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

interACT D.6.1. Methodologies for the evaluation and impact assessment of the interACT solutions

Work package	WP6: Evaluation & Impact Assessment of Human-Vehicle Interaction
Task(s)	Task 6.1. Evaluation methodology for assessing the impact of human-vehicle interaction on road user and on-board behaviour
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Glossary of terms

Term	Description
Addressed messages	Messages that are provided to one or more specific TPs
Non-addressed messages	Messages that are provided to everyone in the environment
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	Human Machine Interface that is presented on the vehicle to provide information to the surrounding traffic participants
Other traffic participants	Other road users in the environment such as cyclists, pedestrians, cars, trucks etc.
Use Case	Functional description of the behaviour of the AV in a traffic situation
Scenario	Description regarding the sequences of actions and events performed by different actors over a certain amount of time
Mixed Traffic	Usually referred to traffic consisting of different types of road users
Vulnerable Road Users	Road users with a higher fatality rate per accident than other groups, such as pedestrians, cyclists, motorcyclists

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List of abbreviations and acronyms

Abbreviation	Meaning
AVs	Automated Vehicles
CCPU	Cooperation and Communication Planning Unit
VR	Virtual Reality
VE	Virtual Environment
eHMI	External Human Machine Interface
iHMI	Internal Human Machine Interface
TTC	Time to Collision
TP	Traffic Participant
HMI ECU	HMI – Executive Control Unit
DGPS System	Differential Global Positioning System
WoZ	Wizard of Oz
LED	Light-emitting-diode
D	Deliverable
WP	Work Package
SAE	SAE International (initially established as Society of Automotive Engineers)
VRU	Vulnerable Road User

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Executive Summary

The interACT project is working on solutions to ensure that automated vehicles (AVs) are able to interact with other traffic participants (TPs) in mixed traffic situations, mainly focusing on pedestrian-AV interactions and vehicle-AV interactions. Work Package 6 (WP6) of the in interACT project aims to evaluate the interACT solutions developed through earlier work packages, namely the CCPU and safety layer developed in WP3, the HMI signal designs developed in WP4, and the prototype vehicles developed in WP5.

In order to develop an evaluation methodology for assessing the effect of these solutions on the behaviours of other road users and the on-board user, it is important to gain an understanding of appropriate tools and techniques available. Therefore, this Deliverable provides a review of the existing literature on road user interactions (e.g. conference papers, journal articles, theses, workshops), to identify the evaluation criteria and methodologies that have been previously used by researchers in the field. The themes and concepts emerging have been amalgamated into an evaluation criteria catalogue, providing a log of useful measurement tools for studying effectiveness criteria such as safety, trust, traffic flow, and interaction comprehension; along with identifying suitable research environments for implementing these tools (e.g. experimental tasks, interviews, questionnaires, real world observations, simulation and modelling). Throughout the review process, previously used methods used have been described in as much detail as possible, to enable their replication in interACT evaluation studies.

This document will serve as an input for Task 6.2 where the evaluation studies will be carried out, and also serve as an input for Task 6.3 to understand the impact of solutions on traffic flow, safety, and efficiency.

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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.

The purpose of the interACT project is to develop interaction concepts for AVs, enabling AVs to behave in an expectation-conforming manner. A Cooperation and Communication Planning Unit (CCP Unit) has been developed within interACT as part of the interaction solution which is to be integrated into our vehicle prototype. The CCP Unit enables all interactions between the vehicle automation, on-board user and other TPs in a time-synchronised manner. In addition, external and internal Human Machine Interface (HMI) concepts have been designed and integrated into our vehicle prototype. These HMIs enable communication between the AVs and on-board users (iHMI), as well as other TPs (eHMI).

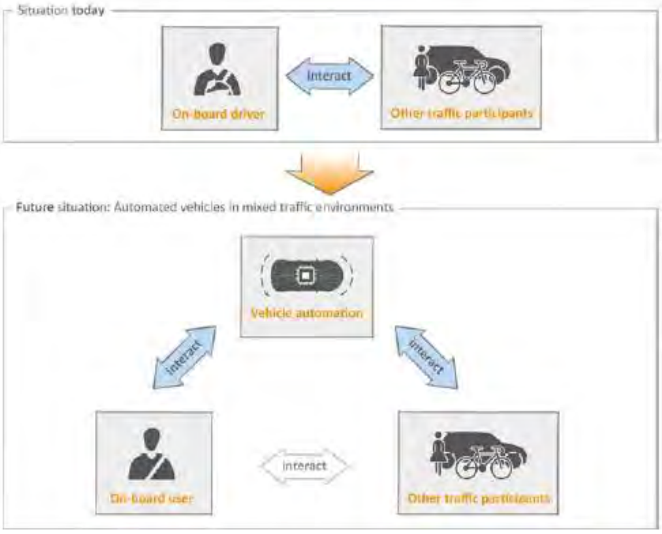

Figure 1: Illustrating the current interaction between on-board driver and other TPs (top). Illustrating the future interaction between AVs in mixed traffic environments (bottom).

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1.1.2 Objectives of WP6

The main objectives of WP6 are to:

(1) Develop suitable methodologies to evaluate the effect of interaction and communication strategies between AVs, their on-board users, and other TPs (see Figure 1).
(2) Carry out a series of studies to evaluate the interACT prototypes and concepts, using multi-actor experiments in simulated and real-world scenarios, looking at both SAE level 3 and level 4 driving.
(3) Evaluate the impact of the interACT prototypes and solutions on road safety, traffic flow, and road infrastructure needs.

1.1.3 Expected Impacts of WP6

It is claimed that about 90% of road accidents are due to human error (Singh, 2015), and that vehicle automation will supposedly reduce the rate of accidents. However, if this is to be the case, it is important to ensure that the behaviour and intentions of the AV meet the expectations of other road users. Therefore, it is important to evaluate the impact of interACT solutions on ***traffic safety***. As part of WP6, the interACT project will develop ***validation procedures*** for the solutions and prototypes proposed in the project, including methodologies to test and assess cooperation and safe interaction between an AV, the on-board user and other road users. These methodologies and evaluation results will be disseminated through scientific journals, academic conferences, international cooperation and standardisation committees. These activities will improve the ***innovation capacity and integration of new knowledge*** in the field. It is also expected that the solutions will improve the ***ease-of use*** *and* ***user acceptance*** *of AVs*, such that the interACT solutions will achieve higher acceptance and trust ratings as compared to AVs that are not using the interACT solutions, both for the on-board user and other traffic participants. Finally, WP6 aims to evaluate the ***societal impact*** of the interACT solutions, in terms of their effects on traffic safety, traffic flow, and how overall societal acceptance of AVs is affected by the introduction of systems which allow better understanding of their intentions.

1.1.4 Task 6.1

The purpose of this Deliverable D6.1 is the development of an evaluation criteria catalogue (see Annex 1), based on a literature review (Chapter 2), expert interviews/workshops (Chapter 3), and research results from WP2 (Chapter 4). This criteria catalogue provides a summary version of how interactions between road users have been studied and evaluated in the past, which is used to inform the selection of suitable evaluation criteria, methodologies, and tools, to evaluate the interACT prototypes, and study their impact on road safety and traffic flow.

1.2 Intended readership

This deliverable provides insight into the evaluation plans of WP 6, and reports on suggested methodologies for the integrated evaluation of the interACT design solutions. Chapter 2 consists of a literature review on the methodologies used in published materials when evaluating interactions between traffic participants, HMIs, and AVs. Input from relevant workshops that we have conducted and attended, including work from our twinning partner AVintent, is provided in Chapter 3. Chapter 4 provides a summary of the methodologies used in WP2 of interACT, which were designed to evaluate current vehicle-to-vehicle and vehicle-to-pedestrian interaction patterns. All of this information is brought together in Annex 1, which provides an evaluation criteria catalogue. Chapter 6 provides a summary of preliminary plans to evaluate the interACT solutions and prototypes, based on the findings from the previous chapter. Finally, Chapter 7, provides a summary of the conclusions reached through this deliverable.

The Deliverable serves as a documentation of the on-going work in WP 6 for our Project Officer, the reviewers and the European Commission, along with providing information for all interACT project partners on potential methodologies for evaluating the design solutions created through WP3, WP4 and WP5. In addition, this deliverable is publicly available. Therefore, it is intended to provide information to stakeholders, other researchers and industrial partners who are interested to know more about the project's approach to AV evaluation.

1.3 Relationship with other Work Packages

Work package 6 has received input from, and is closely linked, with other Work packages (see Figure 2). The prototypes that were integrated within **WP5** 'Integration, Testing and Demonstration' will be evaluated in WP6. These two interACT prototypes - the BMW i3 and Jeep Renegade (from CRF), (see Section 5.3 and 5.4 for more information) - have integrated the **WP3** 'Cooperation and Communication Planning Unit', which includes the interaction planning and executive of the prototype, and **WP4** 'Suitable HMI for successful human-vehicle interaction', which developed suitable eHMI and iHMI for the prototype.

The main use cases tested in WP6 are those that have been proposed in **WP1** 'Scenarios, Requirements and interACT System Architecture' (see Deliverable 1.1; Wilbrink et al., 2018). In addition, a more specific descriptive scenarios catalogue reported in Deliverable 3.1 (Bolovinou et al., 2019) will also be referred to.

The methodologies used in **WP2** 'Psychological Models on Human Interaction and Intention Recognition Algorithms' to investigate interactions between current road users (see Deliverable 2.1, Dietrich et al., 2018), and those used in **WP4** to investigate road users' reactions to HMI solutions

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(see Deliverable 4.2, Weber et al., 2019), will be evaluated, to provide insights into the best methods for testing our prototypes and solutions in WP6.

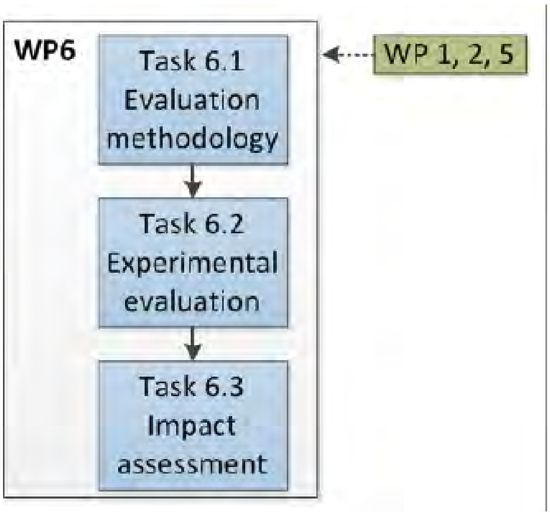

Figure 2: Relationship with other interACT Work Packages

2. Literature Review: Identifying methodologies and measures for understanding road users' interactions

2.1 Understanding cooperation and interaction in mixed traffic

The current Chapter aims to establish what 'successful' interaction for AVs could mean, providing a summary of the literature linked to AV and conventional vehicles' interactions with other TPs, and investigating the criteria and methods used in previous studies to understand these interactions.

In order to evaluate the success of the interACT solutions in improving interactions between AVs and both on-board users and other TPs, it is important to have a consistent terminology for explaining the characteristics of these interactions. In Deliverable 2.1 of the interACT project (see Dietrich et al., 2018), the concepts of interaction, reaction, and communication were defined. Another important concept to consider is that of traffic 'cooperation'. The focus of the interACT use cases selected in WP1 (see Wilbrink et al., 2018) is on unregulated situations, where there are no clear rules about priority such as at parking areas, shared spaces, and intersections without traffic lights. In these situations, in individual goals can occur, and it may be unclear which TP's goals should take precedence. Therefore, these types of scenario require TPs to cooperate and negotiate. For example, in Germany, the Road Traffic Regulations § 11 (3) recommend: "Anyone who, according to traffic rules, may proceed or otherwise has the right of way must relinquish this priority if the traffic situation so requires; a person not having the right of way may proceed only if the person having the right of way has signalled to them to do so (§ 11, Road traffic Regulations 2016)".

Cooperation can be defined as a joint action of two or more agents (in our use-cases the AV and/or non-automated road users) that work or act together for a common goal. To cooperate, agents must communicate (Färber, 2015). Certain types of cooperative behaviours that require negotiation between agents depend on directed communication, aimed at a receiver (Mataric, 1994; Monteil, 2014). It is essential that cooperation partners have the same understanding of the situation. For example, situations between human agents, cooperation is often indicated by explicit gestures such as eye contact, or the use of headlight flashes, in addition to implicit communication through the adaptation of vehicle movements (Imbsweiler, Palyafári, Puente León, & Deml, 2017; Sucha, Dostal, & Risser, 2017). Thus, cooperation with a human agent is limited to situations where the interaction partner is in the close vicinity and is clearly visible.

All type of agents have their own skills and limitations, which will be used to communicate their intentions, create a common plan, and execute it. One of the main aims of this project is to make this communication clear in mixed traffic situations, where AVs are communicating with drivers or

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vulnerable road users, thus facilitating cooperation between these road users. The main challenge here is that the quality of cooperation cannot be measured on a single value. There are several measures, which will be listed in the following sections that can be used to evaluate the quality of communication and cooperation. Examples of these measures include **traffic efficacy, traffic safety, user experience, acceptance, trust, and comprehension**. These concepts can be measured objectively as well as subjectively, and the quality of cooperation can be reflected through these measures.

2.1.1 Identifying appropriate methods

The following sections provide a summary of published materials, including conference papers and journal articles, which are of interest in helping us to understand the processes required for AV cooperation and interaction. Papers were selected for inclusion based on a search of google scholar and Researchgate for any articles relating to AV communication, AV interaction, driver-pedestrian interaction and communication, along with a collection of relevant articles published by each of the WP6 partners. The abstract and method section of each study was reviewed to establish its relevance for interACT. Through this process, a total of 61 articles covering a variety of publication types such as journal articles, conference papers, technical reports, theses and deliverables, were identified for inclusion in the literature review. The papers were then categorised according to the main research environment used for the study. This includes simulator and virtual reality (VR) studies, presented in Section 2.2 (e.g. Lee et al., 2019; Deb et al., 2018; Ackermann et al., 2019), test track studies presented in Section 2.3 (e.g. Clamann et al., 2017; Matthews et al., 2017; Mahadevan et al., 2017), and studies conducted in the real world, presented in Section 2.4 (e.g. Schneemann & Gohl, 2016; Guéguen, Meineri, & Eyssartier, 2015), along with questionnaire studies presented in Section 2.5 (e.g. Hulse, Xie, and Galea, 2018; Deb et al., 2017a, 2017b). In addition, many different tools have been identified for measuring cooperation and interaction performance, including experimental tasks, interviews, questionnaires, real world observations, simulation and modelling (see Section 2.5 and Section 2.6). The focus of this review is the identification of relevant evaluation criteria for the interACT solutions that will be described in Annex 1 of this deliverable. Therefore, the methods used in each paper are described in as much detail as possible, and relevant measurement tools are highlighted in bold text throughout.

2.2 Simulator Studies

Simulators and experimental studies have been widely used to investigate the interaction between AVs and drivers/other road users. They provide a safe testing environment and are cost-effective in collecting behavioural data. There are various ways to conduct simulator studies. Computer screen-based tasks (Section 2.2.1), usually involve the presentation of photographs or videos, and

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participants are asked to provide responses through, for example, pressing a button, or providing a rating. Head-mounted displays and pedestrian simulators allow the creation of virtual environments, in which participants are able to move freely and experience simulated scenes (Section 2.2.2). Finally, driving simulator studies (Section 2.1.3), provide an investigation of the experience and reactions of on-board users to iHMI or other road users actions.

2.2.1 Computer Screen-Based Tasks

Computer-screen based tasks generally involve the presentation of videos or photographs of traffic situations, and usually ask participants to provide some type of judgement or prediction about these situations. These tasks include situations in which participants were asked to predict the next actions of the road users presented e.g. whether or not a pedestrian will cross the road, or a vehicle will stop(e.g. Schmidt and Färber, 2008; Lee and Sheppard, 2016; Ackermann et al., 2019); requests for judgements about why an AV or conventional vehicle was driven in a particular manner (Petrovych et al., 2018); understanding participants' willingness to cross in front of a driverless vehicle (Winter et al., 2019); and understanding the communication intention of eHMI (Fridman et al., 2017).

2.2.1.1 Predicting the intentions of others

Schmidt and Färber (2009) used a **video-based method** to evaluate the parameters that human drivers use to predict pedestrians' intentions. Videos of natural traffic scenes were presented and participants were asked to make statements regarding (a) whether the shown pedestrian would cross the street during the next moment and (b) (what were) the cues used for the participant's judgement. In the first condition, the pedestrian's head was masked (''head condition"), and in the second condition the legs were masked (''leg condition"). In the third experimental condition, the traffic was masked (''traffic condition"). In the fourth condition, the whole pedestrian was masked with a rectangle, leaving only the traffic scene and the trajectory of the pedestrian visible. This was called the ''dynamics condition". Participants had to rate after each video **whether or not the pedestrian would cross the street**. They also had to indicate **their level of certainty,** using a 7-point-scale. Results showed that the condition in which only the trajectory information of the pedestrian was available produced the highest error rate, showing the importance of information about body posture including head, hand and leg movements for predicting pedestrians' intentions.

Lee and Sheppard (2016) used a **video-based study** to investigate the effect of motion and signalling on car drivers' ability to predict the intentions of other cars and motorcycles. A series of one-second video clips and pictures (last frame of the video clips) were presented to participants from the viewpoint of a driver. These videos showed an approaching car or motorcycle coming from the opposite direction, which was continuing to drive straight or turning right. Each clip consisted of a

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vehicle (car/motorcycle) which either provided a valid (turn with indicator and straight without indicator) or invalid (straight with indicator and turn without indicator) signal. The video clips were cut before the manoeuvre of the approaching vehicles became obvious. Participants were then asked to **judge whether the approaching vehicle was turning or going straight**. Using **Signal Detection Theory**, this study concluded the importance of video/motion cues in judging the intention of other vehicles. Although it is important to provide a valid signal to increase accuracy in judging intentions, this study also found that participants were fairly accurate in judging the intention of the vehicles when an invalid signal was provided, suggesting that trajectory-based information was also important in establishing vehicle intent.

Kitazaki and Myhre (2015) also investigated drivers' understanding of other drivers' intentions using an interview-based experiment looking at drivers responses to computer animations of straight-cross-path and left-turn scenarios. Participants were presented with a schematic computer animation showing the plan view of an intersection and two moving cars. The animations were terminated before the two cars reached the intersection. Communication cues consisted of vehicle behaviours (constant speed, speeding up, and slowing down) and hand gestures, demonstrated by the experimenter, symbolising 'go' and 'stop'. **Participants rated yielding frequency, defined as the frequency of yielding in similar situations in their driving experience**, **on a 5-point scale** from never to always. Participants also **rated their confidence level about the inferred intention on a 5-point scale** from not confident at all to perfectly confident. Results indicated that the combination of hand gestures and vehicle behaviours was most effective in consolidating participants' decisions and confidence in situations where the priority rule was ineffective. Hand gestures were also effective in changing yielding frequencies in situations where vehicle cues conflicted with the effective priority rule.

