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Pedestrian and Passenger Interaction with Autonomous Vehicles: Field Study in a Crosswalk Scenario

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ABSTRACT
This study presents the outcomes of empirical investigations pertaining to human-vehicle interactions involving an autonomous vehicle (AV) equipped with both internal and external Human Machine Interfaces (HMIs) within a crosswalk scenario. The internal and external HMIs were integrated with implicit communication techniques, incorporating a combination of gentle and aggressive braking manoeuvres within the crosswalk. Data were collected through a combination of questionnaires and quantifiable metrics, including pedestrian decision to cross related to the vehicle distance and speed. The questionnaire responses reveal that pedestrians experience enhanced safety perceptions when the external HMI and gentle braking manoeuvres are used in tandem. In contrast, the measured variables demonstrate that the external HMI proves effective when complemented by the gentle braking manoeuvre. Furthermore, the questionnaire results highlight that the internal HMI enhances passenger confidence only when paired with the aggressive braking manoeuvre.

KEYWORDS
Autonomous driving; interaction; crosswalk; pedestrian; passenger; eHMI; iHMI

1. Introduction

Trustworthy human-vehicle interaction in the context of Autonomous Vehicles (AVs)[1] has a fundamental impact on the user's sense of agency, perception of risk, and trust (Li et al., 2019). These factors, in turn, are essential to avoid both disuse and misuse of technology, which directly affect user acceptance and safety respectively (Fernández-Llorca & Gómez, 2023).

Human-vehicle interaction in autonomous driving is a multi-user problem that primarily involves two groups of people: those using the AV (passengers) and external road users interacting with the AV (i.e. pedestrians, cyclists, drivers). The absence of a driver to communicate with, from both the perspective of a passenger and an external road agent, alters the nature and dynamics of interactions (Detjen et al., 2021; Rasouli & Tsotsos, 2020). In this new context, AVs need to communicate their intentions to road agents that are not automated or connected, such as regular vehicles, pedestrians, or cyclists, in the same way that regular drivers convey their intentions using visual cues or the vehicle dynamics itself. This communication process becomes especially crucial in scenarios where safety-relevant interactions may occur, such as when a pedestrian is crossing the road in front of a vehicle.

The use of Vehicle-to-Everything (V2X) technology (Parra et al., 2019) facilitates communication between other automated agents, such as other connected vehicles and infrastructure, but it still leaves humans unaware of the vehicle's intentions. Human-vehicle interaction primarily occurs through human-machine interfaces (HMIs), both internal (iHMI) and external (eHMI). The specific modality of these interfaces is tied to vehicle technology and human capabilities (Fernández-Llorca & Gómez, 2023). The behaviour of the vehicle, i.e. its movement dynamics, also serves as an important form of implicit communication with a significant impact on the interaction (Dey et al., 2021; Rasouli & Tsotsos, 2020).

The impact of these forms of explicit or implicit communication on in-vehicle users (drivers or passengers) and other external road users has been widely studied, but always separately, which prevents drawing holistic conclusions. From an experimental perspective, previous work has focused on simulated environments using virtual reality (Martín et al., 2023), or on real environments with two main types of constraints. On one hand, there are cases in which the pedestrian only expresses an intention to cross without actually performing the crossing action (Dey et al., 2021). On the other hand, there are cases where the driving is not truly automatic but mediated by "Wizard-of-Oz" methods (Lagstrom & Lundgren, 2015). In all cases, the results are somewhat limited due to the mismatch with real-world interaction scenarios.

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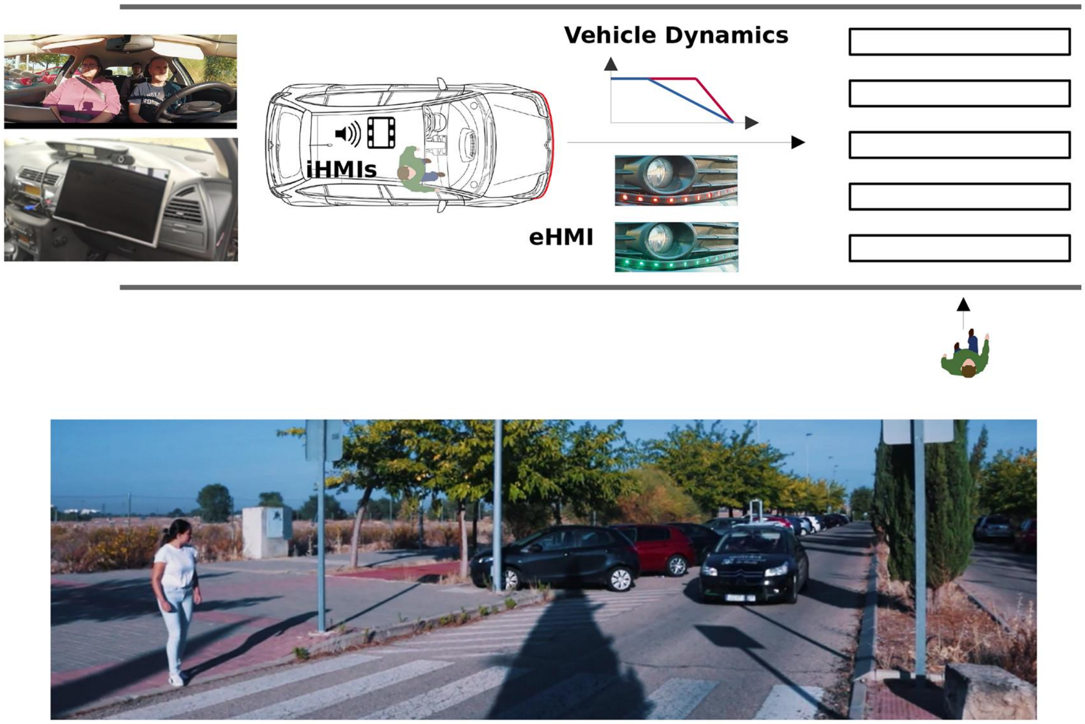

Figure 1. Top: schematic overview of the experiment. Bottom: actual image of the field test scenario.

In this work, we present the results of a real field study on human-vehicle interaction in crosswalk scenarios, involving both pedestrians and passengers (see Figure 1). We expand upon our preliminary study (Izquierdo et al., 2023) by providing more details about the experimental setup, data gathered, results, and discussion. Our automated test vehicle (Parra Alonso et al., 2018) is not mediated by the Wizard of Oz approach. The automation level implemented in the testing scenario is Level 4, so once the Automated Driving System (ADS) is activated, no backup driver is needed. However, for safety, legal and ethical reasons, the effective automation level was set to Level 3, so a backup driver is always present, ready to resume control when necessary.[2] The pedestrians do not explicitly communicate their intention to cross (which adds the difficulty of identifying the exact moment when the pedestrian decides to cross), but decide to cross or not, and complete their crossing action naturally. This approach allows us to draw conclusions that consider both types of users who interact with the AV in a holistic manner. It also enables us to investigate the impact of previous interaction experience as a passenger on pedestrian behaviour and vice versa. Furthermore, we can minimise the gap between the interactions measured in our experimental setup and those that would occur in a real environment. We evaluate different types of internal and external HMIs, as well as implicit communication through vehicle dynamics, using both behavioural and attitudinal evaluation methods.

2. Related work

We focus our analysis on previous works related to human-vehicle interaction, including studies that target pedestrians (i.e. external road users) and those that target passengers (i.e. in-cabin users), covering both explicit and implicit forms of communication (Markkula et al., 2020). We are primarily interested in studies that deal with the highest levels of automation (SAE Levels 4 and 5), where no backup driver is required.

2.1. Methodologies

The most fundamental approach to studying human behaviour in the traffic domain, and more specifically, human-vehicle interactions in the field of autonomous driving, involves utilising questionnaire-based interviews or surveys (Das & Zubaidi, 2021; Deb et al., 2017), without empirical experiments. Although they serve to measure general attitudes of people towards various aspects of autonomous driving, the main shortcoming is precisely the absence of empirical interaction, which makes it difficult to obtain results tailored to the specific context of the study, limiting their generality and validity (Feng et al., 2021).

Another common approach involves analysing behaviours through field observational studies, typically using naturalistic video recordings of traffic scenes captured from static locations (De Ceunynck et al., 2022; Madigan et al., 2021) or from inside the vehicle (Dillen et al., 2020; Wang et al., 2022). Although these methods allow for highly realistic conclusions, they lack the necessary flexibility to study specific phenomena under repeatable conditions.

Another interesting methodology is based on focus groups or participatory workshops (Dong et al., 2024; Kriston et al., 2023; Usai et al., 2023) with users and/or experts, which benefits from group interaction, and enables researchers to capture tailored and more in-depth information on the specific issues addressed.

