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Pedestrian interactions with Automated Vehicles: does the presence of a zebra crossing affect how eHMIs and movement patterns are interpreted?

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Abstract

Previous research has shown that the use of an eHMI can lead pedestrians to make earlier, and more, crossing decisions in front of an AV. However, there has been little exploration of the impact of crossing infrastructure or AV approach direction on pedestrian behaviour. This CAVE-based pedestrian simulator study investigated the individual, and combined, effects of a pedestrian crossing, automated vehicle (AV) approach direction, AV yielding behaviour, and a novel external Human Machine Interface (eHMI) on pedestrian crossing decisions at a four-way crossroads. Thirty eight participants took part in a multi-method study consisting of a pedestrian simulator experiment, an online interview, and a short questionnaire. The main independent variables were: (1) presence or absence of a zebra crossing; (2) the direction from which the AV approached (oncoming/right); (3) the AV's yielding behaviour (yielding/not yielding); and (4) the presence or absence of a light-based eHMI. The AV's yielding behaviour was the most important source of information for pedestrians, followed by the crossing infrastructure. Participants showed a greater willingness to cross in front of yielding than non-yielding vehicles, and were more likely to cross in the presence of a zebra crossing. The eHMI had the most impact in the absence of a zebra crossing, promoting earlier crossings, and encouraging more participants to cross while the approaching AV was still moving. The results of this study show the importance of eHMIs for situations associated with uncertainty about right-of-way between an AV and other road users, and highlights the interaction between formal traffic infrastructure and explicit forms of communication for future AVs. This knowledge increases our knowledge of when and where explicit communication from AVs can reduce the likelihood of pedestrian misunderstanding of AV intentions, thus reducing the likelihood of accidents occurring around these vehicles.

Keywords: Human Factors, Automated Vehicles, eHMIs, Pedestrian Safety

1. Introduction

The introduction of increasingly automated vehicles (AVs) onto our roads is leading to a new set of challenges for traffic participants. One of the key questions in this space is understanding how these vehicles should interact and communicate with other road users in mixed traffic environments (Fuest et al., 2018; Schieben et al., 2019). Video based studies of road user interactions with automated shuttles have found that interaction requirements will vary across different environments, with infrastructural factors such as road width, zebra crossing points, and traffic direction having an impact (Madigan et al., 2019). The lack of any driver to communicate with will also change the nature of these interactions (Velasco et al., 2021)

Studies of current road user interactions with conventional vehicles have shown that pedestrians' understanding of a vehicle's intentions is strongly informed by implicit longitudinal cues such as speed, time-to-arrival, and stopping distance, along with lateral cues such as lane positioning (Dey & Terken, 2017; Lee et al., 2020; Rasouli et al., 2017; Rettenmaier et al., 2021; Sucha et al., 2017; Wang et al., 2021). In addition, for slow-moving traffic, or when movement priority is unclear, human road users also seek explicit communication from a driver, such as hand movements, head movements, or flashing lights (Rasouli et al., 2017; Sucha et al., 2017; Uttley et al., 2020). However, at higher levels of vehicle automation (SAE Level 4 and 5; SAE, 2018), where humans will not have control of the driving task, this type of explicit communication may no longer be possible. Thus, OEMs and researchers have been working on designing a range of externally presented communication concepts for future AVs, to facilitate the communication capabilities of these vehicles with other road users (e.g. Dey, Habibovic, et al., 2020; Fridman et al., 2017; Lee et al., 2019, 2021; see Figure 1; Nissan Motor Corporation, 2015; Semcon, 2016; see Figure 1). These are collectively referred to as external Human Machine Interfaces (eHMIs). Although there is debate around the best design concepts, and ideal locations of these eHMIs, studies evaluating the efficacy of different colours for visibility, discriminability and sense of safety have advocated the use of light based signals in turquoise or cyan to convey messages from AVs (Faas & Baumann, 2019; Werner, 2018). Organisations such as the International Organisation for Standardization (ISO/TC 22/SC 39/WG 8), have adopted this research in their recommendations about how external communication for AV's should be designed ([ISO], 2018; SAE, 2019; UNECE, 2019). Research studies have used a range of these light-based signals to successfully communicate AV intentions in experimental studies (Lee et al., 2021; Weber, Chadowitz, et al., 2019). However it is currently unclear whether the meaning of these signals are intuitive and easily understood by human road users (Fridman et al., 2017; Lee et al., 2021).

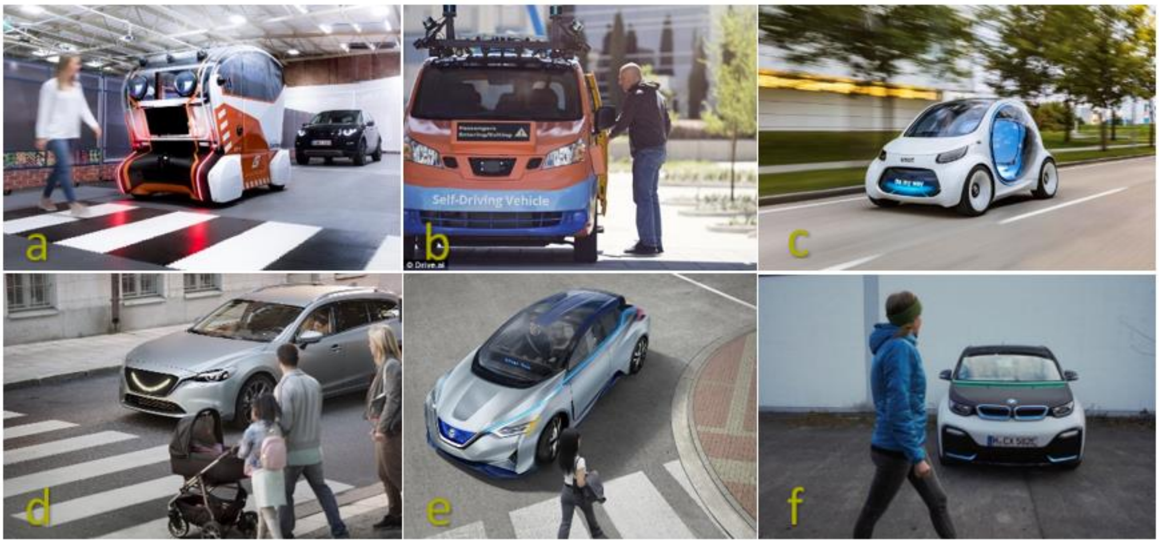


Figure 1: Example of eHMI concepts from (a) Jaguar Land Rover, (b) Drive AI, (c) Mercedes Benz, (d) Semcon, (e) Nissan Motor Corporation, and (f) interACT project

In the past five years, there has been a huge rise in the number of studies investigating pedestrian responses to different eHMIs, with researchers conducting studies in virtual environments (Böckle et al., 2017; Dey & Terken, 2017; Lee et al., 2021; Otherson et al., 2018), test tracks (e.g. Clamann, 2015; Habibovic et al., 2018; Horn et al., 2021), and real-world environments (e.g. Dey, Matviienko, et al., 2020). While results have been mixed, there is an emerging consensus that pedestrians show greater willingness to cross, and cross earlier, in front of a vehicle which includes an eHMI, compared to no-eHMI conditions (Böckle et al., 2017; Deb et al., 2018; Dey, Matviienko, et al., 2020; Holländer, Colley, et al., 2019). They also express higher levels of comfort, trust, acceptance, receptivity, and perceived safety (e.g. Böckle et al., 2017; Deb et al., 2018; Holländer, Wintersberger, et al., 2019).

To date, much of the research into AV-pedestrian interactions has focused on straight, one-way, road environments, with no additional/supporting cues from road- and traffic-based infrastructure. Currently, little is known about pedestrian decision-making during interactions with AVs at crossroads or intersections, where the planned path of the vehicle may not always be clear. However, a number of recent studies have begun to address this issue. For example, using a virtual reality (VR) head-mounted display (HMD) study, Jayaraman et al. (2018) explored the impact of AV driving style (defensive, normal, and aggressive) and type of pedestrian crossing (signalised vs unsignalised) on pedestrians' ratings of trust in an AV. The driving style was manipulated by varying whether the vehicle stopped (defensive), slowed down (normal) or continued at full speed (aggressive) on approach to the pedestrian's position. Results showed that the impact of driving style on propensity to trust was dependent on the type of crossing infrastructure present, with pedestrians displaying higher levels of trust towards an aggressive AV when they were crossing at a signalised crossing, compared to an unsignalised one. This study also reports a strong link between subjective measures of trust, and trusting behaviours such as reduced distance between the AV and pedestrian at crossing time, increased jaywalking time, and increased average waiting time. However, there was no effect on average crossing time or speed. Velasco et al. (2019) conducted a VR study using videos presented on an HMD, where pedestrians were presented with a series of scenarios and asked to make a decision on whether or not they would cross the road. Results showed that the presence of a zebra crossing and a larger gap size between the pedestrian and the AV increased the pedestrian's intention to cross. Taken together, the results of these studies show that the presence of supporting traffic infrastructure, such as a zebra crossing, can have an impact on pedestrians' levels of trust and willingness to cross in front of AVs, particularly in situations where they are reliant on the implicit cues of the vehicle. One recent study has also investigated the potential impact of context on pedestrians' interpretation of and confidence in eHMI communication. In an online, picture-based study, Eisele and Petzoldt (2022) explored the impact of context on the comprehensibility and accuracy of response to three eHMIs. Context was manipulated through the presence of traffic signals such as road markings and pedestrian traffic lights, and the presence of other pedestrians who were acting in accordance with the relevant traffic signals. Results indicated that relevant contextual information influenced the comprehensibility of eHMIs, and that this was particularly beneficial at the first encounter. However, it is not yet known how pedestrians use the combined information from explicit and implicit communication to inform their crossing decisions. In addition, to date, there has been little investigation of how the direction of approach of an AV affects pedestrians' crossing decisions.

