drivers sat inside the AV on the driver's seat, while the vehicle drove by itself. The driver did not have to take over (like SAE Level 5). The test driver executed the SURT as non-driving related task (Wynn & Richardson, 2008). The vehicle encountered other road users (a pedestrian or car) and granted priority. Dependent on the driven condition this was communicated by the internal HMI to the test driver or not. A questionnaire measuring the perceived safety and other variables of the iHMI was given. The ATI was presented once before the simulation was started. The SAM and safety scales were filled out after each scenario. The Van der Laan scale, FOST, understanding and predictability were measured after the conditions with iHMI present only.

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Main results

Due to a small sample size of ten test drivers no statistical analysis was performed. Results are reported by observed frequencies.

The usability was only measured in conditions with HMI active since the usability of an absent device cannot be judged. The data showed a tendency of the iHMI being rated as useful (mean -0.62 with -2 useful and +2 useless). The tendency was even stronger when the secondary task was performed (-0.80) than without secondary task (-0.48) as can be seen in Figure 25. The iHMI display was also rated as generally satisfactory (mean -1.18 with -2 satisfactory and +2 not satisfactory). There was only a small difference in between the condition with and without secondary task. The iHMI was rated as more satisfactory when the secondary task was performed as well (mean -1.25) compared to being driven without a secondary task (mean -1.13) as can be seen in Figure 25.

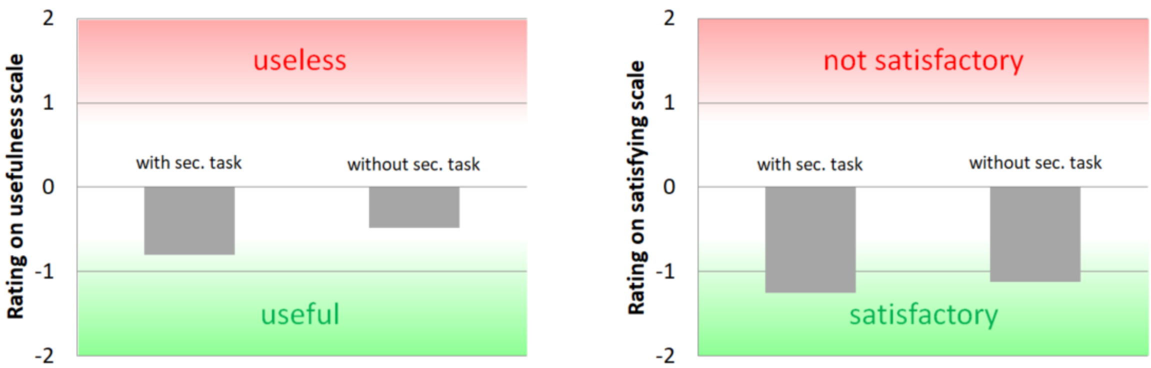

Figure 25: Mean ratings of usefulness and satisfaction for conditions with and without secondary task on the acceptance scale.

The understanding and predictability of the iHMI were also only measured when the iHMI was present, since the ratings refer directly to the device. The ratings showed a trend towards the iHMI being understandable (mean 3.44). Understanding was rated higher when the secondary task was performed (mean 3.88) as when it was not (mean 3.00). The same was true for the predictability, but with only a bit higher rating under the secondary task condition (mean 3.50) than without (mean 3.30). Both differences can be seen in Figure 26.

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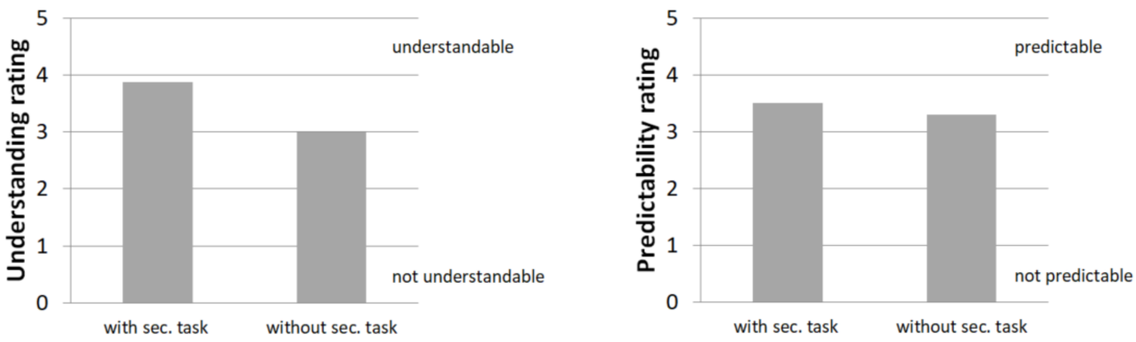

Figure 26: Mean ratings of understanding and predictability for conditions with and without secondary task.

The self-assessment manikin scale was applied after each condition to measure the emotional response. The pleasure ratings show that the driving experience was rated as pleasant in general (Figure 27). The trials with iHMI and secondary task were rated as most pleasant (mean 1.90) and the condition without these devices as least pleasant (mean 3.78). The subjective arousal was generally low (Figure 27). The rated arousal was lower without (mean 6.98) than with iHMI (mean 6.50). It was also perceived as lower with secondary task (mean 7.10) than without (mean 6.38). The perceived dominance was mostly indifferent with a tendency towards a feeling of less control (mean 4.48). Only without iHMI and without secondary task was the perceived control average with a tendency towards higher control (mean 5.38).

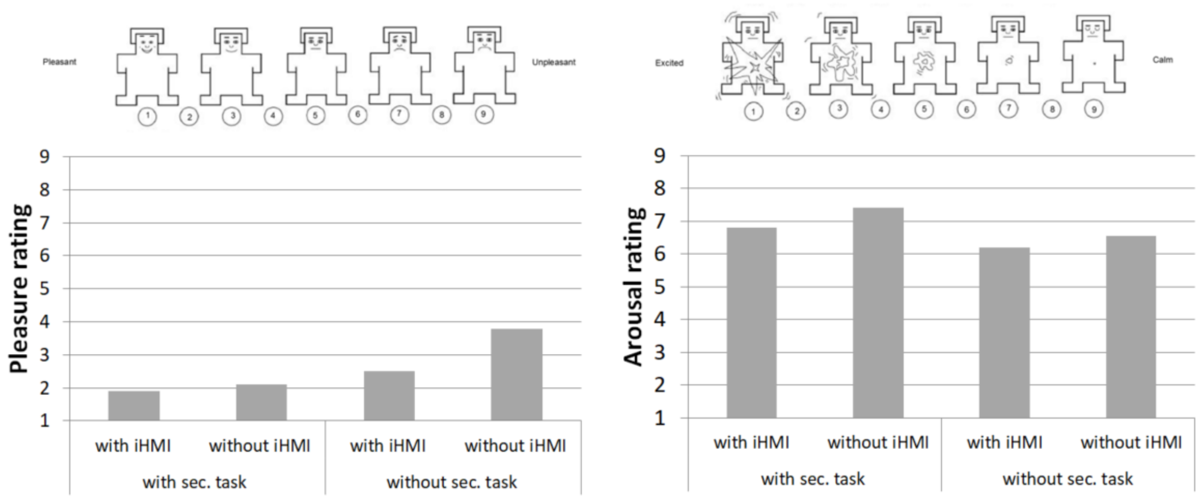

Figure 27: Ratings on the SAM for the subscales pleasure and arousal.

The subjective safety did not depend on the presence of the iHMI and was measured after each condition. The test drivers ratings of trips without iHMI showed a trend towards being perceived as

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safer (mean 0.63) than with iHMI (mean -0.05) as can be seen in Figure 28. There was only a small difference between the ratings with (mean 0.40) and without secondary task (mean 0.18).

Figure 28: Ratings of safety for all four conditions.

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4.2 Results of Demonstrator studies

4.2.1 TUM BMW Wizard of Oz: Test Track Experiment

Objective

The main objective of the test track experiment was to evaluate the BMW demonstrator vehicle, with an emphasis on the interACT eHMIs and deceleration strategies[1]. The demonstrator is driven manually. To ensure that other road users perceive the vehicle as driverless or cannot perceive cues from the actual driver, the vehicle occupants were hidden behind seat covers. Vehicles using this approach are called "Wizard of Oz"-vehicles (WoZ) and have been used in other projects, as user studies need to be conducted before the technology is either ready or legal to use. The main objectives of the test track studies were:

- Effect of different explicit communication strategies on pedestrian crossing behaviour and intention recognition
- Effect of different deceleration strategies on pedestrian crossing behaviour and intention recognition
- Subjective perception and rating of the eHMIs
- Effectiveness of the seat cover for evaluating AVs using a WoZ approach

Methodology

Wizard of Oz Implementation

As the demonstrator is driven manually and required a passenger to control the eHMIs, hiding the vehicle occupants was necessary. This was achieved by designing a cover mimicking a seat. This cover was created using bent aluminium sheets on the sides with cut-outs for the seat belts and peripheral vision. The aluminium covers were encased with black fabric. Vehicle occupants enter the fixed frame and place a soft cover over the edges. This soft cover consists of a sturdier foam covering the torso and a multiple layer mesh fabric to ensure visibility. Pre-tests have shown that the driver was able to perceive all necessary surrounding information, including the mirrors and HMI elements of the vehicle. Soft turns were possible without being seen from outside by holding the wheel at the lower section. Therefore, both driver and passenger are hidden from the direct view of other traffic participants. The seat cover was designed in a way that the driver was not hindered to perform high dynamic manoeuvres (e.g. fast steering), which would however be visible from outside, as the front cover would detach from the frame.