In a slightly different approach to the other studies mentioned, Ackermann et al. (2019a) investigated how different factors affect pedestrians' deceleration detection. In their first study, a series of videos depicting an approaching car arriving at a junction were presented to participants. The approaching vehicle was either travelling at 20 or 40kmh, with a deceleration rate of 5, 3.4, or 1.5 m/s^2. Different onset times for deceleration were also manipulated (early onset or late onset). Finally, video stimuli were either recorded in the morning, at dusk or in the evening. The participants' task was **to press a button** when they were as sure as possible that they had **noticed a change in vehicle movement**, but refrain from pressing a button when the vehicle was driving at a constant speed. Reaction time was analysed. Study 2 was similar to study 1, but in this study, vehicle size was manipulated, while the speed of the approaching vehicle was always at 20kmh, and there was no daylight manipulation. **Reaction time i.e. the time taken to make a button press response**, was also analysed to investigate how these factors affect deceleration perception. Results showed that participants had a significantly

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shorter reaction time while detecting higher deceleration rates and lower speeds, and the onset of deceleration and vehicle size interacted with other parameters. This suggests that AVs should apply smooth and early decelerations taking into account their approaching speed and vehicle size.

2.2.1.2 Attitude towards Automated Vehicles

A study conducted by Petrovych et al. (2018) aimed to understand whether, and to what extent, people have similar judgment on the intentionality and causes of driverless vs human driven cars' behaviour, along with how much they agree in their judgment. In a between-subject design experiment, one group was presented with **a series of pictures** depicting various traffic scenarios with a visible human driver behind the wheel; whereas the other group was given a series of more or less identical traffic scenarios without a human driver. Each of the pictures was also presented with a description of traffic behaviours. Participants were asked to **provide ratings on a 7-point Likert scale** from 'not at all' to 'completely, on **the extent to which the car's behaviour was intentional, controllable, and desirable**. They were also asked to 'Rate how plausible it is that **the cause of the car's behaviour** was a conscious goal, an action, an outcome, an uncontrollable event, a temporary state, a disposition and an attribute of someone or something in the car's environment'. This study found a low agreement in ratings on the behaviour of the driverless car, suggesting that this might be an indication of difficulties while interpreting the goal-directed behaviour of AVs.

Winter et al. (2019) conducted studies to investigate the willingness of pedestrians' crossing at intersections, when driverless cars approached the intersection, compared to a humanly driven car. They also considered the effect of gender, and nationality (US vs India) on participants' willingness to cross in front of a driverless car. Studies were conducted by using the Amazon Mechanical Turk (MTurk) platform to collect survey data. During the first study, participants were provided with one or two **hypothetical scenarios with illustrations**, for example, "Imagine you are approaching a 4-way intersection with no traffic lights or crosswalk indicator signaling you to proceed. You are standing at a right angle to an autonomous vehicle (i.e. DRIVERLESS) with no human driver. The vehicle has stopped at the "STOP" sign. You and the vehicle both need to cross." They were then asked to complete **seven questions about their willingness to cross the street** using a **7-point Likert scale** (strongly disagree to strongly agree). The second study was the same as the first, but had added **an affect scale** (Rice & Winter, 2015) to capture participants' emotional responses to the scenarios. Study 3 duplicated study 2 but instead of providing a general affect scale, specific emotions were used to provide potential mediators (**ratings on the six universal emotions**, based on Ekman and Friesen, 1971, namely, anger, disgust, fear, happiness, sadness, and surprise). Findings show that anger, fear, happiness, surprise, familiarity, fun factor and wariness of new technology were predictors of a pedestrian's willingness to cross in front of a driverless vehicle.

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2.2.1.3 Comprehension and Interpretation of eHMI

Fridman et al. (2017) conducted an online study by using the MTurk platform to investigate the communication intent perceptions for 30 eHMI designs. A **series of pictures** were shown to the participants. These pictures consisted of an approaching vehicle with one of **30 eHMI designs** at a cross walk. The participants' task was to imagine that they were a pedestrian viewing the approaching vehicle and they had to decide whether it was safe to cross or not by choosing 'yes', 'no', and 'not sure'**. The percentage of cross/don't cross/not sure responses** for each design was calculated. This study concluded that the presentation of multiple designs using the MTurk platform enables a useful early-stage evaluation of specific design concepts. Results indicated that none of the eHMI designs were universally understood, although "don't walk" designs were more likely to be interpreted correctly than instructions to "walk".

Beggiato, Witzlack, Springer, and Krems (2017) conducted an experimental study in which **pre-recorded videos of approaching cars** in a parking area were presented to participants on a computer screen. Participants were instructed to **press a defined key at the last moment they would cross the street comfortably**, without running, before an oncoming vehicle. Videos were recorded at day and dusk, and two age groups were sampled – 20-30 years and 50+ years. Vehicle speed was manipulated to range from 10 to 40km/h in seven steps of 5 km/h. Results showed that the higher the speed, the shorter the minimum time gap that was accepted. Participants took significantly longer time gaps at dusk than midday, and older participants chose greater i.e. more conservative time gaps than younger participants. The authors interpreted this finding as showing that there is no one-size-fits-all solution for accepted time gaps that can be incorporated into AV design.

2.2.1.4 Computer-Based Tasks: Summary and Conclusions

Most of the computer-screen studies used videos or images as stimulus material and participant interpretations, subjective ratings, and reaction time measures as an indication for participant decision-making processes. The use of paused video and picture stimuli provide a useful method for understanding road users' capacity to predict the intentions of others, along with providing a cost-effective and fast way to capture how well HMI concepts are understood (comprehension). The use of button-press responses provide a measurement of how quickly road users can perceive and interpret one another's actions, and this limits the speed at which they can make crossing decisions. Rating scale and interview responses to stimuli can also be used to understand perceptions of safety and comfort around crossing-decisions (affect). However, the use of computer-based stimuli does not allow the evaluation of pedestrians' or drivers' behaviour during the scenarios, and thus it is not possible to capture the effects of AVs and / or HMI on objective interaction behaviours, for example asking participants to cross the road.

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2.2.2 Virtual Reality – HMD and CAVE Studies

Head-mounted VR displays have become a popular method for investigating pedestrian interactions with AVs. In general, in these studies, participants have been presented with different types of eHMI signal designs, and objective measurements of their responses have been collected. These studies include establishing the criteria for evaluating eHMI (Ackermann et al., 2019; Kaup et al., 2019; Dietrich et al., 2019; Weber et al., 2019; Kettwich et al., 2019; Merat et al., 2019; Schieben et al., 2019), the comprehension of different eHMI designs by pedestrians (Lee et al., 2019b), the effect of eHMI on receptivity, perceived crossing safety, trust, crossing behaviour and user experience (e.g., Deb et al., 2018; Otherson et al., 2018, de Chercq et al., 2019). Head-mounted displays have also been used to develop an analysis framework to evaluate the impact of different vehicle factors, such as vehicle speed (Lee et al., 2019a), different time gaps (Velasco et al., 2019; Lee et al., 2019a), vehicle deceleration profiles (Lee et al., 2019a), the presence/attentiveness of drivers (Velasco et al., 2019), and AV driving behaviour (Jayaraman et al., 2018), on pedestrian crossing behaviour. Finally, this method has been used to study pedestrians' attitudes towards driverless cars (Pillai, 2018).

2.2.2.1 Vehicle behaviour and effect of drivers on pedestrians' behaviour

Lee et al. (2019a) investigated pedestrians' crossing decisions and behaviour using a VR Head-Mounted Display (HMD), presenting an analysis framework for evaluating the effect of eHMI on pedestrians' crossing decisions and behaviour. Participants were asked to stand at the edge of the road (single lane, 3.5 meters wide). They saw two vehicles approaching from the right, and were required **to cross after the first vehicle had passed, if they thought it was safe to do so**. The two approaching cars were travelling at the same speed (25, 30, or 35 mph), and the time gaps between them ranged from 1 and 8 seconds, with 1-second increments. In addition, the second approaching car was either decelerating to come to a complete stop in front of the participants, or it was travelling at a constant speed, without stopping. Measures included the learnability of the eHMI (in this case, the vehicle's behaviour), which was based on a comparison of participants' **crossing decisions across three experimental blocks.** The efficiency of crossing decisions was studied by measuring **initiation time**, while trust/comfort of crossing was measured through **crossing time.** Finally, the **safety margin** was measured as **the time taken for the second approaching vehicle to arrive at the pedestrians' crossing path, after the pedestrians had crossed the road**. Results showed that only 18% of the crossings occurred during deceleration, with 51% of crossings happening before, and 31% happening after the vehicle had stopped. In addition, a learning effect was shown, with participants crossing earlier as the study blocks progressed.

Velasco et al. (2019) used a similar approach to investigate whether the presence and attentiveness of a driver has an effect on pedestrians' crossing decision. Once again, two approaching cars were

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travelling at a speed of 30km/h, with time gaps between the cars of either 3.5 or 5.5 seconds, and the second car was either decelerating or not. To investigate if pedestrian crossing decisions were affected by the presence and/or attention of a driver, the driver in the second car was either looking ahead (attentive), looking at the phone (non-attentive), or not present at all. The study was conducted in three blocks to study the effect of learning and behavioural adaptation. In addition to objective measures such as **percentage of crossings, initiation time, crossing time and safety margin**; subjective measures were also collected using questionnaires, such as an adaptation of the **trust questionnaire** developed by Payre, Cestac and Delhomme (2016). Perceived Behavioural Control was measured using the **PBC questionnaire adapted from Zhou, Horrey, and Yu (2009)**. Results showed that the vehicle's motion cues (e.g. time gaps between approaching vehicles and deceleration) deceleration) were the most important factor affecting crossing initiation time. Participants also felt more control and safer when a driver was present and attentive, rather than distracted.

Using a similar experimental procedure, Pillai (2017) also examined pedestrian crossing behaviours in a VR environment to understand attitudes towards driverless vehicles. Participants interacted with driverless vehicles, approaching a crosswalk from the left. They were required to determine the intention of the car, and **cross the road when they felt it was safe to do so**. Six different scenarios were introduced in this study: two environmental conditions – clear visibility or low visibility; and three vehicle deceleration profiles. Each scenario was followed by a **semi-structured interview** to understand participants' perception of the scenarios. **Video and audio** were recorded to capture participants' reactions, and **VR recordings** provided information about what participants were seeing. Participants were also asked to use a white board to provide a **sketch of the vehicle's behaviour as it approached**. Analysis of **body language** during the experiment was used to determine participant comfort levels around the vehicles. Results suggested that people actively sought intentional cues by observing the vehicle movement, and sound was particularly important when visibility was low.

Jayaraman et al. (2018) took a slightly different approach to the previously mentioned studies in their investigation of the effects of AV driving behaviour (defensive, normal and aggressive) and traffic situation (signalised and unsignalised) on **pedestrians' trust in AVs**. This study used the uncertainty reduction theory (URT), which states that when uncertainty levels are higher, people are more likely to seek for information to reduce these uncertainties. A VR headset and an omni-directional treadmill were used to conduct the study. Attitudinal measures such as **trust, propensity to trust** (Muir, 1987) were collected, and participants also completed a **simulation sickness** questionnaire. Behavioural measures used included **average distance to collision**, **average waiting time**, **average crossing time**, **average jaywalking time,** and **average crossing speed**. Trusting behaviours of interest included reduced distance between the AV and the pedestrian, reduced waiting time before crossing, reduced crossing speed, and increased jaywalking time. Findings showed that trust in AVs was significantly

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related to reduced distance between the AV and the pedestrian, increased jaywalking time, and increased average waiting time, but there was no difference for the other measures.

In addition to the HMD VR studies, pedestrians' crossing behaviour has also been studied with CAVEs (Cave Automatic Virtual environment), using projector screens to build an immersive simulated environment, which also allow participants to walk around the space. One of the early studies was conducted by Oxley et al (2005), investigating the effect of pedestrians' age group (younger, young-old, and old-old) on crossing gap selection. This study manipulated the time gap (1, 4, 7, 10, 13s) and the speed (40, 60, 80km/h) of approaching vehicles. These stimuli were projected onto a large white curved screen. Participants' task was to **press buttons to indicate whether they would 'cross'** the road or not, 'yes' and 'no'. Five measures were recorded and analysed, such as participants' **walking time over distance, decision times, yes/no responses, safety margins, and safety rating responses.** A second experiment was conducted to investigate crossing behaviour under time pressure, using similar method. Overall, the studies found that crossing decisions were mainly based on vehicle distance and less so on time-to-arrival, and that this finding was consistent across all age groups. Older pedestrians also selected larger gaps as compared to younger pedestrians, despite having enough time for crossing.

A similar study was conducted by Lobjois and Cavallo (2007), who investigated how age (20-30; 60-70; and 70-80 years old) affects crossing decisions in an estimation task. Two experiments were conducted; experiment 1 was conducted with time constraint (respond as soon as possible) whereas experiment 2 had no time constraint. Vehicle speed (40 and 60km/h) and inter-vehicle distance (10-135 m, in 5m increments) were manipulated, and participants were asked to decide whether **they would cross between the two cars or not by pressing buttons**. Several measures were analysed, such as **crossing time (CT), response time (RT) in the estimation tasks, mean selected distance and time gap, safety margin, and categorising the decisions.** Experiment 1 (with time constraint) showed that a shorter time gap was selected for the higher speed of approaching vehicles. Experiment 2 (without time constraint) found that younger participants' crossing decisions were similar regardless of speed, whereas older participants' accepted smaller gaps as speed increased.

Two years later, Lobjois and Cavallo (2009) investigated the effect of aging on actual pedestrian crossing behaviour. The setup was similar to Lobjois and Cavallo (2007), and participants' task was to **cross the street between two cars** when they thought it was safe. Vehicle speed (40, 50, 60km/h) and the time gap between cars (1-8 s, in 1 s increments) were manipulated, and several measures were analysed, including **mean accepted time gap, crossing behaviour and behavioural adjustment to the available time, and categorisation of decisions**. This study found that the crossing decisions made by younger participants are more affected by time gaps in this actual crossing tasks, as compared to the estimation tasks in 2007.

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2.2.2.2 Effect of eHMIs

Ackermann et al. (2019b) explored the effectiveness of various eHMI strategies through a two-stage study consisting of a focus group study followed by an experimental video simulation study. During the focus group discussion phase, **opinions on different types of eHMI designs** were gathered. These included different types of visual eHMI such as projections, LED displays, LED light strips, and portable communication devices (e.g. smart watch); different positioning of eHMI (windscreen, radiator grille); the use of symbolic or text based eHMI; and the presentation of vehicle status information compared to pedestrian advice. A series of evaluation criteria were also derived from the focus group including, **recognisability** (defined as a reliable visual capture of the eHMI message), **unambiguousness, interaction comfort, and intuitive comprehensibility**. During the experimental video simulation study, a series of eHMI signals were designed and presented, by using augmented real-world videos recorded in a parking area. The approaching vehicle was travelling at a constant speed of 10km/h. Dependent measures were collected, based on the four evaluation criteria mentioned above, by asking participants to provide a **rating** score between 0 and 100. They were then asked about their **favoured position**, and **the coding and content of the message** (qualitative measures). Results showed that participants preferred direct instructions from the AV rather than receiving status information. Projections and displays were preferred to LED light strips, and large-scale text-based messages were shown to be less ambiguous, compared to symbols.

The **comprehension of 10 eHMI signal designs** was also the subject of a study conducted by Lee et al. (2019b), to investigate participants' preferred visual signal for one of three messages: '*I am giving way*', '*I am in automated mode*' and '*I will start moving*'. Two different methods were used in this study. Firstly, a **Forced Choice Paired Comparison task** was used, where participants were asked to choose which of two eHMI signal designs best conveyed a particular message. This method provided a ranking of signal designs for each of the three desired messages. The second method used a **6-point rating scale,** where participants were asked to rate the extent to which the eHMI signal designs communicated a certain message. This study illustrated that there was a good correlation between the Forced Choice Paired Comparison task and the rating task. Results showed that the top two eHMI signal designs for conveying the message 'I am in automated mode' were 'Slow Pulsing Light Band' and 'Slow Pulsing Single Lamp'. For the message 'I am giving way', the top three designs which best convey the message were 'Fast pulsing Light Band', 'Multiple Modality (fast pulsing light band with fast auditory cue)' and conventional Flashing Headlights. Finally, the Multiple Modality signal was the clear winner for conveying the message 'I will start moving'. This study concluded that the same eHMI signal design could be interpreted in different ways, leading to potential misinterpretation, which could lead to dangerous behaviour.

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In their HMD study, Deb et al. (2018) investigated the effect of eHMIs in helping pedestrians to understand the intention of an AV at a crosswalk, improve receptivity (i.e. the willingness to accept a new idea that may be uncertain, unfamiliar, or paradoxical), and understand how the eHMI would affect crossing behaviour. 16 eHMI designs were presented once (4 visual x 4 auditory), and participants were told that they should **cross when they felt it was safe to do so**. In this study, the car always stopped at the crosswalk. Objective measures such as **waiting time before crossing** and **crossing time** were used to evaluate pedestrians' preferences for eHMI features. Questionnaire items measured the pedestrians' **perceived safety** while crossing the roads, and **personal innovativeness scores** (adapted from Agarwal and Prasad (1998) were used to explore the effect of participants' personal opinions towards this new technology (eHMIs). Finally, two more questionnaires were presented: **the pedestrian behaviour questionnaire** (PBQ, Deb, Strawderman, Carruth, et al., 2017) and **pedestrian receptivity questionnaire for Fully Automated Vehicles,** using two scenario-based survey responses (PRQF, Deb, Strawderman, DuBien et al., 2017). Results showed that participants' receptivity towards AVs increased with eHMI, and that distracted pedestrians and pedestrians who violated traffic rules were also more cautious when eHMI was presented. Walking silhouette symbols or 'braking' in text were the most preferred visual eHMI, and a verbal message was the most preferred audible eHMI.

Otherson, Conti-Kufner, Dietrich, Maruhn, & Bengler (2018), also used a HMD study to investigate differences in response to four different eHMI concepts across two age groups (20-30 years and 60-70 years). The **crossing initiation time to vehicle stop** (CIT_{vs}) was used to quantify pedestrians' **road crossing behaviour**. This refers to the difference between the time at which the vehicle comes to a full stop, and the time at which the pedestrian initiates their crossing. If the value is negative, it means that the participant started to cross the road before the vehicle stopped completely. The **User Experience Questionnaire** (UEQ) and an eHMI variant ranking were used to understand participants' **preferences** regarding the eHMIs presented, as well as providing participant input into how to improve the eHMIs design. Results showed that pedestrians started to cross the road earlier when eHMI was present, with 28% of pedestrians crossing the road before the vehicle came to a full stop when eHMI was present, as compared to only 9% when there was no eHMI. No differences were found between the two age groups.