However, the most prevalent approach to study human-AV interactions is by means of empirical studies under somehow controlled environments, including real subjects interacting with AVs. The predominant methodology involves the use of immersive virtual reality (VR) and simulated environments (Tran et al., 2021) either using VR headsets or CAVE-like simulators (Cave Automatic Virtual Environments) (Pala et al., 2021). VR-based experiments overcome many significant limitations of real-word testing, such as the need for actual prototypes, compliance with safety testing regulations, or risks to participants. Additionally, they provide a high degree of control over most of the experimental variables, and they facilitate researchers to reproduce the work of others (Feng et al., 2021) as well as to study cross-cultural factors (Martín Serrano et al., 2024a). Their use is very common for studying the behaviour of pedestrians or passengers in different interaction contexts (Deb et al., 2018; Morra et al., 2019; Serrano et al., 2023a; Tian et al., 2022; Zou et al., 2021). Recently, they have also been proposed for generating virtual datasets with real behaviours to train action and motion prediction systems (Serrano et al., 2022; 2023b). Nevertheless, the primary limitation of this methodology is the potential discrepancy between simulated and real conditions, that is, the classic concept of *sim-to-reality gap* (Fremont et al., 2020; García Daza et al., 2023), as well as the more recent concept of *behavioural gap* (Martín Serrano et al., 2024b). To partially overcome these limitations, an interesting approach is to conduct empirical evaluations on simulation platforms or at proving grounds using augmented reality (AR) (Pokam et al., 2019; Riegler et al., 2021; Weiguo et al., 2024), or to employ a combination of real and virtual environments (Drechsler et al., 2022; Németh et al., 2019; Zofka et al., 2018).

Finally, the methodology that most closely approximates reality while allowing for the study of specific aspects under certain controlled conditions involves the use of real platforms interacting with actual subjects. Due to potential risks to individuals and the platforms themselves, these studies must be conducted under strict safety conditions. Three dimensions are worth noting. The first is the testing environment, which typically involves closed test circuits or proving grounds (Antkiewicz et al., 2020), or specific areas, such as within university campuses (Alvarez et al., 2019), and can extend to real-world environments on public roads. The second dimension is related to the level of automation of the vehicle. In most cases, the vehicles are manually operated using "ghost driver" or "Wizard-of-Oz" techniques (Rodríguez Palmeiro et al., 2018; Rothenbücher et al., 2016), to emulate autonomous driving conditions. The last dimension is the behaviour of the subjects, which may be constrained to minimise risks - for example, by merely signalising their intention to cross without actually crossing the road (Dey et al., 2021; Rodríguez Palmeiro et al., 2018) - or considered without any type of limitation. It is evident that the most challenging scenarios arise when experiments are conducted in real-world driving conditions with an ADS and without limitations on the behaviour of the subjects, for which we have not found any prior studies beyond our preliminary research (Izquierdo et al., 2023), which we further expand upon in this paper.

2.2. Human-AV communication

The absence of a driver in higher levels of automation has motivated a wide spectrum of research focusing on human-vehicle communication. We can identify two main communication approaches. The first is implicit communication, which is based on the perception of the vehicle's kinematics and dynamics, primarily through different deceleration or braking patterns (Dietrich et al., 2020a; Tian et al., 2023). The second approach is explicit communication by means of Human-Machine Interfaces (HMIs), either external (eHMI) for external road agents (e.g. pedestrians) (de Clercq et al., 2019; Dey et al., 2020a), or internal (iHMI) for in-cabin users (e.g. passengers) (Detjen et al., 2021). We also find multiple studies that investigate the combined effect of both approaches (Dey et al., 2021; Dietrich et al., 2020b; Lee et al., 2022).

The primary eHMI modalities encompass signal lights, text, icons, and projections (Carmona et al., 2021). Yet, consensus is lacking on the most effective and user-friendly form for conveying a vehicle's intentions to external road users. Signal lights and text are prevalent, but text can be complex, requiring bigger displays. Overly complex textual signals might overwhelm pedestrians cognitively. Consequently, signal lights appear to be a more practical choice (Feng et al., 2023). Additionally, previous studies have shown that egocentric messages, which are focused on the targeted humans, are less ambiguous than allocentric messages that focus on the intentions of the AV (Bazilinskyy et al., 2019; 2020; Eisma et al., 2021). As for colours, despite the lack of unanimous agreement (Bazilinskyy et al., 2020), numerous studies suggest adopting egocentric traffic light patterns (green for "go" and red for "stop") to take advantage of users' instinctive associations (Bazilinskyy et al., 2019; Dey et al., 2020b; Nguyen et al., 2019; Rouchitsas & Alm, 2019). This is probably the most widely studied approach, and is the one used in our study.

Although there is evidence suggesting that road users are more prone to rely on implicit communication when interacting in traffic (Dey & Terken, 2017; Lee et al., 2022), the significance of explicit communication has been substantiated in numerous studies (Carmona et al., 2021; Dey et al., 2020a), particularly when combined with implicit communication (Dey et al., 2021; Dietrich et al., 2020a; Izquierdo et al., 2023; Wilbrink et al., 2021). In any case, it is important to highlight that we have not found previous field studies analysing the impact of both implicit and explicit human-AV communication for both pedestrians and passengers, in a real-world setting with an AV without employing Wizard-of-Oz strategies, and involving a complete crossing action, as is the case with the work we present here.

2.3. Pedestrians and passengers studies

The number of studies that focus on concurrently evaluating the interaction of pedestrians and passengers with AVs within the same experiments is very limited. In Colley et al. (2022), the authors investigate the influence of gestures, eHMI, passenger/user position, and their interactions on pedestrian behaviour using a ghost-driver protocol and pre-recorded videos. In Brown et al. (2023), based on the analysis of publicly available videos of AVs operating in real environments, the authors document some compelling examples of unclear communication between AVs and pedestrians, as well as instances where passengers had to apologise for the AV's behaviour. The holistic design of HMIs (Bengler et al., 2020) that accounts for interactions between passengers and pedestrians is clearly an interesting area of research, from which only preliminary insights are currently available (Dong et al., 2024). There is a need for new experiments involving both types of road users.

3. Experiment description

The goal of the study is to determine which factors including the internal and external HMIs and the behaviour of the AV itself contribute to improve the level of confidence perceived by both pedestrians and passengers when interacting with an AV in a crosswalk area. With this goal in mind, an experiment with a total of five tests, four interactions plus a control one was designed.

Our hypothesis is that the use of internal and external HMIs could help to increase the confidence of passengers and pedestrians when interacting with an AV. Furthermore, we believe that the AV's behaviour plays a crucial role in instilling confidence. The smoother the behaviour of the AV, the greater the confidence it imparts to both passengers and pedestrians.

The tests were designed in accordance with reproducibility standards, aiming to guarantee uniform interactions between the AV and all the participants. Following this criteria, the vehicle was programmed to change its speed profile at a specific point depending on the distance to the pedestrian, or more specifically, the distance to the edge of the crosswalk area. This mechanism enables the replication of a consistent behaviour among all participants. The activation of the external and internal HMIs also relies on identical distance thresholds.

The experiment was conducted using the automated and autonomous platform of the INVETT research group (Izquierdo et al., 2019; Parra Alonso et al., 2018). This platform is a commercially available vehicle, modified to be externally controlled by a computer. It is equipped with a comprehensive setup for environmental detection and allows Real-Time Kinematic (RTK) positioning based on GPS (Izquierdo et al., 2019). For this study, we used the front RGB camera and the GPS-based positioning system. Additionally, an internal camera mounted above the HMI was used to record the passengers' reactions. As shown in Figure 2, the experiment was conducted with a backup driver for both legal and safety reasons. We also used a person seated in the rear seats to supervise the operation of the ADS at all times. However, all subjects were duly informed that neither the backup driver nor the system supervisor were intervening during the vehicle's autonomous operation.

Figure 2. View of the vehicle's passenger compartment. 1) The subject is seated in the passenger seat. 2) The backup driver is present but no action is required. 3) The system supervisor is seated in the rear. 4) Internal HMI.

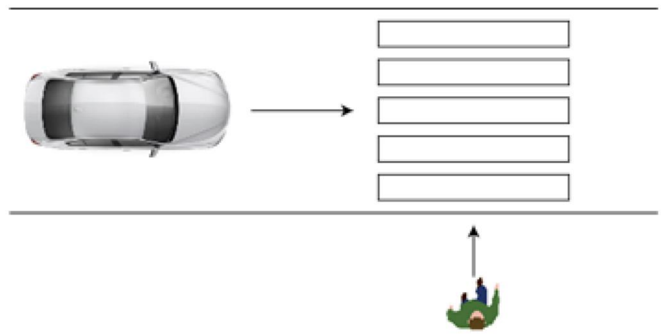
Figure 3. Schematic representation of the experiment use case.

3.1. Use case scenario

The use case evaluated in this study is a complete stop at a crosswalk yielding to a pedestrian that approaches, stands, or crosses the crosswalk. The vehicle drives at a constant speed and at a specific point, (depending on the experiment) reduces its speed to finally stop before the crosswalk, even if the pedestrian chooses not to cross and stands at the limit of the sidewalk. The fact that the vehicle is going to stop under any circumstance is deliberately omitted to the subjects of the experiment to preserve the perception of risk. Figure 3 shows a schematic representation of the interaction between the AV, the passenger, and the pedestrian.