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[1] Acknowledgements: This study was conducted with the help of the three master students Johanna Angerstorfer, Selina Kling and Jasmine Huwer.

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Figure 29: Driver and passenger hidden from the participant's view under seat covers

Experimental Design

Overall Setup

The WoZ Vehicle accelerates and passes a light barrier in 50m distance to the pedestrian activating its eHMI and lifting the visual occlusion from the participant. As the first trials had shown that participants perceived the deceleration acoustically, relying on the roll noises and sound engine of the BMW, an audible occlusion was introduced. The first two participants were excluded from the objective data analysis, as all other participants wore noise-cancelling headphones playing back city noises. The pedestrian had the following tasks:

A) Pedestrian makes on step forward indicating that he/she feels safe to cross

B) Participants presses a button to indicate that the condition was understood.

After the participant's activity, the view was occluded and the pedestrian asked to turn towards the experimenter, filling out 4 questions. 3 deceleration distances (40, 31 and 23 meters from the stopping point of the vehicle) and 4 eHMI conditions were presented with additional 4 conditions where the vehicle passed the participant without displaying an eHMI.

After completing all vehicle encounters, participants were asked to fill in a final questionnaire, aimed to understand, whether they perceived the eHMI, how they interpret the eHMI and how they rate it. These questions were asked twice – without any additional information and after an explanation, what the different eHMIs mean. Finally, participants were asked how they thought the vehicle was controlled and whether they perceived a passenger or driver. Completing the questions all participants received a debriefing showing them the WoZ vehicle and the drivers.

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Hardware Setup

- 1 PC with unity application communicating with an Arduino (see below) and recording objective data
- 1 laptop with questions that were asked within the experiment using LimeSurvey
- 1 tablet with questions (and videos) used to interview the participant before and after the experiment
- Others:
    - Cables on the road for haptic cues on when the WoZ-driver needs to initiate the deceleration
    - 2 Light barrier setups consisting of 2 retroflective infrared light-barriers and 2 reflector plates
    - 1 Arduino to detect light barrier passings and button presses as well as control the transparency of the occlusion goggles
    - 1 Pair of Occlusion Goggles
    - BMW i3 WoZ vehicle, described in D6.1

Figure 30: Participant crossing in front of the yielding vehicle

The experiment lasted 75 minutes and participants were compensated with 20€.

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Main Results

Subjective Reports

Overall 38 participants (23 female, 15 male) took part in the experiment (mean age 34.3 ± 16.5 years, age span 19 – 70 years).

After completing all conditions, participants were asked first, if they perceived something special. Table 10 shows that 31 (81.6%) participants reported to have noticed additional lighting elements with 18 (47.4%) perceiving different signals. Only four (10.3%) participants directly reported having perceived different deceleration strategies.

Eight participants perceived the pulsing light-band and nine participants the perception based design. Only three participants noticed the directed signal lamp.

Table 10 Perception of unusual features on the approaching vehicle

Category	Subcategory	Number of mentions
Perception of an eHMI	Without a hint by the experimenter	31
	With a hint by the experimenter	4
Meantion of different light signals		18
Meaning of the signal	Confusing	3
	Not understood / no connection to driving behaviour	7
No driver present		9
Variation of braking maneouvres		4

After the initial question, videos of the stationary BMW with all eHMI variants (including the fast flashing light band indicating that the AV will start soon) were shown, without any further explanation. Study participants were asked how they interpret each individual eHMI. As the answers were given freely, they were coded into categories. Combining sub-categories but counting a participant's answers only once, allows concluding, whether the understanding of the individual eHMIs matches the AVs intention:

22 (57.9%) participants reported to understand the perception based signal as to be perceived by the AV sensors. 5 (13.2%) participants reported the perception based signal to indicate a future trajectory or manoeuvre of the AV. 12 (31.6%) of the participants interpreted that the AV displaying the perception based signal will also come to a stop and/or lets the pedestrian cross. 16 (42.1%) participants

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interpreted the intention based signalling as a yielding of a vehicle, 18 (47.4%) understood the combined signalling correctly. The fast flashing of the light-band, meaning that the car will accelerate again shortly, was mistakenly interpreted as yielding by 12 (31.6%) participants with 15 (39.5%) understanding it as a signal that the vehicle does not yield the right of way for pedestrians.

After a debriefing by explaining the actual functionalities of the individual eHMI with the corresponding vehicle intentions, participants were asked to rate the presented eHMIs individually using a 5 point Likert scale based on Brooke (1996) and Jander et al., (2012). As Figure 31 shows, the median scores of intention based and perception based signalling were equal and received mediocre scores. The combined design was rated worse in each category.

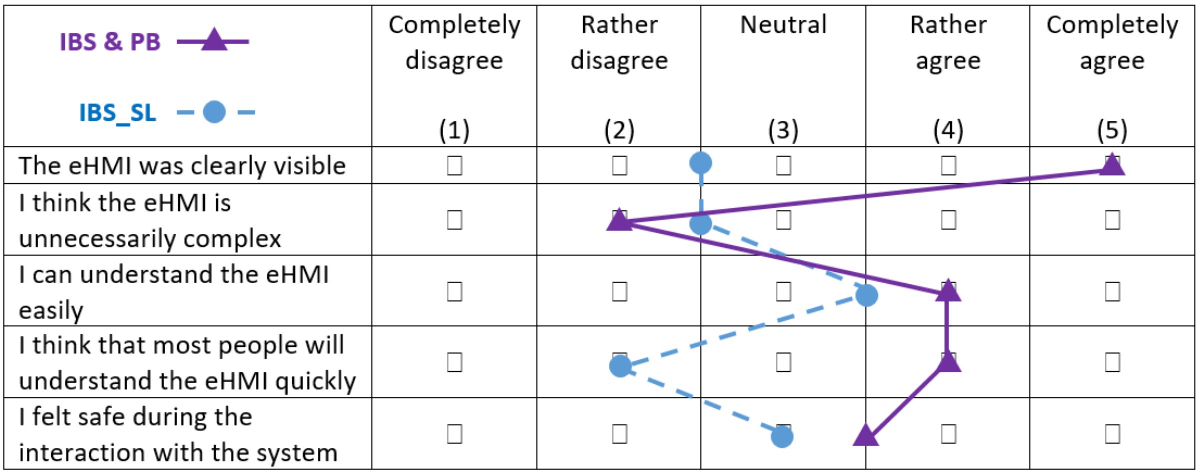

Figure 31: Graphical representation of the eHMI rating

Finally, participants were asked to rank the presented eHMIs. The intention based signalling was preferred by 16 (42.1%) participants, followed by the perception-based design (12, 31.6%) and the combined design (8, 21.1%). Only 2 (5.3%) participants preferred no visual communication over the other eHMI designs. 92.1% of the participants stated that future AVs should be equipped with the preferred external HMI.

None of the study participants reported to perceive a driver in the vehicle. 24 (63.2%) participants believed that the vehicle was driven autonomously, 9 (23.7%) participants thought that had some sort of longitudinal automation (e.g. in the form of a driving robot). The remaining 5 (13.2%) participants stated that the car was driven manually – either in the form of teleoperation or with a driver hidden somewhere in the vehicle.

Objective Measures

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Objective data from 36 participants (21 female, 15 male; mean age 34.3 ± 16.5 years) was analysed.

The intention recognition time (IRT) was measured as the time difference between the vehicle passing the light-barrier (50m to the pedestrian) and the pedestrian pressing the button. A 4x3 repeated measures ANOVA revealed no statistical significant interaction between the effects eHMI and deceleration strategy ($F(6, 204) = .75$, $p = .614$). Simple main effect analysis revealed no significant differences for the factors eHMI ($F(3, 102) = 1.06$, $p = .369$) and deceleration strategy ($F(2, 68) = .19$, $p = .832$).