The current study aimed to address this research gap by investigating the impact of an AV's implicit cues i.e. speed and acceleration profile, and additional explicit messages from an eHMI in a number of different traffic settings. Specifically, we investigated the individual, and combined, effects of a zebra crossing, vehicle approach direction, vehicle yielding behaviour, and a novel eHMI on pedestrian crossing decisions at a four-way crossroads. In the UK, regulations at the time of this study meant that drivers were only required to give way when a pedestrian stepped onto a zebra crossing, while pedestrians should not start to cross until vehicles on the road have stopped (RAC, 2021). However, in practice it is common for pedestrians to step out while approaching vehicles are still moving. Thus the inclusion of an eHMI to clarify an AV's intention could help to improve the efficiency of an interaction for both the vehicle and the pedestrian (Pekkanen et al., 2021). It was anticipated that the crossroad junction scenario, where there is increased uncertainty about a vehicle's intended trajectory, would provide further insights into the potential benefits of an eHMI in clarifying an AV's intentions. Although there is much research outlining the potential benefits of eHMIs in terms of changing pedestrians' attitudes and behaviours, as stated earlier, there is little knowledge about the factors that improve the intuitive comprehension of these novel signals (Fridman et al., 2017; Lee et al., 2021). Clearly, the more intuitive the message, the higher the likelihood that an AV's intention is correctly understood and responded to by other road users; and the impact of this seems to be most important for the first encounter with a novel vehicle (Eisele & Petzoldt, 2022). Previous research has shown that the same eHMI format could convey different messages equally well in a non-meaningful environment (Lee et al., 2019). Thus, a final aim of this study was to investigate whether the traffic context and movement behaviour of an AV could effect how quickly the meaning of messages conveyed from a novel, light-based, cyan eHMI can be learned by crossing pedestrians.

2. Method

2.1 Participants

Following approval from the University of Leeds Ethics board (Ref: LTTRAN-107), 38 participants (20 female, 18 male) were recruited to take part in the experiment using a database of volunteers who had signed up to take part in simulator studies. Participants' age ranged from 22 to 58 years (M=33.82, SD=10.30). All participants had lived in the UK for a minimum of 1 year prior to participation. 21 (71%) participants held a driving license, with an average driving experience of 15.04 years (SD = 12.13). Participants were given £30 for their participation in the experiment, which involved one visit to the University of Leeds HIKER lab, two online questionnaires, and a short interview.

2.2 Pedestrian Simulator Study

The experiment was conducted in the Highly Immersive Kinematic Experimental Research (HIKER) lab at University of Leeds, a CAVE-based pedestrian simulator. The HIKER lab provides walking space in a 9 m × 4 m room, formed by three glass panel walls and a wooden floor, which can present the virtual road environment and respond to the pedestrians' position, using a set of body trackers and a lightweight pair of glasses with integrated reflective trackers. The glasses provide appropriate visual cues of the stereo virtual environment, adjusted to the pedestrians' height, and track the pedestrians' head movements over time. Unity 3D software was used to incorporate the vehicle parameters and pedestrian state into the virtual environment (see Figure 2).

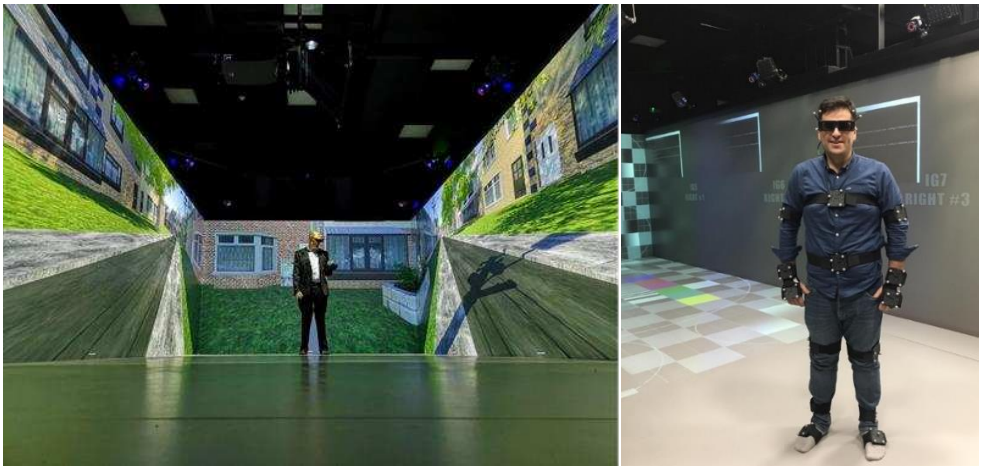


Figure 2: The HIKER Lab showing the full room (left) and body trackers and glasses (right)

The experimental scenario consisted of a crossroads in a residential area, where two one-way, single-lane roads met (3.6 metres wide, see Figure 3). Participants began the experiment standing at the edge of the road on the spot marked X in Figure 3. A single vehicle approached from either the pedestrian's right (marked A on the overhead schematic in Figure 3) or from the oncoming road (marked B on the overhead schematic). The pedestrian's task was to cross the road at any time they felt comfortable to do so. This could be before or after the vehicle had passed. Once a road crossing was completed, the trial ended and the pedestrian returned to the yellow X to start the next trial.

Figure 3: Overhead schematic of the roadway design with blue and red arrows denoting the pedestrian's range of vision (left) and pedestrians' view of an AV approaching from the right (right). Pedestrians' starting position at the beginning of each scenario was marked with a yellow x. A broken white line was used to indicate that vehicles would have to stop at the junction.

This study utilised a within-subjects, repeated-measures design, where all participants experienced 52 trials involving 4 independent variables (see Table 1) as follows:

- Zebra Crossing (present / absent),
- Vehicle approach direction (oncoming / right),
- Vehicle yielding behaviour (Yielding / Not yielding / No encounter i.e. AV does not enter pedestrian's path),
- eHMI (present / absent).

The 52 trials were presented across two counterbalanced blocks. To reduce confusion for the participants all of the zebra-crossing trials were included in one block, and all trials without a zebra-crossing were included in the other block. The order of trials within each block was randomised.

Table 1: Experimental Design - Number of trials in each condition

Presence of Zebra	Vehicle approaching direction	Vehicle yielding behaviour	Presence of eHMI	No. of trials
Zebra	Oncoming	Yielding	eHMI	3
		Yielding	No eHMI	3
		Not Yielding	n/a	6
		No encounter	n/a	1
	Right	Yielding	eHMI	3
		Yielding	No eHMI	3
		Not Yielding	n/a	6
		No encounter	n/a	1
NoZebra	Oncoming	Yielding	eHMI	3
		Yielding	No eHMI	3
		Not Yielding	n/a	6
		No encounter	n/a	1
	Right	Yielding	eHMI	3
		Yielding	No eHMI	3
		Not Yielding	n/a	6
		No encounter	n/a	1

2.2.1 AV Behaviour

In this experiment, the AV either approached from the oncoming road (see Figure 3 and top images in Figure 4) or from the pedestrian's right (bottom images in Figure 4). The initial approaching speed was always 25 mph.

If the AV was approaching from the oncoming road, it always travelled in one of two directions: (i) it turned right, intersecting pedestrians' crossing path (yielding or not, depending on the trial), or (ii) it continued to drive straight through the intersection (no encounter). Similarly, for AVs which approached from the right, they either (i) continued along the road, and therefore intersected with the pedestrians' crossing path (yielding or not), or (ii) they turned left (no encounter). Table 1 provides an overview of the number of trials in each condition.

The aim of including "no encounter trials", was to include variability and reduce pedestrians' ability to predict the AV behaviour. However, these trials were not included in the analyses. For those trials where the AV did cross the pedestrians' path, 50% were yielding trials and 50% were non-yielding trials. A turn indicator was used for all turning trials, and this was activated when the AV was 15 m from the centre of the crossroads. All movement patterns of the oncoming and right vehicles were designed to provide as realistic an experience for participants as possible. Thus, there were some differences in how these vehicles moved which will be discussed in detail in the coming sections. The eHMI used in this study was based on the design selected in the interACT project (see Weber, Sorokin, et al., 2019) of a slow pulsing cyan light-band, presented at a pulsing rate of 0.4 Hz, and placed around the front windscreen of the vehicle, as shown in the pictures on the left of Figure 4. Depending on the angle of the vehicle, it was not always possible to see the whole of this lightband, and the light at the side furthest away from the participant may not have been visible at all times. This eHMI was switched on for the yielding trials as the vehicle started to move away from the junction (more details in Section 2.2.1.1). A video showing all of the experimental trials can be accessed at https://youtu.be/1t1svxGlghk.