The ground test site must meet certain requirements. First, the pedestrian must not be influenced by any other vehicles. Therefore, a single-lane road is necessary. There must be a crosswalk to perform the tests for the use case. A low-traffic area is also desired so as not to block the road during the trials and not to have other vehicles queuing. Based on these requirements, tests were carried out in the vicinity of the Polytechnic School within the Technological Campus of the University. Figure 4 shows the designated area. The red arrow shows the trajectory of the AV, the green arrow the pedestrian's path, and the yellow circle marks the crosswalk area. While Google Maps aerial images indicate an empty parking area, it was, in fact, occupied by cars during the test. The crosswalk in question is linked to

Figure 4. Location of the experimentation area (40°30′58.1″N 3°20′40.6″W). The red arrow represents the travelling direction of the AV, the green arrow the path of the pedestrian, and the yellow circle the interaction area over the crosswalk.

another one where potential interactions with vehicles moving in the opposite direction may occur. Participants were instructed to only cross to the central island and avoid proceeding further to remove undesired interactions and maintain the pedestrian focus on the experiment.

3.2. Vehicle communication setup

The vehicle is equipped with two HMIs to interact with the passenger inside the AV and the road users. The external HMI (or eHMI) is called GRAIL (Parra Alonso et al., 2018). It is a adjustable RGB LED strip located in the front bumper of the vehicle to interact and communicate with the road users. The intensity and brightness of the illumination are adjustable. The internal HMI (or iHMI) consists of a 16-inch audio-capable screen located on the dashboard in front of the co-pilot to interact with the passenger. Both the eHMI and the iHMI devices are explicit communication tools. In addition, vehicle dynamics are considered as an implicit communication tool and are consequently explored.

3.2.1. External HMI (eHMI)

The external communication device (GRAIL (Parra Alonso et al., 2018)) was configured with three possible states; *off*, *solid red*, and *solid green*. When the state is *off* the LED strip looks like a black strip on the black bumper of the vehicle and it is practically not visible. When GRAIL is actively used, the strip emits a solid red or green light. The *solid red* state is used while the vehicle is travelling at its cruising speed. The *solid green* state is used when the vehicle changes its behaviour and starts to slow down. Note that the goal of the eHMI is not to establish a target-based communication with the pedestrian, but to convey the vehicle's intentions. Figure 5 shows the two active states of the GRAIL device.

The sequence of states the eHMI exhibits during a test, when it is activated, is the following: *LEDs off* (at the beginning of the test with the vehicle stop) → *solid red* (while the vehicle travels towards the interaction area with no obstacles or pedestrians detected) → solid green (at the moment the vehicle starts to brake because has detected the pedestrian) → *LEDs off* (once the vehicle has stopped and the test has concluded). The eHMI has been tested in extreme lighting conditions on sunny days (in summer), and the visibility was found appropriate for the distances required in the experiment.

Figure 5. External HMI (eHMI) - left *solid green* state and right *solid red* state.

Figure 6. Internal HMI (iHMI) states: top left *off*, top right *pedestrian detected*, bottom left *autonomous mode*, and bottom right *manual mode*.

3.2.2. Internal HMI (iHMI)

The internal communication device is a 16-inch audio-capable screen located in front of the co-pilot over the dashboard. It has four possible states; *off*, *autonomous mode*, *manual mode*, and *pedestrian detected*. Figure 6 depicts the four possible states of the iHMI. The default state is *off*, and the screen remains black with no sounds. When it is actively used the screen shows different images or video sources together with audio messages. The *autonomous mode* plays the sentence "*autonomous mode activated*" once at the time the screen changes to its corresponding static image showing the text *AUTONOMOUS MODE* in the Spanish language. When the state changes to *manual mode* the sentence "*autonomous mode deactivated*" is played at the time the screen changes to its corresponding static image showing the text *MANUAL MODE* also in the Spanish language. The state *pedestrian detected* is triggered at a specific distance based on the experiment requirements playing the sentence "*pedestrian detected*" while the exterior camera video stream is reproduced on the iHMI together with a red bounding box over the detected pedestrian and a flashing red rectangle around the limit of the screen. The sequence of states the iHMI exhibits during a test, when it is activated, is the following: *screen off* (at the beginning of the test with the vehicle stop) → *autonomous mode* message displayed on the screed and played on the speakers (when the vehicle starts to move towards the interaction area) → *pedestrian detected* displayed on the screen and pedestrian detected message played on the speakers (at the moment the vehicle starts to brake because has detected the pedestrian) → *manual mode* message displayed on the screen and played on the speakers (once the vehicle has stopped and the test has concluded).

3.2.3. Vehicle dynamics

Vehicle dynamics can be used as an implicit way of communication. In this experiment, the message to be communicated is the intention of the vehicle to stop (or not) at the crosswalk and to yield to the pedestrian. Two alternatives have been proposed to explore this kind of communication.

- *The gentle braking manoeuvre*: This braking manoeuvre is characterised by a smooth and early deceleration. This situation replicates the performance of early detection systems that can provide sufficient anticipation by detecting and predicting the intention of the pedestrian. Consequently, the anticipation of the breaking manoeuvre leads to increased comfort and safety for both passengers and road users.
- *The aggressive braking manoeuvre*: It is characterised by a delayed and stronger deceleration, in opposition to the early braking manoeuvre. This situation replicated the performance of classic Advance Driver Assistance Systems (ADAS) or last-second reaction systems. The delayed initiation of the braking manoeuvre causes a stronger deceleration to stop the vehicle at the limit of the crosswalk compared with the gentle braking manoeuvre.

For practical purposes, these two braking manoeuvres have been generated following a constant acceleration (deceleration) movement according to the desired distance to the stop point at the limit of the crosswalk area. The trigger distances to the stop point are 40 meters for the gentle braking manoeuvre and 20 meters for the aggressive one. The vehicle travels at 30 km/h before the initiation of the braking manoeuvre. Consequently, the constant acceleration is $-0.86\ m \cdot s^{-2}$ and $-1.73\ m \cdot s^{-2}$ for the gentle and aggressive braking manoeuvres, respectively.

3.3. Test configuration

Following the definition of the use case and the possibilities to use the explicit and implicit ways of communication, several tests have been proposed to evaluate how each of these features affects the passenger's and pedestrian's experience interacting with the AV. Note that the iHMI and the eHMI are independent devices that produce independent effects on the passenger and the pedestrian, respectively. The passenger does not perceive the eHMI and the pedestrian does not perceive the iHMI, and more importantly, none of them has the ability to affect the behaviour of the other. For this reason, the combination of the three sources of variability is reduced to two, resulting in a total combination of four variations or tests. Table 1 summarises the configuration for each test. In addition to these four tests, a preliminary test denoted by test 0 was added to create the illusion that the vehicle could cross through the crosswalk without stopping or yielding to the pedestrian.

Table 1. Configuration of experimentation tests.

Test Number	Braking Maneuver	Explicit (Fernández et al., 2021) Internal	Explicit (Fernández et al., 2021) External	Stop
0	–	–	–	No
1	Gentle	–	–	Yes
2	Aggressive	–	–	Yes
3	Gentle	HMI	GRAIL	Yes
4	Aggressive	HMI	GRAIL	Yes

[1]eHMI and iHMI are simultaneously tested. While braking profiles influence both passenger and pedestrian, each HMI system affects only its respective subject.

Tests from 1 to 4 were performed in random order. Test 0 was always performed first. The experimental subjects do not know the order or configuration of each test with the exception of test 0.

3.4. Participants

Participants were recruited from university staff, friends, relatives, and others. They must be over 18 years of age.[3] They were informed of the purpose of the study and what was expected to occur during the study. To formally comply with legal requirements, an informed consent and an informed consent statement were developed to record evidence of the user acceptance and to anonymise the participant's personal information by assigning an anonymous ID.

Participants were instructed to participate in couples and to play both pedestrian and passenger roles. Firstly, one of them performs the passenger role while the other performs the pedestrian role. After finishing the complete set of tests, the participants swap roles to perform the complete set of tests again in the same random order. With this mechanism, we can observe differences in the perception of the interaction between those who were first passengers or pedestrians in case those differences exist.

A total of 34 people joined the experiment but two of them could not complete the whole set of tests due to technical problems and their information was discarded. Therefore, the final number of subjects is $N = 32$, comprising 18 men (56%) and 14 women (44%) with an average age of $\mu = 39.7$ and a standard deviation of $\sigma = 12.6$ years. In Figure 7, we can observe the diversity of the sample distribution differentiated by gender and age.

Each participant needed an average of 90 minutes to complete the experiment, both as a passenger and as a pedestrian. This includes travel time to and from the field testing area, time for explanation of the experiment, handling

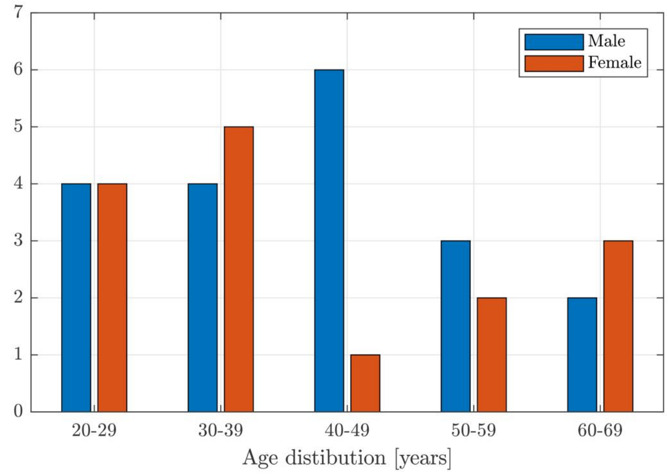

Figure 7. Sample distribution of the subjects participating in the study differentiated by gender and age.

the signing of the consent form, and the time needed to complete the questionnaires after and before the experiment.