The crossing initiation time to vehicle stop (CIT_VS) represents the time difference of the vehicle coming to a full stop and the participant crossing the light-barrier indicating the crossing. A Greenhouse-Geiser corrected 4x3 repeated measures ANOVA showed no significant interaction effects between the factors eHMI and deceleration strategy ($F(3.58, 93.30) = 0.98$, $p = .426$). The presence and/or type of eHMI showed no significant difference in the CIT_VS ($F(3, 78) = 0.97$, $p = .410$). The ANOVA showed significant differences for the deceleration strategies on the CIT_VS ($F(2, 52) = 70.03$, $p < .001$).

Figure 32: Boxplots showing the CIT_VS. * p < .05

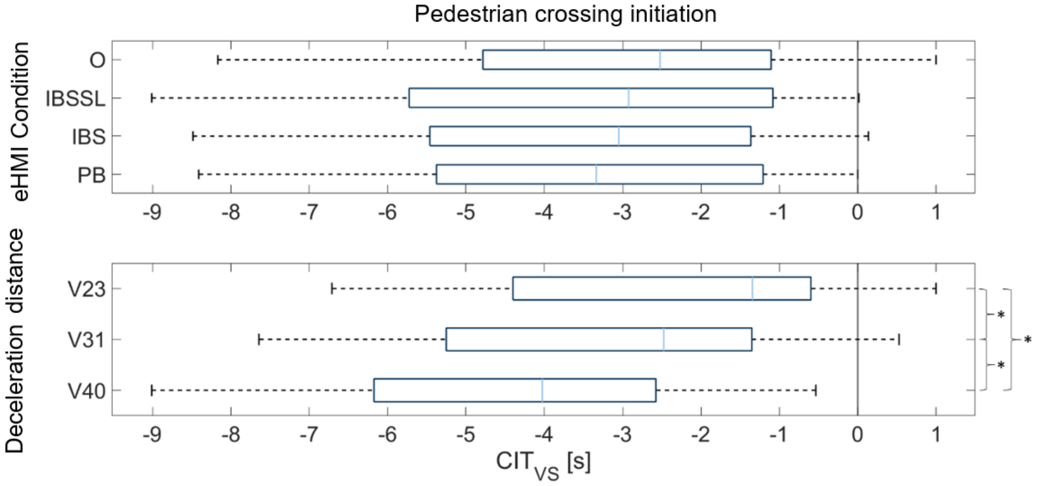

Figure 32 shows that participants initiated their crossings significantly earlier in relation to the vehicle coming to a full stop the earlier the AV initiated its deceleration. However, this difference is diminished when including the time, the vehicle takes for the deceleration (shown in Figure XX, where the y axis represents the time between the vehicle passing the first light-barrier and the participant activating the second one). While the differences in the mean values showing a trend comparable to the simulator studies conducted in WP2 and WP4 (see D2.2, Dietrich et al. 2019 and D4.2, Weber et al. 2019), the variance of results in the test track study was much higher.

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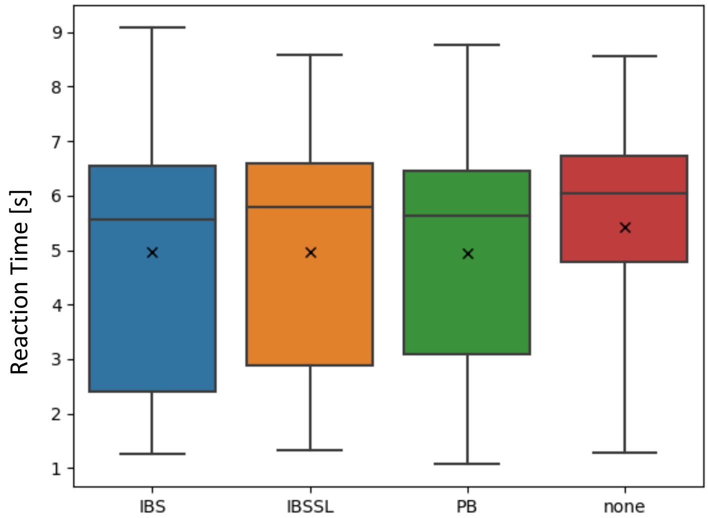

Figure 33: Boxplot showing the reaction times with varying eHMIs.

Conclusions

- The test track study showed no effects of the presence or activation of the eHMI on pedestrians crossing initiation or intention recognition times.
- The deceleration strategy had a significant effect on the CIT_VS: the earlier the vehicle started to brake, the earlier the pedestrian initiated his/her crossing relative to the vehicle coming to a full stand still. Therefore, by braking early AVs could avoid full standstills and minimize the time lost in the interaction.
- The intention-based eHMI was ranked highest, with the perception-based eHMI being a close second. The signalling lamp was only perceived by few participants. Most participant preferred to have an eHMI present on AVs.
- Test track studies are a valuable tool to verify results acquired in simulator studies. The difference in the mean values for the CIT_VS are comparable to those in simulator studies. However, the absence of a leading vehicle lead some participants to initiate their crossing before the vehicle even started to decelerate and some pedestrians to wait until the car fully stopped leading to very high variances. Further studies should either introduce a leading vehicle or reduce the distance to the approaching vehicle at which the occlusion is lifted.
- The Wizard of Oz concept successfully made the pedestrian believe that they encountered a driverless vehicle. None of the participants perceived a human driver.

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4.2.2 TUM BMW Wizard of Oz: Instructed Walking

Objective

The objective of this study was to test the eHMI solutions under conditions that are less controlled but therefore more realistic than test-track environments. This methodology can be seen as an intermediate step between test-track experiments and field studies.

We conducted this study on private premises (University Campus) in an area that is usually not very frequented by cars or pedestrians. This allowed us to leave the area open for the usual traffic while conducting our participant study in the area. The benefits of our approach are:

1. The environment is natural and real. Studies following the described approach can be conducted nearly anywhere.
2. Participant's reactions can be observed in a partly controlled setup and multiple reactions can be recorded for each participant (unlike in a field study) as the environment is more controllable than in a real field study, but at the same time more natural than a test-track environment.
3. Participants do not necessarily have to be aware of the actual study purpose (cover story). The benefit of using of a cover story is that participants might show more natural behaviour (like in a field study).

Method

Cover Story

In this study, participants were not informed about the actual study purpose. Instead, they were told, that the study objective was to investigate GPS positioning accuracy using smartphone data. Therefore, participants were given a smartphone to carry throughout the experiment. They were furthermore informed that their walking path had been exactly measured and marked previously and that they would need to follow the path markings as exactly as possible and stop at predefined markings. Furthermore, they were told that connectivity problems could occur occasionally and that they would therefore be accompanied by an experimenter who is in constant contact with another experimenter why is monitoring the connection quality throughout the experiment and who would let them know if they would need to interrupt walking in order to regain a better connection.

Setup

The BMW Wizard-of-Oz demonstrator was used for this study. The driver steered the test vehicle manually and the co-driver controlled the eHMI. Both, driver and co-driver were occluded from the participant's view using seat covers. Hence, the vehicle appeared to be unmanned. The outlined cover story allowed the experimenters in the car and the one outside with the participant to communicate with each other in order to control the timing of vehicle and pedestrian so that they would meet in a

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similar fashion at each crossing. Furthermore, this setup allowed the experimenters to ask the test person to wait in order to account for any delays, such as another traffic participants (vehicle or other pedestrian) entering the test site.

The test site was not closed for other traffic participants in order to be able to evaluate the method for its robustness and applicability in regular field-testing without having to interrupt usual traffic. Moreover, the buildings occluded the test person's view so that the test vehicle could move into position without the test person's knowledge. The streets were wide enough for the vehicle to pass the pedestrian securely but did only partly provide pedestrian sidewalks.

Figure 34 provides an overview of the test site setup. The test vehicle stopped at two pre-defined stopping points and the test persons had to wait at pre-defined waiting points until the experimenter told them that they could move on. This way, two crossings were defined in which the test vehicle and the pedestrian would meet multiple times. Cameras were placed near both crossings and an additional camera was mounted behind the windshield of the test vehicle.