Finally, a VR HMD study conducted by De Clercq et al. (2019), investigated the effects of eHMI on pedestrians' **perceived crossing safety**, by observing how crossing was affected by vehicle behaviour (yielding/non yielding), size (small, medium, large), and types of eHMIs (4 types of visual eHMI were compared to a no-eHMI condition), using 3 timings (early, intermediate, and late). Participants were asked to **press a handheld button when they 'felt safe' to cross**. Results showed that the average number of button presses was significantly higher for yielding vehicles with the presence of eHMI. For

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non-yielding vehicles, the presence or type of eHMI did not have any effect, but larger vehicles led to lower numbers of button presses

A study was conducted by Dietrich et al. (2019) to investigate the effects of deceleration and eHMI on pedestrians' crossing behaviour. Multiple cars approached participants at a speed of 30km/h. After two to four cars passed the participants with time gaps of 2.1 or 2.4 seconds (to prevent participants crossing in between), the experimenter vehicle would then either yield (using one of six deceleration rates) with or without eHMI; and the vehicle stopped at 2.5 m before the pedestrian. The eHMI signal design was a slow pulsing light band presented in cyan colour (0.33 Hz), defined within interACT project (Kaup et al., 2019). The participants' task was to **cross the trafficked lane whenever they felt safe**. **Crossing Initiation Time to Vehicle Stop (CITvs)** was used as a dependent variable, it measures the time when pedestrians starts to cross before the vehicle stop, providing a negative value. The study shows significant main effect of the presence of eHMI as well as deceleration rates, whereby crossing was made sooner with the presence of eHMI as compared to no eHMI, and crossing was also made sooner if the vehicle decelerated at a further distance (lower deceleration rate).

Weber et al. (2019) conducted a HMD study to investigate any cross-cultural effects (Mountain View USA, Shanghai China, and Mannheim Germany) on crossing behaviour with the presence of eHMI. The AV's intention was either to yield (by decelerating 20 m before pedestrian at a rate of $3.5m/s^2$) or not yield (by continuing at a constant speed of 25mph). Priority was manipulated by changing the traffic scene to denote who had right of way, with the AV having priority in a 2-lane street, the pedestrian having priority at a zebra crossing, and priority being undefined in a parking scenario. The eHMI solutions included no eHMI, an icon, or a light band. During conditions where the AV was not yielding, pedestrians were never given the priority. The participants' task was to **press a button as soon as they understood the intention** of the AV. **Intention Recognition Time (IRT)** was measured as the time taken to press the button. The authors found that when the AV was yielding, the eHMI did not show intention recognition benefits in China, but it was found to be beneficial in USA and Germany. When the AV was not yielding, the presence of eHMI was found to deteriorate the intention recognition of AV, and this finding was consistent across cultures.

2.2.2.3 VR Studies: Summary and Conclusions

The use of Virtual Reality environments allows the exploration of scenarios that it would not be possible to capture through videos or pictures of real-world driving. HMD and CAVE set-ups provide an immersive virtual environment and stimuli, and also facilitate the capture of pedestrian behaviours around both conventional vehicles and AVs, although for safety reasons not many of the studies used these tasks. Crossing times, crossing initiation times, safety margins, and gap acceptance were all commonly used measurements to explore participants' behaviour, and the effects of both explicit

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eHMI and implicit vehicle motion cues on pedestrians' crossing behaviours. Button-press responses provide an alternative tool when actual crossing behaviour is deemed unsafe or impossible to implement in these environments. The use of rating scales and questionnaire items within these experimental studies allowed researchers to compare subjective measures of trust, perceived safety, and receptivity, with objective measures of crossing behaviour. Alternative approaches, such as those of Ackermann et al. (2019b) and Lee et al. (2019b), show how the immersive experiences provided by HMDs can facilitate a deeper understanding of how pedestrians might respond to different eHMI concepts. The results shown through the studies in this section, provide a baseline of pedestrian responses to various vehicle behaviours and eHMI, which can be used as a comparison for the interACT evaluation studies within WP6.

2.2.3 Driving Simulator Studies

Driving simulators offer a safe environment to test and evaluate novel HMI design. In a fully automated vehicle, driving time can be used for non-driving-related tasks (NDRT), and indeed, being able to do other things while being in a vehicle is one of the expected benefits of AVs. In the current project, persons on-board of the AV can be considered as passengers since they cannot intervene the trajectory of the AV. Thus, the main objective of the project is to assess the effects of on-board users' propensity to engage in other tasks on their interactions with the AV, and their behaviour in the presence of other road users. If on-board users are distracted by NDRT, this may cause confusion for other road users who expect a person in the driving seat to be paying attention to the road (see Lagström & Lundgren, 2015). In addition, an on-board user may not be sure whether the AV is aware of other road users, and what, if any, message it intends to convey to them. This type of interaction is relatively new and there are not many studies investigating the 3-way interaction. A **survey** conducted by Konig et al. (2017) found that the possibility of engaging in other activities than driving was reported as one of the most valued benefits of automated vehicles. Naujoks et al. (2016) found in an **on-road study** that drivers engaged more heavily in non-driving related tasks as the level of vehicle automation increased. Pfleging et al. (2016) conducted a **web-based survey** on activities that drivers would like to perform during automated driving. The most often mentioned secondary tasks were talking with passengers, looking out of the window, texting, eating/drinking, and surfing in the Internet. Schoettle and Sivak (2014) reported that drivers would like to spend their time during an automated ride on activities like reading, texting/talking to friends, watching movies, and working.

In one of the few studies that investigated the effect of iHMI, outside of driver take-over requests, Naujoks et al. (2017) investigated how a visual-auditory HMI may affect user experience in an automated vehicle. The iHMI of the automated driving system consisted of a visual-auditory HMI with either generic auditory feedback (i.e., standard information tones) or additional speech output, and

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provided information about upcoming manoeuvres. Drivers were asked to perform a common NDRT during the drive. Participants **rated the usefulness** of visual and auditory components of the iHMI. Constructs of the questionnaires were **level of interference with secondary task, assessment of usefulness, visual workload, and acceptance**. Results revealed that compared to generic auditory output (i.e., standard information tones), communicating upcoming automated manoeuvres by speech led to a decrease in self-reported visual workload and reduced interference with secondary tasks.

Within the InterACT project, two studies have also investigated on-board users' experiences of iHMI designs (reported in D4.2, Weber et al., 2018). The aim of these studies was to understand the **expectations and preferences** of on-board users with regards to their information needs. In a simulator environment the **comprehensibility** of the designs (a 360 degrees light band vs. head down display) was measured using a **questionnaire**, and afterwards the **usability** was measured using the **van der Laans scale**. Finally, the designs were ranked according to **intuitiveness** and general **preferences (using card sorting)**. The results revealed that in the first, naïve run, the light band was ranked the least intuitive because participants found some parts especially the "next manoeuvre" difficult to understand. However once the design was explained, the light-band was one of the most preferred designs ranked best by majority of the participants for both automated drive distracted and non-distracted. Based on these results, a follow up study was conducted in a VR environment. The main research questions addressed in this study were whether different iHMI interaction approaches (light-band vs. HDD), delivered additional information about an AV's interaction with a pedestrian (perception (i.e "I have seen you") - vs. intention-based ("I will brake") vs AV's automation level only), are perceived more or less favorably, and whether they thereby enhance the on-board **user's acceptance** in different use cases. Participants were instructed about the different iHMI versions before the test runs and rated their **perceived safety and comfort** using the AV and its iHMI as well as its usability. In general participants significantly preferred light-band-based iHMI versions, and perception-based interaction approaches both for the light-band and HDD. The baseline only was the least preferred interaction approach for both output media. With regard to ease of information access provided by the iHMI versions, no differences were found for the HDD, but differences for the light-band-based interaction approaches emerged for both use cases. The intention-based, and especially the perception-based, interaction approach were rated as significantly easier to understand, i.e., to access the provided information, compared with the baseline.

Two studies have also investigated the use of iHMI to support interactions with other road users. Firstly, Haar, Kleen, Schmettow, and Verwey, (2018) conducted a simulator based study to investigate the impact of three iHMI systems on supporting interactions between drivers through connected automation. In the first condition, the indicator of the merging car distinguished between planning

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and executing the manoeuvre. In the second, a head-up display (HUD) signalled an upcoming lane-change of a partner car, and in the third condition the HUD distinguished between the planning and execution of this manoeuvre. **Permissive versus non permissive behaviour was measured by analysing whether a participant insisted on their right of way**, when another vehicle wished to enter their lane. Participants **evaluated cooperative behaviour using a questionnaire** developed by Zimmerman, Fahrmeier and Bengler (2015).

With regards to the comprehension of other road users' intent, Powelleit, Winkler, & Vollrath (2018) conducted a small-scale (7 participants) simulator-based study to investigate two different eHMI communication concepts, comparing **drivers' ratings of comprehensibility**, **appeal, and distraction potential**. In the first scenario examined, participants gave way to a vehicle entering their lane by flashing the headlights. The lead vehicle then expressed gratitude via a backwards light projection consisting of a check mark, a smiley face, or a thumbs-up. The positioning of these symbols was varied between the road and the lead vehicle. In second scenario, the participants' car was continuously projecting its driving path in front of the vehicle. It was anticipated that this would make it easier for other road users to recognise its intent. Participants were instructed to **think aloud** while driving, expressing their spontaneous thoughts, emotions and reactions to the concepts. **Structured interviews** and **rating scales** were used to evaluate factors like **appearance** and **understandability**. Participants were also asked to pick their **favourite** version for each scenario.

2.2.3.1 Driving Simulator Studies: Summary and Conclusions

Up until now, the majority of driving simulator studies have focused on driver responses to take-over requests from automation, and there have been relatively few investigations of on-board users interactions with iHMI systems outside of this context. In these situations, subjective ratings, interview responses, and think-aloud protocols have been used to understand on-board users' acceptance, ratings of usefulness, and comprehension of iHMI, along with their attitudes towards the cooperative behaviour of an AV. These types of measures can also be used for the evaluation of iHMI within interACT.

2.3 Test Tracks studies and Closed-up areas

Experiments conducted on test-tracks and closed-up areas have been used to understand pedestrians' crossing behaviour (Schmidt and Färber, 2008); and investigate the effect of different eHMIs and communication tools on pedestrian behaviour (e.g. Clamann et al., 2017; Matthews et al., 2017; Mahadevan et al., 2017). This setup has also been used to gain an understanding of interactions with AVs by using a Wizard of Oz methodology (Habibovic et al., 2018; Lagström & Lundgren, 2015;

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Palmeiro et al., 2018). More details on each of these methodologies is provided in the following sections.

2.3.1 Understanding crossing behaviour

Schmidt and Färber (2008) conducted a test-track experiment, whereby participants were asked to **make a decision about whether or not they would cross in front of, or behind, an oncoming car**. The speed of the vehicle was manipulated, as was the distance at which the pedestrian was asked to make the decision. Participants were walking along a pavement, either in the same direction as vehicles travelling in the nearside lane (i.e. with their back to them), or in the opposite direction (facing them). On hearing an acoustic signal, participants' crossing decisions were measured by asking them to cross the road, deciding whether to do so before, or after, the oncoming car. **Safety of decisions** was measured using **time to collision (TTC), distance, and speed**. Results showed that pedestrians relied on the distance of the car rather than the time to collision (TTC) for their decision. The further away the car, the higher the probability that the pedestrian would cross, regardless of speed. In addition, when the car was travelling in the same direction as the pedestrian (i.e. coming from behind), shorter distances were chosen to cross.

2.3.2 Effect of eHMIs and communicating with other road users

Clamann et al. (2017) compared the effectiveness of various methods of presenting vehicle-to-pedestrian street crossing information on participants' crossing decisions. In this study, a van, which participants were told was an AV, was used to present information to pedestrians regarding when to cross a street, from one of two locations: a marked crosswalk, and an unmarked midblock location. Three different interfaces were presented: conventional silhouette symbols for 'walk' and 'don't walk', and a numerical presentation of the vehicle speed. Participants were introduced to a scenario that they were late for a job interview, and were required to receive directions from the experimenter for their destination. The participant started with their back to the street, and the experimenter started the trial by providing a vocal cue to cross, at which point the participant would turn to face the vehicle and make a **decision about whether it was safe to cross** by walking forward from the start position. The **knowledge acquisition phase** of this study **was measured as the time between starting the trial and turning to face the vehicle**, and the **decision phase was the time between turning and starting to cross**. Results showed that the majority of participants relied on *implicit information* such as the oncoming vehicle's distance and speed to inform their crossing decisions, with less reliance on the explicit messages on the van.

In another study, Matthews, Chowdhar, and Kieson (2017) equipped a golf-cart with sensors to give it autonomous capabilities, and to enable it to communicate with pedestrians through a specially

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designed intent communication system (ICS). The vehicle was controlled via a transmitter. The ICS consisted of an LED word display and speakers. Participant interactions with the golf-cart were compared across four different conditions, with half of the participants receiving information about how the system worked prior to the experiment, while half did not. In addition, half of the participants encountered an automated system with ICS, while the other half did not. Analysis of **video-based data** showed that participants who encountered a vehicle with no ICS acted more hesitantly around it. Participants who had received information about how the automated system worked had faster **crossing times** than participants who did not, regardless of whether the ICS was on. Questionnaire results showed that participants gave higher ratings of **trust** and **safety** when there was an ICS than when there was not.

Mahadevan, Somanath, and Sharlin (2017) compared the success of different coloured LED lights, animated faces, and auditory messages in conveying different messages to pedestrians. In their first study, participants were asked to **sketch their ideas for AV design solutions**, while also **ranking their designs in terms of their appropriateness for certain scenarios**. Designs were categorised in terms of the visual, audio and physical cues (e.g. vehicle motion patterns, or haptic feedback through wearable devices) they provided for AV communication. For communicating awareness, the use of an LCD display on an AV was more popular than wearable devices, and for communicating intent, LED lights featured the most often. This analysis was used to design proof-of-concept interfaces which were presented on a Segway and a car, across 2 separate experimental studies. Participants interacted with either a Segway or a car which used 4 different interfaces to communicate. They were asked to **provide ratings of their confidence in their understanding of the vehicle awareness and intentions**. Results indicated that the LED strip was ranked higher compared to other auditory and physical cues, and that a small majority of participants (6 out of 10) expressed a liking for audio feedback from the vehicle for awareness communication. However, there was some concern that the use of four different LED colours with different meanings could cause confusion. The animated face was the worst performing cue.

2.3.3 Wizard-of-Oz / ghost driver studies

Due to current legislation and safety concerns, it is very difficult to test road user interactions with AVs in real-world scenarios. One of the ways to get around this issue is to use a human driver who is hidden in some way from other road users, either through the use of dummy equipment or by limiting the visibility of the driver. This is known as a Wizard-of-Oz (WOZ) technique. WOZ is a well-established approach for evaluating user interfaces in various domains from robotics to automotive applications, and is based on the idea of a human operator simulating a fully working technical system (Habibovic et al., 2018). It allows researchers to gather data from users who believe that they are interacting with

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an automated system, thus providing a more realistic experience for participants than simulated or video based studies. In recent years, this method has been used in both test track studies (Habibovic et al., 2018; Lagström & Lundgren, 2015; Palmeiro et al., 2018) and real-world studies (see Fuest et al., 2018a; Rothenbücher et al., 2016, Section 2.4.3).

Habibovic and colleagues (Habibovic et al., 2018; Lagström & Lundgren, 2015) conducted a series of experiments using a Wizard-of-Oz methodology, whereby a dummy steering wheel was installed in a right-hand steered vehicle (a Volvo V40), and the real steering wheel was concealed. The purpose of the experiments was to examine the comprehension of their eHMI design variants using the automated vehicle interaction principle (AVIP), a visual interface incorporating lights at the top of the windscreen. In their first experiment, they compared 4 design variants to communicate the messages of "I'm in automated mode", "I'm about to yield", "I'm waiting" and "I'm about to start driving". Pedestrians were asked to observe the test vehicle from the pavement and report their **interpretation of the signals** to the test leader. To study perceived safety, pedestrians were asked to assess **whether they would cross the street when they first saw the vehicle**. After each encounter, the pedestrians' **reasoning behind their (un)willingness was explored** as well as their **emotional experience**. In a familiarization phase, eight out of nine participants were unable to understand the AVIP function, but a short explanation was sufficient for them to learn how to successfully interpret the different signals. **Interpretation confidence** was measured using a 5-point confidence scale. Pedestrians were also asked to complete the **Self-Assessment Manikin (SAM) questionnaire** (Bradley and Lang, 1994), which provides a non-verbal assessment of the valence, activity, and control associated with a person's affective reaction to stimuli. The second experiment was carried out in a parking lot, using a wall to block visibility of the approaching vehicle until the required time. In this experiment, pedestrians' self-assessed **level of perceived safety was measured on a 1–5 Likert scale**, where 1 is unsafe, and 5 is safe. After a short training course, participants deemed that the AVIP was easy to interpret, and also stated that they felt significantly less safe when they encountered the AV without the interface, compared to the conventional vehicle and the AV with the interface. This suggests that the interface could contribute to a positive experience and improved perceived safety in pedestrian encounters with AVs, which the authors claim might be important for general acceptance of AVs.

Palmeiro, van der Kint, Vissers, Farah, de Winter, and Hagenzieker (2018) investigated the effect of AVs on pedestrians' gap acceptance, stress levels and use of visual cues in a closed-road study. Participants encountered a Wizard-of-Oz AV in which a fake 'driver' sat at the drivers' side while the vehicle was driven by a passenger using a joystick. Participants experienced twenty different scenarios manipulating vehicle conditions (traditional vehicle, 'driver' reading a newspaper, inattentive driver in a vehicle with ''self-driving" sign on the roof, inattentive driver in a vehicle with ''self-driving" signs on the hood and door, attentive driver), vehicle behaviour (stopping vs. not stopping), and approach

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direction (left vs. right). They were asked **to indicate their critical gap acceptance by taking one step to the front in the first moment that they would cross the road**, and one step backward at the last moment they would cross the road. **Questionnaire and interview items measured participants' awareness of AV status** and **interpretation of AV signs**, along with providing a measure of participants' **sensation seeking** and **trust** in automation. Results did not reveal any significant differences in critical gaps between the AV and joystick driven traditional vehicle conditions. Post-interaction interviews showed that most pedestrians reported that speed and distance from the vehicle were the main factors used when making the decision not to cross the road. Questionnaire results indicated that most participants had perceived the self-driving signs and claimed to have been influenced by these when crossing the road. They also reported feeling less safe and more doubtful when interacting with a traditional vehicle in which the driver did not make eye-contact.

2.3.4 Test-Track Studies: Summary and Conclusions

The experiments conducted on test-tracks and closed-up areas have mainly been used to understand pedestrians' crossing behaviours in response to various vehicle behaviours and eHMI signals. These types of studies allow an exploration of participant responses to real-world vehicles, while also providing an environment that can be controlled. Decisions about whether or not to cross, decision times, crossing times, time to collision, and safety margin were all commonly used measures of pedestrian behaviours. These methods were often supplemented with questionnaire and interview items, which assessed participant awareness of AV status, interpretation of eHMI signals, trust, and perceived safety. The use of wizard-of-oz / ghost-study techniques provide a promising method of simulating automated vehicle effects in a controlled environment, when safety regulations or lack of technology prevent real AVs from being used.

2.4 Real-World studies

All of the studies mentioned thus far have been conducted in controlled environments, where experimenters could carefully regulate the environment and the visual and acoustic information available to participants. These types of studies can provide valuable insights into the effects of specific stimuli on participant reactions. However, they can lack realism, and for that reason it is important to also collect more ecologically valid data about road user interaction patterns (see Deliverable 2.1, Dietrich et al., 2018). Real-world studies enable a broader understanding of the multitude of factors, which have the potential to impact AV's interactions. The following sections (2.4.1 to 2.4.3) provide a synopsis of the most relevant real-world studies for the interACT project, outlining the methodologies and measures used to understand road users' experiences. In Sections 2.4.1 and 2.4.2, a series of studies investigating interactions between current, manually driven,

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vehicles and other road users are reported. By gaining an understanding of how road users currently interact, we can draw conclusions about the typical situations AVs will be required to deal with, thus ensuring that we incorporate appropriate interaction capability into their design. Section 2.4.3 provides an overview of the limited number of recent studies which have evaluated AV interactions in real-world settings.