3.5. Briefing

Participants were given an explanation of what to expect and what to do in the experiment. This information was repeatedly without variation to all the subjects with the goal of not introducing any external source of change in the experimentation. The participants received an explanation for the tests conducted as a passenger and another as a pedestrian.

As passengers, they were told:

1. There is an HMI which consists of a screen that can display images and reproduce messages.
2. There is a webcam recording the co-pilot seat area.
3. There is a backup driver just to comply with legal requirements.
4. The backup driver is instructed not to intervene unless critical and imminent damage.
5. The vehicle will drive itself autonomously and interact with the pedestrian.

As pedestrians, they were told:

1. There is an HMI consisting of an LED strip that could be off, red, or green (all three modes are displayed to the pedestrian prior to testing).
2. If the LED is off there is no information about the behaviour of the vehicle. If the LED is red, it means that the vehicle is driving at its cruising speed. If the LED is green, it means that the vehicle has detected something in its path and is acting accordingly (note that the specific behaviour of the vehicle is not stated).
3. There is a camera on the vehicle that can see you and record you.
4. There is a backup driver just to comply with legal requirements.
5. The backup driver is instructed not to intervene unless critical and imminent damage.
6. The vehicle will drive itself autonomously and interact with the pedestrian.

Three staff members and two participants are required to conduct the experiment. The participants interact with the vehicle as a passenger and as a pedestrian and the staff is responsible for (1) backup driver, (2) commanding the tests in the AV software, and (3) letting the pedestrian know when to start moving into the interaction area. The pedestrian stands on the sidewalk backward to the crosswalk with no information about the traffic status. At a specific position of the AV the pedestrian is requested to turn around and walk towards the crosswalk area generating a proper and credible interaction.

Furthermore, we rigorously followed internal and institutional ethical assessment and validation procedures, which included informing the participants and obtaining their written consent, ensuring data privacy, allowing subjects to withdraw from the experiment at any time, and implementing data anonymisation, among other protocols.

4. Experiment evaluation

The experiment was evaluated using two different sources of information. Questionnaires are one of the sources of data used for the analysis. With these elements, the analysis was made using subjective information about the interaction from the participant's point of view. Direct measures recorded from the AV's sensors are also used to complete the data for the analysis. This information is objective and allows us to objectively analyse the interactions.

4.1. Questionnaires

Two questionnaires were developed to record the participants' opinions. The first questionnaire records general knowledge about AVs, past experiences and interactions with AVs, and expectations. This questionnaire is filled out by participants before and after the experimentation. We refer to this questionnaire and its questions as **QBAx** where x is the question number. The goal is to verify with a manipulation check if the participants correctly understood that they have interacted with an AV and to evaluate how their experiences and expectations about AVs have changed after the experimentation. The second questionnaire is designed to assess passenger and pedestrian confidence and feelings about the interaction with the AV after each test. These questions were formulated using the 7-step Likert scale when possible. Right after each test and before starting the following one all the questions were answered. We refer to this questionnaire and its questions as **Qy-Key-variable** where y is the question number and key-variable is the variable measured in the question. This questionnaire has three questions that are answered when interacting as a pedestrian (**Q1-Pedestrian-Confidence-Yield**, **Q2-Pedestrian-Brake-Manoeuvre** and **Q3-Pedestrian-eHMI-Improvement**) and four for passenger interaction (**Q4-Passenger-Confidence**, **Q5-Passenger-Brake-Manoeuvre**, **Q6-Passenger-iHMI-Improvement** and **Q7-Passenger-iHMI-Preference**). See Appendices A and B for a complete description of the questionnaires.

4.2. Direct measuring

Different sources of information are needed to directly measure the interaction between the AV and the participants in addition to the questionnaires. For each experiment, the following information was recorded by the AV software:

- AV logging file including vehicle position, speed, and distance to the pedestrian.
- In-vehicle external video and time logging.
- Internal video of the co-pilot area and time logging.
- Communication log between AV and HMI systems.

By processing video and data information it is possible to determine when and where the pedestrian decides to cross through the crosswalk. This event is of utmost importance because it is ultimately affected by the type of interaction between the AV and the pedestrian and can reveal how the eHMI and the implicit communication affect the interaction.

The crossing decision event is defined as the moment in which the pedestrian makes the mental decision to cross. We follow the hypothesis that the decision to cross is a hidden state with an external and delayed manifestation that can be observed. The delay between the decision and its external manifestation can vary depending on the person and the situation. Alternatively, to the crossing decision event, we propose to use the crossing event as the metric to evaluate the behaviour of the pedestrian using direct measurements. The crossing event is defined as the frame in which the pedestrian enters the vehicle lane and physically exposes his/her body to a potential and real injury. The background idea is that an early crossing decision will produce an early crossing event and a late crossing decision will produce a late crossing event. The main difference is that the crossing event is not a hidden state. It is directly observable and can be unequivocally identified when the vehicle lane is defined using the road marks. Figure 8 shows the vehicle lane boundary at the crossing event frame. It is defined as the moment the pedestrian enters the area of the vehicle's lane. See Figure 9 for a crossing sequence description example.

Figure 8. Crossing event example. Vehicle lane is defined by road marks unequivocally for all the tests.

Several physical variables can be used to analyse the interaction between the AV and the pedestrian. The recording platform provides two direct measurements, the distance to the zebra crossing and the speed of the vehicle. However, other dependent variables such as the Time To Collision (TTC), the solid angle represented by the vehicle (Ω), or its change rate ($d\Omega/dt$) are commonly used in the analysis of dynamic time-distance problems. The TTC is a *vehicle-centric* variable that depends on the vehicle's speed and the distance to the pedestrian. It can effectively measure the potential risk perceived by the pedestrian. However, if we analyse the interaction from the pedestrian point of view, and more specifically from the optical point of view, the volume of the vehicle (or its solid angle) and its change rate must be considered to correctly measure the potential risk perceived by the pedestrian.

The TTC is a magnitude measured in seconds that represents how many seconds the vehicle needs to hit the

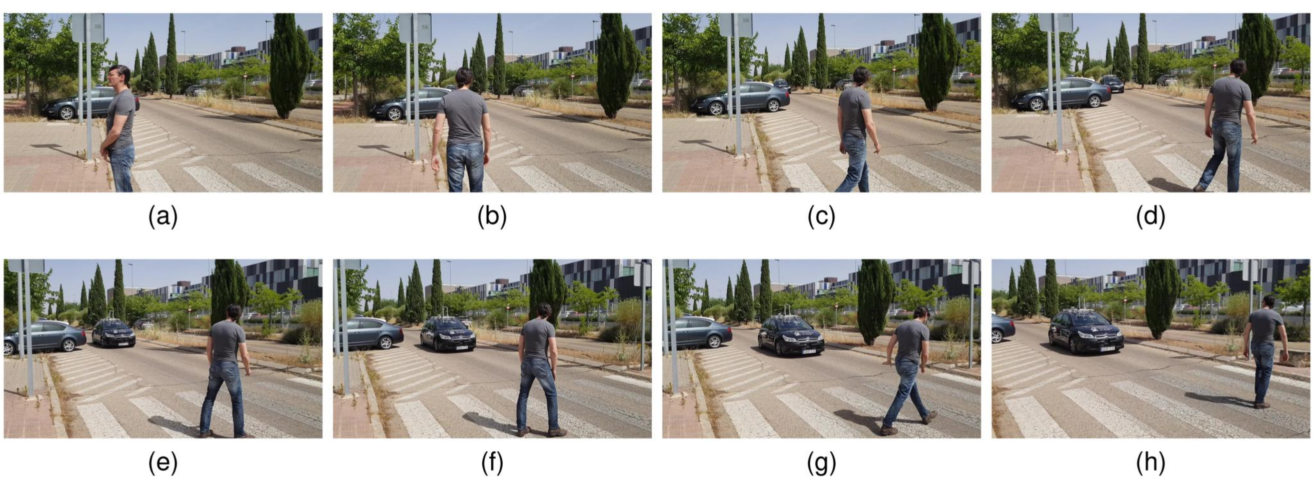

Figure 9. Example of vehicle-pedestrian interaction - exterior camera. (a) Initial position of pedestrian back to the crosswalk. (b) The pedestrian turns and faces the crosswalk. (c) The pedestrian starts walking and sees the vehicle approaching. (d) At this point, the pedestrian hesitates to cross. (e) The pedestrian is still waiting for the vehicle's reaction. (f) The pedestrian does not feel comfortable crossing while the vehicle is moving. (g) The pedestrian decides to cross when the vehicle is almost stopped. (h) The pedestrian crosses the crosswalk.