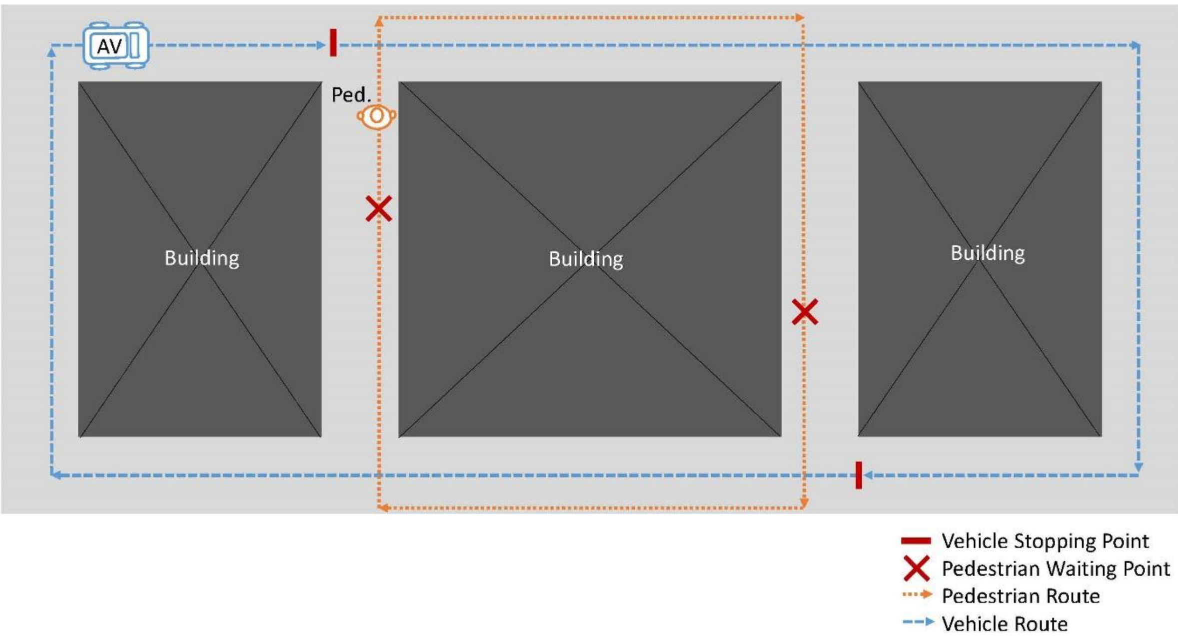

Figure 34: Schematic Representation of Test Site

The vehicle was travelling at 20 km/h, decelerated and came to a full stop at the pre-defined stopping points. The pedestrian waited at the pre-defined markings if necessary to ensure an appropriate timing when encountering the vehicle at the crossing. The vehicle always came to full stop and let the test person cross the street for safety reasons. Participants were informed, that the test site was not closed

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for traffic and that they should pay attention to oncoming vehicles and other traffic. The co-driver manipulated the eHMI manually. It was activated in a constant distance from the vehicle's stopping point. The test vehicle moved on, after the pedestrian had crossed the street.

Test persons were met in a laboratory room to give information on the experiment and obtain written consent as well as demographic data. Each test person walked the course once prior to the experiment to familiarize with the stopping points and the exact walk path. Test persons walked the pre-defined loop six times (encountering the vehicle a total of 12 times at the two crossings). The succession of eHMI variants (intention based, perception based, combined design, without eHMI) were randomized for each participant. Trials with poor timing between test vehicle and test person or greatly diverging eHMI manipulation were repeated, occasionally resulting in an additional walking round for test persons. After the walking part, test persons were escorted back to the laboratory room for an open interview. Perceived safety and acceptance (Van der Laan et al., 1997) for the eHMI were also assessed after participants had been informed about the cover story and the actual purpose of the study after the experiment.

The study procedure was presented to the ethical committee of the Technical University of Munich. The committee raised no objections against the conduction of the study (reference number 24/20 S). Participants obtained 10 € for participation, the study took about 45 minutes in total.

Measures

1. CIT: Vehicle-Pedestrian interactions were videotaped and annotated for data analysis. Crossing Initiation Time was defined as the time difference, when the test person started crossing the street (start of continuous motion) and a pre-defined reference distance of the test vehicle.
2. Open Questions: Preferences for eHMIs (after information on study purpose and eHMI functionality)
3. Perceived safety for the interaction with each eHMI
4. Acceptance (van der Laan)

Sample description

30 Participants, mainly students, mean age 24.53 years (SD 2.37 years), 16 female, 14 male. One participant had to be excluded from data analysis.

Main Results

The two crossing scenarios were analysed separately, as they featured different street geometries.

In crossing scenario one, a significantly lower CIT was observed when any eHMI (arithmetic mean over all eHMI conditions) was used compared to using no eHMI: $t(24) = 3.82$, $p = .001$, $d = 0.76$ (medium sized effect). Using any eHMI lowered CIT by 0.71 seconds. A similar result was found for crossing

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scenario two: $t(22) = 2.31$, $p = .031$, $d = 0.48$ (small effect). Using any eHMI lowered CIT by 0.40 seconds in crossing scenario two.

Analysing the differences between different eHMI variants shows a significant effect of eHMI in crossing one: $F(3) = 6.45$, $p = .001$. Post-hoc comparisons revealed significantly lower CIT for the intention-based eHMI compared to using no eHMI ($p = .002$) as well as intention-based with signal lamp compared to no eHMI ($p = .031$). No significant differences were found between eHMI variants nor between perception-based eHMI compared to displaying no eHMI. A different picture was found in crossing scenario two. For this crossing, no significant differences in CIT were found, neither between eHMIs nor in the comparison of eHMIs to displaying no eHMI: $F(3) = 1.37$, $p = .272$.

The analysis of the acceptance questionnaire (van der Laan) shows high satisfaction and usefulness scores for all eHMIs, while intention-based and and perception-based were rated better than intention-based plus signal lamp. Analysis of variance shows no differences between the usefulness: $F(2) = 2.52$, $p = .09$ nor the satisfaction scores of the eHMIs: $F(1.53) = 2.29$, $p = .13$ (Greenhouse-Geisser corrected degrees of freedom). Table 11 shows the mean ratings for usefulness and satisfaction for all eHMIs (minimum -2; maximum +2). Furthermore, perceived safety was measured on Likert scale ranging from 1-5, for each eHMI. The results are also displayed in Table 11 below.

Table 11: Usefulness and satisfaction scores, as well as perceived safety for eHMIs

eHMI	Usefulness		Satisfaction		Perceived safety	
	Mean	SD	Mean	SD	Mean	SD
Intention-based	1.23	0.71	1.16	0.72	4.24	0.87
Perception-based	1.28	0.63	1.04	0.74	4.28	1.00
Intention-based plus signal lamp	0.92	0.73	0.78	0.92	3.90	1.08

*Item range for usefulness and satisfaction -2 to 2; for perceived safety 1 to 5.

The structured interview gave further insights in the test persons' thoughts concerning the used eHMIs. Table 12 gives an overview.

Table 12: Results of structured interview

N *	Statement

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Question: Did you notice anything uncommon during the study? (Participants were not yet informed about the actual study purpose)	
29	The vehicle
14	Light signals (eHMIs)
13	Inferred that the eHMI was directed at them and signalled that they could cross the street
7	The vehicle had no driver
Question: Which light signals (eHMIs) did you notice? (Participants were now informed on the study purpose)	
27	Noticed intention-based eHMI
24	Noticed perception-based eHMI
8	Noticed the signal lamp
Question: Which eHMI do you prefer?	
13	Preferred the intention-based eHMI
12	Preferred the perception-based eHMI
4	Preferred the intention-based eHMI plus signal lamp
26	Find the general idea to apply eHMIs for external communication to automated vehicles useful
Question: Which information did you rely on, when making your crossing decision?	
9	Stated, that they took the light signals (eHMIs) into account for their crossing decision
17	Referred to the vehicle's trajectory (braking) to make their decision
9	Stated, that they used the eHMI as information to infer the vehicle's intention (pass or stop)
7	Stated, that the presence of an eHMI made them feel safer when interacting with the vehicle
Question: In your opinion, how intuitive or easy to learn are the eHMIs?	
9	Stated, that they inferred the meaning of the eHMI (the vehicle lets me cross the street) throughout the experiment by themselves, mainly due to the repeated encounters with the vehicle
11	Inferred the meaning from the eHMI colour (mainly interpreted to be green)
7	Found the eHMi intuitive

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4	Stated, that they would want the eHMI to use the colour red to imply that they should not cross/ the vehicle will not stop (this was not used in this study)

* N: Mentioned by n participants out of 30 participants in total

Conclusions

- Partly contradicting results for CIT for crossing scenarios one and two. Crossing one: Significant differences between intention-based and no eHMI as well as intention-based plus signal lamp versus no eHMI. Crossing two: No significant differences between any eHMIs nor to baseline (no eHMI).
- When averaging CIT over all eHMIs and comparing this to baseline (no eHMI) we do find significantly lower CIT with eHMI compared to displaying no eHMI for both crossings.
- Perceived Safety and Acceptance: The perception-based and intention-based eHMI gained the highest scores on user satisfaction, usefulness and perceived safety. The combined eHMI intention-based plus signal lamp received lower ratings. The differences are not statistically significant.
- The study setup proved applicable for a medium-controlled real-world prototype evaluation in the middle ground between test-track experiments and field studies. It therefore provides an interesting framework for future evaluations.