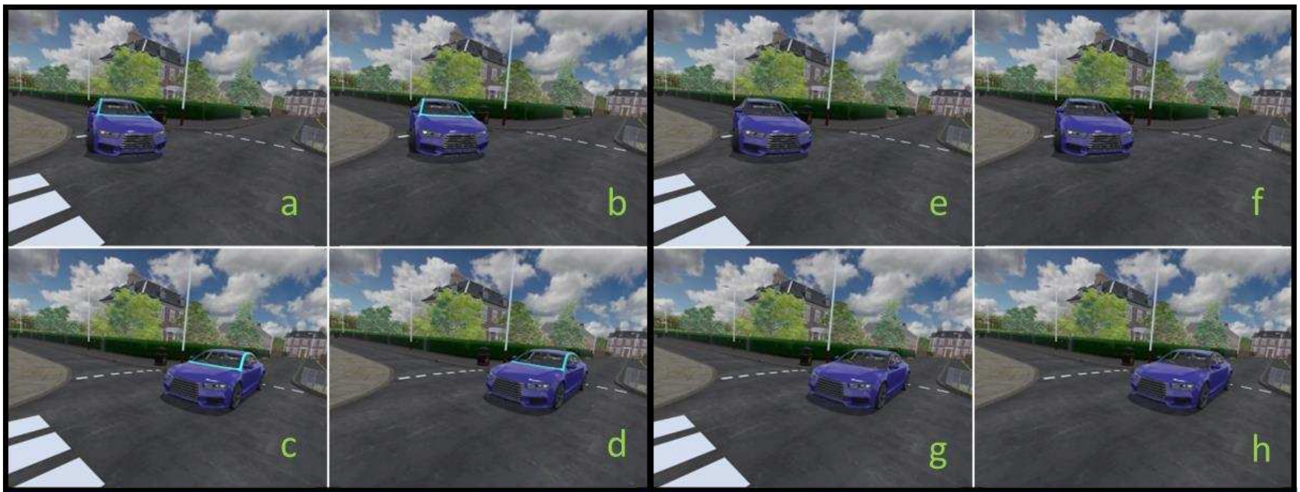
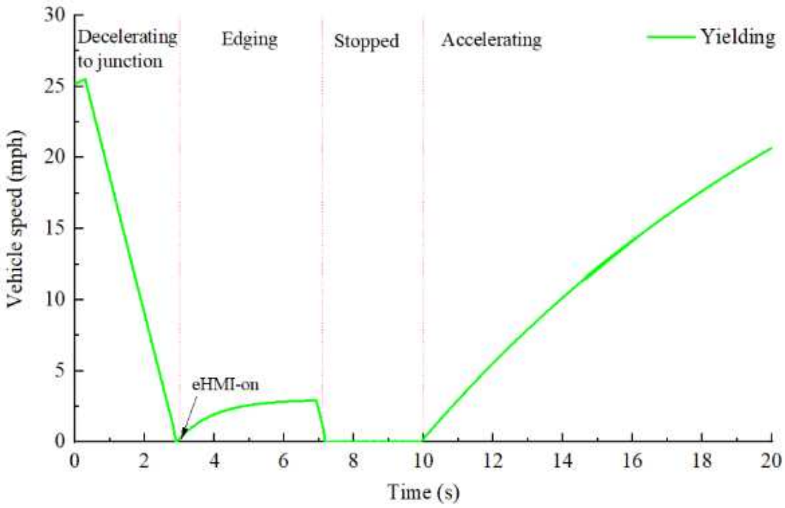


Image	Experimental Condition	Image	Experimental Condition
a	Oncoming vehicle, yielding at zebra, eHMI	**e**	Oncoming vehicle, yielding at zebra, No eHMI
b	Oncoming vehicle, yielding, No zebra, eHMI	**f**	Oncoming vehicle, yielding No zebra, No eHMI
c	Vehicle from right, yielding at zebra, eHMI	**g**	Vehicle from right, yielding at zebra, No eHMI
d	Vehicle from right, yielding No zebra, eHMI	**h**	Vehicle from right, yielding No zebra, No eHMI

Figure 4: Examples of yielding AVs approaching the pedestrian from the oncoming road (top) and from the right (bottom). In half of the yielding trials, the AV displayed an eHMI (see images a, b, c, d) while in the other half it did not (images e, f, g, h). In addition, in half of all of the trials, there was a zebra crossing to indicate the pedestrian's crossing path, whereas for the other half, there was no pedestrian crossing infrastructure.

2.2.1.1 Yielding Trials



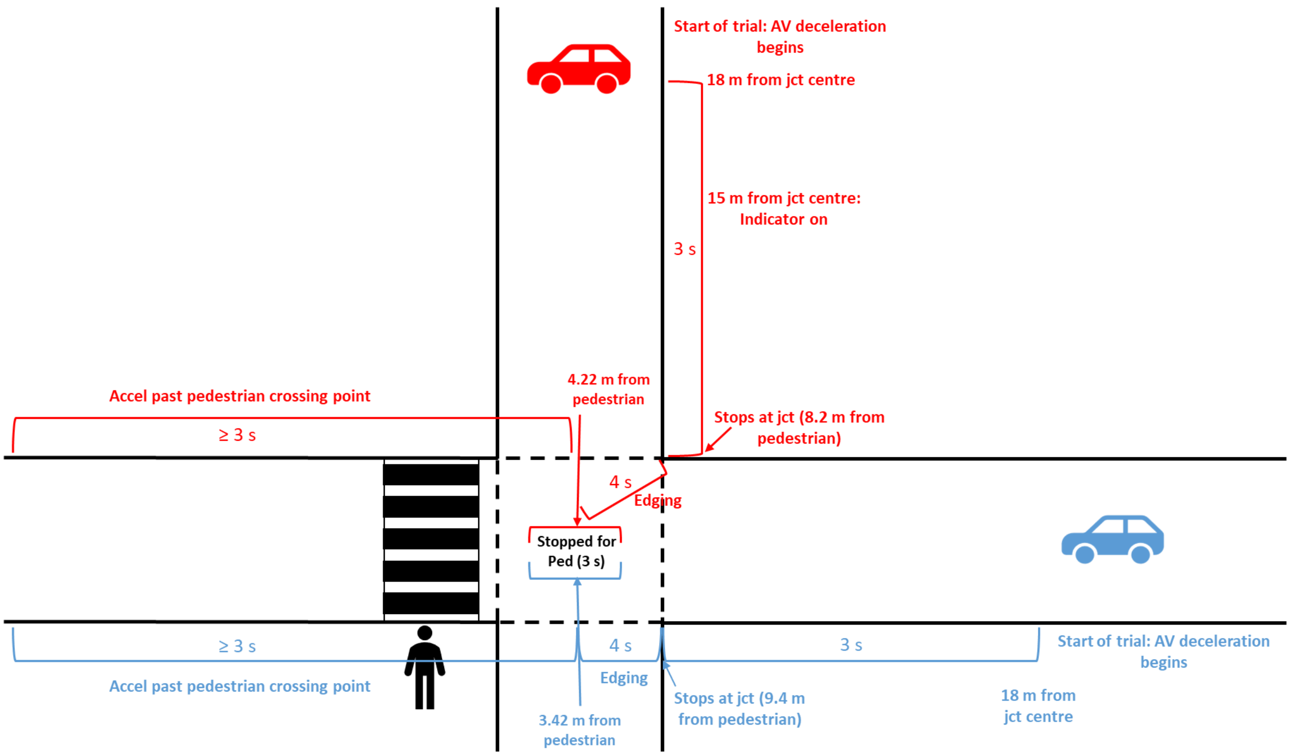


Figure 5: Vehicle speed pattern (top) and timings (bottom) for yielding trials. For all measures up until the vehicle stops at the junction, distances are calculated based on the centre of the crossroads. For all measures from the junction onwards, distances are calculated in relation to the pedestrian, who was located 5.6m from the centre of the junction. The eHMI was switched on for half of the yielding trials.

The vehicle speed pattern and timings for **yielding trials** are shown in Figure 5.

To understand pedestrian responses to different vehicle behaviours, the AV engaged in four separate movement phases, regardless of approach direction, and whether or not there was a zebra crossing present:

1. ***Decelerating*** to come to a stop at the junction:

   To simulate how vehicles behave in the real world while approaching junctions, the AV always decelerated and came to a stop at the junction. This deceleration took place over a 3-second period, whereby the AV decelerated from 25 mph to 0 mph, at a rate of -8.33 m/s^2, to come to a complete stop at the white lines of the junction (see Figures 3 and 4), which was located 9.4 m from the pedestrian for AVs approaching from the right (marked A in Figure 3), and 8.2 m from the pedestrian for vehicles approaching from the oncoming road (marked B in Figure 3).

2. ***Edging*** towards the participant**:**

After stopping at the junction, the AV then immediately started moving extremely slowly between the junction and the pedestrian crossing point, for a period of 4 seconds, to indicate yielding intent (we term this behaviour edging). The aim of this edging behaviour was to replicate real-world yielding behaviour at similar junctions (Dietrich et al., 2018), which is thought to provide an implicit cue for pedestrians, allowing more time for them to cross. For oncoming vehicles, the edging speed was 1.5 mph, while for vehicles approaching from the right, the edging speed was 3 mph. This discrepancy was to ensure that the vehicles reached their stopping point within the same time period.

For half of the yielding trials, the vehicle displayed an eHMI to provide further evidence of its yielding intentions. This consisted of a cyan pulsing light-band around the vehicle windscreen (see Figure 4), which switched on at the start of the "edging" phase, as prior to this stage any deceleration was due to the need to stop at the junction stop line, rather than yielding for the pedestrian. Participants were not provided with any information about the meaning of this eHMI.