2.4.1 Understanding current vehicle-pedestrian interactions

Studies of current road user interactions have generally focused on the factors influencing pedestrian crossing decisions in current traffic situations; including measurements of driver behaviours and gaze patterns (Schneemann & Gohl, 2016; Guéguen, Meineri, and Eyssartier, 2015); qualitative categorisation of pedestrian and driver behaviours (Brosseau et al., 2013; Rasouli, Kotseruba and Tsotsos, 2017; Risto et al., 2017), and quantification of vehicle and pedestrian movement patterns (Donmeyer, Dinparastdjadid, Lee, Douglas, Alsaid, and Price, 2019)

Schneemann & Gohl (2016) conducted a driving study in open traffic to understand current vehicle-pedestrian interaction and its impact on traffic safety. The route used for this study included five crosswalks in Ingolstadt (Germany). Pedestrians were positioned at two of the five crosswalks, chosen because of their low traffic volume to ensure an uncluttered view of the crosswalk area. Each driver experienced three interaction scenarios at the two test crosswalks: baseline (no pedestrian present), the pedestrian either crossing the crosswalk, or the waiving the right of way (not using explicit gestures, e.g. hand waving). The test drivers were split into two groups, based on the pedestrians' approaching times to the crosswalk (at two different times to collision, TTC). TTC was 3 seconds for the first and 4 seconds for the second group. Interactions were analysed from both the pedestrian's and the driver's perspective. The vehicle's CAN bus provided the driving behaviour data, combined with a GPS unit and a video camera, mounted behind the windshield. **Analysis of driving parameters and video data** revealed **typical driving patterns** of drivers approaching a crosswalk as well **as typical crossing behaviours of pedestrians**. They found that drivers tend to use more anticipatory driving behaviour with increasing initial speed by braking significantly earlier and that **pedestrians' decision time** is shortened by lower approaching speed and early braking. Furthermore, in higher initial speed condition (50 km/h) most pedestrians stated that they fixed their gaze on the approaching vehicle to make their crossing decision. In contrast, in the lower speed condition (30 km/h) substantially more pedestrians stated that they rather sought the eyes of the driver than fixating the vehicle itself. The authors conclude that proper and anticipatory approach behaviours can help resolve interactions at crosswalks efficiently (minimal time loss) and that this should be used to inform autonomous vehicles' driving strategies. They furthermore suggest that autonomous vehicles should employ an alternative communication technique that can substitute for the drivers' gaze direction during interactions.

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Guéguen et al. (2015) conducted a **field study examining the impact of pedestrian eye contact on the likelihood of drivers stopping** at a zebra crossing. Experimenters stood at one of four pedestrian crossings and attempted to stare at the approaching driver's face until the driver either stopped or continued past. This was compared to a condition where they looked in the general direction of the car without making eye contact. Results indicated that significantly more drivers stopped to permit to a pedestrian to cross the street when he or she looks the driver in the eye a few seconds before as opposed to looking above the driver's head. Drivers stopped more often for female experimenters than male experimenters, and results showed that male drivers were more likely to be influenced by the experimenter's gender than female drivers.

Rasouli, Kotseruba and Tsotsos (2017) compiled a novel dataset containing **behavioural data of pedestrians** in the context of street crossings. The dataset was extracted from **video material** of 240 hrs driving in urban and suburban areas. Analysis of this dataset revealed that over 90% of pedestrians allocate their gaze to the approaching car to convey their crossing intention in an unmarked crossing. **Explicit communication** such as nodding or hand gestures were found to be generally rare and usually used in response to an action by the driver. Pedestrians were more likely to use **implicit communication**, e.g. by slowing down or stopping when realizing that the approaching car would not yield. The crossing itself is influenced by additional factors such as **TTC**, explicit driver reaction and **structure of the crosswalk**. Pedestrians crossed more often without paying much **visual attention** to the approaching traffic when TTC was high (10 seconds and more), while visual attention was always present for crossing with TTC less than 2 seconds. Furthermore, the looking duration towards the oncoming traffic depends on TTC: The further away the approaching vehicle is, the longer pedestrians tend to look at it, possibly taking more time evaluating the driver's intention. **Looking time** was found to increase up to TTC of 7 seconds (adults) and decline drastically for higher TTC. The structure of the crosswalk was found to influence the probability that pedestrians actually cross the street after indicating their crossing intention (e.g. by head orientation and gaze direction). The **driver's reaction** to the crossing intention strongly influences **crossing decisions**, especially in unmarked crossways. Crossings were less likely in unmarked crossings when the driver sped up while being more likely if the driver slowed down or stopped. If pedestrians decide not to cross in an unmarked crossway although the driver yields by slowing down or stopping, pedestrians often used hand gestures to communicate that they would wait for the car to pass.

Risto et al. (2017) conducted a similar study using **qualitative video analysis** to **investigate road user interactions with vehicles**. They highlight, that interactions and communications gain meaning when evaluated taking **road geometry**, **road activity** and **culture** into account. They suggest the use of movement cues (as gestures) to inform pedestrians about driver intentions, along with inherent vehicle movements. For the purpose of this study, multiple intersections were **video recorded** from

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stationary locations adjacent to the intersection as well as first-person recordings using dashboard mounted cameras. Additionally, **semi-structured interviews** were used in a participant study. Twenty participants viewed eleven video scenes selected from the previously recorded material in order to gain insight on **the perception and understanding of the shown road user activities**. Road users' behavioural patterns were extracted from the data, showing how drivers communicate their intentions through movement gestures. **Behavioural patterns** in interaction scenarios included advancing slowly, slowing down early and maintaining the low speed to allow pedestrians to pass, stopping short of the location required by law (e.g. at stop lines or crosswalks) was more likely when pedestrians were on or near the intersection compared to no pedestrians being close. If drivers did not stop short of a crosswalk pedestrians often showed discomfort (changing the walk path, staring at the vehicle/driver).

Domeyer et al. (2019) conducted video observations to examine the timing of existing vehicle–pedestrian interactions in order to make conclusions about how time and space can be used as a communication tool. **Videos were coded** to describe the interactions between vehicles and pedestrians, with a main focus on the short stop time. The **short-stop time** was measured as the time between the vehicle beginning to accelerate, after reaching a minimum speed or full stop, to when the vehicle entered the intersection crosswalk. The **pedestrian-start time** was incorporated into this measure to include times when the pedestrian entered the crosswalk before the vehicle reached its minimum speed or full stop, and times when the pedestrian waited for the vehicle to reach its minimum speed or full top. Video annotation was completed using a tool called ANVIL which allows a researcher to place **timestamps** at points of interest in the video. **Safety margin** was measured as the gap between when a pedestrian was in the crosswalk and when the vehicle entered it. **Inefficiency** was measured as the total time for the pedestrian and vehicle to clear the intersection, and values of **fairness** referred to the delay that the vehicle experienced relative to that of the pedestrian. Results indicated that kinematic cues such as short-stop times were used to convey drivers' intent to other road users.

Brosseau et al. (2013) investigated underlying factors of pedestrian violations of traffic signals and dangerous crossings at intersections. Thirteen intersections in Montreal, Canada were **observed manually** over at least 2 hours. Additionally, **video recordings** were used for validation. All counts were performed by two people, one counting pedestrians and the other one counting violations and dangerous crossings. Violations were defined according to the Quebec Highway Safety Code and crossing behaviours were classified into categories. **Mean waiting time** (depending on phasing length of traffic signal and arrival time), **number of pedestrians**, **number of dangerous legal crossings** (starting to cross at green light but finishing during red phase), **number of violations**, and **clearing time** (the time needed to cross the intersection) were assessed for the intersections. They found

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several factors that influence the proportion of pedestrian violations. Younger age, male sex and intersection mean waiting time increased violations, while bigger a group size and the presence of pedestrian signals decreased violations. Furthermore, higher intersection clearing time, especially with the green phase being too short to finish crossing within the phase impacted the number of committed dangerous crossings as pedestrians finish their crossing during red phase. The authors suggest that pedestrian be provided with signals with countdown displays as these reduce the number of violations.

2.4.2 Understanding current driver-driver interactions

Portouli et al. (2014) collected **video recordings** of the traffic scene in front and to the rear of a vehicle, along with **participants' running commentary while driving**. 22 experienced drivers drove their own vehicle along a 15 km route on an urban ring-road with right-hand traffic, at least two lanes per direction, and a central barrier. Analysis was conducted while watching the video recordings in parallel to the transcribed commentaries. The aim was to annotate **verbalisations of intent anticipation and communication in relation to lane changes**. Results show that in 43 out of 67 such verbalisations, drivers referred to implicit cues. Such cues included any disturbance of the expected smooth motion of the other vehicles that could not be attributed to road geometry or obstacles on the road, i.e. driving at speed different than that of the traffic flow, unjustified speed changes, close following of lead vehicle, driving on the lane marking, observed variation in lateral position and steering angle of other vehicles, and any unusual manoeuvring. Any such disturbance was interpreted as an effect of an intentional action and was used to anticipate intent. 13 verbalisations referred to explicit communicative acts by other drivers (i.e. flashing of headlights, use of direction lights, hand signals and head movements). Six (6) verbalisations referred to cues from the environment related to the road geometry and to physical obstacles, such as the presence of a slower truck in front. Finally, five (5) references to cultural stereotypes were identified.

2.4.3 Understanding AV-pedestrian interaction

The following studies investigated the interaction between AVs and pedestrians during real-world demonstrations and experiments. Different approaches were used such as questionnaires (Merat Louw, Madigan, Wilbrink, & Schieben, 2018), coding of video observations (Madigan et al., under review), interviews (Hensch et al., 2019) as well as 'ghost studies' (Fuest et al., 2018a; Rothenbücher et al., 2016).

Merat, Louw, Madigan, Wilbrink, & Schieben (2018) administered a **questionnaire** to participants interacting with live demonstrations of an Automated Road Transport Systems (ARTS; SAE Level 4), as part of the CityMobil2 project in three European cities (see www.citymobil2.eu). The ARTS consisted

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of slow-moving driverless buses, designed to provide an alternative public transport solution. The questionnaire **sought the views of pedestrians and cyclists on whether they felt safe interacting with ARTS in shared space**, **who they believed had priority** in that space, and **what externally presented information** from the ARTS was important to them. Results showed that most pedestrians felt safer when the ARTS were travelling in designated lanes, rather than in shared space, and the majority believed they had priority over the ARTS, in the absence of such infrastructure. Regardless of lane demarcations, all respondents highlighted the importance of receiving some communication information about the behaviour of the ARTS, with information on whether they had been detected by the vehicle being the most important message. There were no clear patterns across the respondents regarding modality preferences for these external messages, but conventional signals (lights and beeps) were preferred to text-based messages and spoken words.

A study by Madigan et al. (under review) investigated the interaction requirements of pedestrians, cyclists, and drivers through an analysis of video footage of the CityMobil2 AV demonstrations in La Rochelle (France) and Trikala (Greece). **Manual and automated video-analysis techniques** were used **to identify typical interactions patterns between AVs and other road users**. Video data was obtained from the sides and front of the AV. Trained coders **categorised road user behaviours around the AV** into categories of crossing in front of the AV, changing trajectory around the AV, stopping to let the AV pass, passing alongside the AV, and testing the AV. The relationship between these behaviours and **road infrastructure features** such as road width, crossing infrastructure, and **road user characteristics** including type of road user, and demographic information were examined. Results indicate that road infrastructure and road user factors had a major impact on the type of interactions that arose between AVs and other road users. Automated video analysis of interactions coded as **critical situations** showed that any road user passing up to 3.25 m ahead of an AV travelling at an average speed of 3.10 m/s is likely to be of high risk.

Rothenbücher et al. (2016) used a **ghost-driver methodology** to study pedestrian and cyclist interactions with AVs. The “ghost-driver” was a human driver concealed in a car seat costume to create the appearance of a “driverless” vehicle. Data included **video recordings** collected at a parking lot and a pedestrian crossing, and participant responses to post-interaction questionnaires. The driving style was varied across the two days of data collection, with the driver adopting a conservative approach on the first day and a more aggressive and ambiguous approach on the second day, by travelling at a higher speed and stopping later. The car also briefly started after it came to a full stop as the pedestrian was about to cross. **Video analysis** was used to identify **behavioural patterns in response to the car**. Open-ended **questionnaire items** measured whether people **believed** the car was driving autonomously, and their **impressions** of the car, along with measuring their belief about their **behaviours** and their **expectations** of the car. Pedestrians who encountered the car reported

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that they saw no driver, but were still able to manage interactions smoothly in most cases, provided the vehicle behaved predictably. Measures of **initial observation of the car** were based on whether people noticed the car through peripheral vision or turned their head. **Participant crossing behaviour** was evaluated by judging the paths participants walked around the car. Measures of **uncertainty**, **response to aggressive behaviour**, **expectations of the car**, and **positive responses to breaching** (i.e. the different behaviour of the AV) were all elicited through the post-interaction survey. Results indicated that people generally adhered to existing interaction patterns with cars, unless the AV behaved in an erratic manner.

Fuest et al. (2018a) investigated **the use of different vehicle trajectories in communicating an automated vehicle's (AV's) and traditional vehicle's intention** when approaching pedestrians in shared space. The effects of the visual presence of the driver, and the vehicles' driving behaviour during approach, on **pedestrians' intention recognition time** (whether the vehicle would yield or not) were assessed. The study encompasses two parts, first, **the extraction of meaningful driving profiles** and second, **the evaluation of these by pedestrians** measuring their intention recognition time. A parking lot in Munich (Germany) was used as the study location. Participants were told that the parking lot was being used as a shared space with undefined right of way, thereby requiring AV-pedestrian communication to ensure safe interaction. In the first study, participants drove a vehicle along the parking lot. They encountered an informed pedestrian and were instructed to drive in a manner that would, in their opinion, clearly convey one of two vehicle/driver intentions: Firstly, indicate that the pedestrian should stop and let the vehicle pass, or secondly, that the vehicle would stop and let the pedestrian cross. Two driving patterns were extracted to convey that the pedestrian should go first: Braking constantly, and braking harder earlier and then slowly accelerating when the pedestrian started to cross. Furthermore, three driving patterns were identified to convey that the AV will go first (preparing to brake and thereby slowly losing speed, driving at constant speed and accelerating slightly). These patterns were evaluated in the second study, where an AV (with **a ghost driver** hidden under a seat cover) approached a pedestrian driving according to the extracted patterns. Participants were asked indicate when they think they understood the vehicle's intention by raising their hand (**intention recognition time**). The accuracy of their assumption was assessed using a short **questionnaire** including a **rating of perceived situation criticality**. Clearly perceivable, early braking was the preferred driving behaviour to convey that the AV would yield, while driving at constant speed was the preferred behaviour to show that the AV would not yield for the pedestrian. No differences in criticality ratings or intention recognition time were found due to visual presence or occlusion of the driver.

Hensch et al. (2019) conducted another ghost study to investigate **the effects of eHMIs and vehicle type** (appearing to be a driverless AV in contrast to visible driver). A seat cover was used to conceal

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the driver of an approaching vehicle from pedestrian's view. eHMI consisting of different light signals were presented as a light bar on the vehicle's roof, with a steady light used to convey that the vehicle was operating in automated mode, flashing lights as a starting signal (approaching car), and sweeping lights to indicate that the pedestrian may cross in front of the vehicle. The study was conducted in a parking are on University of Chemnitz' Campus. In total, 173 pedestrians randomly passing by the vehicle were **interviewed**. Interview quotes were **clustered into categories for evaluation**. The results show that pedestrians felt **subjectively safer** when they could see a driver in the vehicle. The used light signals were rated as partially **trustworthy** and rather **unintuitive** to understand, while the general application of light signals was perceived generally **useful** in the context of automated driving.

2.4.4 Real-World Studies: Summary and Conclusions

Real-world studies enable an analysis of road user interactions in a naturalistic setting. A wide variety of data collection tools and measurement techniques have been developed to study these interactions. Video-based analyses facilitate the categorisation of pedestrian and driver behaviours, road and environmental features, and demographic information. Measures of pedestrian behaviours in this context include decision time before road crossings, crossing start times, safety margins, inefficiency, and use of explicit communication gestures and implicit communication. Measures of driver behaviour included speed on approach to an intersection / crosswalk, short-stop times, deceleration rates, and use of explicit gestures or eye contact patterns. Experimental manipulations in real world settings include investigations of the effects of pedestrian and or driver eye-contact or gaze patterns on other road users' behaviours. Questionnaire and interview studies of road users who had interacted with AVs provide insights into the factors affecting feelings of safety, priority, impressions, expectations, and trust. As with the test-track studies, the wizard-of-oz approach proved a suitable mechanism for simulating an AV in situations where it is not yet feasible to use a real AV. Finally, the use of commentary driving provided a useful methodology for understanding how drivers anticipate the actions of other vehicles and pedestrians while driving.

2.5 Questionnaire and Interview Studies

A number of questionnaire studies have evaluated participants' perceptions of and attitudes towards AVs, without participants necessarily having knowledge of, or interaction experience with AVs. In this section, the results of four large-scale questionnaire studies investigating general attitudes towards AVs (Bikeleague, 2014; Hulse et al., 2018; Deb et al., 2017a, 2017b; Penmetsa et al., 2017) will be presented, along with a questionnaire study examining participant reactions to different types of HMI (Bazilinskyy et al., under review).

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Bikeleague (2014) provide the results of a **three-question survey** asking cyclists to evaluate whether they think **AVs will increase or decrease safety,** what **concerns they have about sharing the road with AVs**, and **whether or not they would use smart technology (e.g. a radio beacon or smartphone app) to communicate with AVs**. Results indicated that the majority of participants felt that they did not have enough information to judge the safety implications of AVs, although over 40% believed that AVs would increase safety. Over 60% participants would be willing to use smart technology if it would improve their safety. Participants' biggest concern was whether AVs would distract from efforts to promote biking and walking.

Hulse, Xie, and Galea (2018) **surveyed almost 1000 participants** on their perceptions with regards to **safety and acceptance of AVs**. Participants were asked to **rate the level of risk** they associated with various modes of transport from the point of view of different populations, namely the driver/rider of a car, motorcycle and bicycle; the passenger of a train and car, both human-operated and autonomous; and a pedestrian in an area with cars, both human-operated and autonomous. Perceived risk was defined as "the potential for an accident to occur, resulting in unwanted negative consequences to one's own life or health". AVs were not rated as particularly risky compared to motorcyclists and bicycles. When responding as a pedestrian, autonomous cars were perceived to be significantly less risky than their human-operated counterparts.

Deb at al. (2017b) developed and validated a **self-reporting Pedestrian Behavior Questionnaire (PBQ)** for the U.S. population to measure the frequency of **risky behaviours** among pedestrians. In this questionnaire behaviours are divided into five categories: **violations**, **errors**, **lapses**, **aggressive behaviours**, and **positive behaviours**. A short version of the PBQ with 20 items was also created by selecting four items with high factor loadings from each of the five factor categories. Regression analyses investigated associations with scenario-based survey behavioral responses to validate the five-factor PBQ subscale scores and composite score. For both long and short versions, each of these five individual factor scales were found to be reliable and valid, except in the case of positive behaviours which requires further expansion.