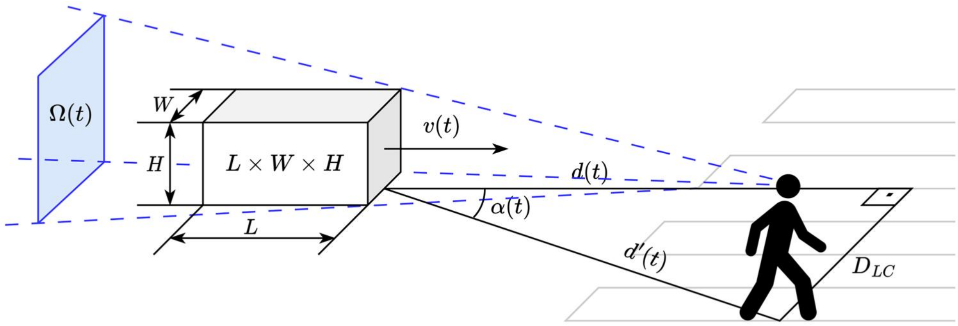

Figure 10. Schematic representation of a simplified moving vehicle and its observation from the pedestrian's point of view.

Figure 11. Example of vehicle-pedestrian interaction - in-vehicle camera. Images from (a) to (h) correspond to the same frames and descriptions as in Figure 9.

pedestrian if the vehicle continues at the same speed. Its calculation is simple and it is the quotient of the distance to the pedestrian d over the vehicle speed v.

$$TTC = d/v \quad (1)$$

Figure 10 shows a representation of a vehicle simplified by a rectangular parallelepiped with dimensions $L \times W \times H$ (Height, Width, and Length) driving towards a crosswalk area at a distance $d(t)$ with a given velocity $v(t)$. The constant D_{LC} represents the distance from the pedestrian standing point to the vehicle's lane centre. The pedestrian observation angle $\alpha(t)$, formed by the vehicle's moving direction, and the pedestrian observation line is computed according to Equation 2.

$$\alpha(t) = \tan^{-1} D_{LC}/d(t) \quad (2)$$

Given the observation angle $\alpha(t)$, the apparent distance $d'(t)$ between the vehicle and the pedestrian can be computed as it is shown in eq. 3.

$$d'(t) = d(t)/\cos\alpha(t) \quad (3)$$

$\Omega(t)$ is the solid angle represented by the vehicle being observed from the pedestrian's point of view and it is computed as:

$$\Omega(t) = \frac{A(t)}{r(t)^2} = \frac{H(W\cos\alpha(t) + L\sin\alpha(t))}{d'(t)^2} \quad (4)$$

The change rate of the solid angle, $d\Omega(t)/dt$, is often used as a parameter to measure the reaction to a moving object. Usually, 0.2 rd/s is considered the threshold to visually trigger a reaction.

4.3. Experiment samples

Figures 9, 11, and 12 show different instances of one of the test from three different perspectives. Figures 13 and 14 depict different calculated variables for the same experiment.

Figures 9 and 11 show the four main states of the pedestrian during an interaction with the AV. First, the pedestrian is standing back to the crosswalk (Figure 9a). Then, the pedestrian turns around (Figure 9b) and walks towards the crosswalk (Figure 9c) and observes the vehicle approaching (Figure 9d). The pedestrian decides if it is safe or not to cross and delays the action if it is not safe enough (Figure 9e,f). Finally, the pedestrian feels confident enough to cross through the crosswalk (Figure 9g).

Figure 12 depicts different instances of the passenger interacting with the iHMI while the AV is interacting with the pedestrian at the crosswalk. It can be observed how the iHMI draws the passenger's attention when voice messages are played (Figure 12b,d).

Figure 13 shows some recorded variables such as the distance to the pedestrian, the speed of the vehicle, and the calculated TTC. On the time axis, there are two time-events

Figure 12. Example of vehicle-passenger interaction - Internal video of the co-pilot area. (a) The passenger, just before the start of the test, looks forward. (b) “autonomous mode on” displayed on the screen and played back on the speakers. (c) The test begins and the vehicle starts to move forward. (d) Outdoor video with detections displayed on the iHMI and “pedestrian detected” played on speakers. (e) The passenger looks at the pedestrian after the interaction with the iHMI. (f) The passenger follows the pedestrian with his eyes as s/he crosses the road.

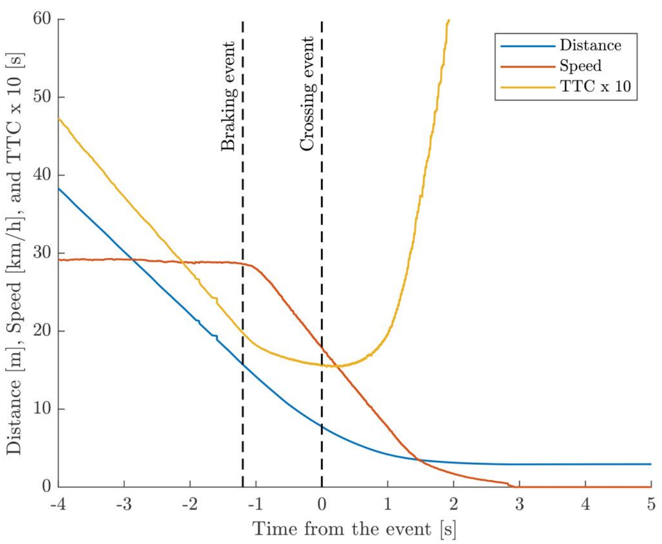

Figure 13. Observed time to collision based on the distance to the pedestrian and the vehicle speed for one of the tests. Time axis is referred to the *crossing event* and the vertical dashed lines represented the *crossing event* and the *braking event*.

marked, one at $t = 0$ which corresponds with the labelled crossing event (exemplified in Figure 9f) and another at $t = -1.2$ approximately, corresponding with the trigger of the braking manoeuvre. Figure 14 depicts the recorded variable distance to the pedestrian and the computed solid angle $\Omega(t)$ and its temporal variation $d\Omega(t)/dt$ for the same experiment. Time marks are the same as for Figure 13. By combining the recorded and computed variables with the *crossing event* a set of statistics related to the interaction can be generated. For this example it is known that the pedestrian enters the vehicle lane when the vehicle is at 8 meters distance, driving at 17 kph, representing a 0.5 sr solid angle with a change rate of 0.45 sr/s.

The solid angle represented by the vehicle follows an opposite trend as the distance and the speed. While speed and distance decrease when the vehicle is approaching the pedestrian the solid angle increases. The change rate of the solid angle $d\Omega/dt$ has a different behaviour. It is similar to the solid angle Ω at far distances, but as a result of the vehicle deceleration, it starts to decrease while the solid angle continues growing. This inflection point can be observed in Figure 14, approximately at $t = 1s$. It can be observed that the *crossing event*, which is a posterior manifestation of the *crossing decision*, is produced 0.6 seconds after the change rate of the solid angle reaches the 0.2 sr/s threshold.

5. Results

This section presents and analyses systematically for each type of interaction with the AV the responses to the questionnaires in subsection V-A and the measured and derived variables in subsection V-B. Descriptive statistics and the Wilcoxon signed-rank test for paired samples have been used to conduct the analysis of the questionnaires. On the other hand, the Student t-test has been used to extract information from the direct measured and computed variables.

5.1. Questionnaire results

This subsection presents the results of the surveys conducted before, during, and after the experimentation. The answers to questionnaire 2 (Appendix B) are presented as the frequency for each question and test on Table 2. The most repeated value (mode) is presented in bold for each question and test.

The responses of the participants are now evaluated against tests, by means of the alternative hypothesis matrix. Using the Wilcoxon signed-rank test with Bonferroni correction for paired samples the answers provided by each participant are evaluated to find differences with statistical significance among the interactions. For the significance level, a parameter $\alpha=0.05$ has been selected. The alternative hypothesis matrix systematically evaluates the null hypothesis of the specific test against others. As the null hypothesis, we propose $H_0 : \mu_i \leq \mu_j$ and as the alternative hypothesis, we take $H_1 : \mu_i > \mu_j$. A checkmark in a specific cell in the matrix means that H_0 is rejected and H_1 is accepted when comparing the answers provided in test *i* (row) with test *j* (column). In this specific context, the rejection of H_0 means that there is a difference with statistical significance between the answers for tests *i* and *j*, and the answers for test *i* have a higher score in the Likert scale than for test *j*.

Table 3 shows the alternative hypothesis matrix. Cells with a checkmark represent cases in which the null hypothesis H_0 is rejected and the alternative hypothesis H_1 is accepted. This table will be used in section VI to interpret the effect of the different test configurations on the participants and their confidence in the AV. Figure 15 shows in a boxplot representation the distances, speeds and TTCs for each test in the upper row. The lower row shows the *crossing event's* distribution for each analysed variable as a histogram representation for the four conditions. It can be observed that the median distance in Figure 15a presents a higher median and higher extreme values for *gentle* and *gentle + HMIs* compared with *aggressive* and *aggressive + HMIs*. The distribution of the *crossing event* with respect to the distance variable shown in Figure 15c, on the other hand, shows how the distribution is shifted to the left (smaller distances) for the *aggressive* and *aggressive + HMIs* conditions while the *gentle* and *gentle + HMIs* are shifted to the right (greater distances). This information will be analysed in depth in section VI.