3. ***Stopping*** to allow the pedestrian to cross:

After 4 seconds of edging behaviour, the AV stopped completely, to allow pedestrians to complete, or initiate, their road crossing. If the pedestrian had initiated a crossing, the vehicle remained stopped until they had reached the opposite side of the road. However, if the pedestrian had not moved, the AV remained stopped for a total of 3 seconds, before starting to move forwards again. This time limit was set to avoid a stand-off situation, where neither actor moved for a long period of time.

When the AV was approaching from the right, the front centre-point of the vehicle was 3.42 m from the pedestrian when it came to a complete stop. When the AV was approaching from the oncoming road, the distance from the front centre-point of the AV to the pedestrian was 4.22 m, but the vehicle was angled so that the front right-hand side of the vehicle was closer to the crossing path (see Figure 4). This variation was due to the fact that AVs approaching from the right were located in the centre of the lane in which the crossing path was located, whereas, the position of AVs approaching from the oncoming road was based on the turning angle from that road.

4. ***Accelerating*** away to drive past the pedestrian crossing point:
   Once the pedestrian crossing movement was complete and/or the 3-second waiting period was over, the AV accelerated away from its stopping position, at a rate of 0.89 m/s^2, moving past the pedestrian crossing point. Any pedestrian who had not yet crossed had the opportunity to do so once the AV had passed.

2.2.1.2 Non-Yielding Trials

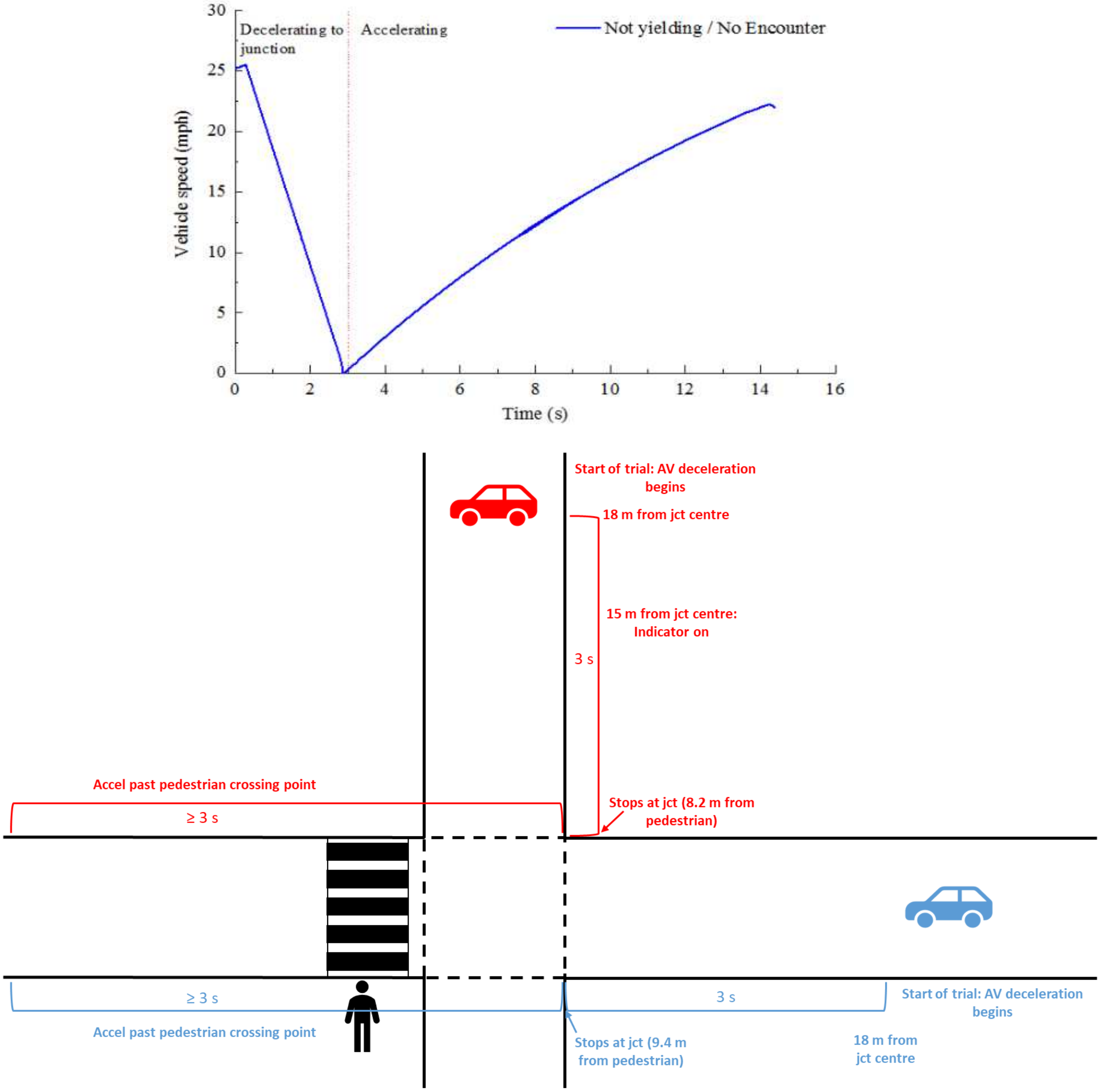


Figure 6: Vehicle speed pattern (top) and timings (bottom) for non-yielding trials. There was no eHMI in non-yielding trials.

The vehicle speed pattern and timings are for **non-yielding trials** are shown in Figure 6.

In these trials, the AV engaged in two separate movement phases, regardless of approach direction, and whether or not there was a zebra crossing present:

1. ***Decelerating*** to come to a stop at the junction:

Similar to the yielding trials, this deceleration took place over a 3-second period, whereby the AV decelerated from 25 mph to 0 mph to come to a momentary stop at the white lines of the junction (see Figures 3 and 4), which denote a requirement for drivers to stop.

2. ***Accelerating*** away to drive past the pedestrian crossing point:
   The AV then immediately accelerated away from the junction, at a rate of 0.89 m/s^2, moving past the pedestrian crossing point without any change in behaviour.

2.3 Questionnaires and Interview

Due to Covid19 restrictions, all efforts were made to minimise the time participants spent in the HIKER lab, along with minimising their interactions with the experimenter. Therefore, prior to scheduling an experiment time, participants were sent a copy of the information sheet, consent form, and a short questionnaire to complete online, through the University of Leeds Qualtrics platform. This online questionnaire requested demographic information such as participants' age, gender, nationality, and driving experience.

Once participants had completed the experiment, they were asked to take part in a short online interview, using Microsoft Teams, to gain additional insights into the factors influencing participants' crossing decisions. This interview was scheduled within 48 hours of completing the experiment, and lasted between 5 and 10 minutes. The questions were semi-structured, covering the following topics:

- What information did you use to decide whether or not to cross the road?
- Did this change over time or across trials?
- Did the direction of the vehicle approach have an impact on your crossing decision?
- Did the presence of a zebra crossing have an impact on your crossing decision?
- Did the light-band have an impact on your crossing decision?
- How did you interpret the light-band?

Interviewers supplemented these questions with follow-up probes and explorations of any interesting comments. Due to scheduling and recording issues, interview data is only available for 31 out of the 38 participants. Interviews were automatically transcribed using the transcription function on MS Teams, and these transcripts were then manually checked and revised by one of the authors.

Finally, after the interview had been completed, participants were asked to fill out a second online questionnaire. This 37-item questionnaire included questions about what information participants had used to make their crossing decisions, how they had interpreted the eHMI, their knowledge of automated vehicles, and the Sensation Seeking Scale (Arnett, 1994). Due to space constraints, only information about participant responses to the eHMI questions are included in the current paper.

2.4 Procedure

Upon arrival at the HIKER lab, the instructions for the study were briefly repeated by the experimenter, and participants were given an opportunity to practice the crossing task over 8 trials. The practice trails consisted of four trials with a zebra crossing, where the vehicle approached from the oncoming road, and four trials without a zebra crossing, where the vehicle approached from the right. Within these eight trials, participants experienced two trials where the vehicle yielded with eHMI, two trials where it yielded without eHMI, and four trials where it did not yield.

For the experimental blocks, participants started each trial by standing on a yellow cross, which was marked on the ground in HIKER at the edge of the road to the left of the crossroads (See X marked in Figure 3). They were instructed to cross the road when they felt safe to do so, either before or after the approaching vehicle. After crossing the road, they had to walk back to the initial position to trigger the next trial. The experiment was presented in two blocks of 26 trials each – one block with a zebra crossing, and the other block with no zebra crossing, presented in a counterbalanced order. Participants were given a short break between blocks. The total experiment lasted for approximately 30 minutes. Within 48 hours of completing the experiment, the participant attended an online interview lasting approximately 5-10 minutes. The final step in the study was the completion of another short online questionnaire, after which participant payments were processed.

2.5 Data Analysis

This study adopted a mixed methodology approach to investigate four main research questions. Firstly, in order to understand the individual and combined effects of (1) zebra crossing presence, (2) vehicle approach direction, (3) vehicle yielding behaviour, and (4) novel eHMI on pedestrian crossing behaviour at a four-way crossroads, two within-groups analyses of variance were run, with one examining yielding trials and one investigating non-yielding trials. The independent variables were *Zebra Presence* (Zebra/No Zebra), *Vehicle Approach Direction* (Oncoming/Right), *eHMI Presence* (eHMI/no eHMI), and *Encounter Number* (either 3 or 6 depending on whether they were yielding or non-yielding trials); and the dependent variable was *Crossing Initiation Time* (CIT). CIT was calculated as the time from the initiation of a new trial to the time at which participants started to cross the road (see Section 2.4).