In a second paper, Deb, Strawderman, Carruth, DuBien, Smith, and Garrison (2017a) developed **a sixteen item questionnaire study**, measuring pedestrians' **receptivity** towards fully autonomous vehicles (FAVs). Receptivity here is defined as "the willingness to accept a new idea that may be uncertain, unfamiliar, or paradoxical" (p. 180). The questionnaire **measured participants' attitude, social norms, trust, compatibility, and system effectiveness**. Three subscales described pedestrians' receptivity toward FAVs in terms of perceived safety, vehicle-pedestrian interaction, and compatibility with existing infrastructure. Participants also provided responses to the Pedestrian Behaviour Questionnaire (Deb et al., 2017). Pedestrians' **intention to cross the road in front of FAVs** was significantly predicted by both safety and interaction scores, but not by the compatibility score.

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Accepting FAVs in the existing traffic system was predicted by all three subscale scores. Finally, results showed that people who show positive pedestrian behaviour (as measured by the **pedestrian behaviour questionnaire**) believed that the addition of FAVs would improve overall traffic safety. Those who show higher violation, lapse and aggression scores, were found to feel more confident about crossing the road in front of a FAV.

Penmetsa, Adanu, Wood, Wang, and Jones (2019) explored the **opinions of pedestrians and cyclists regarding the perceived benefits and challenges of AVs**, along with investigating **whether interaction experiences with AVs influence perceptions** among vulnerable road users. Using an **eight-item questionnaire**, the opinions of cyclists and pedestrians towards AVs were sought. Items included measures of the potential of AVs to reduce fatalities and injuries, beliefs about the safety of sharing roads with human drivers and AVs, the necessity for regulations for testing AVs, and their interactive experience with AVs on the road in Pittsburgh. Results showed that respondents with direct experience interacting with AVs reported significantly higher expectations of the safety benefits of the transition to AVs than respondents with no AV interaction experience. This finding did not differ across pedestrian and cyclists.

Bazilinskyy, Dodou, and de Winter (under review) conducted two large **survey studies** to examine **how clear and interpretable different eHMI concepts were**. In the first survey participants **rated the clarity** of 28 images, videos, and patent drawings of eHMI concepts presented by the automotive industry. Results showed that text-based eHMIs were generally regarded as the clearest. Among the non-textual eHMIs, a projected zebra crossing was regarded as clear, whereas light-based eHMIs were seen as relatively unclear. A considerable proportion of the respondents mistook non-text-based eHMIs for a sensor. In the second survey they examined **the effects of eHMI colour and perspective of the message** i.e. egocentric 'Walk'/'Don't Walk' vs. allocentric: 'Will stop'/'Won't stop', **on whether participants felt safe to cross** in front of the AV. Results showed that text-based messages were most popular, and that the eHMI that received the highest percentage of 'Yes' responses was the message 'Walk' in green font, which the authors interpret as showing an egocentric perspective of the pedestrian.

2.5.1 Questionnaires: Summary and Conclusions

The questionnaire studies outlined in this section were all conducted in isolation, and did not relate to particular experiences participants might have had with an AV or automated system. However, they provide some useful insights into how initial ideas for HMI could be evaluated through measurements of clarity, perceived safety, receptivity, and acceptance. In addition, measurements such as the Pedestrian Behaviour Questionnaire, and Receptivity Questionnaire provide insights as to how individual difference variables might impact on people's interactions with, and interpretations of, AVs.

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These types of measures may be useful for capturing individual difference variables which might impact how participants behave around AVs within the WP6 evaluation studies.

2.6 Simulation/Modelling Studies

With regards to **mathematical modelling** and **computer simulation**, there has not been much prior work using such methods to study or evaluate human-AV interactions at the level of granularity that is needed for the interACT project. There is a considerable literature on the topic of how vehicle automation might influence traffic on the more **global level of traffic flow**, quantified in terms of metrics such as average vehicle speed, vehicle throughput, frequency of "shockwaves" in car-following, and critical vehicle speed above which the simulated traffic becomes unstable (e.g., van Arem et al., 2006; Talebpour and Mahmassani, 2016). This modelling research has suggested that traffic flow can be improved by the presence of automated vehicles, even at limited penetration rates, not least thanks to the stable speed control of AVs. These model predictions have also seen preliminary confirmation in a real-life experiment (Stern et al., 2018). However, the types of scenarios addressed in interACT have a different focus, emphasising the details of **individual interactions at a local level**, rather than the infrastructure-level behaviour of a large number of interacting road users. In recent years, some simulation models emphasising interaction at the local level have begun emerging (Rudloff et al., 2013; Anvari et al., 2015; Rinke et al., 2017), but as far as we are aware, these models have so far only been applied to human-human interactions, not as a tool for evaluating interactions with AVs.

2.7 Conclusions drawn from Literature Review

As this literature review shows, the state of the art around the implementation of interactive AVs is evolving at a rapid rate, and research is beginning to address some of the issues around how these systems might work. However, there are still a number of outstanding issues, which need to be addressed, and there is little consistent use of specific measurement tools and techniques across the field. Annex 1 provides a starting point for bringing together all of the different measurement tools into a detailed evaluation criteria catalogue. This catalogue helps to identify the different ways in which evaluation criteria such as safety, perceived safety, user experiences, road user comprehension, traffic efficiency etc. have been measured, providing a reference point for the selection of appropriate criteria for the interACT evaluation studies. A number of promising research approaches have emerged from the literature, including the use of pedestrian simulators, head-mounted displays, test-track studies, and wizard-of-oz type studies. These research environments have all been shown to have strengths and weaknesses in terms of capturing information about road users' interaction

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patterns, and thus the use of a combination of these tools should allow a comprehensive understanding of the numerous factors impacting road users' interactions with AVs.

A number of clear research themes and common evaluation concepts have emerged from the literature, although these criteria are often operationalised in different ways. The majority of the evaluation concepts relating to external communication could be described as either 1) measurements of the feelings/affect of other road users about AVs; 2) measurements of road users' comprehension of others' intentions; or 3) measures of road users' behaviours around each other. Thus, the evaluation criteria catalogue in Annex 1 is separated into these three themes.

Measures of affect refer to any measure of a person's feeling about an object, in this case road users' feelings about interactions with other traffic participants, and interactions with AVs. These measures included evaluations of road users' perceived safety and risk around AVs, their trust in AV technology, and their emotions around AVs. Road users' affect was generally measured using questionnaire items assessing reactions to wizard-of-oz vehicles, or pictures or videos of AVs. Of these concepts, the most commonly evaluated was perceived safety, or feelings of safety/risk around AVs, a concept of great importance in understanding pedestrian and VRUs comfort around AVs and acceptance of these vehicles (Fuest et al., 2018b). In general, this concept was measured through questionnaire items, with scales including the Self-Assessment Manikin, simple likert scales, and measures of perceived criticality, risk and stress. More quantitative measures of perceived safety, based on road users behaviours, include using experimental manipulations to understand whether or not pedestrians will cross the road in front of an AV using different explicit and implicit communication techniques. Other important measures of affect, which can be captured using questionnaire items and interviews, include measures of interaction experience such as pedestrian comfort around AVs and their trust of these systems.

In terms of capturing information about road users' comprehension of AV intent, the use of open-ended questions, whereby participants are asked to describe the meaning attached to eHMI signals and implicit vehicle movements provides one promising method of evaluation. Although many questionnaire studies (e.g. Fridman et al., 2017; Ackermann et al., 2019b) have suggested that users have a preference for symbolic or text-based eHMI solutions, the implementation of these types of eHMI in real-world contexts is problematic, with visibility issues arising. Promisingly, a number of studies have shown that light-based solutions can provide a valid alternative, with road users' quickly learning the meaning of these types of signals after a few interactions (see Habibovic et al., 2018; Lagström & Lundgren, 2015). As the selected interACT HMI solutions are all light-based, this finding highlights the importance of addressing the learnability of these solutions within the interACT evaluation studies, a concept that can be measured by testing participants understanding after multiple interactions with an automated system.

Measures of affect and comprehension are important in developing our understanding of road users' attitudes towards AVs. However, of most importance, is how these feelings impact on actual behaviour around the vehicles. The majority of studies, to date, have used pedestrians' crossing behaviour as a measure of how well they comprehend AVs intentions, and the vehicle / driver parameters used to inform this comprehension. Quantitative measures include pedestrian waiting times, the distance between the pedestrian and vehicle during various points of the crossing manoeuvre, the time taken to complete a crossing in different circumstances, and the different crossing decisions made in relation to different eHMI stimuli. Objective measures of safety generally refer to TTC or safety margin at crossing. In terms of measures of the impact of AVs on traffic flow, measures of timings or delays experienced by both pedestrians and vehicles during an encounter can provide some insights into how AV behaviour might impact movement patterns. In addition, measures of vehicle speed and throughput obtained through simulations and test-track experiments have been used to model traffic flow parameters.

Finally, one of the important aspects of the interACT project is to gain an understanding of the three-way interactions between the AV, the user on-board, and other TPs. There has been a limited amount of research into the impact of iHMI on the on-board users' experience. In these situations, subjective ratings, interview responses, and think-aloud protocols have been used to understand user acceptance, ratings of usefulness, and comprehension of iHMI, along with their attitudes towards the cooperative behaviour of an AV. These types of measures can also be used for the evaluation of iHMI within interACT.

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3. Input from Workshops Attended

3.1 Road Simulation Conference, The Hague, October 2017

To align the interACT research questions, compare methodologies and exchange concepts with other researchers in the field, a workshop was conducted at the Road Safety and Simulation conference 2017 in The Hague (Figure 3). The workshop was attended by VW, TNO, TU Delft as well as TUM, ITS Leeds and DLR, and focused on a discussion of human factors requirements of automated vehicles in urban traffic.

The workshop commenced with elevator pitch-like presentations of attendees, where a specific research item was presented focusing on the utilized methodology within three minutes. Afterwards, the interACT use cases from WP1 were presented. Participants received handouts consisting of applicable literature (Fuest et al. 2018b & Schieben et al. 2018) and pictures of real world locations representing the WP1 use cases. The overall goal of the workshop was to identify human factor challenges of automated vehicle interaction with other road users in urban scenarios and identify approaches to solve these challenges, with an emphasis on methodologies. Therefore, the aim was to generate questions rather than find answers.

Attendees were divided into four groups each of which had to address one of the four use cases. In 40 minutes, each group had to come up with answers to the following questions:

a) What information would the AV need from the other road user?
b) What information would the other road user require from the AV?
c) What metrics or methods would you use to study the above?
d) What might be the limitations of this method?
e) What are the technological advances that would help?

The groups developed different emphases on the various questions, with some groups focusing more on the methodology and others on actual concepts to tackle the identified challenges. However, most findings overlap between groups:

a) Pedestrians (or other road users) will require some sort of explicit communication, if the driver is not available. However, this communication is highly dependent on the situation. For example, an AV getting out of a parking lot might need different ways to communicate its intention or next manoeuvres than an AV yielding to a pedestrian at a crosswalk. Overall honking or auditory messages were not regarded as a good way to communicate.
b) Proposed methodologies to identify road user needs and study the effect of automated vehicles ranged from **traffic observations** creating an understanding of current road user

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behaviour, to **controlled experiments** analysing the effects of communication strategies on other traffic participants, to **mathematical models** identifying optimal interaction strategies.

c) Due to the limited amount of time, limitations of proposed methodologies were not identified. However, it was discussed that the introduction of automated driving onto urban roads could be enabled by modifying the infrastructure or traffic regulations so that AVs are treated differently than humanly road users.

Figure 3: Presenters at the RSS2017 in The Hague

3.2 interACT workshop, Vienna, April 2018

A Workshop was organized and conducted by the InterACT Project on April 19th 2018. The half-day workshop took place as an ancillary meet-up next to TRA2018. 20 leading international researchers in the field of eHMI were present, representing industry and academia such as from Nissan Research Center Silicon Valley, Toyota Research Institute, Massachusetts Institute of Technology, Delft University of Technology University of California San Diego etc. interACT partners were represented by BMW, University of Leeds, DLR and TUM (see https://www.interact-roadautomation.eu/e-hmi-workshop-tra-conference-2018/).

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The goal of the workshop was to foster cross-continental knowledge exchange (Europe, USA, Japan), with a special focus on exchanging knowledge **to identify the most important, urgent, and difficult issues in regards to building sustainable e-HMI solutions for automated vehicles**. Major challenges regarding **methodologies, design/ technology**, as well as important areas that require further research were discussed.

The participants were split up into three groups, each of which discussed research topics which had been identified by each individual expert in a first part of the workshop. In the second part, participants had to come up with their own 'Board of importance' to cluster and rate the relevance of a challenge or research need. Several overlapping topic clusters between the three groups could be identified and were further discussed by all participants of the workshop (see Figure 4). Three overall topic clusters were identified: **Designing eHMI solutions; Developing appropriate methodologies and metrics for evaluation; Future effects of eHMI.**

For Deliverable 6.1, evaluation methodologies and metrics for evaluation are the most important topic cluster. As the design space is quite complex the question arose as to how the complexity of different interaction scenarios, cultural and contextual differences, as well as design for different vehicle types, can be tackled using the methodologies we currently have.

Questions were raised about **which constructs and metrics are relevant** for measuring and deriving the impact of specific eHMI designs. At which stage in development should each method be used to ensure efficient and valid research? The **ecological validity** of controlled experiments was discussed, along with whether the results are scalable and generalizable to naturalistic settings. The question was also raised as to whether **longitudinal studies** are necessary to assess the long term impact and changes in perception and behavior of traffic participants, once AVs are introduced into traffic.

A further point raised was the **target criteria** for assessing the impact of eHMI. Should the goal be manually driven traffic today? Or should the target be a different one? One of the most important questions identified in the rating process of the workshop, was the potential **negative effects of eHMI**, specifically considering if other traffic participants check for other traffic when interacting with an AV equipped with eHMI (see https://www.interact-roadautomation.eu/interact-tra-2018-conference/).

Even though multiple disciplines were represented at the workshop (predominantly human factor researchers, but also mechanical-, or ergonomic engineers, and techno-anthropologists), all three groups agreed that the research community has to conduct more studies and further international knowledge exchange to identify: **when, where and for what exactly e-HMI will actually be needed** in the future.

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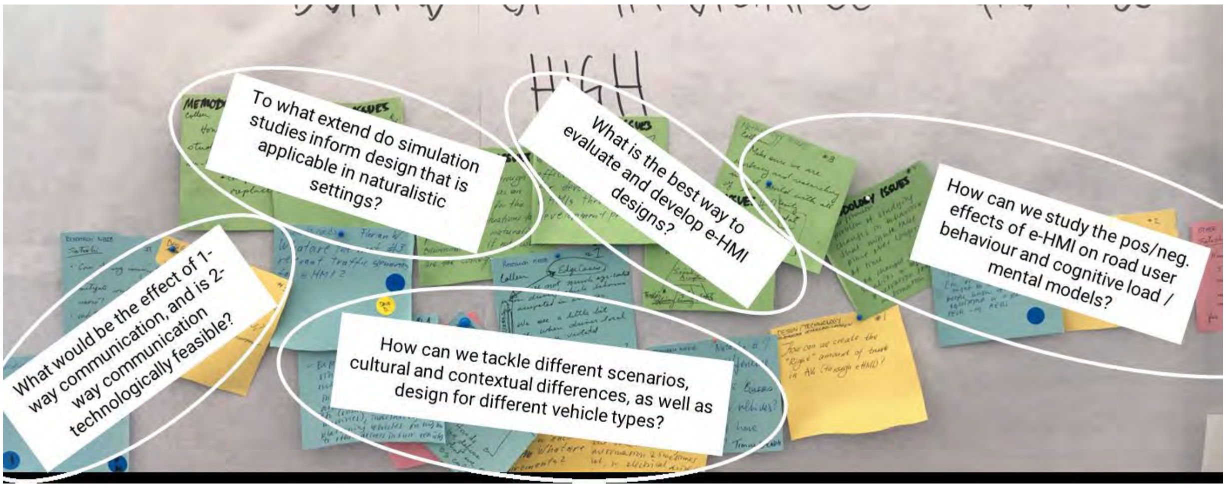

Figure 4: Example of board of importance from eHMI workshop in Vienna

3.3 eHMI Harmonisation Workshop, San Francisco, July 2018

An external HMI Harmonisation Workshop was conducted on the 9th of July 2018 in San Francisco, California, USA (Figure 5). This workshop was attended by approximately 25 multi-disciplinary experts from around the world, such as Andy Schaudt from Virginia Polytechnic Institute and State University, Dr. Rainer Neumann from University of Hamburg, Dr. James Jenness from Westat, Dr. Deborah Forster from UCSD, Professor John Lee from The University of Iowa, Rebecca Currano & David Sirkin from Stanford University, Stefanie Faas & Benno Loffler from Daimler and more. Professor Natasha Merat represented interACT and University of Leeds attended the workshop as one of the discussants. This workshop focused on a few important topics such as eHMI and AV identification, cross-cultural implications, and solution testing.

The most relevant topics to Task 6.1 that were discussed and presented were the selection of important research questions, along with the methodologies used and evaluation criteria to study various topics, which concern **eHMI designs and interaction of eHMI and AVs with other road users**. Daimler presented a study using **expert evaluation** as the methodology to **investigate the most suitable chromatic range for an eHMI** to be used in AVs. This study takes into account expertise on **colour and visual perception** and the colours that were considered were turquoise, yellow, green and violet. The evaluation criteria that were taken into account include **visibility, saliency, discriminability, uniqueness and emotional acceptance (Werner, 2018).** The findings show that turquoise was deemed the best colour to be used, with 92% of pedestrians preferring turquoise over yellow, and the colour was associated to innovation and calming. Turquoise colour preference was also in line with another presentation during the workshop by Dr. Neumann. Despite ‘colour’ being one of the important topics for discussion, it was also mentioned that the eHMI should still work without being able to discriminate the colour (e.g. colour agnostic).

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One of the studies involved presenting a vehicle with different graphics and symbols as eHMI in a laboratory, and studying **the intuitiveness of symbols** (e.g. first reaction on display), **by asking participants the estimated message and their reaction time**. During the workshop, it was also pointed out that one of the most important factors to consider is educating the public, **focusing on designs which are 'more easy to learn' instead of intuitive,** and being cautious about symbols and icons which could lead to misinterpretation.

Some other topics regarding to eHMI include, **whether a signal is needed**. If yes, **how should it look**, and **where should it be positioned** (e.g. 360 degree, single lamps)? A study presented by Daimler using **Wizard-of-Oz Field** study which consists of 65 participants demonstrated that **81% of pedestrians would like to see an indication that the Automated Mode is activated** and **79% of pedestrian preferred a 360° view eHMI**. Similar findings were also shown in a **focus group study.**

Finally, the workshop also mentioned the **importance of quantitative measures**. It is also important to **move beyond safety as evaluation criteria**, considering measures such as **efficiency in traffic flow, acceptance, trust and confidence** etc. It was also noted that it is important to create harmonised signal demands globally, **taking cross-cultural aspect into account**, as well as **different user group such as older age, and children**.