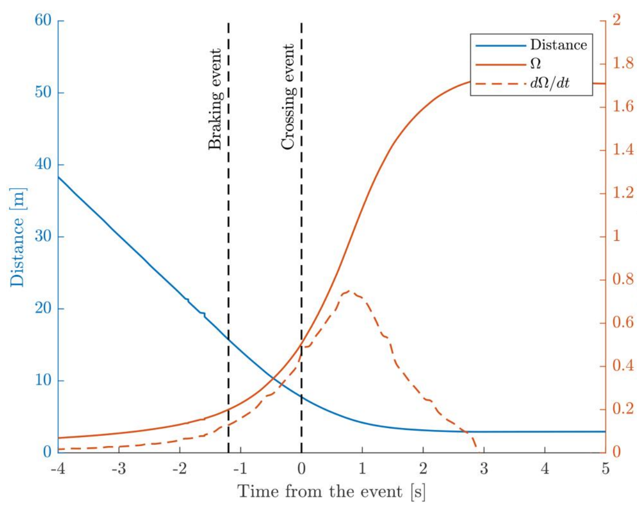

Figure 14. Observed vehicle solid angle and its temporal change rate calculated based on the distance to the pedestrian for one of the tests. Time axis is referred to the *crossing event* and the vertical dashed lines represented the *crossing event* and the *braking event*.

Another investigation is whether participating first as a passenger and then as a pedestrian or vice versa has any effect on the interaction experienced with the AV. Table 4 follows the same alternative hypothesis matrix analysis of the responses provided by the subset of participants being first passengers and the subset of participants being first pedestrians. No consistent differences have been found between these two groups. Only two different questions in two different tests show differences with statistical significance in their responses.

The previous and after-experimentation questionnaire (**QBA**) shows the change in general confidence when interacting with the AV as a pedestrian and passenger. Tables 5 and 6 show the transition matrix for the responses to questions **QBA3**-"Level of confidence interacting with an AV as a passenger" and **QBA4**-"Level of confidence using an AV as a pedestrian", respectively. The red area of the table represents transitions in which the answer has a higher value after the experimentation than before. The blue area represents a lower value for the answer after the experimentation and the green one represents no change in the answer. It can be observed that the general confidence as a user of an AV has been increased after the experimentation (**QBA3** - Table 5) with 18 increases (total counts in red area) in the confidence versus 1 decrease (total counts in blue area). The confidence interacting with an AV as a pedestrian (**QBA4** - Table 6) has also increased with 24 responses with a higher confidence value after the experimentation (total counts in

Table 2. Answers' frequency by test and question.

		Question 1				Question 2				Question 3				Question 4				Question 5				Question 6				Question 7			
Test n °		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Answer code	0	0	0	0	0	0	0	0	0	**32**	**31**	2	1	0	0	0	0	0	0	0	0	**32**	**32**	1	1	**32**	**32**	1	1
	1	0	0	0	0	4	0	3	0	0	0	1	1	0	0	0	0	2	0	0	0	0	0	3	3	0	0	7	10
	2	1	2	0	1	5	0	9	0	0	0	0	2	0	0	0	0	6	0	3	0	0	0	0	1	0	0	9	9
	3	4	4	1	3	9	0	7	3	0	0	1	2	0	2	0	0	4	1	3	0	0	0	1	2	0	0	**15**	**12**
	4	5	**11**	1	4	**14**	**21**	**13**	**18**	0	1	2	5	2	9	1	5	**20**	7	**25**	11	0	0	6	7	0	0		
	5	7	5	4	7	0	11	0	10	0	0	8	5	9	**13**	6	**11**	0	**19**	1	**17**	0	0	**10**	**11**	0	0		
	6	6	5	12	**11**	0	0	0	1	0	0	**9**	**11**	10	3	12	10	0	5	0	3	0	0	8	6	0	0		
	7	**9**	5	**14**	6	0	0	0	0	0	0	**9**	5	**11**	5	**13**	6	0	0	0	1	0	0	3	1	0	0		

Frequency distribution of answers to each question (Q1-Q7) for the study questionnaire 2 for every test (1-4) under the Likert scale codification (1-7 plus 0 in case it is not answered or perceived). Mode values for each question-test are represented in bold.

Table 3. Wilcoxon signed rank test for questions Q1-Q6.

			Test number j			
$H_1 : \mu_i > \mu_j$			1	2	3	4
Test number i	Q1 - Pedestrian level of confidence that the vehicle stops and yield					
	90	1	–			
		2		–		
		3	✓	✓	–	✓
		4		✓		–
	Q2 - Pedestrian perception of the braking manoeuvre					
	90	1	–			
		2	✓	–	✓	
		3			–	
		4	✓		✓	–
	Q3 - Effect of the eHMI on the pedestrian’s confidence					
	90	1	–			
		2		–		
		3	✓	✓	–	
		4	✓	✓		–
	Q4 - Passenger level of confidence on the vehicle					
	90	1	–	✓		✓
		2		–		
		3		✓	–	✓
		4		✓		–
	Q5 - Passenger perception of the braking maneouvre					
	90	1	–			
		2	✓	–	✓	
		3	✓		–	
		4	✓		✓	–
	Q6 - Effect of the iHMI on the passenger’s confidence					
		1	–			
		2		–		
		3	✓	✓	–	
		4	✓	✓		–

Question description is a short-simplified version of the full question.
Refer to Appendix B for full description.

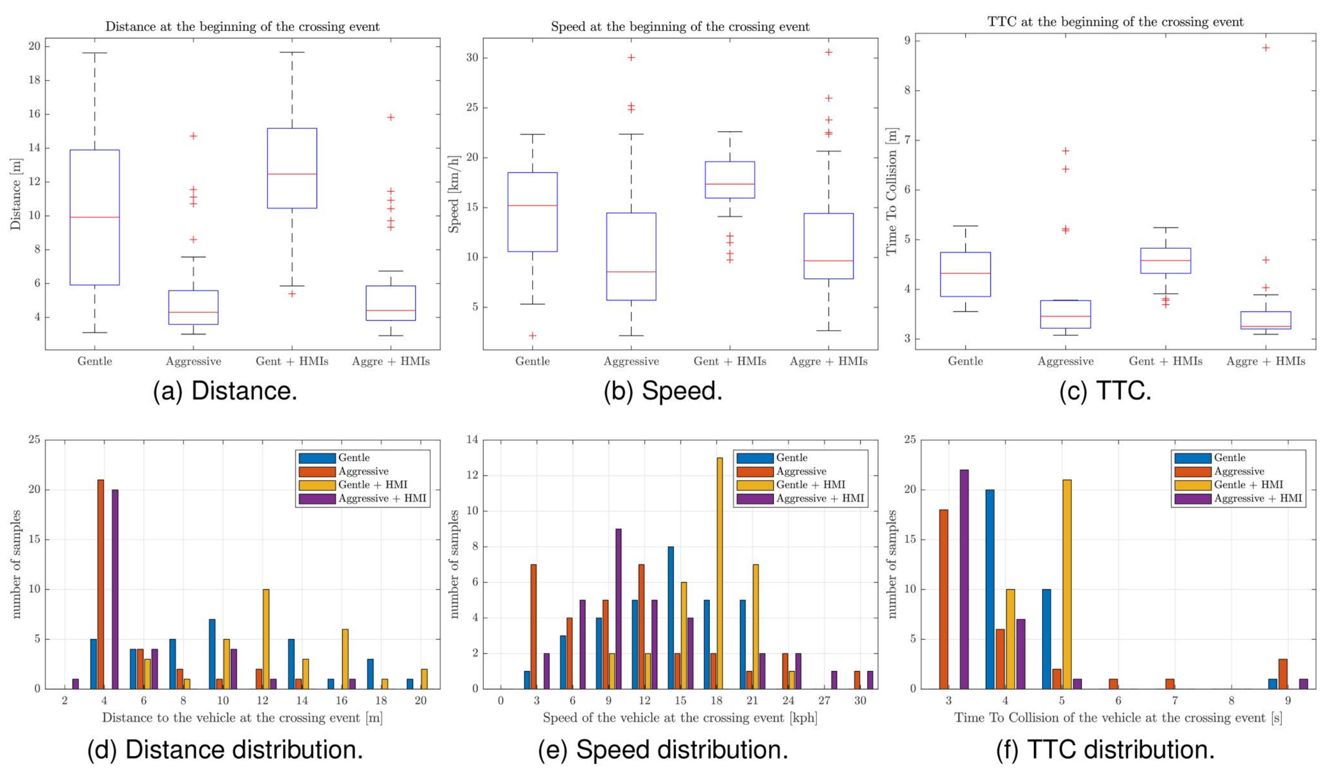

Figure 15. Upper row - Representation of distance, speed and TTC variables for the four tests at the crossing event. Each boxplot represents the median (red line), 25 and 75 percentiles (lower and upper limit of the box), the upper and lower limit of the data (upper and lower whiskers) and outliers (red plus) for a *whisker* value equal to 1. Lower row - Histogram representation of the *crossing event’s* distribution for each one of the analysed variables. Each test is represented with different colours as stated in the legend.