Three sets of chi-squared analyses were used to investigate the relationship between *Zebra Presence* (Zebra/No Zebra), *Vehicle Approach Direction* (Oncoming/Right), *eHMI Presence* (eHMI/no eHMI), and the *Percentage of Road Crossings* during each of the four AV movement phases (Decelerating / Edging / Stopping / Accelerating; see Section 2.2.1.1) during yielding trials. The *Zebra Presence* and *Vehicle Approach Direction* analyses were also conducted for non-yielding trials.

In order to gain additional insights into the factors that informed pedestrians' decision making during the experiment, interview and questionnaire data were used. Within 48 hours of completing the road-crossing experiment, all participants took part in a short semi-structured online interview to help us understand their experiences during the experiment. A basic qualitative content analysis (see Schreier, 2012) was conducted to code participant responses. The interview questions were separated into five main question topics i.e. main influences on crossing decisions, changes across the experiment, impact of vehicle approach direction, impact of zebra crossing, and impact of eHMI.

Responses to each of these five topics were analysed separately by two coders. The main author began by reading the responses of the first five participants to build a coding frame and generate response categories for each of the five topics. This was achieved by reading an individual participant's response, extracting raw quotes of interest, and identifying the underlying meaning or category of the quote. Each time a new concept was encountered it was checked against the existing coding framework and new categories were added if there was no suitable existing one. Once the initial coding framework was developed based on the first five responses, the same process was then repeated by two coders for the remaining participants.

Interrater reliability was calculated using the procedure set out by Miles and Huberman (1994) by dividing the number of agreements by the total number of agreements plus disagreements (agreements + disagreements). The overall interrater reliability was 0.95, indicating a high level of agreement between the coders. In instances where there was a discrepancy in the codes selected, the first author went back to the initial text to review the content once more, and then discussed the coding with the second coder to reach a consensus.

Finally, in order to understand the link between participants' understanding of the eHMI and their objective crossing decisions, a mixed between-within groups ANOVA was conducted to evaluate the impact of *eHMI Presence* (Present/Absent) and *eHMI Influence* (eHMI influenced crossing decisions/eHMI did not influence crossing decisions) on *Crossing Initiation Time (CIT).*

3. Results

In the following sections we present data on participants' crossing behaviour (Sections 3.1 and 3.2) and the factors affecting their decision making (Sections 3.3 and 3.4). As we were mainly interested in understanding the impact of eHMIs and zebra crossings on pedestrian actions, the "no encounter" trials are not included in the analyses.

3.1 Crossing Initiation Time (CIT)

Pedestrians crossed before the AV in 77.03% of yielding trials, compared to 25.93% non-yielding trials.

For **yielding trials**, a 4-way ANOVA was conducted to examine the impact of *Zebra Presence* (Zebra/No Zebra), *Vehicle Approach Direction* (Oncoming/Right), *eHMI Presence* (eHMI/no eHMI), and *Encounter Number* (1st/2nd/ 3rd – participants encountered each of the two eHMI conditions 3 times) on *Crossing Initiation Time* (CIT).

Results indicated a significant effect of Zebra Presence ($F(1, 36) = 26.05$, $p < 0.001$, $\eta p^2 = 0.42$), with participants having a significantly shorter CIT when there was a zebra crossing ($M = 6.08$ s, $SE = 0.65$, 95% CI [4.77, 7.40]) than when there was not ($M = 8.93$ s, $SE = 0.56$ 95% CI [7.80, 10.07]). There was also a significant effect of eHMI Presence ($F (1,36) = 5.70$, $p < 0.05$, $\eta p^2 = 0.14$), with shorter CITs when there was an eHMI ($M = 7.21$ s, $SE = 0.55$, 95% CI [6.10, 8.31]) than when there was not ($M = 7.81$ s, $SE = 0.56$). Finally, there was a significant main effect of Encounter ($F (2,72) = 3.95$, $p < 0.05$, $\eta p^2 = 0.09$), with participants' CIT reducing between the first encounter with a particular trial type i.e. eHMI vs no eHMI trials ($M = 7.78$ s, $SE = 0.53$, 95% CI [6.70, 8.86]) and the last ($M = 7.33$ s, $SE = 0.57$, 95% CI [6.19, 8.48]). There was no main effect of Approach Direction on CIT ($F(1,36) = 0.33$, $p = 0.57$).

There was also a significant interaction between Zebra Presence and eHMI Presence ($F (1,36) = 6.66$, $p < 0.05$, $\eta p^2 = 0.16$), which is shown in Figure 7 below. For the No Zebra condition, participants crossed significantly earlier when the vehicle was displaying an eHMI than when it was not. There was no significant effect of eHMI in the zebra condition.

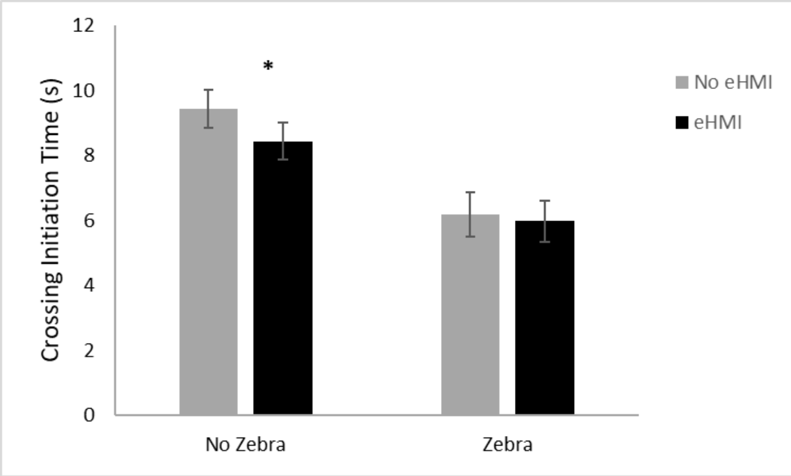


Figure 7: Interaction between Zebra Presence and eHMI Presence on CIT (error bars represent SE)

For the **non-yielding trials**, a 3-way ANOVA was conducted to examine the impact of *Zebra Presence* (Zebra/No Zebra), *Vehicle Approach Direction* (Oncoming/Right), and *Encounter Number* ($1^{st}/2^{nd}/3^{rd}/4^{th}/\ 5^{th}/\ 6^{th}$ – there were 6 encounters with no eHMI) on *Crossing Initiation Time* (CIT).

There was a significant main effect of Zebra Presence ($F\ (1, 36) = 17.88$, $p < 0.001$, $\eta p^2 = 0.33$), with participants crossing significantly earlier when there was a zebra crossing (M = 5.22 s, SE = 0.45, 95% CI [4.30, 6.13]) than when there was not (M = 6.75 s, SE = 0.30, 95% CI [6.13, 7.36]). There was also a significant effect of Approach Direction ($F\ (1,36) = 6.24$, $p < 0.05$, $\eta p^2 = 0.15$), with participants crossing significantly earlier when the vehicle was oncoming (M = 5.84 s, SE = 0.34, 95% CI [5.15, 6.52]) than when it was approaching from their right (M = 6.13 s, SE = 0.35, 95% CI [5.42, 6.84]). There was no significant effect of Encounter Number ($F\ (5,180) = 0.52$, $p = 0.77$), and no significant interaction effects.

3.2 Impact of AV Movement Phase on Pedestrian Crossing

In order to understand whether pedestrians' crossing decisions were impacted by an AV's kinematic behaviour, a series of chi squared tests were conducted to explore the effect of AV movement phase on pedestrian crossings.

Chi-squared analyses were conducted to explore the relationship between the *AV movement phase at which pedestrians decided to cross (Decelerating / Edging / Stopping / Accelerating)* and *Zebra*

Presence (Zebra / No Zebra), *Vehicle Approach Direction* (Oncoming / Right), and *eHMI Presence* (eHMI / no eHMI).

For **yielding trials**, there was a significant relationship between AV Movement Phase at pedestrian crossing initiation and Zebra Presence ($\chi^2(3) = 101.06$, $p < .001$). As Figure 8 shows, when there was a zebra crossing, participants were more likely to cross while the vehicle was decelerating to the junction, or edging towards the crossing point. However, when there was no zebra crossing, they were more likely to wait until the AV had stopped or had passed them.

There was also a significant relationship between AV Movement Phase at pedestrian crossing initiation and eHMI Presence ($\chi^2(3) = 10.51$, $p < .05$; See Figure 8 right). Compared to the no eHMI condition, when there was an eHMI, pedestrians were significantly more likely to cross while the AV was edging towards the crossing point. An additional chi-square analysis showed that this effect only emerged in the no-zebra condition ($\chi^2(3) = 8.69$, $p < .05$). There was no significant effect of Vehicle Approach Direction in yielding trials ($\chi^2(3) = 2.70$, $p = 0.44$).