Figure 5: eHMI Harmonisation Workshop in San Francisco

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3.4 AutomotiveUI, Toronto, September 2018

Within the AutoUI 2018 Conference, a workshop was conducted on 23rd September 2018 at the Bahen Centre of the University of Toronto (Figure 6). The workshop was organised by the German Aerospace Center, the Eindhoven University of Technology in Netherlands, the Research Institutes of Sweden (RISE), and the University of Leeds Institute for Transport Studies. The focus was on **identifying the strengths and weaknesses of various methodologies** that could potentially be used to evaluate interactions between automated vehicles and other road users. Based on predefined scenarios the objective was **determining the proper experimental design, sensitivity of metrics for measuring user behavior, ecological validity, generalizability of findings, extraction of insights regarding how findings can be translated into actionable requirements**, and the alternatives to conducting **longitudinal field studies**.

The workshop was introduced with challenges that researchers are facing when evaluating interaction with automated vehicles and other road users. In addition, some of the main themes that were covered during the workshop were: the **ecological validity of (controlled) experiments**, the **effective measurement of behavioural impact**, the question of **which methodology should be used for which type of insight**, and **the efficacy of Wizard of Oz (WOZ)** setups for studying interactions.

Five use cases with and without eHMI were identified. The workshop group split in five subgroups and worked on a use case. Each organization partner acted as a moderator in a group. The groups were asked to design a study to investigate efficient interaction for their particular use case. In addition, groups were requested to create a 90 seconds video of their study design to introduce their solution towards the end of the workshop.

The two use cases which are relevant for the InterACT project are:

1. Automated truck / cyclist – One automated truck (eHMI) is turning right across a cyclist lane/crossing, leading to interactions with cyclists. The system will indicate a new path for the cyclist to follow by using lights to display a new bicycle lane on the road.

A two stage process with workshops and a bicycle simulator is planned. In the workshop the eHMI will be designed. Later, the designs will be tested for **comprehensibility with potential users** to make sure they understand the system.

A simulator study will evaluate the effectiveness of the HMI. In this phase of the design there are no disadvantages in using a **cycling simulator** as long as it can properly capture the dynamic capabilities of the rider and has sufficient resolution to properly display the HMI. The aim is to see whether cyclists take and give way appropriately. This will be done with **eye tracking**. In addition, a **questionnaire** will be used to **assess the trust.**

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2. A garbage collection truck is able to drive in automated mode when in low speeds. To ease interaction with pedestrians in its vicinity, the truck is equipped with an external HMI (eHMI) communicating its intent. The eHMI is visual and audio. There are only a few trucks with this capability in the city.

A **mixed methods approach (quantitative and qualitative methods)** was envisioned. **A VR study** at the beginning is planned to measure **perceived safety and usability**. Within this study the **learning curve** of participants interacting with the automated garbage truck will be measured.

After the simulator study it is envisioned to have a field study **(observation study) repeated over time**. Since, the garbage truck comes to an area every (or two) week, observing an area with cameras would be inefficient. Therefore, it would be more beneficial to use a camera mounted on top of the truck. Over the course of year the **number of pedestrian crossing in front or behind the vehicle** will be recorded and analysed. It is predictable that over the period of time the number of pedestrians crossing in front of the garbage truck will **increase over time** because they will learn how to interact with the truck, and because the trust in this system will build.

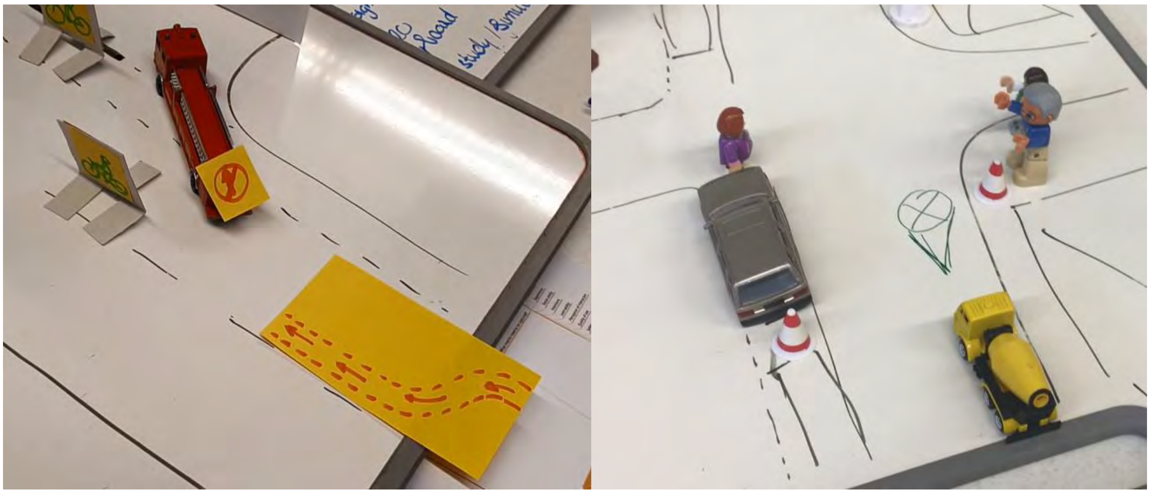

Figure 6: Illustrating the material used to study interaction in the AutoUI Conference, 2018

3.5 25th ITS Congress, Copenhagen, September 2018

The 25th ITS Congress was conducted in Copenhagen from 17-21 September 2018 (Figure 8). A workshop on “User-centric approaches enabling wider acceptance of Automated Vehicles in mixed traffic” was organised specifically relevant to the ‘Topic: 3. Connected, cooperative and automated transport’ under the sub-topic of ‘Understanding HMI, behavioural aspects and social impact’.

In this session, speakers from the EU, USA and Japan examined the **evolution of research and technologies that can help AVs become widely accepted by the general public by increasing their overall safety and integration within mixed traffic environments**. Focus was given to **user-centric**

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approaches to AVs implementation, and to communication issues with other road users. This workshop was organised by Anna Schieben, the team leader of Human-Machine Integration, DLR, Germany, and moderated by Evangelia Portouli who is a senior researcher at ICCS, Greece. There were about 90 attendees during the session.

List of Speakers and the important points, which are relevant to our work includes:

1. Anna Schieben, Team leader Human-Machine Integration, DLR, Germany, "The interACT approach"

2. Daniel Watzenig, Head of Department Electrics/Electronics & Software, Virtual Vehicle Research Center, Austria, "Improved reliability and robustness of conditionally Automated Vehicles in Mixed Traffic Scenarios":

   The methodology behind EU project TrustVehcile ("Improved Trustworthiness and Weather-Independence of Conditionally Automated Vehicles in Mixed Traffic Scenarios", http://www.trustvehicle.eu/) August 2018 field study was presented. It included both real-world tests and simulation and the focus was on the driver behaviour assessment under specific "difficult" scenarios for SAE L3 AD driving. Potentially relevant points to our work:

   - Co-simulation framework (see D3.1): Driver simulator (HiL) + Real Road Tests (ViL**)**

3. Florent Anon, European projects manager, Mov'eo, France, "Innovative Human-Machine Interfaces To Improve Safety and Market Adoption of Automated Vehicles"

   The methodology behind the EU project BraVE ("BRidging gaps for the adoption of Automated VEhicles", http://www.brave-project.eu/) was presented. Potentially relevant points to our work:

   - Virtual reality use-cases: Study of pedestrian trust, acceptance and behavior w.r.t. ADAS systems available on the market

4. Melissa Cefkin, Principle Researcher and Senior Manager, Nissan Research Center-Silicon Valley, United States, "Communications Between AVs and Other Road Users" (Figure 7):
   The results of their research study with regards to (a) Field Testing with a Wizard of Oz Vehicle with Intention Indicator and (b) Simulated Testing of Encountering Multiple AVs with Intention Indicator were presented. Potentially relevant points to our work:
   - Challenges for evaluation:
     - most studies focus on driver, with not so many studies on other traffic participants

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- AVs do not really exist in the world today in a recognizable fashion. People's **encounters will have with a degree of novelty, and no prior experience**. So this raises a question of what the status of user feedback and test results on today's concepts really means.
- What objectives or goals should be pursued? Presumably **safety** is key, but there is also **efficiency** on the road – but how does efficiency look from the standpoint of different people on the road? **Comfort?**

- In terms of **how people feel** about additional signalling for autonomous vehicles to communicate vehicle intent, results were positive, based on **questionnaires**.

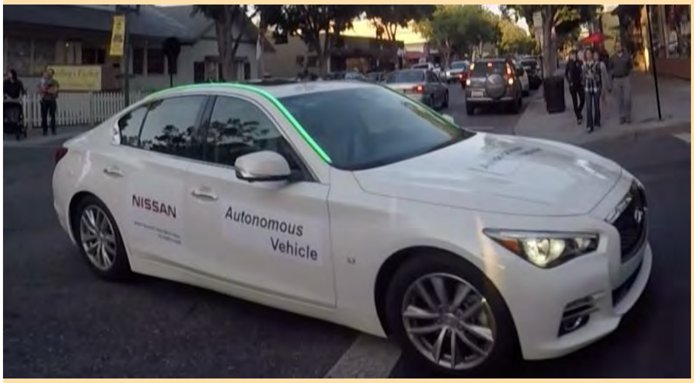	**HMI developed for testing the concept of AV's "intention" indicator. Tests with other road participants showed no cognitive load increase for other road users due to the added "intention" indicator, while also implied shorter crossing times for all participants in complex scenarios.** **Note: "So far ours and others' testing has not confirmed that there is a safety benefit."**

Figure 7: HMI developed for testing the concept of AV's "intention" indicator

5. Satoshi Kitazaki, Director, National Institute of Advanced Industrial Science and Technology (AIST), Automotive Human Factors Research Center, Japan
6. "'To Make Automated Vehicles Communicative and Sociable on Roads"

The results of their closed track research study for evaluating AVs to Drivers and Avs to VRUs interactions was presented. Potentially relevant points to our work:

- Different to interACT, **text messages were used to eliminate ergonomic design factors of e-HMI**.
- Real subjects acting as pedestrian were used, **equipped with a communication "button" that was supposed to be activated when the subject felt AV was yielding for him/her**. **"Simulated" AV was used.**

7. James Jenness, Senior Research Scientist, Center for Transportation, Technology & Safety Research, Westat, U.S.A

"Some Thoughts on Automated Vehicles and Shared Road Users"

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Potentially relevant points to our work:

- Would it be possible for automated vehicles to **rely only on implicit communication without adding any new external signaling systems for shared road users?**

Figure 8: 25th ITS Congress Copenhagen

3.6 AVintent twinning call, June 2019

AVintent is our twinning partner; it is a project funded by NHTSA and conducted by the University of Michigan and Westat. In the most recent twinning call, three studies were conducted. Study 1 investigated experts' (driver training instructors and occupational therapists) **opinions about necessary cues** for drivers to determine the intention of other drivers. In **structured interview**s, experts were asked to rate a series of observable driving behaviours/cues found in the literature review. Study 2 investigated the key information used by cyclists, drivers, and pedestrians **to understand the intention** of nearby vehicles by using **a think-aloud method** while riding/driving/walking in a predetermined routed and also in routes chosen by participants. During the think-aloud process, participants were asked to report any cues from others; conflicts encountered as well as errors made by themselves or others. **Audio and video data** were also collected to observe the participants' viewpoint and the roadway context. Study 3 investigated the **communication intention of different eHMI concepts**. This study used projections, which are approximately life-size to provide proper perspective to present **a series of videos** of an approaching vehicle from a pedestrian's perspective at a crosswalk. Data collected include participants' **confidence ratings** about whether the vehicle was **automated or driven by a person,** whether the vehicle was **going to yield to them,** and whether the vehicle (or driver) **detected** them.

3.7 Conclusions drawn from Expert Workshops

The content of the expert workshops attended by the interACT partners provide an overview of the current concerns within the field. Some of the themes which have emerged from this include:

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- Understanding where in the research cycle particular constructs and metrics are most relevant
- The generalisability and ecological validity of experimental research approaches
- The target criteria for assessing the impact of eHMI
    - Comparison with current interactions or something else?
- Whether, and when, explicit eHMI signals are required
- The potential negative effects of eHMI e.g. distraction
- The colour and positioning of eHMI
- The importance of developing quantitative measures for evaluating AV interactions
    - Moving beyond safety to concepts such as efficiency, acceptance, trust, confidence, comfort
- How to translate research findings into actionable requirements?
- The impact of the current novelty of AV-interactions – how can we draw conclusions about long term effects?
- The importance of considering the complexity of interaction scenarios
- Cultural, contextual, and demographic differences in interaction patterns

These questions provide a starting point in the selection of appropriate evaluation criteria for the appraisal of AV interactions with other road users, and should be taken into account in any decisions about how to understand the success of the interACT solutions. The methods outlined in Chapter 5 aim to address many of these issues through experimental and real-world studies, and subjective analyses of road users' experiences while interacting with AVs. The collection of tightly controlled and replicable data at this early stage of AV implementation will provide the basis for future projects to investigate the longer-term impacts of AVs.

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4. Input from Work Package 2 of interACT

This section provides input from WP2, which aimed to develop psychological models on human interaction; including a summary of the methodologies, measures and testing environments used in WP studies, and what we have learned from them. These methods were used to provide insights into current road interactions, but the methods used also have the potential to provide insights into AV interactions with other road users.

4.1 Video recording from Top-down view, Observation Protocol and Questionnaire

To investigate current pedestrian-vehicle and vehicle-vehicle interactions at intersections and car park scenarios, a series of studies using different methods were conducted within InterACT Work Package 2, such as video recording, observation protocols, and questionnaires. Firstly, outdoor HD wireless IP camera video cameras were placed at elevated locations in Leeds, Athens, and Munich to record any interactions at area of interest. These **video recordings** did not allow tracking or identification. Approximately 600 hours of video data were collected at each location (see more about video recording in Portouli et al., 2019; Section 3.3; Dietrich et al., 2018; Merat et al., 2019).

In addition to the video recordings, pedestrian-vehicle and vehicle-vehicle interactions were **manually observed** by researchers in Leeds, Athens and Munich. An **observation protocol** was created to provide a standardised data collection by using a HTML application at all locations (see Section 3.2.3 Dietrich et al., 2018), which allowed cross-cultural comparisons, along with comparisons of different area of interest such as intersections and car parks (Lee et al., under review; Uttley et al., under review). The use of observation protocol has benefits such as enabling a lot of data collection in a short period of time, and allowing a standardised procedure across locations. However, the researchers need extensive amounts of training to be skilful in observing and capturing the interactions, which often happened in a very short period of time.

After the pedestrians crossed the road at junctions, a series of questions were asked about the crossing decision that they have made. The **questionnaire** provided more in-depth information that might not be observable by the researchers, such as **what information they used while making a crossing decision** (see Lee et al., under review). Asking questions after the crossing and not during it, ensured natural crossing behaviour occurred, which did not affect participants' crossing decision. However, having participants try to recall what had just happened might not be completely accurate.

Video recordings provide rich objective information and data, including the position, velocity, trajectories and type of traffic participants which are well synchronised. However, this methodology can be very time consuming and technical. Moreover, some information cannot be captured through an elevated video camera, such as the hand gesture of drivers or if the pedestrian was not facing the camera. On the other hand, the observation protocol and questionnaire provide efficient observations of vehicle-vehicle and vehicle-pedestrian interactions, such that the data analysis can capture more information about drivers' and pedestrians' explicit behaviour. However, they do not provide much information regarding the speed, trajectories, positions of the observed agents, which are also important. Therefore, a combination of these methodologies has provided a full overview of interactions, taking into account the subjective measures from the observers' perspectives and pedestrians' self-reports, as well as the objective measures of the interactions captured through video data.

4.2 Drivers' retrospective commentary and eye tracking

An **on-road, video-assisted observational study with retrospective commentary by drivers** was conducted to collect empirical evidence relevant to drivers' interactions with other drivers and pedestrians. Twenty-one experienced drivers were asked to drive their own passenger car on a predefined urban course, while **wearing an eye glass mounted gaze sensor**. This system records the traffic scene from the driver's point of view and identifies the driver's eye-fixations points with a 50Hz sampling frequency and gaze position accuracy of 0.5°. The course consisted of a circular route of 0.75 km which was driven 5 times by each driver. The total course length was 3.75 km and the mean driving duration was 18 minutes. The course included left turning from a two-way street and right turning from a smaller to a two-way street. Turns were not regulated by a traffic light and given the traffic density it was expected that there would be a lot of interactions between drivers relevant to the left and right turns.

After arriving at the lab, participants were introduced to the general setup and were calibrated on the eye-tracker, while seated on driver's seat their own passenger car, with a five-point procedure. Then they were instructed to drive at the selected site in their normal style and to repeat the selected course five times in a row. Immediately following the driving session, participants returned to the lab and were asked to watch their eye-gaze video recording while commenting aloud on their behaviour and decision making for each case of interaction with another driver or pedestrian. The commentary was recorded through video and voice capture software.

Afterwards, an analyst watched the participant's eye gaze and scene video as well as his/her retrospective commentary, and **labelled the interactions between the participant and another driver**. An interaction start with another driver was defined as the time point when i) the participant had to wait for a gap in the oncoming traffic before turning or ii) the participant started turning knowing that the oncoming driver would have to modify his/her vehicle motion. For each interaction, the analyst labelled the type of the interacting vehicle and whether the other driver reacted. The **signals or cues by the participant and his/her vehicle and by the other driver and his/her vehicle and their sequence** were labelled for each interaction.

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An interaction case with another pedestrian was defined when a pedestrian in the vicinity of the participant driver (i) affected the car movement and/or the driver's behaviour in an observable manner and (ii) received at least one eye-fixation from the driver. The starting point for each interaction case was defined by the observers according to the following criteria: either (i) the drivers' first fixation towards to the pedestrian or (ii) the first cue from the pedestrian interpreted as intention to cross. For each interaction case with a pedestrian, the video data were analysed by labelling the following indices: (i) **participant-drivers' eye-fixations** on the pedestrians, (ii) **eye-contacts** between pedestrian and participant-driver, (iii) **cues denoting a pedestrian's projected direction** (i.e. pedestrian's head orientation, body movement/orientation), (iv) **cues denoting pedestrians awareness** of the participant's vehicle (i.e. pedestrian's eye-gazes towards to the participant's vehicle). In addition, based on the video-assisted retrospective commentary (v) **participants' expressed confidence** about the future intended action of a pedestrian was noted when mentioned.

4.3 Modelling

In interACT WP2, work has also been carried out to develop models of road user interactions, with one of the goals being to allow simulation-based impact assessments in WP6. For a full description of this experimental and modelling work in WP2, see interACT Deliverable D2.2 (Dietrich et al., 2019) or the associated papers (Markkula et al., 2018; Giles et al., 2019). In brief, what has been developed are **models of road crossing decisions** as a function of the behaviour of an approaching car/AV in two scenarios: a pedestrian crossing scenario, and a driver right turn across (left-hand driving) traffic. For both scenarios, models have been separately calibrated to data collected both in the UK and in Japan. The models are probabilistic in nature, and can thus predict entire probability distributions of how a road crossing interaction can play out, as a function of the specific approaching or yielding trajectory adopted by an AV; see Figure 9 for an illustration. Extending the models to also account for effects of the eHMI developed in interACT WP4 is planned as part of the WP6 work (see Section 5.5). The models allow **simulation-based predictions** about **traffic efficiency** in terms of the amount of time lost in the interaction for both involved road users, and tentative predictions about **safety** can also be made by studying quantities like **time-to-arrival (TTA) at crossing onset** (a quantity that seems to correlate with subjectively perceived safety in these scenarios; Dietrich et al., 2019) and the **acceleration levels applied by the AV** to pass safely behind the crossing road user.