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4.2.3 ITS CRF Demonstrator Test Track Study

Objective

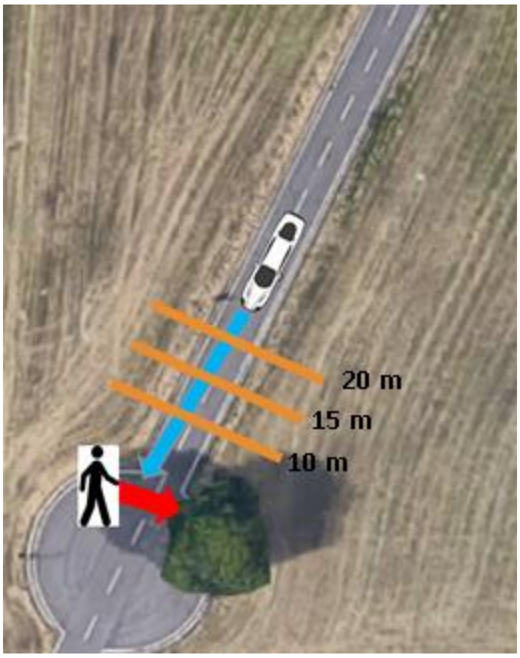
The purpose of the CRF evaluation was to understand pedestrians' experience of interacting with an AV, and to evaluate the impact of the two interACT eHMI solutions on pedestrians' behaviours and perceptions. A mixture of subjective and objective measures were used to address three key areas:

1. Pedestrians' evaluations of the different eHMI solutions (perception and intention-based; see Section 3.2 and Figure 36)
2. Pedestrians' ability to perceive AV yielding/deceleration behaviour
3. Pedestrians' crossing decisions around an approaching AV

Method

The study took place on a straight test-track at the CRF facilities in Torino, Italy (see Figure 35). 24 participants (14 male, 10 female) took part in the study (Mean age = 36.96 years, SD = 12.57). All participants were employees of CRF. On arrival at the test track participants were informed that they would be interacting with a fully automated vehicle, and that the purpose of the study was to examine pedestrians' interactions with AVs, and their decision-making processes when crossing the road.

Figure 35: CRF evaluation study set-up



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Participants started the experiment standing at the side of the test track, and facing straight ahead (see pedestrian placement in Figure 35). The experimenter stood next to them, facing in the direction of the vehicle. On the experimenter's instruction, the participant was asked to step into the area of interest (the point at which the AV could detect them) and turn their head to face the AV, which was approaching from their left. The AV approached at a maximum speed of 12 km/h and pedestrians were asked to step into the area of interest when the AV was either 20 m, 15 m, or 10 m away (AV Distance). There were three potential eHMI design variations: no eHMI, Intention-Based eHMI (Figure 36a) and Perception-Based eHMI (Figure 36b).

Figure 36: (a) Intention-Based eHMI and (b) Perception-Based eHMI solutions

Depending on the condition, participants were asked to raise their arm straight up as soon as they would feel safe to cross in front of the vehicle (crossing decision) / as soon as they could see the eHMI (eHMI visibility) / as soon as they noticed that the vehicle was decelerating (deceleration perception). After each of the crossing decision trials, participants were asked to provide a verbal rating of how confident they felt in their crossing decision, and how safe they felt in the encounter with the AV. Participants completed a total of 24 trials - the first 9 trials always consisted of crossing trials (3 eHMI X 3 AV distances), where the order of the remaining 15 trials was counterbalanced across eHMI visibility (2 eHMI X 3 AV distances) and deceleration visibility trials (3 eHMI X 3 AV distances).

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Table 13: CRF Evaluation Study Design

Study Set-up	Independent Variables	Objective Measures	Subjective Measures
• 24 trials • 1.5 hours	(5) **eHMI Design:** None, Intention-Based (slow pulsing light band), Perception-Based (directed-light band), (6) **AV Distance:** 20m, 15m, 10m (7) **Trial Type:** Crossing decision, eHMI visibility, Deceleration perception.	(5) Distance / Time from AV at crossing decision (6) Distance / Time from AV at eHMI visibility perception (7) Distance / Time from AV at deceleration perception	Post-trial questions: - 'I felt confident in my decision of when to cross the road', - 'I felt safe during this encounter with the AV', where 1 = 'Strongly Disagree', and 10 = 'Strongly Agree'. Post-experimental questionnaires measuring: - Usability (SUS, Brooke, 1986), acceptance, attitude (van der Laan et al., 1997), learnability, and effectiveness (Jander et al., 2012) of eHMI solutions. - evaluations of comfort and safety in relation to the speed and stopping distances of the AV.

Main results

Objective Measures

A comparison of participant crossing decisions found a significant effect of AV Distance (the distance at which the participant turned to look at the AV) on the distance at which they indicated they felt comfortable to cross. The crossing decision distance differed significantly between all three turning times, with participants indicating their crossing decision significantly earlier the further away the vehicle was. There was no significant effect of eHMI Design (no eHMI, Intention-Based eHMI, Perception-Based eHMI) on crossing decision distance, suggesting that participants were not using the presence or absence of eHMI to inform their crossing decisions.

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There was also a significant effect of AV Distance on how quickly participants identified AV deceleration behaviour, with participants exhibiting significantly faster response times when the AV was nearer to them when they turned to face it. However, there was no significant effect of eHMI Design (no eHMI, Intention-Based, Perception-Based) on how quickly participants perceived deceleration behaviour, suggesting that the presence of eHMI did not improve participants' ability to detect AV yielding behaviour.

Finally a comparison of the effects of AV Distance and eHMI Design (Intention-Based vs Perception Based) on response times, showed that there was a significant effect of both AV Distance and eHMI Design. Participants detected the Perception-Based eHMI significantly more quickly than the Intention-Based eHMI. This finding was unexpected, as the Perception-Based eHMI covered a much smaller area of the vehicle, but may be due to the fact that the light remained on constantly but moved across the black light-band according to the pedestrian position, whereas the Intention-Based eHMI pulsated. In addition, the contrast between the small light and the vehicle colour may have been easier to detect, as there was more black space between them. Some further explanations can also be gleaned from participant responses to the questionnaire reported in the next section.

Subjective evaluations of eHMI and AV behaviours.

A comparison of the verbal response scales administered after each crossing decision trial found that there was a significant effect of AV Distance for both safety ratings and confidence ratings, but no significant effect of eHMI design. Participants felt significantly safer and more confident in their crossing decisions the further away the AV was. However, the ratings were high for both scales on the whole, suggesting that participants felt quite safe at all distances. When asked what information they used to inform their crossing decisions, participants indicated that they were significantly more likely to use speed or distance information to inform their crossing decisions than eHMI. There were also no significant differences in the usability, acceptance, attitude, learnability, or effectiveness ratings of the Intention-Based and Perception-Based eHMIs, with the majority of participants indicating that they believed both eHMI solutions could be used on future AVs. However, participants were significantly more likely to rate the speed of the AV with no eHMI as too fast in comparison to the Perception-Based eHMI, while the stopping distance of the AV was rated as significantly more comfortable and safer with Perception-based eHMI. There were no significant differences in ratings between Intention-Based eHMI and the other conditions. These results, combined with the objective results suggest that the Perception-Based eHMI had a greater effect on participant perceptions of the AV's movements than the Intention-Based eHMI. Responses to open-ended questions suggested that participants also seemed to have a clearer interpretation of the Perception-Based eHMI, with comments such as "the system detected me" and "the vehicle understands where I was positioned in relation to the car",

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whereas interpretations of the Intention-Based eHMI were less specific with comments such as “the vehicle has detected me”, “it was not so visible”, “the vehicle is working correctly”.

Conclusions

(1) Pedestrians generally felt safe and comfortable interacting with the interACT demonstrator in a test-track setting.
(2) Both eHMI solutions were generally well received, with high ratings of usability, acceptance and learnability for both.
(3) The Perception-Based eHMI was perceived more quickly than the Intention-Based eHMI, and led to better ratings of AV speed and stopping behaviours compared to no eHMI conditions.
(4) However, the results suggest that in naturalistic lighting conditions neither of the eHMI solutions impact on pedestrian crossing decisions or ability to detect AV yielding behaviour, with AV speed and distance having a much greater effect.

Overall, the results of this study suggest that the interACT eHMI solutions may not impact on road users crossing decisions, but the Perception-Based design, in particular may lead to greater confidence and comfort in the AV behaviour compared to no eHMI. Thus, increasing the visibility or contrast of a light-based eHMI may help to enhance pedestrian perceived safety around AVs.

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4.2.4 ICCS Parking Lot Experiment

Objective

The objective of the ICCS driving study was to study drivers' interactions with an AV compared to interactions with a manually driven vehicle during a left turn at low speed and the impact of external HMI on such interactions. The scenario of left turns is typical of dense or speed restricted areas.

Method

The study took place at a parking lot within the National Technical University of Athens campus at Zografou, Greece, from 24 October to 8 December 2019, at afternoon hours when traffic is low and at good weather conditions.