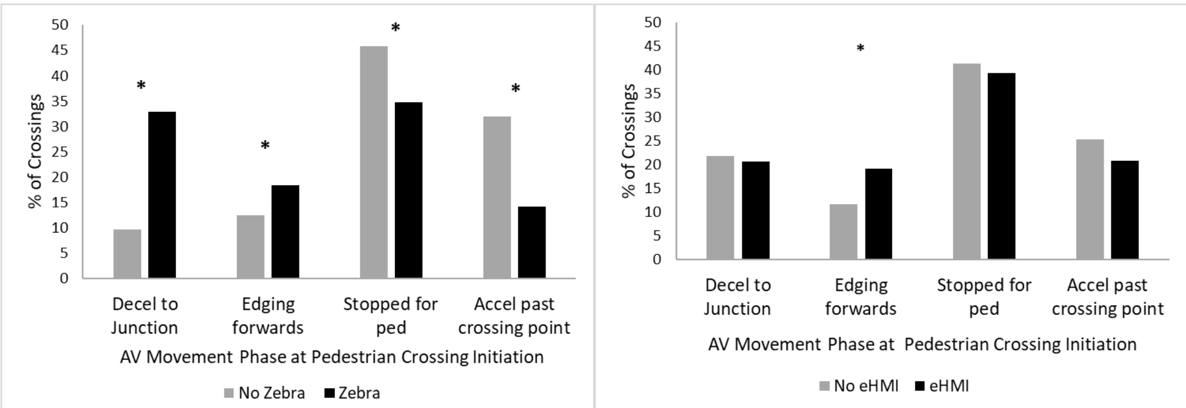


Figure 8: Vehicle state at crossing initiation time for Zebra and No Zebra trials (Left), and eHMI and no eHMI trials (right)

Results showed that, for **non-yielding trials**, there was a significant relationship between AV Movement Phase at pedestrian crossing initiation and Zebra Presence ($\chi^2(1) = 63.15$, $p < 0.001$). Participants were significantly more likely to cross while the vehicle was decelerating to the junction when there was a zebra crossing (33% total crossings), than when there was not (11.2% total crossings). There was no significant effect of Vehicle Approach Direction ($\chi^2(1) = 0.01$, $p = 0.908$).

3.3 Interview analysis: Participant decision making

Within 48 hours of completing the road-crossing experiment, all participants took part in a short semi-structured online interview to help us understand their experiences during the experiment. As described in the Methods section, a basic qualitative content analysis (see Schreier, 2012) was conducted to code participant responses, allowing us to group the main topics identified by participants as influencing their crossing decisions.

The first question we asked participants was what information they used to decide whether or not to cross the road. Table 2 provides an overview of the main factors participants identified. Data from 31 participants are included, and each participant could mention multiple factors in their responses.

Table 2: Factors influencing participants' crossing decisions

Code	Example quotes	No. of participants
Vehicle Speed	"Speed of the car"; "how fast it was going"; "if it was slowing down"	18
Turn Indicator	"if they had the turn signal on"; "whether they were indicating"	13
Presence of Zebra Crossing	"if there is a zebra"; "If there was a zebra I was confident I could cross"; "the presence of a zebra I think made a difference"	12
Vehicle Stopped	"whether or not the car had stopped"; "if the car came to a complete stop and it didn't move then I felt happy to cross"; "making sure the car stopped"	11
eHMI	"the illuminated area around the windshield"; "I realised there was a blue light indicating they would let me cross"; "blinking light – probably indicate it detected me"	6
Approach Direction	"Direction"; "First the car drives on the right or the left is very important"; "when the car was turning right";	5
Distance	"the distance between the vehicle and me"; "How far away the car was when I first spotted it"	4
Vehicle Hesitating / Edging	"Then noticed floating so realised the car was letting me past"	3
Vehicle positioning	"positioning of car at the junction"	3
Waited for car to pass	"Waited for car to pass"	2
Road markings	"Markings on the road"	1

As shown in Table 2 , vehicle speed was the most commonly identified factor influencing participants' crossing decisions, with participants describing a search for acceleration and deceleration patterns to understand the vehicle's intentions. 13 participants also mentioned checking the turn indicator as an important way of understanding if the vehicle would be crossing their path. 12 participants mentioned the presence of a zebra crossing as a factor which increased their likelihood of crossing, and 11 participants said that they generally waited until the vehicle had stopped before starting to cross, regardless of other factors. Less commonly mentioned factors included the vehicle eHMI or lightband, the approach direction and distance of the vehicle, and its' "nudging"/edging behaviour in some trials. Of the three participants who mentioned the edging behaviour of the vehicle, two people said that it made them more likely to cross, while another person said that it made them hesitate.

This inconsistency across participants also emerged when it came to the impact of the vehicle approach direction. When asked about the factors influencing their general crossing decisions, only five participants identified this as a factor. However, when specifically asked whether vehicle approach direction had affected their decisions, 23 participants said that it did. Of these 23 participants, 12 found it easier to cross when the vehicle was oncoming, 7 found it easier when it was approaching from the right, and 4 were unsure. The common themes which emerged around a preference for the oncoming vehicle included the slow travelling speed (N = 5) and knowing that it needed time to stop for the turn (N = 7). However, others felt that the vehicle was "more aggressive" when turning (N = 2), and that it may not be able to detect them as easily (N = 2). A small number of participants felt that the vehicle approaching from the right was travelling more quickly (N = 3), and that the potential for that vehicle to build up speed was greater. It is possible that these participants had correctly identified the slightly faster travelling speed during the edging phase of the vehicle's approaching from the right (3 mph vs 1.5 mph for oncoming vehicles).

When specifically asked to provide details about the impact of the zebra crossing on their crossing decisions, 23 participants stated that the presence of a zebra crossing affected their decision making. Themes included increased feelings of confidence/safety (N = 12), feelings of "right of way" (N = 9), and permission to behave more forcefully/"boldly" (N = 2). However, two participants noted that they actually felt more hesitant around the zebra, as the right of way is not always obeyed in the UK, and they had more uncertainty about what the vehicle would do. Others (N = 3) noted that the vehicle did not always behave as they would expect around the zebra, and did not always stop when they felt it should.

Finally, when asked specifically about the impact of the eHMI, 12 participants claimed that it did affect their crossing decisions, with one unsure, and 18 saying it did not. When participants were asked about how they had interpreted the message conveyed by the eHMI, the most common answer was that the vehicle was yielding/going to stop (N = 9), although almost the same number said that it was an indication from the vehicle telling them to go (N = 10). Other interpretations included: that the light-band provided an additional indicator (N = 6), information on whether the participant had been detected (N = 5), and that it emphasised the existence of the vehicle (N = 2). A total of 10 people said that they were completely unsure of what the light-band meant.

3.5 Questionnaire Analysis: Linking participant actions and beliefs

After the interviews, participants were asked to fill out a questionnaire about the information they used to make their crossing decisions. As the majority of the questionnaire results supported the findings of the interview analysis, the main focus in this section is on the link between participants' understanding of the eHMIs and their objective crossing decisions.

In the questionnaire, participants were asked once again about whether or not they noticed the eHMI, and whether or not it influenced their crossing decisions. 37 out of 38 (97.4%) participants stated that they noticed the eHMI. There was an almost equal split around whether or not it had influenced their crossing decisions, with 18 participants saying it had, and 19 saying it had not (similar to the interviews, which had a smaller number of participants). Of the 18 participants who said that the eHMI had impacted their crossing, 12 correctly interpreted the eHMI as meaning that the AV was yielding to them or it was safe for them to cross, two interpreted it as showing that the AV had seen them, two believed it was an indicator, and the final two participants' responses were unclear.

In order to understand the accuracy of participants' interpretation of whether or not the eHMI influenced their crossing decisions, a mixed ANOVA was conducted to evaluate the impact of *eHMI Presence* (Present/Absent) and *eHMI Influence* (eHMI influenced crossing decisions/eHMI did not influence crossing decisions) on *Crossing Initiation Time (CIT).* Results showed a significant main effect of eHMI Influence ($F(1,35) = 4.12$, $p = 0.05$, $\eta p^2 = 0.11$) and eHMI Presence ($F(1, 35) = 7.13$, $p < 0.05$, $\eta p^2 = 0.17$); along with a significant interaction effect ($F(1, 35) = 11.89$, $p < 0.01$, $\eta p^2 = 0.25$). As Figure 9 shows, when an eHMI was displayed, participants who claimed that the eHMI had an influence on their crossing behaviour had significantly shorter CITs than those who said they were not influenced by the eHMI ($t(17) = -3.28$, $p < 0.01$). However, there was no difference between the CIT of the two groups when no eHMI was displayed ($t(18) = 0.95$, $p = 0.36$). The group who used the eHMI as a cue also had significantly shorter CITs when an eHMI was present, compared to when there was no eHMI ($t(35) = 2.88$, $p < 0.01$), while there were no eHMI-related differences in CIT for the other group ($t(35) = 1.19$, $p = 0.24$).