Table 4. Wilcoxon signed rank test for questions begin first passenger vs pedestrian.

$H_1 : \mu_{pass} > \mu_{ped}$		Test number j 1	2	3	4
Question number	Q1 - Ped-Confidence-Yield		✓		
	Q2 - Ped-Brake-Manoeuvre				
	Q3 - Ped-eHMI-Improvement				✓
	Q4 - Pass-Confidence				
	Q5 - Pass-Brake-Manoeuvre				
	Q6 - Pass-iHMI-Improvement				

Question description is a short-simplified version of the full question. Refer to Appendix B for full description.

Table 5. QBA3 - Answer Transition matrix.

		Answer Code After 1	2	3	4	5	6	7
Answer Code Before	1							
	2							
	3				1	2		
	4				4	8	2	
	5					4	5	
	6					1	5	
	7							

Change in the responses to question QBA3 from questionnaire 1 - "Level of confidence using an AV as a passenger" with respect before and after conducting the experiment. Values in the diagonal (green background) show the number of subjects that manifest the same level of "confidence". Values above the diagonal (red background) represent the number of subjects that manifest an increment in the confidence and its magnitude (2 subjects changed their confidence level from 4 to 6 for example) after the experimentation. Values below the diagonal (blue background) represent the number of subjects that manifest a decrement in confidence. 18 subjects manifested an increment in confidence after experimenting with the AV as a passenger, 13 stated the same level of confidence and 1 stated a decrement.

Table 6. QBA4 - Answer Transition matrix.

		Answer Code After 1	2	3	4	5	6	7
Answer Code Before	1				1			
	2							
	3				4	2	1	
	4				3	6	4	
	5					1	6	
	6					1	3	
	7							

Change in the responses to question QBA4 from questionnaire 1 - "Level of confidence interacting with an AV as a pedestrian" with respect before and after conducting the experiment. Values and colors follow the same codification as in Table 6. 25 subjects manifested an increment in confidence interacting with an AV as a pedestrian after experimenting with it, 7 stated the same level of confidence and 1 stated a decrement.

red area) versus 1 with a lower confidence (total counts in blue area).

5.2. Measurements results

This subsection analyzes the direct measures recorded during the experimentation and the variables computed from them. The recorded measures are the position and the speed of the AV which endows the calculation of the distance to the pedestrian, the TTC, and the solid angle and its change rate.

Table 7. Student t-test for distance, speed, TTC, Ω and $d\Omega/dt$ at the crossing event.

$H_1 : \mu_i > \mu_j$			Test number j 1	2	3	4
Test number i	Distance	1	–	✓		✓
		2		–		
		3	✓	✓	–	✓
		4				–
	Speed	1	–	✓		
		2		–		
		3	✓	✓	–	✓
		4				–
	TTC	1	–	✓		✓
		2		–		✓
		3	✓	✓	–	✓
		4				–
	$\mathbf{\Omega}$	1	–		✓	
		2	✓	–	✓	
		3			–	
		4	✓		✓	–
	$d\mathbf{\Omega}/dt$	1	–		✓	
		2	✓	–	✓	
		3			–	
		4	✓			

In contrast to the questionnaires, these variables are analysed using the Student-t test with Bonferroni correction for paired samples together with the alternative hypothesis matrix. The confidence parameter is also set to α =0,05. Table 7 shows the systematical analysis of the variables for each test configuration of the experiment.

There is a special consideration in Table 7. The distance, speed, and TTC are decreasing monotonic variables, at least until the *crossing event* in most of the cases. The TTC starts to grow at a specific point that can take place before or after the *crossing event*. However, the solid angle is an increasing monotonic variable, and its change rate is also an increasing monotonic variable until a point that usually takes place after the *crossing event*. This opposite behaviour of the study variables produces that the responses have the opposite difference and the alternative hypothesis matrix shows complementary results for these two variables. It can be observed clearly at the column of test number 3 in Table 7. None of the null hypotheses are rejected in the column of test number 3 according to the distance, speed, or TTC, but it is rejected according to the solid angle and its change rate.

Following the same structure for the analysis as in Section V-A, the alternative hypothesis matrix is also studied for the subset of participants being first pedestrians and passengers. There is no difference in the observed or computed variables between the two groups. For simplicity, this matrix has been deliberately omitted because it is populated only with zeroes.

6. Discussion

This section analyses and discusses how the different ways of communication affect the level of perceived confidence of pedestrians and passengers when interacting with the AV based on the results provided in Section V. It also summarises the primary limitations of the study.

6.1. General findings

Findings provided in this subsection are supported by the responses to questionnaires 1 and 2, direct and indirect measurements and their analysis.

The following conclusions can be drawn for pedestrians:

- **The use of the gentle braking manoeuvre does not increase pedestrians' confidence in the AV to yield compared with the aggressive braking when the eHMI is not used**. This statement is supported by responses to **Q1-Ped-Conf**, comparing tests with gentle braking (test 1) versus aggressive braking (test 2). The notation (**Q1-Ped-Conf**: t1 vs t2) is used to denote the relevant comparisons.
- **The use of the gentle braking manoeuvre increases pedestrians' confidence in the AV to yield compared with the aggressive braking when the eHMI is used** (**Q1-Ped-Conf: t3 vs t4**).
- **The eHMI increases pedestrians' confidence in the vehicle to yield independently of the braking manoeuvre** (**Q1-Ped-Conf-Yield**: t3 vs t1 and t4 vs t2).
- **Pedestrians perceived aggressive braking manoeuvres as more aggressive than gentle braking manoeuvres** (**Q2-Ped-Brake-Man**: t2 vs t1 and t4 vs t3). This manipulation check confirms the intended perception of the braking manoeuvres.
- **The gentle braking manoeuvre anticipates the crossing event compared with the aggressive one, independently of using the eHMI** (dist.-speed-TTC: t1 vs t2 and t3 vs t4), which implies an earlier crossing decision. This aligns with the increased confidence in the AV to yield observed in the questionnaire responses. As the deceleration profiles are fixed, a higher distance will result in a higher speed and commonly (above 10 meters of distance) a higher TTC.
- **The use of the eHMI combined with the gentle braking anticipates the crossing event** (dist.-speed-TTC: t3 vs t1). However, this effect is not observed with aggressive braking (dist.-speed-TTC: t4 vs t2). This discrepancy suggests that while the eHMI increases perceived confidence, it does not significantly alter crossing behaviour in high-risk scenarios.

These conclusions present findings that align with and, in some cases, diverge from previous works. In line with Dey and Terken (2017), the results demonstrate that implicit cues (gentle vs. aggressive braking) and explicit signals from eHMI influence pedestrian confidence. However, our findings suggest that gentle braking is more effective in increasing pedestrian confidence when eHMI is used, supporting the importance of combining these signals, as emphasised in Dey and Terken (2017). Similarly Dey et al. (2021), highlights the role of vehicle behaviour in modifying pedestrian responses, which aligns with our finding that gentle braking anticipates crossing decisions and, when combined with eHMI, further enhances pedestrian confidence. In contrast Dey et al. (2020b), suggests that eHMI should have a significant impact even in high-risk scenarios, while our study shows that in aggressive braking scenarios, eHMI does not significantly alter crossing behaviour. This indicates that confidence may not be reinforced under critical conditions where aggressive braking manoeuvres are involved. Lastly, studies such as Lee et al. (2022) and Carmona et al. (2021) emphasise the importance of familiarity with eHMI for effective interpretation, which corresponds to our finding that eHMI combined with gentle braking generates more positive responses, likely due to a more intuitive understanding of the system in less risky situations. This idea reinforces the choice of green and red colours for eHMIs in opposition to Rouchitsas and Alm (2019) where turquoise is recommended.

The following conclusions can be drawn for passengers:

- **The gentle braking manoeuvre increases passengers' confidence in the AV compared with the aggressive one** (**Q4-Pass-Conf**: t1 vs t2 and t3 vs t4).
- **The iHMI increases passengers' confidence in the vehicle during aggressive braking manoeuvres** (**Q4-Pass-Conf**: t4 vs t2).
- There is no statistically significant difference indicating that the iHMI increases passengers' confidence during gentle braking manoeuvres (**Q4-Pass-Conf**: t3 vs t1). The data suggest that with smooth driving behaviour, the vehicle's dynamics anticipate enough the intention to stop and the information provided by the iHMI is unnecessary, while in the case of the aggressive braking manoeuvre, the iHMI reinforces the idea of the detection of the pedestrian and the stopping behaviour.
- **Passengers perceived aggressive braking manoeuvres as more aggressive than gentle braking manoeuvres** (**Q5-Pass-Brake-Man**: t2 vs t1 and t4 vs t3), confirming the manipulation check.
- **Passengers preferred the combined mode (audio plus video) for the iHMI over audio or video alone** (**Q7-Pass-iHMI-Preference**: t3 y t4 in Table 2).