Two experimental vehicles were used, both driven by the same driving instructor. The first vehicle (Fiat Stilo) was driven normally (condition "Manual"). The second vehicle (Toyota Yaris Hybrid 2018 model) was driven via double pedals from the driving instructor who was seated on the co-driver's seat. This simulated the autonomous vehicle, the "AV". The second vehicle was used either without any external HMI (condition "AV no eHMI") or with a LED stripe fixed on the external of the front dashboard (condition "AV with eHMI"). The LED stripe flashed according to the specifications for the interACT eHMI from WP4.

Figure 37: "AV" used in the ICCS study and LED stripe used as external HMI in the condition "AV with eHMI"

The position, speed and acceleration of both vehicles were logged using RTK GNSS technology. A force sensor was fixed on the accelerator pedal of both vehicles.

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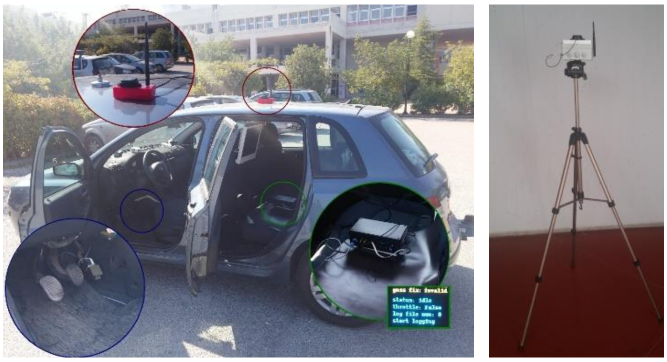

Figure 38: System to log vehicles position, speed and acceleration

Two test setups were used with the following conditions:

- Setup 1:
  Condition (1a): "Manual"
  Condition (1b): "AV with eHMI"
- Setup 2:
  Condition (2a): "Manual"
  Condition (2b): "AV no eHMI"

Each participant in Setup 1 or in Setup 2 drove three runs per condition, for example: 1a, 1b, 1a, 1b, 1a, 1b, the order of conditions was randomized.

When arriving, the participants were explained that they would participate in a study involving an autonomous vehicle and they were instructed about the meaning of the LED stripe flashing. They were explained the whole process and they were familiarised with the "AV" driving around with or without the LED stripe, depending on the Setup, via videos. The participants were asked to drive their own vehicle on the green route depicted in the following figure. The driving instructor was driving on the orange route, both in the "Manual" and the "AV" conditions. An experimenter on-board instructed the participant when to start driving from position A. An external facilitator at position C synchronized both vehicles, so that they both started from the positions B and D at the same time. The distance between positions B and D was around 60 m. Red traffic cones were positioned at the crossing, so that simultaneous turning of both vehicles was not possible.

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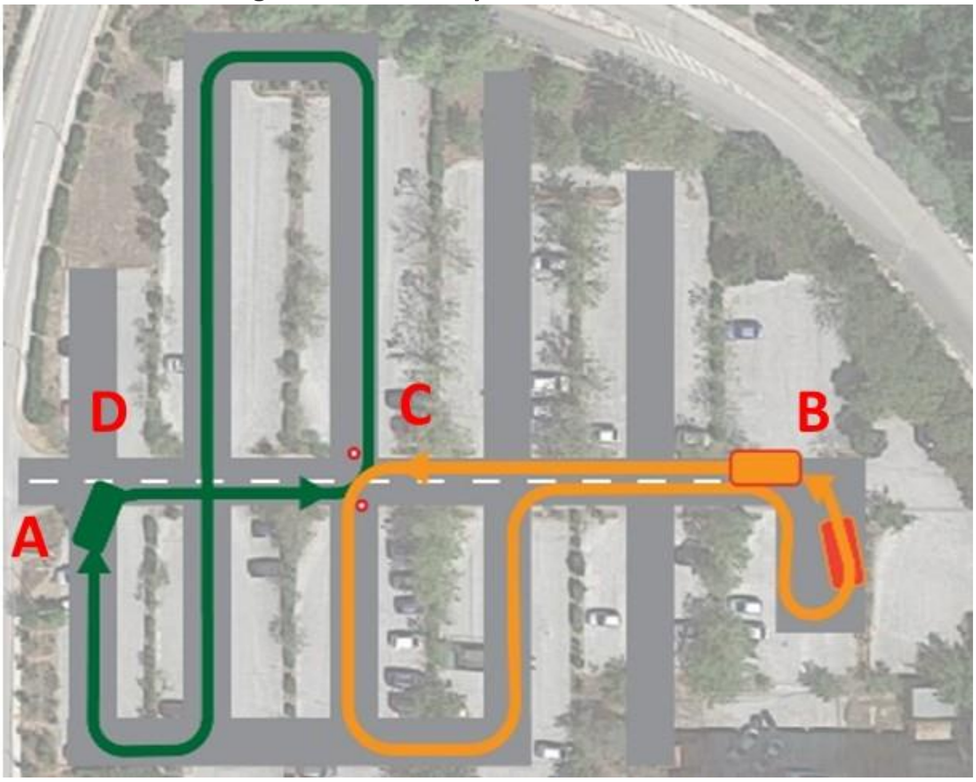
Figure 39: ICCS study location and routes



Using observations from pilot runs, an interaction zone was defined as drawn below, as the area where interaction took place. According to the pilot runs, the most ambiguous case for the participants when an interaction was clearly needed, was when the driving instructor entered the interaction zone a bit after the participant. Specifically, it was observed that if the driving instructor would enter first in the interaction zone, hard braking would be needed so his yielding would be clear for the participant. If the participant would enter the zone much before the driving instructor, the participant would have time to turn without needed to interact and understand if the other vehicle is yielding or not. So, the driving instructor was instructed to accelerate starting from position B until reaching 20 km/h and then decelerate or brake so as to enter the interaction zone a bit after the participant and yield.

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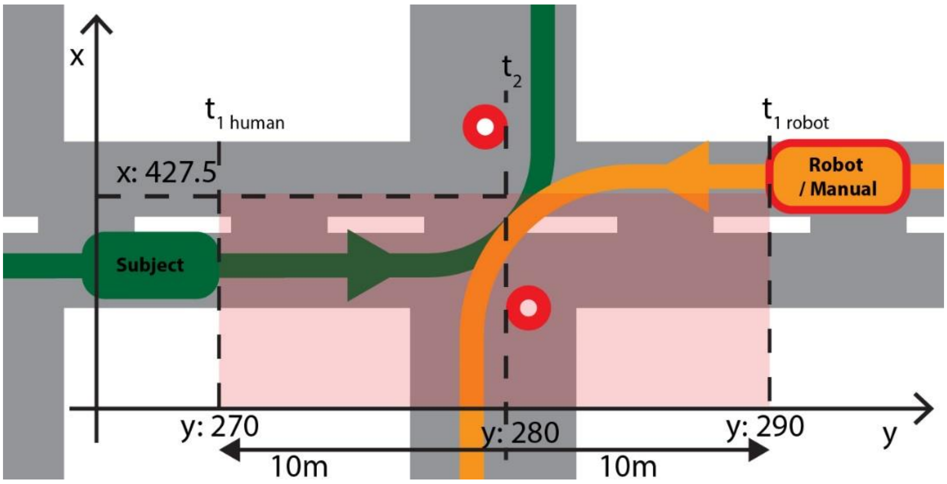

Figure 40: Interaction zone defined in the ICCS study

According to the pilot runs, it was determined that the LED stripe should not start flashing as soon as the driving instructor starts braking, as this was before the participant would typically focus on the other vehicle. In most cases that this happened, the participant did not perceive at all any change in the LED stripe status. So, it was decided that the LED stripe should start flashing when the two vehicles were at a distance of 30 m.

Using the logged data, the time when the participant and the driving instructor entered the interaction zone was determined, t_{1human} and t_{1other} respectively, and the time when the participant crossed the line with y = 280, t_2 was determined. For comparison reasons, the aim was that there would be no difference as regards the $\Delta t_{entrance} = t_{1human} - t_{1other}$ between the two conditions in each Step.

The dependent variable was the interaction duration, defined as $\Delta t_{duration} = t_2 – t_{1human}$.

After the end of the driving, participants were asked to complete a questionnaire about their understanding of the other's intention and their perceptions.

Main results

20 participants, 10 male and 10 female participated in Setup 1 ("Manual" vs "AV with eHMI"). Their mean age was 40.4 years (min 32, max 53 years) and they had a driving license for a mean 20.5 years (min 12, max 34 years). Cases where $\Delta t_{entrance}$ was greater than 3 s were considered unsuccessful and were not included in the analysis. 61 interactions in condition "Manual" and 59 in condition "AV with eHMI" were analysed. The LED stripe started flashing at an average distance of the two vehicles of 29.1 m, when the driving instructor's vehicle speed was on average 19.6 km/h and the participant's vehicle speed was 11.9 km/h.