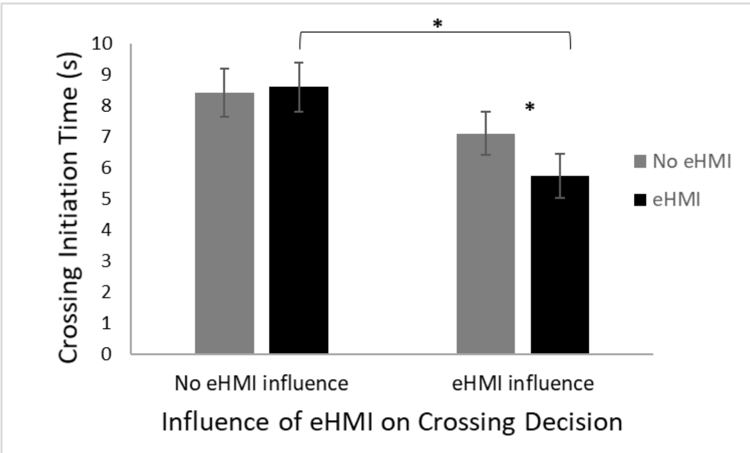


Figure 9: A comparison of the impact of claimed eHMI influence on participants' crossing initiation times

4. Discussion

The purpose of this study was to investigate the impact of an AV's movement pattern and eHMI on pedestrians' crossing decisions, as well as understanding how this was influenced by the presence of a zebra crossing. More specifically, the study aimed to gain an understanding of the individual and combined effects of infrastructure-based information, vehicle approach direction, vehicle yielding behaviour, and a novel eHMI, on pedestrians' crossing decisions at a four-way crossroads. A combination of data collection methods was used to understand participants' objective crossing behaviours, along with how these were influenced by subjective evaluations of the scenario.

Overall, the results support the findings of previous studies that vehicle kinematic behaviour is one of the most important factors influencing pedestrians' decisions about whether or not to cross the road in front of an approaching vehicle (Dey & Terken, 2017; Lee et al., 2020; Rasouli et al., 2017). The multi-method data collection approach used in this study provides additional interesting insights about the factors influencing pedestrians' decision-making around AVs. All three data sources provided unique and complementary information. Specifically, the interview data allows us to understand the subjective decision making processes which influenced participants' road crossing behaviours in the experiment, while the combination of the questionnaire and experimental responses to eHMIs allowed us to understand how well participants' interpretation of events matched their actual behaviours. The interview and questionnaire data confirm the experimental findings that vehicle kinematics were the most important source of information for pedestrians, followed by the traffic infrastructure. Participants crossed more often in front of a yielding vehicle than a non-yielding vehicle, and follow-up interviews and questionnaires found that participants identified speed, vehicle stopping/braking behaviour, and vehicle positioning as the most important cues for helping their crossing decisions. Interestingly, however, the impact of the AV's kinematic cues appeared to vary depending on the explicit communication provided by the vehicle, and the presence of a pedestrian crossing. Pedestrians were more willing to cross in front of a vehicle which was decelerating as it approached the junction, or edging forwards from the junction, when there was a zebra crossing or eHMI present.

In particular, a key new finding of this study was that the eHMI only appeared to have an impact on pedestrians' crossing behaviour in the absence of a zebra crossing. Specifically, when there was no zebra crossing, the presence of an eHMI led to earlier crossings, and more crossings were made during the vehicle edging stage. This result suggests that even a novel eHMI can influence crossing decisions and aid pedestrians' understanding of the implicit cues provided by the vehicle. Previous research has shown that novel eHMIs tend to be more effective in low speed situations, with shorter time gaps (Lee et al., 2021). The results of the current study build on this finding, by suggesting that eHMIs may be of most benefit to pedestrians in uncertain situations, where there is no clear right of way, and some negotiation between the pedestrian and a vehicle is required. Thus, future research should consider how eHMIs may enhance the impact of kinematic cues, such as edging or slow moving behaviour, in real world situations or around different types of junctions. The implementation of explicit AV communication is likely to reduce the frustration of both road user types, and enhance throughput and traffic flow (Pekkanen et al., 2021).

It is interesting that although the light-band eHMI was not identified in the interviews or questionnaires as a key variable for influencing participants' crossing decisions, it still had a tangible impact on behaviour. Participants expressed a lack of certainty about how the eHMI should be interpreted, highlighting the importance of conveying the correct meaning of any light-based communication tools in advance. The fact that almost a quarter of participants had no understanding of the meaning of the eHMI by the end of the experiment shows that this type of communication is unlikely to be intuitively learned or understood. However, for those who correctly interpreted the eHMI as indicating an AV's yielding intentions, it provided a useful cue which led to shorter crossing initiation times. Future research should investigate the impact of education and training about the meaning of different eHMIs on pedestrian crossing behaviours, across different road settings and crossing scenarios.

Road infrastructure was also found to be an important factor influencing pedestrians' crossing decisions. Similar to Jayaraman et al. (2018) and Velasco et al. (2019), the current study found that participants had shorter crossing initiation times, and crossed ahead of the AV more often, in the presence of a zebra crossing, regardless of the yielding behaviour of the vehicle, or any explicit communication provided. During the interviews, participants mentioned feeling safer and more confident when there was a zebra crossing. However, some participants noticed that the AV did not necessarily behave as they would expect around the zebra crossing, by not always yielding as anticipated, and this led to some hesitation in crossing. This hesitation highlights the importance of consistent behaviour from the AV (see also Rothenbucher et al., 2016).

Finally, it appears that the direction from which a vehicle approaches has an impact on pedestrians' willingness to cross in front an AV, particularly in non-yielding trials. Participants expressed feelings of greater comfort in crossing ahead of AVs approaching from the oncoming road rather than from the right. They also had shorter crossing initiation times in relation to these vehicles in the non-yielding conditions. The interviews found that some participants perceived the oncoming vehicles as moving more slowly, and this, combined with their knowledge that the vehicle had to take some time to make the turn, helped them to feel more comfortable about crossing in this situation. When the vehicle was approaching from the pedestrians' right-hand side, a small number of participants perceived that these vehicles were travelling at a faster speed, and others also believed that the potential for that vehicle to build up speed was greater. These factors once again draw attention to the importance of both current and anticipated vehicle movement patterns in influencing pedestrian decisions.

4.1 Limitations

As with every study, there are limitations which must be acknowledged. First of all, the experiment took place in a virtual environment, which may have led to a greater feeling of safety (REF), and less ecological validity than a real-world study. However, the enhanced simulated realism of the HIKER lab ensured that the road-crossing experience was as realistic as possible, and the fact that participants could move around reduced the risk of cyber sickness commonly associated with VR technology. None of the participants reported any symptoms or had to stop.

Another potential study limitation was the inconsistent behaviour of the AV at the zebra crossing. UK regulations at the time this study was conducted meant that drivers were only required to give way when a pedestrian stepped onto a zebra crossing, while pedestrians should not start to cross until vehicles on the road have stopped (RAC, 2021). Thus we felt it was important to investigate if participants would rely more on the road infrastructure, or the vehicle's behaviour and communication, when making their crossing decisions. Participants reported feeling safer and more confident when there was a zebra crossing, and their crossing behaviours showed that they the eHMI had no effect on crossing initiation time when there was a zebra crossing. Taken together, these findings suggest that although manually driven vehicles do not always yield as they should, participants expected the AV to yield to them when obliged to do so, and that this influenced their crossing decision more than any vehicle behaviour or communication. Thus, it is important that AV behaviour takes the traffic infrastructure into account, and that these vehicles obey traffic rules around yielding when required.

4.2 Conclusions and Future Research

Overall, the results of this study show the importance of considering the traffic environment when deciding where to implement explicit communication solutions for AVs. Previous studies have shown that pedestrians tend to seek out explicit communication with a vehicle in slow moving or uncertain situations (Lee et al., 2021; Rasouli et al., 2017; Sucha et al., 2017; Uttley et al., 2020). The current research supports this finding, showing that eHMIs are most likely to be useful in situations where there is no clear right of way. In addition, the findings show that eHMI can enhance pedestrians' ability to interpret implicit communication cues such as edging behaviour (Dietrich et al., 2018), helping them to make earlier crossing decisions, particularly in situations where there is no zebra crossing. In order to maximise the effectiveness of any explicit communication tools, the meaning of eHMIs should always be advertised or explained in advance. However, it should be noted that this research was conducted in a VR environment and, thus, more research is needed to understand whether similar results would emerge in a real-world scenario, where the degree of risk experienced by pedestrians is greater. In addition, future research should focus on identifying and investigating similar uncertain scenarios, including other junction types, where eHMIs might be of particular benefit.

References

[ISO], I. O. for S. (2018). *Road Vehicles: Ergonomic aspects of external visual communication from automated vehicles to other road users*.

Arnett, J. (1994). Sensation seeking: A new conceptualization and a new scale. *Personality and Individual Differences*, *16*(2), 289–296.

Böckle, M.-P., Brenden, A. P., Klingegård, M., Habibovic, A., & Bout, M. (2017). SAV2P: Exploring the impact of an interface for shared automated vehicles on pedestrians' experience. *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*, 136–140.

Clamann, M. (2015). Evaluation of Vehicle-to-Pedestrian Communication Displays for Autonomous Vehicles. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *57*(3), 407–434. https://trid.trb.org/View/1437891

Deb, S., Strawderman, L. J., & Carruth, D. W. (2018). Investigating pedestrian suggestions for external features on fully autonomous vehicles: A virtual reality experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*, *59*, 135–149.

Dey, D., Habibovic, A., Löcken, A., Wintersberger, P., Pfleging, B., Riener, A., Martens, M., & Terken, J. (2020). Taming the eHMI jungle: A classification taxonomy to guide, compare, and assess the design principles of automated vehicles' external human-machine interfaces. *Transportation Research Interdisciplinary Perspectives*, *7*, 100174.

Dey, D., Matviienko, A., Berger, M., Pfleging, B., Martens, M., & Terken, J. (2020). Communicating the intention of an automated vehicle to pedestrians: The contributions of eHMI and vehicle behavior. *It-Information Technology*, *1*(ahead-of-print).