Our study's findings on passengers' confidence and perception of AV behaviour align with several insights from existing research, although certain distinctions are observed. The increase in passenger confidence during gentle braking manoeuvres, as demonstrated in our study, is consistent with the idea that smoother vehicle dynamics enhance user comfort and trust, which aligns with the guidelines provided in Carmona et al. (2021), emphasising the importance of clear, reassuring communication. Furthermore, the role of iHMI in reinforcing confidence during aggressive braking is in agreement with Dey and Terken (2017), which highlights the importance of explicit communication in high-risk situations. However, the lack of significant improvement in passenger confidence, when iHMI is used during gentle braking contrasts with the suggestion in Dey et al. (2020a), that multimodal communication (such as iHMI) should generally enhance trust. This discrepancy may be explained by the finding that, as shown in our study, passengers perceive smooth driving behaviour as sufficiently communicative, making additional input from iHMI unnecessary during gentle braking. Finally, the passengers' preference for a combined audio-visual iHMI, observed in our research, supports the conclusions from Dey et al. (2020b), which advocate for multimodal communication to improve the clarity and effectiveness of AV signals.

Finally, the analysis of the **QBA** reports a generalised increase in confidence in the AV as a pedestrian and passenger has been reflected after participating in the experiment. Based on **QBA4**, 24 participants (75%) reported increased confidence interacting with an AV as a pedestrian after the experiment, 7 (21.88%) reported no change, and 1 (3.125%) reported decreased confidence. Based on **QBA3**, 18 participants (56.25%) reported increased confidence in AVs after the experiment, 13 (37.5%) reported no change, and 1 (3.125%) reported decreased confidence.

An investigation into whether the initial role played by participants influenced their confidence in the AV revealed no additional findings, as shown in Table 4. Participants who started as pedestrians exhibited similar levels of confidence both as pedestrians and as passengers, compared to those who initially started as passengers.

6.2. Main limitations

Human-factors studies in the context of autonomous driving are highly complex and costly to conduct. The results and conclusions drawn are always bound to the specific conditions of the studied scenario (i.e. a one-lane road with human-vehicle interaction within a crosswalk).

On the other hand, while the sample size of participants in the study is reasonably large in comparison to the state of the art, and particularly diverse in terms of age and gender, the interpretation of the results should be conservative as the sample size will always be insufficient to draw universal conclusions. For instance, underlying biases such as cultural factors must always be taken into account. Other variables include weather and lighting conditions, which were kept constant in our study for daytime conditions on a sunny day. Consequently, the obtained results cannot be generalised to other lighting or weather conditions. It would be particularly interesting to study the effect of the eHMI in nighttime or rainy conditions, where paradoxically, it would be more visible due to the higher contrast compared to the general lighting conditions. Lastly, it is important to highlight a demographic that was not included in our study, namely children and teenagers. The results and conclusions, thus, cannot be extrapolated to minors.

7. Conclusions and future work

This work explores the capabilities of explicit and implicit ways of communication to affect the confidence of passengers and pedestrians in AVs when interacting in a crosswalk through real-world experimentation. Two different braking speed profiles in combination with the use (or not) of internal and external HMIs have been evaluated under this study. Questionnaires related to the user's experience during the interaction and direct measures such as the distance at the crossing event have been used to extract conclusions from the experiment.

Questionnaires and direct measurements have proven that the iHMI and eHMI in combination with a gentle braking manoeuvre help to increase the confidence in the AV when interacting with a pedestrian in a crosswalk for both the pedestrian and the passenger. However, there is a relevant difference between conclusions derived from questionnaires and measured variables. When comparing the tests using the aggressive braking manoeuvre, pedestrians express more confidence when using the eHMI than when not using it. However, it does not result in an earlier crossing event and consequently in an earlier crossing decision. This fact suggests that the perception of risk due to the vehicle dynamics has more weight in the decision than the information shared from the eHMI.

As future work, this study could be replicated and expanded to include different traffic scenarios. A logical extension would involve examining the same types of interactions in non-signalised crossing areas where pedestrians do not have priority over oncoming vehicles. The study could also be broadened to include demographics not present in the current sample, such as children and teenagers. Other elements to consider include different weather or lighting conditions, or even different types of HMIs. However, it should be noted that the complexity of human-factors studies increases significantly when additional variables are introduced for analysis. Moreover, some variables, such as weather, lighting, or traffic conditions, are difficult to control. Given these challenges, along with the difficulty of conducting this study in a controlled real-world environment and extending it to minors, a potential solution could involve replicating the study in Virtual Reality (VR). This would not only allow for the inclusion of a wider demographic in the study but also provide a means to measure the reality gap among users already present in the current study.

Notes

1. With respect to the terminology, in this work, we follow the proposal presented in Fernández et al. (2021). We use *automated vehicle/driving* for SAE Level 3 (a backup driver/user is in charge), and autonomous vehicle/driving for SAE Levels 4 and 5 (passenger/unoccupied). We use Automated Driving System (ADS) to generically refer to SAE Levels 3 to 5 (automated and autonomous driving). Finally, when we use the acronym AV, we refer to automated and/or autonomous vehicles indistinctly.
2. All participants are instructed to take into account that the backup driver is not participating in the driving tasks, and is just there for safety reasons.
3. Due to the innovative nature and special features of our experimental work, which includes interactions in real traffic conditions with an AV and a pedestrian executing a complete and realistic crossing action, minors were not included in our study sample. Nonetheless, the insights gained from our research allow us to propose the inclusion of minors as an area for future investigation.

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Safety and ethical considerations

The fundamental pillar guiding the design of the experiment has been the safety of all participants above any other consideration. On one hand, we chose to implement Level 3 automation in our testing conditions, despite the fact that Level 4 automation (where the subject is a passenger and the sole occupant of the vehicle) could have been possible. This decision necessitated the presence of a backup driver ready to resume control when needed. In addition, a human supervisor in the rear seats was monitoring the status of all perception and control systems, including access to an emergency stop function. Therefore, human intervention was always possible, both by the backup driver and the supervisor. On the other hand, our braking profiles are designed to be extremely conservative. Even the "aggressive profile" maintains a substantial margin for reaction, prioritising safety above all else. Furthermore, we rigorously followed internal and institutional ethical assessment and validation procedures, which included informing the participants and obtaining their written consent, ensuring data privacy, allowing subjects to withdraw from the experiment at any time, and implementing data anonymisation, among other protocols.

Disclaimer

The views expressed in this article are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission.

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The authors report there are no competing interests to declare.

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Appendix A. Study questionnaire 1

- **QBA1**: What is your knowledge about autonomous vehicles?
  1) None; 2) Very little; 3) Little; 4) Medium; 5) Quite a lot; 6) A lot; 7) Expert.
- **QBA2**: Have you had any experience as a user or pedestrian with an autonomous vehicle?
  1) Yes; 2) No; 3) Do not know / Do not answer.
- **QBA3**: What is your confidence regarding the use of an autonomous vehicle?
  1) Not at all; 2) Very little; 3) Little; 4) Medium; 5) Quite a lot; 6) A lot; 7) Total.
- **QBA4**: As a pedestrian, what is your confidence regarding interaction with an autonomous vehicle?
  1) Not at all; 2) Very little; 3) Little; 4) Medium; 5) Quite a lot; 6) A lot; 7) Total.

The prefix **QBA** indicates that the questions were answered both before (**QB**) and after (**QA**) conducting the experiment.

Appendix B. Study questionnaire 2

When participating as a pedestrian the questions are:
- **Q1**: What was your level of confidence that the vehicle would stop and yield to you?
  1) No confidence; 2) Very little confidence; 3) Little confidence; 4) Medium confidence; 5) Quite a lot of confidence; 6) A lot of confidence; 7) Total confidence.
- **Q2**: How did you perceive the braking of the vehicle?
  1) Too conservative; 2) Quite conservative; 3) Somewhat conservative; 4) Adequate; 5) Somewhat aggressive; 6) Quite aggressive; 7) Too aggressive.
- **Q3**: Has the visual communication interface improved your confidence to cross?
  0) Do not perceive any visual signal; 1) Not at all; 2) Very little; 3) A little; 4) Somewhat; 5) Quite a lot; 6) A lot; 7) Very much.

When participating as a passenger the questions are:
- **Q4**: What has been your confidence in the vehicle?
  1) No confidence; 2) Very little confidence; 3) Little confidence; 4) Medium confidence; 5) Quite a lot of confidence; 6) A lot of confidence; 7) Total confidence.
- **Q5**: How did you perceive the braking of the vehicle?
  1) Too conservative; 2) Quite conservative; 3) Somewhat conservative; 4) Adequate; 5) Somewhat aggressive; 6) Quite aggressive; 7) Too aggressive.
- **Q6**: Has the audiovisual communication interface improved the level of confidence in the vehicle?
  0) Do not perceive any visual signal; 1) Not at all; 2) Very little; 3) A little; 4) Somewhat; 5) Quite a lot; 6) A lot; 7) Very much.
- **Q7**: Which signal was most helpful to you?
  0) iHMI not detected; 1) Visual; 2) Audio; 3) Both.