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20 participants, 10 male and 10 female participated in Setup 2 (“Manual” vs “AV no eHMI”). Their mean age was 41.8 years (min 30, max 59 years) and they had a driving license for a mean 20.6 years (min 7, max 39 years). 58 interactions in condition “Manual” and 55 in condition “AV no eHMI” were analysed.

The results as regards the two Setups are shown in Table 14. There is no difference between conditions as regards $\Delta t_{entrance}$. The interaction duration is lower in condition “AV with eHMI” (4.61 s) compared to “Manual” (5.83 s) in Setup 1, while there is no difference in Setup 2 between condition “AV no eHMI” (5.54 s) compared to “Manual” (5.28 s). The external HMI reduces the interaction duration.

Table 14: Results of the parking lot experiment

		Setup 1			Setup 2		
		“Manual”	**“AV with eHMI”**	**p**	**“Manual”**	**“AV no eHMI”**	**p**
N (interactions)		61	59		58	55	
t_{1other}	Other speed (km/h)	10.99	9.55	$< 10^{-4}$	10.50	9.51	< 0.05
	Participant speed (km/h)	6.51	8.13	$< 10^{-3}$	7.69	6.85	ns
	Distance (m)	13.09	12.65	ns	12.77	12.19	ns
t_{1human}	Other speed (km/h)	12.87	17.98	$< 10^{-2}$	15.00	15.31	ns
	Participant speed (km/h)	8.82	10.61	< 0.05	11.08	11.12	ns
	Distance (m)	17.78	19.28		17.95	18.54	ns
	TTC	3.41	2.44	< 0.05	2.56	2.62	ns
t_2	Other speed (km/h)	0.36	0.15	< 0.05	0.47	0.12	< 0.05
	Participant speed (km/h)	14.24	13.76	ns	13.68	13.20	ns
	Distance (m)	6.54	6.65	ns	4.24	4.58	< 0.01
$\Delta t_{entrance}$		0.74	0.95	ns	0.79	1.08	ns
$\Delta t_{duration}$		5.83	4.61	$< 10^{-6}$	5.28	5.54	ns

The results of the two samples in the “Manual” condition are shown in Table 15. Comparing the “Manual” conditions between the two setups, there is no difference as regards $\Delta t_{entrance}$, as shown below, which means that the objective was achieved. The participants in Setup 2 drove at higher speeds

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than the participants in Setup 1. The interaction duration of the sample in Setup 2 was shorter than in Setup 1, which strengthens the finding that the eHMI shortens the interaction duration.

Table 15: Results of the two samples in the "Manual" condition

	Setup 1 "Manual"	Setup 2 "Manual"	p
N (interactions)	61	58	
$\Delta t_{entrance}$	0.74	0.79	ns
$\Delta t_{duration}$	5.83	5.28	< 0.05

It must be noted that the signal from the force sensor the accelerator pedal did not produce useful results. It was expected that the participant would stop stepping on the accelerator pedal while approaching the interaction zone and would step again once he/she would decide to turn. A lot of participants never lifted their foot from the pedal, adjusting their speed by adjusting the force on the pedal. A typical speed vs distance graph of the two vehicles is shown in Figure 41.

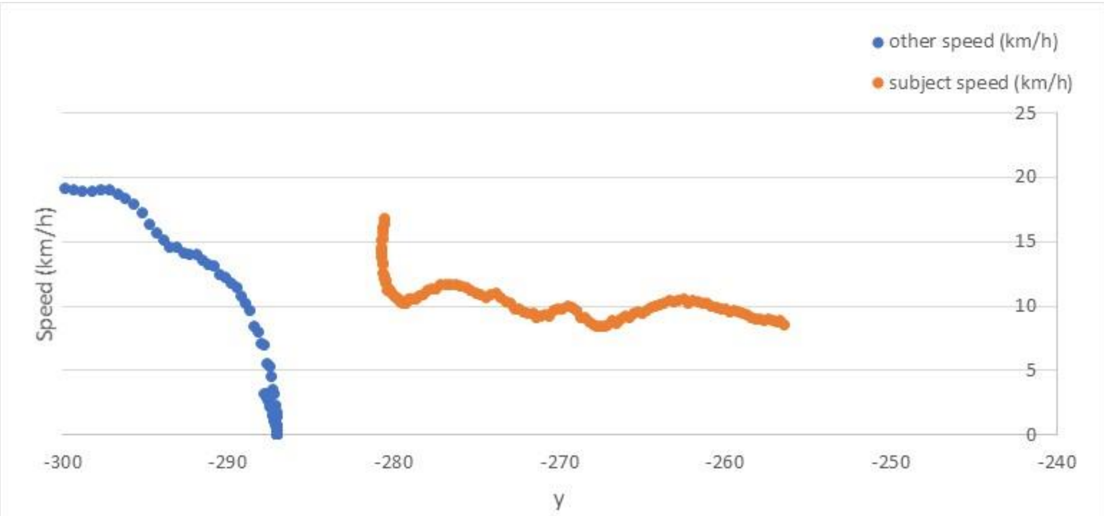

Figure 41: Speed versus distance of the two vehicles

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Conclusions

- The eHMI reduced the duration of interaction, which was lower when interacting with an AV with eHMI compared to when interacting with another driver while there was no difference when interacting with an AV without eHMI compared to when interacting with another driver
- Timing when the eHMI starts flashing is crucial to ensure that the users perceive it.

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5. Key Findings and Recommendations

The evaluation studies of the interACT technologies enable an in-depth look on the effects of AV interaction strategies on surrounding traffic participants and the on-board user. Eleven studies with overall 370 participants were conducted with various underlying research questions and research methods enabling a rather holistic evaluation of the developed technologies.

While the main findings of the individual studies can be read in the dedicated sections, this chapter aims to generalize these findings and formulate them in simple sentences with detailed explanations below them. The comparision of the results from the individual studies was carried out carefully as the studies used partly different metrics, methods and test environments. Following these findings, the various insights of the interACT evaluation studies are used to formulate some requirements for the future work on AVs utilizing external and internal HMIs.

5.1 Key Findings

eHMIs might be beneficial for the interaction AVs with other traffic participants in urban traffic

eHMIs seem to increase acceptance towards AVs (see *ITS Pedestrian Simulator Studies*, study 1 and 3) and most participants prefer some sort of eHMI over none when asked after the study (see *TUM BMW Wizard of Oz: Test Track Experiment* and *ITS CRF Demonstrator Test Track Study*). Furthermore, eHMIs were found to increase the perceived safety of the interacting traffic participant (see *TUM BMW Wizard of Oz: Instructed Walking*), as they improve understanding the AV's intention. In situations where the interaction partner was not relying on the eHMI, the vehicle was used to understand the approaching AVs intention, thus an eHMI did not compromise the interaction. This shows that road users prefer having additional information when encountering an AV.

Most of the studies presented in this work package, but also conducted in WP2 and WP4 showed that yielding AVs equipped with eHMIs produced earlier crossing initiations of pedestrians, especially when encountered repeatedly. Therefore, by reducing the time lost in interactions, eHMIs are likely to have a positive impact on traffic flow (see D6.3, Lee et al. 2020). Further research to assess the impact of faster interactions on the traffic flow is necessary, especially when looking at increasing numbers of AVs in urban traffic. No evidence was found that the use of eHMIs increases the time for interaction and thus negatively influence traffic flow – the results either showed lower crossing initiation times or were statistically not significant with a trend towards lower CITs.

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Human road users are able to make decisions based on the implicit communication of AVs only

Most of the studies conducted throughout the project (see chapter 4; for further studies, also see D4.2 Weber et al. 2019 and D2.2 Dietrich et al., 2019) presented a baseline condition where the study participant encountered an AV with no eHMI present. While some of these studies report potential benefits of eHMIs (see also the key finding below), no safety issues or other unresolvable problems were found when traffic participants were interacting with an AV without eHMI in the baseline condition. Therefore, it can be assumed that drivers and pedestrians alike mostly rely on the AV's position and movement when making decisions. eHMIs are supporting this decision making process in some situations by shortening the time the interaction partner needs to react.

Overall, this assumption is comparable to findings of the observation study (D2.1), where explicit communication was found to occur infrequently in current traffic. Furthermore, most interactions where a traffic participant communicated explicitly could have most likely been resolved without it. However, these findings are heavily reliant on the senarios and could change in other traffic situations, such as dense traffic with multiple different road users, which were not covered within the evaluation studies of WP6.