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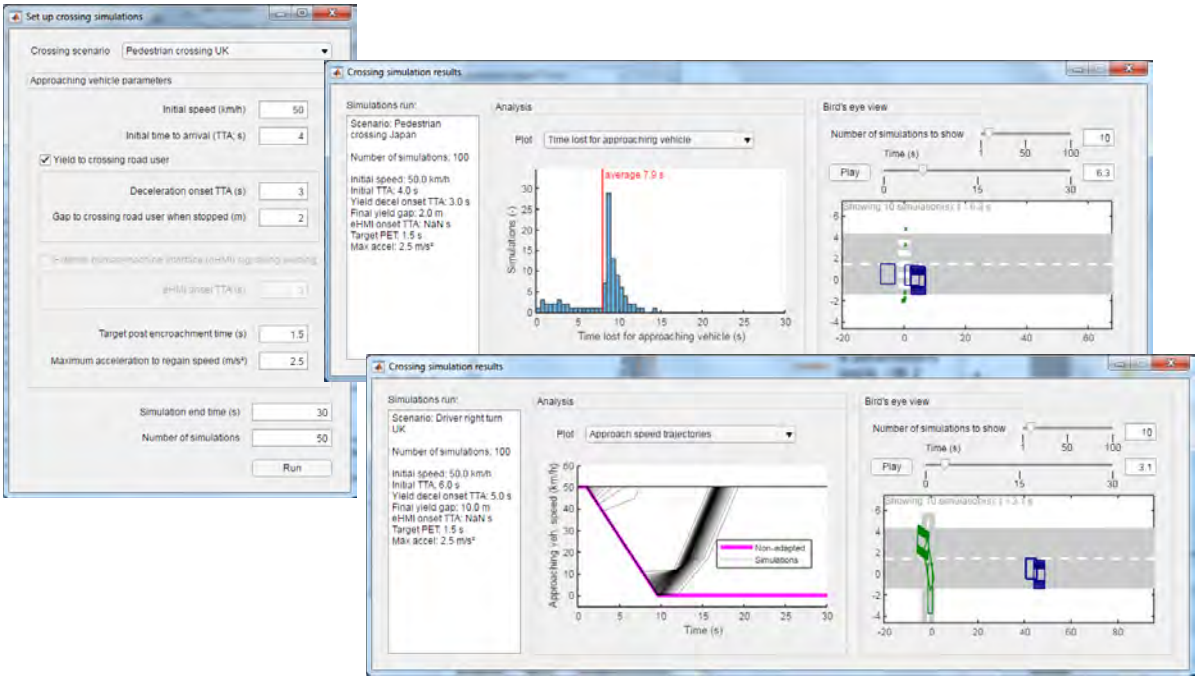

Crossing scenario: Pedestrian crossing UK

Approaching vehicle parameters

Initial speed (km/h): 50

Initial time to arrival (TTA; s): 4

☑ Yield to crossing road user

Deceleration onset TTA (s): 3

Gap to crossing road user when stopped (m): 2

☐ External human-machine interface (eHMI) signalling yielding

eHMI onset TTA (s): 3

Target post encroachment time (s): 1.5

Maximum acceleration to regain speed (m/s²): 2.5

Simulation end time (s): 30

Number of simulations: 50

Scenario: Pedestrian crossing Japan

Number of simulations: 100

Initial speed: 50.0 km/h
Initial TTA: 4.0 s
Yield decel onset TTA: 3.0 s
Final yield gap: 2.0 m
eHMI onset TTA: NaN s
Target PET: 1.5 s
Max accel: 2.5 m/s²

Plot: Time lost for approaching vehicle

Number of simulations to show: 10

Time (s): 6.3

Scenario: Driver right turn UK

Number of simulations: 100

Initial speed: 50.0 km/h
Initial TTA: 6.0 s
Yield decel onset TTA: 5.0 s
Final yield gap: 10.0 m
eHMI onset TTA: NaN s
Target PET: 1.5 s
Max accel: 2.5 m/s²

Plot: Approach speed trajectories

Number of simulations to show: 10

Time (s): 3.1

Figure 9: The graphical user interface of the road crossing behaviour simulation software provided with interACT Deliverable D2.2

4.4 Conclusions drawn from WP2

The studies conducted as part of WP2 provided insights into the psychological models used by current road users to understand one another's actions. Tools such as video analysis and manual observations of real world interactions have increased our understanding of the naturalistic pedestrian-vehicle and vehicle-vehicle interactions which occur in the UK, Germany, and Greece, and the differences and similarities that emerge across cultures. These methodologies will be further evaluated as part of WP6. The questionnaire developed to understand the information used by pedestrians in their crossing decisions with conventional vehicles, can also be used within WP6 to understand if similar information is used when interacting with AVs in both real-world and simulator contexts. Similarly, the video and commentary labelling processes used to understand current driver-driver and driver-pedestrian interactions can be used to understand driver-AV and pedestrian-AV interactions within WP6. Finally, an important part of the work in WP6 will be to further develop the methodologies used in WP2 for applying models of road user interactions in simulation-based impact assessment (see Section 5.5).

5. Evaluating interACT solutions

In Chapters 2 – 4, we have provided an outline of the types of evaluation criteria currently being used in the literature (Chapter 2 and 4), along with the research concerns of experts in the field (Chapter 3). In the current Chapter, we put forth our plans of how these evaluation criteria (see Annex 1) can be used to assess the interACT solutions as part of WP6. In Section 5.1, we outline a series of planned simulator-based studies to evaluate pedestrian-AV interactions and vehicle-vehicle interactions. Section 5.2 provides a description of an ICCS vehicle which has been equipped with some of the interACT solutions, along with a field study which will be conducted to evaluate these solutions. Finally, Sections 5.3 and 5.4 provide a summary of the BMW and CRF demonstrator vehicles developed as part of WP3 and WP5, and the scenarios which will be used to evaluate them.

5.1 Simulator studies

5.1.1 Pedestrian-Vehicle Interaction

5.1.1.1 DLR

The interaction of pedestrians and AVs with an eHMI will be examined using a virtual reality pedestrian simulator at DLR. A central European city is going to be simulated. An AV with an eHMI, conventional vehicles, and AVs without an eHMI will all occur in the simulation. In the experiment, the participant has to decide whether it is possible to cross the street and when he or she wants to do it. The checking behavior of the oncoming traffic, the crossing decision point, the perceived certainty of the own decision to cross the street, and the self-assessment-manikin scale will be measured.

A second study is planned to investigate the negative effects in vehicle to pedestrian interaction. This study will investigate whether the communication of an AV through an eHMI has a negative impact on pedestrians when checking the oncoming traffic before and after stepping on the street. Three different eHMI designs of the interACT project will be used, and varied between the subjects. The first design is intention based, the second one perception based, and the third one is a combination of the other two designs (Figure 10).

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Figure 10: The automated vehicle signals with the eHMI that it gives priority.

5.1.1.2 ITS

The ITS studies will make use of the Highly Immersive Kinematic Experimental Research (HIKER) pedestrian lab (Figure 11), as well as the VIVE Head-mounted Display (Figure 12) at the University of Leeds. HIKER lab is the largest 4K-resolution 'CAVE-based' pedestrian simulation environment in the world, providing a 9 x 4 m walking space, allowing participants to interact with different environments created. https://uolds.leeds.ac.uk/facility/hikerlab/

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Figure 11: Highly Immersive Kinematic Experimental Research (HIKER) pedestrian lab at University of Leeds

Figure 12: HTC VIVE Head-Mounted Display pedestrian lab at University of Leeds

Within WP6 a series of experiments will test the effects of the interACT eHMI solutions on pedestrians' crossing decisions and behaviour, by using the objective measures and evaluation framework developed in Lee et al. (2019a), and subjective measures on acceptance and trust, selected from the evaluation criteria catalogue in Annex 1. In addition, different scenarios will be tested by creating negotiation/ambiguous crossing situations during pedestrian – AV interactions to investigate

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the effect of congruent and incongruent eHMI on pedestrians' crossing behaviour, along with the impact of different speed, deceleration rates, and deceleration onsets on crossing behaviour.

Finally, an investigation of the interaction between drivers and pedestrians in real time is also planned, by connecting the HIKER with a driving simulator at the University of Leeds. This methodology will enable two participants (AV user and pedestrians) to interact at junctions.

5.1.1.3 BMW

A study will be conducted to assess the influence of 3 different eHMI interaction strategies on pedestrians' crossing behaviour. In a WP4 Simulator study on vehicle-vehicle interaction it has been 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 were 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. Also the traffic scenario, and the position of the ego driver, the AV, and the simulated third car, did not have an influence on driver behaviour.

In WP 6 one study will be conducted which will replicate the scenarios and eHMI solutions tested in WP 4 in a similar setting, however with a focus on AV-pedestrian interaction instead of AV-driver interaction. Participants will take part in this study as pedestrians encountering various vehicles including an AV equipped with one of the 3 different eHMIs, or no eHMI. A further – simulated – pedestrian will be present to identify scenarios in which one of the eHMIs might perform better than the other when multiple users are engaged in potential interaction with the AV.

5.1.2 Vehicle-Vehicle interaction: DLR

The goal of this study is to evaluate the HMI concept that was developed within the interACT project on car to car traffic cooperation. To generate a holistic picture of the interaction effects of interACT prototypes with other road users, it was important to address a broad range of research questions. While most work within the project focuses on investigating the information to be displayed by the HMI (objects, manoeuvres, automation status), the modality of the signal (directed or undirected), the technical form of displaying the signal (LEDs vs projection) and having several levels of signal (escalation), it became clear that negative and learning effects from the eHMI on incoming vehicles are an important topic that needed to be addressed.

These two research topics benefit from multiple repetitions under highly comparable conditions (learning effects) in a safe environment (negative effects). A high level of control of the environmental conditions is necessary to reduce unwanted influences on the measured variables. The learning effects, in particular, could be small. If so, it would require a clear, controlled research environment to

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be able to identify weak changes. These needs can best be addressed by a simulator study. Here multiple scenarios can be tested in a short time and nobody can get hurt in staging a critical scenario.

Accepted gap size (AGS) can be used to measure the quality of communication between drivers at a t-junction. At an intersection or t-junction, the decision to turn in front of, or behind, the other vehicle depends on variables such as gap size, speed of trailing vehicle, driver age, gender (Yan, Radwan, & Guo, 2007), waiting time (Abou-Henaidy, Teply, & Hunt, 1994), distraction, condition of the street (Cooper & Zheng, 2002), type of vehicle, number of rejected gaps (Teply, Abou-Henaidy, & Hunt, 1997) and alcohol consumption (Leung & Starmer, 2005). Imbsweiler, Ruesch, Weinreuter, Puente León, and Deml (2018) investigated cooperation behaviour of road users (mixed traffic) in t-intersections during deadlock situations. The results show that in complex scenarios, human road users prefer not to drive first. An explanation for this phenomenon is that there is a communication problem between the AV and human driver. This should be addressed with solutions developed within the InterACT project. A reduction of AGS can indicate that the drivers are learning to understand the message expressed by the eHMI. However, if fewer gaps are accepted with eHMI than without, this would indicate a negative effect of the display. Consequently the AGS was selected as a major dependent variable.

In a vehicle-to-vehicle communication scenario generated inside a simulator, the AGS depends on a realistic display of the movement and position of the vehicle instrumented with the eHMI relative to the test driver. To create the impression of a natural turning manoeuver into the gap it is also important that the dimensions and structural occlusions of the own vehicle are realistic. The DLR Virtual Reality Lab (VR-Lab) simulator is well suited to address the need to investigate the AGS as main performance indicator, since it features a continuous 360° surround display with enough room to fit a realistic mock-up of a vehicle inside.

The VR-Lab is a highly dynamic and scalable simulation environment providing a 360° field-of-view with high-resolution visualisation. The flexible integration of different Mock-Ups and vehicles allows the testing and evaluation of automation and assistance functions through repeatable and reproducible scenarios. It features a 360° round projection generated by 12 projectors. Each projector has a resolution of 1920x1200 pixels vertically mounted (Figure 13).

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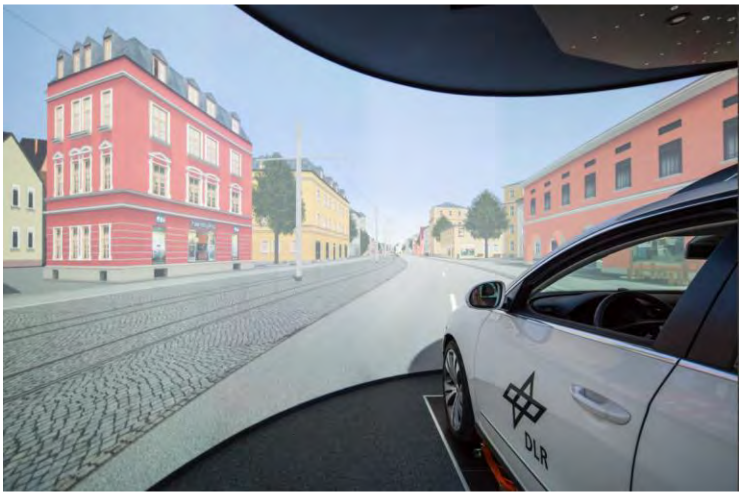

Figure 13: Vehicle in the DLR VR-Lab

This setup will be used to investigate negative and learning effects of the eHMI on other vehicle drivers. This will be achieved by presenting test drivers with negotiation scenarios at t-junctions where it is not entirely clear if they can turn or not (Figure 14). They may receive a signal to be given way and the reaction over time will be observed. There will also be a critical situation to investigate if the eHMI could be misunderstood in its message. After the turn, the test driver will be asked if they noticed a communication attempt by the incoming vehicle and what the purpose of the communication was.

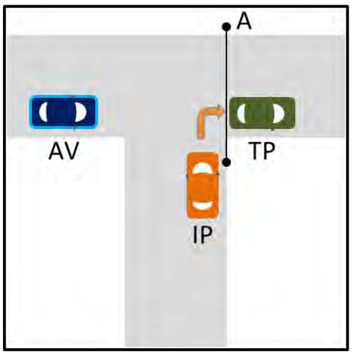

Figure 14: Basic schematic scenario design. The IP will always have to turn in between two passing vehicles (AV and TP). The gap size and the scenario will be slightly varied.

5.2 Field study of eHMI impact on AV–drivers interactions: ICCS equipped vehicle

ICCS will equip a Toyota Yaris Hybrid 2018 model, equipped with an external HMI (eHMI) for interaction with other traffic participants. The ICCS tests will focus on interactions between AVs and other drivers during left turns. The vehicle will be driven via double pedals by a driving instructor seating on the co-driver's seat.

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A field study has been designed to ensure that interactions between a driver of a passenger car with an oncoming AV occur in a structured way in slow driving conditions, typical of dense traffic or speed-restricted areas. The aim is to study the impact of the interACT eHMI on the driver's turning time and perceptions.

Participating drivers, accompanied by a facilitator, will be asked to drive their own vehicle (in green in Figure 15) on a predefined route along a two-way street segment (on normal road or within a parking lot) with the intention to turn left at a designated junction. Concurrently, an instrumented experimental vehicle (in orange in Figure 15) will start driving towards the designated intersection from the opposite direction with the intention to also turn left turn at the same junction.

The instrumented vehicle will be driven by a driving instructor, who is able to repeat the same driving manoeuvre in all test runs. The orange vehicle will first reach a speed of 20km/h and will then start decelerating at a steady rate until it comes to a full stop right before the junction. The driving instructor is able to control the orange vehicle motion appropriately, so that the two vehicles trajectories intersect each other at the designated junction and the participating driver definitely will have to interact with the orange vehicle before turning. The effective width of the junction will be narrowed using traffic cones (red circles in Figure 15), so that simultaneous manoeuvre of the two vehicles will not be possible.

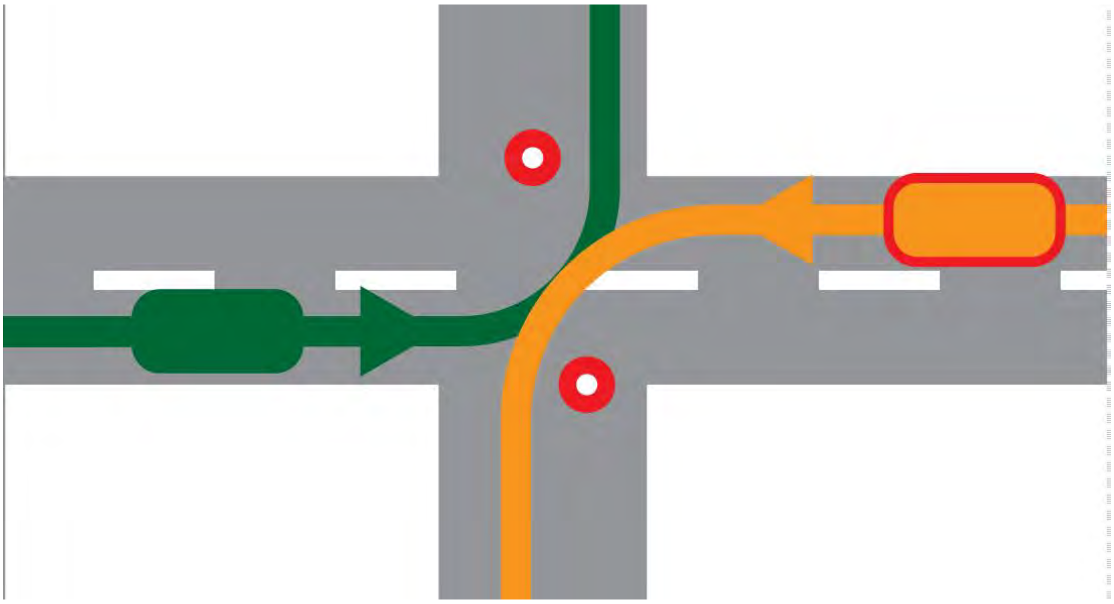

Figure 15: Planned scenario for the ICCS study

Given the above set up, it is expected that the participating drivers will initiate the left turn manoeuvre while the orange vehicle decelerates or shortly after it comes to a full stop.

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Three conditions are planned for the orange vehicle: i) driving instructor driving from the driver's seat (human-driven), ii) driving instructor driving from the passenger seat (AV – no eHMI mode) and iii) driving instructor driving from the passenger seat and eHMI on the vehicle signalling yielding (AV – with eHMI mode). The eHMI will be a LED stripe according to the specifications in D4.2.

20 participants will be involved in the study that is envisaged to be conducted in July 2019. Each participant will execute the left turn once per condition in a randomized order. The three manoeuvres will be executed consecutively in the same driving session as presented in Figure 16. Synchronization of trajectories will be achieved by an external facilitator.