AVs equipped with eHMIs might induce or introduce problems

With multiple traffic participants in one interaction-demanding situation, road users, who might not be the intended recipient, will perceive the intent of the vehicle using undirected signalling such as the 360° light band. Simulator studies addressing this potential issue present mixed results but outline a potential negative effect of miscommunication and overreliance that might occur with the new technology:

In the *BMW Pedestrian Simulator Study* none of the situations resulted in potential conflicts. In the *DLR Vehicle-Vehicle-Interaction Simulator Study* four (18%) crashes and six (27%) near miss situations were observed in one scenario, where the vehicle communicated a yielding intention explicitly to another road user who had right of way over the participant. These contradicting findings are likely to be caused by the underlying experimental design. In the pedestrian simulator study, participants were not pressured into crossing the street and reported the situation to be clear and safe with situations being permutated. In the driving simulator study, participants completed 27 scenarios with a yielding AV in a rather short timeframe before the critical situation was presented. An analogous situation was observed in the *ITS Pedestrian Simulator Studies* (study 3) – in the 37th and 50th encounter of a pedestrian with an automated vehicle, the approaching AV indicated a yielding behaviour using its eHMI but did not decelerate for the pedestrian. For approximately 30% of participants this lead to collisions, as the approaching AV kept it velocity constant. While the underlying interactive scenarios are rather

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unlikely to occur that frequent in real future traffic, the results show that other road users might overly rely on eHMIs, especially when they were the intended addressee in previous encounters.

An additional source of potential miscommunication is the on-board user, who is still able to communicate explicitly, even when the vehicle is driven automatically. Therefore, it needs to be ensured that the on-board user is informed about potential communication of the AV and its intent. Furthermore, hand overs in situations where the automation intends to yield and/or communicates explicitly need to be researched further, to assess other potential issues.

The effects of eHMIs are highly depending on the underlying scenario

The evaluation studies were focused on interactions on roads, as these scenarios were chosen within WP1 as they occur frequently in traffic (see D1.1 Wilbrink et al. (2018)). In these scenarios, kinematic movement resolved most of the encounters and eHMIs were utilized to indicate the intention of the yielding AV. However, especially in low speed scenarios, such as shared spaces or actual deadlocks, additional messages via explicit communication might be necessary to resolve a potential conflict. Therefore, the aforementioned statements are only valid for the underlying scenarios and further studies in future projects will be needed to assess other scenarios.

The experimental design of evaluation studies as well as the underlying metrics and methods have a high impact on the results

Many potential influencing factors might confound a direct comparison of results – e.g. the CRF Demonstrator (see section 3.2) vehicle drove 12 km/h in the *ITS CRF Demonstrator Test Track Study* and allowed participants to look at the vehicle at distances of 10, 15 and 20m the while the TUM BMW Woz drove 30 km/h with participants able to perceive it from a 50m distance. Another example is the *TUM BMW Wizard of Oz: Instructed Walking*, where only the physical road layout changed between the two crossing locations representing the same scenario. However, different results were observed in regards to the effect of eHMIs on crossing decisions. Therefore, other surrounding factors seem to have influenced the study participants to behave differently in the seemingly same scenario in this particular study.

Subjective reports help to generate a deeper understanding on how study participants personally perceive situations and measure their general attitude towards exposed elements. However, there are very few standardized questionnaires to evaluate eHMIs from the point of view of an interacting pedestrian. Within the conducted studies a variety of questionnaires were used to ascertain subjective data. As the studies had individual focuses, the questionnaires varied from study to study. As the numerical values are not directly comparable, the key findings are based on the conclusions from the individual studies rather than the data itself.

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The underlying experimental design affects the perception of eHMIs – in the *BMW Pedestrian Simulator Study* subjective ratings were showing no differences before participants were instructed on the function of eHMIs. *TUM BMW Wizard of Oz: Instructed Walking* study also showed decreasing crossing initiation times after the first few encounters with the yielding AVs. Therefore, instruction and preceding exposure in experiments influence results on the effects of eHMIs. This underlines the assumption that future eHMIs will need to be learnt. A first encounter will probably not yet see the potential benefits of eHMIs when compared to later encounters (see *BMW Pedestrian Simulator Study*, *TUM BMW Wizard of Oz: Instructed Walking* study, *DLR Vehicle-Vehicle-Interaction Simulator Study*)

5.2 Recommendations

Following the key statements, the following recommendations for equipping AVs with eHMIs and conducting studies can be derived, based on the results of the studies conducted within interACT, including work from WP2 and WP4. These recommendations will ensure that the positive effects of eHMIs are maximized and the potential issues described in section 5.1 avoided, yielding an overall increase in traffic safety and efficiency.

The explicitly communicated intention needs to be consistent with the vehicle's movement and intended manoeuvre.

Road users will likely understand any perceived information of an approaching vehicle as addressed towards themselves. Explicitly communicating a yielding intention without actually planning to decelerate for the first potential addressee, could lead to miscommunication and hazardous situations (*ITS Pedestrian Simulator Studies*, study 3). Furthermore, communicating a message for "not yielding" could be misinterpreted, as conventional vehicles and drivers usually do not transmit any additional information, when moving forward (see D4.2, section 4.2.2 (Weber et al., 2019) or Weber, F., Chadowitz, R., Schmidt, K., Messerschmidt, J., & Fuest, T., 2019). Displaying a yielding intention too late or too shortly might decrease the potential effects of eHMIs, as esp. drivers were found to look at the interacting vehicle only for a limited amount of time (see *ICCS Parking Lot Experiment*). In occupied vehicles that are driving automated, passengers are still able to convey messages, e.g. by waving. This could potentially be contradicting to the AV's intended manoeuvre therefore the internal HMI should inform passengers, whenever the AV is interacting.

communication addressed to other road users would be minimized using this approach.

eHMIs should be introduced in safe situation, first.

Interaction demanding situations in urban traffic were identified to take place below certain velocity thresholds – which likely depends on the underlying scenario. In D2.2 (Dietrich et al. 2019) the threshold for interactions when merging into a T-junction was described to be below between 25 and 35 km/h,

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meaning that above these velocities cooperative behaviour is unlikely to occur or to be expected. In pedestrian-AV encounters, this threshold is likely to be even lower, as crossing a road requires a smaller time gap than a merge from standstill.

eHMIs might be useful at greater distances, as they can convey an intention over a larger distance than a waving driver behind a windshield can be perceived. Therefore, AVs equipped with eHMIs have the potential to not just replace a driver's communication capabilities but also to extend them. However, many side effects are not yet fully understood and thus eHMIs should be used in slow situations, in which the AV can come to a quick standstill, first.

Based on the observations in WP2, situations where explicit communication is anticipated are more likely to occur at low speeds. These situations should be addressed first and tested in real traffic before exploring the potential of eHMIs broadcasting a yielding intend over larger distances. Introducing novel communication strategies into the established urban traffic conditions should be done very cautiously – while limiting potential benefits, this approach would limit potential issues due to miscommunication and overreliance.

Studying the effects of novel communication interfaces needs to be holistic.

Within the interACT project, numerous studies have been conducted to explore a large variety of research questions. Despite the fact that the studies differed in their methodological approaches, each of them provided crucial insights into how traffic participants use visual information of automated vehicles. While cost-efficient studies evaluating the effects of eHMIs and iHMIs using questionnaires and VR setups, the demonstrator evaluations revealed less clear results. Simulator studies offer a high repeatability and controllability of confounding variables, allowing to generate valuable knowledge on the perception and handling of interaction-demanding traffic scenarios. The demonstrator studies were less able to control every aspect of the experiment. However, urban traffic is very volatile and unnoticed influences may have large effects on road user behaviour. Therefore, utilizing a variety of methods to study traffic interaction is inevitable to understand the effects of novel communication technologies in urban traffic.

Simulator studies are a very good way to assess the effects of different communication strategies – ranging from eHMIs to deceleration profiles and onset timings – on road user behaviour quickly and to explore potential negative (and critical) effects in a safe and reproducible way. Studies in real world settings should be conducted, to verify the studied effects in realistic settings and thus to validate these results or to identify shortcomings or other influencing factors.

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6. Summary and Conclusion

This deliverable presents a variety of studies conducted to evaluate the effect of the interACT interaction strategies and the interACT demonstrators on the behaviour and perception of on-board users and other traffic participants.

Overall, the multitude of methodologies utilized within the studies gives a holistic view of different types of road users interacting with automated vehicles in different experimental setups, including VR, an immersive pedestrian simulator, driving simulators as well as test track and real-world studies.

The presented results indicate that there might be benefits of eHMIs in regards to the time an interaction takes (thus potentially increasing traffic flow) as well as perceived safety, comprehension and trust. However, potential issues in the form of miscommunication and overreliance were identified, which could potentially lead to critical situations. While balancing the potential benefits against the possible drawbacks of eHMIs requires further evaluation, the absence of eHMIs in interaction demanding situations did not lead to a complete standstill, as TPs were able to base their decisions on the kinematic movement of the AV. These findings are however limited to the examined use-cases and experimental designs.

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Designing cooperative interaction of automated vehicles with other road users in mixed traffic environments