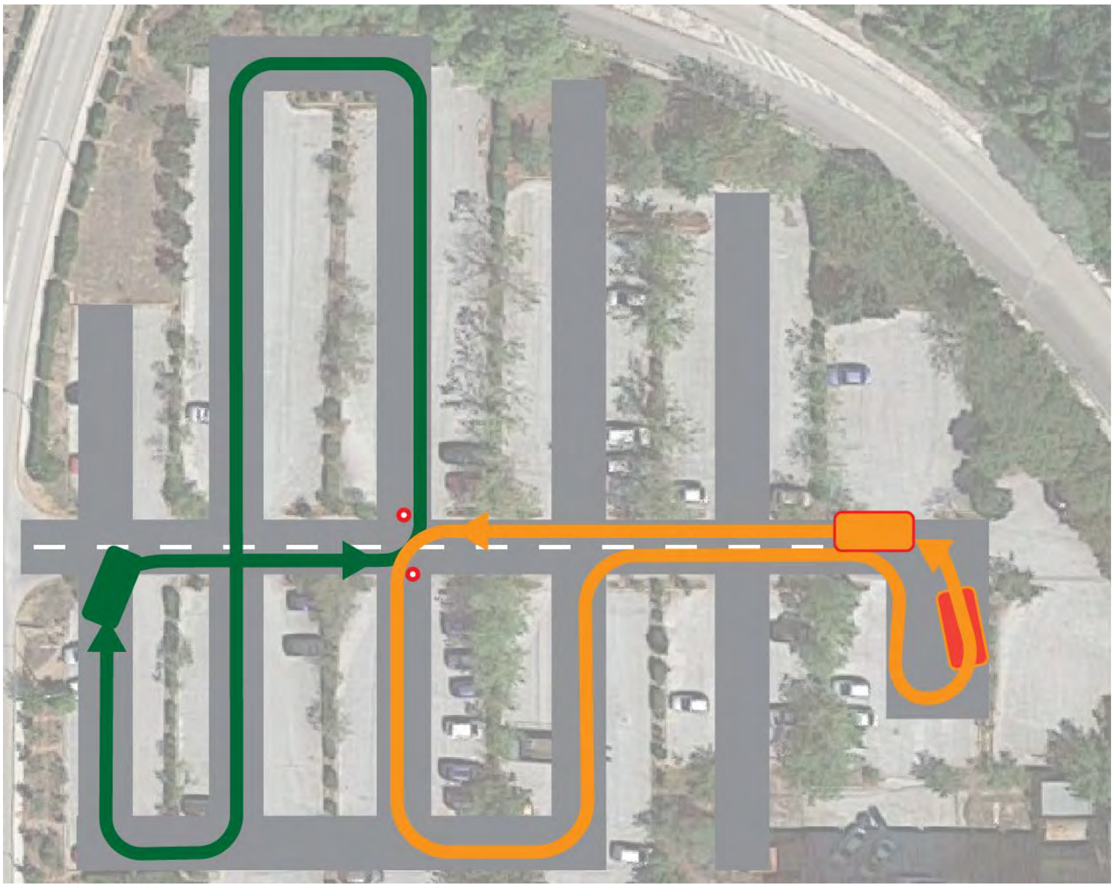

Figure 16: The planned trajectories of the two vehicles at a university parking lot.

The dependent variables will be:

- t1 (= participating driver starts turning) - to (orange vehicle starts yielding)
- vehicles distances at t1 and to

- participants' comprehension and feelings of safety and comfort

More detailed data about the participants' decision-making will be captured after the end of the driving sessions via structured interviews.

5.3 Evaluation of BMW demonstrator vehicle by TUM

5.3.1 BMW

The BMW prototype is a BMW i3, an electric car with a 94 Ah lithium-ion battery (Figure 17).

Figure 17: BMW demonstrator

This demonstrator is focussing on the interaction between the vehicle and other traffic participants, such as pedestrians, in an urban environment, and will be tested in real-world environments in Munich by the Technical University of Munich. The demonstrator vehicle is equipped with fully integrated external HMI (eHMI) components, which have been developed within WP4. The WP4 partners designed the following interaction strategies based on two eHMI concepts – a 360° LED light-band and a directed signal lamp which is only visible for one individual traffic participant (Weber et al., 2019, Deliverable 4.2):

- **Main eHMI design:** Fully illuminated LED light-band communicates the intentions of the AV (such as giving way or starting to move).
- **Secondary eHMI design I:** Specific segments of the LED light-band are illuminated to communicate the perception of another traffic participant.
- **Secondary eHMI design II:** A combination of the signal lamp (communicates the perception to only one individual traffic participant) and the light-band (communicates the intention of the AV 360°) are used to communicate both AV intention and perception at the same time.

As part of WP4, the concrete eHMI strategies have already been evaluated in simulator and virtual reality-based user studies, and will be further refined within the evaluation studies in WP6.

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In addition to the eHMI components, the BMW demonstrator is equipped with a DGPS System, cameras, and a measuring computer (PC). The eHMI components (light-band and signal-lamp) are controlled by a HMI – Control Unit (HMI ECU) which receives the input signals via the eHMI-control panel, which can be operated by passengers from inside the vehicle. Furthermore, the PC receives current vehicle data such as velocity and vehicle position from the DGPS System as well as video material from the cameras which are observing the environment outside of the vehicle during the studies. The PC collects all data from each component (HMI ECU, DGPS System, cameras) to enable a time-synchronised analysis of the entire data at the end of each study.

Due to the approach of evaluating the BMW demonstrator in the real world and the need for driving permission for real road testing, the BMW i3 will be driven manually. In order to simulate an autonomous driving vehicle the BMW prototype will be equipped with a seat cover, to hide the driver of the car (see Figure 18).This "Wizard-of-Oz" approach means that the vehicle appears to be automated, while it is actually being steered by a hidden human driver. This is essential as the demonstrator is intended for data collection in natural traffic and the simulated automated driving technology is not yet market-ready.

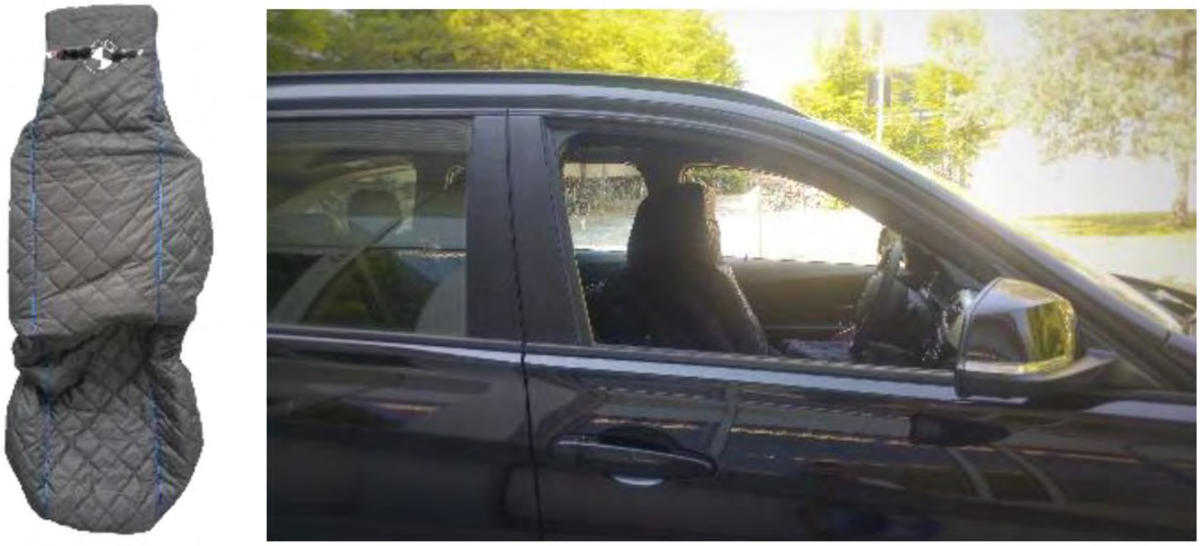

Figure 18: Example of a seat cover to hide the driver and simulate an autonomous driving vehicle (Fuest et al., 2018a)

The following sections describe the evaluation plans for the BMW demonstrator. These evaluation studies will mainly be conducted by the Technical University of Munich.

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5.3.2 Scenarios

The focus for the BMW evaluation is on AV-pedestrian interaction. The objective is to evaluate the impact of the developed light-based interaction strategies. As the vehicle is designed in order to obtain permission for use on roads in Germany, pedestrian behaviour in real-world and natural traffic situations can be measured, using the Wizard-of-Oz approach described above.

A combination of several testing environments (see Table 1) will be used to answer the proposed research questions:

Table 1: Advantages and Disadvantages of each of the proposed testing environments for the BMW Evaluation

	Testing Environment	Advantages	Disadvantages
1	Closed Test-Track	– High controllability of events – No disturbing, uncontrolled other traffic – Clear, unobstructed view	– Intuitive / natural behaviour hard to measure – No natural traffic conditions
2	Real-World Experiment (e.g. area with low traffic volume)	– More natural setting than closed test-track – Informed participants	– High organizational effort – Low controllability of events (other traffic participants)
3	Field Study (defined course e.g. including marked pedestrian crossings)	– Natural behaviour as pedestrians need not know that they are being observed	– Ethical Questions need to be addressed (concealed observations) – Low controllability of events (other traffic participants)

The BMW demonstrator will be evaluated on a closed test-track to ensure a high controllability of events as well as in a real-world experiment to draw conclusions AV-pedestrian interaction from more natural scenarios. The inclusion of both testing environments allows us to overcome some of the disadvantages of each of the methods.

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5.3.3 Studies plan (Research Environment, Methodologies, Evaluation Criteria, Measures)

Three main research questions are raised for the BMW evaluation:

1. Do Pedestrians understand the vehicle's intention, as conveyed through the eHMIs?
    a. Learnability: Is there a behavioural adaptation/ adaptation of mental models from the first compared to following encounters?
    b. Compliance: If the vehicle intention is understood, would pedestrians also act as intended?
2. Does the usage of eHMIs lead to faster crossing decisions?
    a. Efficiency: Faster intention recognition of the AV and faster crossing initiation?
3. How does the eHMI influence pedestrians' perception of AVs?
    a. Perceived Safety
    b. Technology Acceptance
    c. Trust in Automation

As the literature review (Chapter 2) revealed several promising measurements – objective as well as subjective ones – we will apply a combination of both to cover human perception, understanding, and reactions to the demonstrator. Subjective data collection will focus on a structured interview and a questionnaire, as used for example in Fuest et al. (2018), will be adapted to draw conclusions on understanding and perception. The objective reaction of pedestrians to the demonstrator will be operationalized measuring intention recognition time ("What is the vehicle's intention?") as well as crossing initiation time.

5.4 Evaluation of CRF demonstrator vehicle by ITS

5.4.1 CRF

The CRF car is a Jeep "Renegade" MY2018 1.4 MultiAir 140 CV 4x2 Limited DDCT (Figure 19):

Figure 19: CRF demonstrator

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It is equipped with the Perception Platform (PP) of BOSCH, including six (6) Laser-scanners (3 in front and 3 rear) and four (4) frontal cameras, as well as DGPS. In addition, the CCPU is integrated on the same PC used for the PP. The set-up is shown in Figure 20:

Figure 20: Visualisation of the Perception Platform installed on the CRF vehicle.

In addition, the CRF vehicle is equipped both with a dedicated internal HMI (iHMI) for communication with the on-board user, and with an external HMI (eHMI) for communication with other traffic participants. The CRF demonstration vehicle focuses on the parking area scenario. It can travel autonomously in this dedicated area at a maximum speed of 15-20 km/h, searching for a parking slot, during which time the car must interact with other participants (such as pedestrians, cyclists, and other vehicles).

5.4.2 Scenarios

The test-track environment for the CRF vehicle consists of a car-parking area at the FCA Safety Center, Turin (see Figure 21). This is a quiet area where visitors and employees of the Safety Center park. Traffic leaving the two-way road at the bottom of figure 21 enters a one-way stream around the central parking area.

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Figure 21: Test-track area for CRF evaluation

A minimum of two scenarios will be selected for testing from the WP3 scenario catalogue (Bolovinou et al., 2019, Deliverable 3.1), based on their capacity to reflect the vehicle's interaction capability within this test-track environment. Both AV-pedestrian and AV-vehicle interactions will be examined.

5.4.3 Studies plan (Research Environment, Methodologies, Evaluation Criteria, Measures)

The purpose of the CRF evaluation will be to understand both the on-board user's and other road users' experience of AV interactions. A mixture of qualitative and quantitative techniques will be used to address three key questions:

1. How do pedestrians evaluate the usability of the AV communication tools (both implicit and explicit)?
2. How do other drivers evaluate the usability of the AV communication tools (both implicit and explicit)?
3. How do on-board users evaluate the usability of the AV's internal communication tools for interactions with both pedestrians and other vehicles?

Implicit communication tools refer to the aspects of the vehicle's movement parameters which convey intent to other road users e.g. speed and trajectory. Explicit communication tools refer to the eHMI design variants proposed in Deliverable 4.2.

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Measures will include questionnaire and interview data to understand users' perceptions of safety, trust and acceptance around the AVs in a real-world environment; along with objective measures of crossing decisions made. On-board users' perceptions of iHMI will be collected to evaluate how well the AV's intended interactions are conveyed, along with how well the interaction decisions conform to their expectations within the given scenarios. Measures of comfort, perceived safety, trust, and acceptance will also be collected.

These measures will provide an evaluation of the success of the interACT solutions in addressing the interaction requirements identified through the use-cases in WP3.

5.5 Simulation and Modelling (ITS)

The pedestrian crossing and cross-traffic vehicle turning models developed in WP2 will be applied in WP6 to evaluate different types of vehicle-human interaction strategies developed in the project. The models developed can already be used to investigate effects of different approaching trajectories, or implicit communication, on the efficiency (e.g., in terms of time lost in the interaction) and comfort (e.g., in terms of perceived time to arrival at crossing onset, or models derived from such metrics) of vehicle-vehicle and vehicle-pedestrian interactions (see Section 4.3). The current models have been made available in a software simulation tool (interACT Deliverable D2.2). Table 2 lists the analyses that can be made directly from within the graphical user interface of that tool (a much wider range of analyses is possible if using the software programmatically directly from MATLAB).

Going forward, incorporation of eHMI in the model will be based on evaluation data gathered as part of WP6, and eHMI effects on crossing decisions will be estimated with and without interaction-optimized trajectories. Data from the evaluation experiment's subjective safety estimates will also be incorporated in the modelling tool to predict subjectively experienced safety of different interaction approaches. Objective safety and comfort will be modelled based on frequency and severity of excessive decelerations required to avoid collisions.

It will also be attempted to estimate the wider effects of the interaction strategies will be calculated by incorporating the crossing decision models and interaction solutions in simulations with traditional car following models. This will be used to tentatively estimate the effects of different interaction types on traffic flow (in terms of metrics such as vehicle throughput, as mentioned in Section 2.6) on roads with pedestrian crossings and unsignalised intersections across traffic.

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Table 2: A listing of the types of analysis plots accessible via the simulation software GUI, together with explanations and possible interpretations and uses. A and C refer to the approaching and crossing/turning road users, respectively (See interACT Deliverable D2.2 Dietrich et al., 2019).

Plot	Explanation	Possible interpretation/use
Crossing onset times	Showing distributions (continuous and discrete) of simulation times at which the modelled road user C initiates crossing.	Larger values mean that C needed to wait longer before crossing.
Approach speed trajectories	Showing A's speed over time, both for the "non-adapted" case where A remains stationary after yielding to a full stop (or keeps initial speed in the non-yielding case), and for the actual model simulations where A also responds to C's crossing behaviour.	Reductions to lower speeds for A indicate a less efficient interaction.
Approach acceleration trajectories	As above, but for A's acceleration over time.	Large decelerations for A may have implications for comfort and safety for occupants in A, for C, and road users behind A.
Apparent TTA at crossing onset	Showing distributions of TTA for A, at the time at which C initiated crossing.	Smaller TTA values at crossing onset suggest an interaction that is potentially subjectively less safe for C (and any occupants in A).
Time lost for approaching vehicle	Showing distributions of the time delay for A as a result of the interaction (comparing A's distance travelled over time to a baseline case without road user C).	Larger delay times for A indicate a less efficient interaction.

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6. Summary and Conclusions

Within this Deliverable, we have provided an outline of the current state-of-the-art in relation to measuring road users' interactions, identifying the research environments, methods, and tools which have previously been used (Chapter 2). This has been supplemented by an overview of workshops conducted with subject matter experts, who have identified the key questions which need to be addressed when it comes to understanding how to implement these types of interactive AVs. The criteria catalogues presented in this Annex 1 provide a starting point for the selection of any measurement tools for the interACT solutions. These tools should be complemented with measures of the other criteria identified through the stakeholder workshops, including an understanding of where in the research cycle particular measurements are most relevant, based on the interACT team experiences in work packages 2 to 5.

One of the main findings arising from the literature review is that different research environments can be more or less appropriate for examining particular research questions. Therefore, the interACT partners have taken this as a guidance, and have chosen a number of different complementary methods to test our prototypes and solutions in a comprehensive manner (Chapter 5). For instance, as the CRF demonstrator vehicle will be automated, it is important to maximise safety in any testing environment, and ensure adherence to legal restrictions around AVs. Therefore, this vehicle will be tested on a test-track, which will allow more stringent safety controls than a real-world environment, while also facilitating more controlled experimental research, which will make it easier to draw conclusions on specific research questions around pedestrian, drivers, and on-board users' evaluations of the usability of the AV communication tools (Section 5.4).

On the other hand, and the main aim of the BMW evaluation is to provide an assessment of the integrated eHMI solutions developed in previous work packages. Thus, the BMW vehicle will be controlled by a driver, and driven in a real-world environment to provide information on how pedestrians' perceive and react to the eHMI in a natural context (Section 5.3). One of the key considerations for testing the BMW prototype, is the importance of making other road users believe that the BMW prototype is automated. In order to do so, Wizard of Oz method will be used to hide the visibility of the driver.

interACT will also be carrying out simulator studies (Section 5.1), which allow research questions to be tested in a safer and more controlled environment, and also provide a more cost-effective solution for evaluating the effects of many different vehicle manipulations. This type of environment will allow us to investigate research questions around the effects of eHMI variations, the potential negative effects of AV interactions, and the effects of priority and ambiguity, by setting up different scenarios within a

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virtual world, and allowing both within and between-subjects comparisons of the effects of different manipulations.

As mentioned previously in the Expected Impacts of WP6 (Section 1.1), there are some evaluation criteria which will be prioritised in the interACT evaluations. These include safety, ease-of-use, user acceptance, and also the societal impact of AV implementation. As seen in Chapter 2 and Annex 1, safety refers to the objective measures of how safe an interaction is including time to collision and safety margin; while perceived safety refers to participants' feelings of safety around an AV. Both of these objective and subjective measures are important while evaluating road user safety, and data will be collected through actual crossing behaviours in virtual and real-world environments, and rating scales. interACT will take the gathered previous studies as guidance, and choose metrics which are most suitable for each of the planned studies mentioned in Chapter 5. Similarly, the criteria of ease-of-use can be investigated from the perspective of 'Comprehension', 'Uncertainty' and 'Usefulness'. User acceptance can be investigated by using measures such as 'Attitude towards AV', 'Emotions', 'Interaction experience', 'Openness technology', 'Perceived behavioural control', 'Receptivity', and 'Trust'. Finally, in order to understand the societal impact, modelling and simulation will mainly be used (Section 5.5), such as traffic flow and stability.

In conclusion, evaluation studies (Task 6.2 of interACT) will be carried out by using simulators, test tracks and real world studies. The evaluation criteria that interACT will be prioritising include, safety, perceived safety, comprehension, efficiency, usefulness and trust by using both objective and subjective measures.

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