Dey, D., & Terken, J. (2017). Pedestrian interaction with vehicles: roles of explicit and implicit communication. *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 109–113.

Dietrich, A., Bengler, K., Portouli, E., Dimitris, N., Ruenz, J., Jingyuan, W., Merat, N., Madigan, R., Lee, Y. M., Markkula, G., Giles, O., Fox, C., & Camara, F. (2018). *interACT D2.1: Preliminary description of psychological models on human-human interaction in traffic*. https://www.interact-roadautomation.eu/wp-content/uploads/interACT_WP2_D2.1-_PsychologicalModels_v1.0_approved_Uploadwebsite.pdf

Eisele, D., & Petzoldt, T. (2022). Effects of traffic context on eHMI icon comprehension. *Transportation Research Part F: Traffic Psychology and Behaviour*, *85*, 1–12.

Faas, S. M., & Baumann, M. (2019). Light-based external Human Machine Interface: color evaluation for self-driving vehicle and pedestrian interaction. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *63*(1), 1232–1236.

Fridman, L., Mehler, B., Xia, L., Yang, Y., Facusse, L. Y., & Reimer, B. (2017). To walk or not to walk: Crowdsourced assessment of external vehicle-to-pedestrian displays. *ArXiv Preprint ArXiv:1707.02698*.

Fuest, T., Sorokin, L., Bellem, H., & Bengler, K. (2018). Taxonomy of traffic situations for the interaction between automated vehicles and human road users. *Advances in Intelligent Systems and Computing*, *597*, 708–719. https://doi.org/10.1007/978-3-319-60441-1_68

Habibovic, A., Lundgren, V. M., Andersson, J., Klingegård, M., Lagström, T., Sirkka, A., Fagerlönn, J., Edgren, C., Fredriksson, R., Krupenia, S., Saluäär, D., & Larsson, P. (2018). Communicating Intent of Automated Vehicles to Pedestrians. *Frontiers in Psychology*, *9*(August). https://doi.org/10.3389/fpsyg.2018.01336

Holländer, K., Colley, A., Mai, C., Häkkilä, J., Alt, F., & Pfleging, B. (2019). Investigating the influence of external car displays on pedestrians' crossing behavior in virtual reality. *Proceedings of the 21st International Conference on Human-Computer Interaction with Mobile Devices and Services*, 1–11.

Holländer, K., Wintersberger, P., & Butz, A. (2019). Overtrust in external cues of automated vehicles: an experimental investigation. *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 211–221.

Horn, S., Madigan, R., Lee, Y. M., Tango, F., & Merat, N. (2021). *Pedestrians' perceptions of* *automated vehicle movements and light-based eHMIs in real world conditions: A test track study*.

Jayaraman, S. K., Creech, C., Robert Jr, L. P., Tilbury, D. M., Yang, X. J., Pradhan, A. K., & Tsui, K. M. (2018). Trust in AV: An uncertainty reduction model of AV-pedestrian interactions. *Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, 133–134.

Lee, Y. M., Madigan, R., Garcia, J., Tomlinson, A., Solernou, A., Romano, R., Markkula, G., Merat, N., & Uttley, J. (2019). Understanding the messages conveyed by automated vehicles. *Proceedings - 11th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications, AutomotiveUI 2019*. https://doi.org/10.1145/3342197.3344546

Lee, Y. M., Madigan, R., Giles, O., Markkula, G., Garach-Morcillo, L., Fox, C., Camara, F., Rothmueller, M., Vendelbo-Larsen, S. A., Rasmussen, P. H., Dietrich, A., Nathanael, D., Portouli, E., Schieben, A., & Merat, N. (2020). Road users rarely use explicit communication techniques when interacting in today's traffic: Implications for Automated Vehicles. *Cognition, Technology and Work*. https://doi.org/10.1007/s10111-020-00635-y

Lee, Y. M., Madigan, R., Uzondu, C., Garcia, J., Romano, R., Markkula, G., & Merat, N. (2021). Learning to interpret novel eHMI: The effect of vehicle kinematics and eHMI familiarity on pedestrians' crossing behaviour. *Journal of Safety Research*. https://doi.org/https://doi.org/10.1016/j.jsr.2021.12.010

Madigan, R., Nordhoff, S., Fox, C., Ezzati Amini, R., Louw, T., Wilbrink, M., Schieben, A., & Merat, N. (2019). Understanding interactions between Automated Road Transport Systems and other road users: A video analysis. *Transportation Research Part F: Traffic Psychology and Behaviour*, *66*. https://doi.org/10.1016/j.trf.2019.09.006

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*. sage.

Nissan Motor Corporation. (2015). *Nissan IDS Concept: Nissan's vision for the future of EVs and autonomous driving*. https://europe.nissannews.com/en-GB/releases/release-139047

Otherson, I., Conti-Kufner, A. S., Dietrich, A., Maruhn, P., & Bengler, K. (2018). Designing for automated vehicle and pedestrian communication: Perspectives on eHMIs from older and younger persons. *Proceedings of the Human Factors and Ergonomics Society Europe*, 135–148.

Pekkanen, J., Giles, O., Lee, Y. M., Madigan, R., Daimon, T., Merat, N., & Markkula, G. (2021). *Variable-drift diffusion models of pedestrian road-crossing decisions*.

RAC. (2021). *Pedestrians and cyclists given right of way in new Highway Code*. https://www.rac.co.uk/drive/news/motoring-news/pedestrians-and-cyclists-given-right-of-way-in-new-highway-code/

Rasouli, A., Kotseruba, I., & Tsotsos, J. K. (2017). Agreeing to cross: How drivers and pedestrians communicate. *IEEE Intelligent Vehicles Symposium, Proceedings*, *Iv*, 264–269. https://doi.org/10.1109/IVS.2017.7995730

Rettenmaier, M., Dinkel, S., & Bengler, K. (2021). Communication via motion--Suitability of automated vehicle movements to negotiate the right of way in road bottleneck scenarios. *Applied Ergonomics*, *95*, 103438.

Rothenbucher, D., Li, J., Sirkin, D., Mok, B., & Ju, W. (2016). Ghost driver: A field study investigating the interaction between pedestrians and driverless vehicles. *25th IEEE International Symposium on Robot and Human Interactive Communication, RO-MAN 2016*, 795–802. https://doi.org/10.1109/ROMAN.2016.7745210

SAE. (2018). *Definitions for terms related to on-road motor vehicle automated driving systems (J3016B).* https://www.sae.org/standards/content/j3016_201806/

SAE. (2019). *Automated driving system (ADS) marker lamp (J3134_201905*.

Schieben, A., Wilbrink, M., Kettwich, C., Madigan, R., Louw, T., & Merat, N. (2019). Designing the interaction of automated vehicles with other traffic participants: design considerations based on human needs and expectations. *Cognition, Technology & Work*, *21*(1), 69–85.

Schreier, M. (2012). Qualitative content analysis in practice. In *Qualitative content analysis in practice*. Sage.

Semcon. (2016). *The smiling car*. http://semcon.com/smilingcar/

Sucha, M., Dostal, D., & Risser, R. (2017). Pedestrian-driver communication and decision strategies at marked crossings. *Accident Analysis and Prevention*, *102*, 41–50. https://doi.org/10.1016/j.aap.2017.02.018

UNECE. (2019). *Taskforce on Autonomous Vehicle Signalling Requirements Draft Report: 4th meeting (Report AVSR-04-05; United Nations Economic Commission for Europe)*. https://wiki.unece.org/download/attachments/78742442/AVSR-04-05e.docx?api=v2

Uttley, J., Lee, Y. M., Madigan, R., & Merat, N. (2020). Road user interactions in a shared space setting: Priority and communication in a UK car park. *Transportation Research Part F: Traffic Psychology and Behaviour*, *72*, 32–46. https://doi.org/https://doi.org/10.1016/j.trf.2020.05.004

Velasco, J. P. N., Farah, H., van Arem, B., & Hagenzieker, M. P. (2019). Studying pedestrians' crossing behavior when interacting with automated vehicles using virtual reality. *Transportation Research Part F: Traffic Psychology and Behaviour*, *66*, 1–14.

Velasco, J. P. N., Lee, Y. M., Uttley, J., Solernou, A., Farah, H., van Arem, B., Hagenzieker, M., & Merat, N. (2021). Will pedestrians cross the road before an automated vehicle? The effect of drivers' attentiveness and presence on pedestrians' road crossing behavior. *Transportation Research Interdisciplinary Perspectives*, *12*, 100466.

Wang, P., Motamedi, S., Qi, S., Zhou, X., Zhang, T., & Chan, C.-Y. (2021). Pedestrian interaction with automated vehicles at uncontrolled intersections. *Transportation Research Part F: Traffic Psychology and Behaviour*, *77*, 10–25.

Weber, F., Chadowitz, R., Schmidt, K., Messerschmidt, J., & Fuest, T. (2019). Crossing the Street Across the Globe: A Study on the Effects of eHMI on Pedestrians in the US, Germany and China. *International Conference on Human-Computer Interaction*, 515–530.

Weber, F., Sorokin, L., Schmidt, E., Schieben, A., Wilbrink, M., Kettwich, C., Dodiya, J., Oehl, M., Kaup, M., Willrodt, J.-H., Lee, Y. M., Madigan, R., Markkula, G., Romano, R., & Merat, N. (2019). *interACT D.4.2. Final interaction strategies for the interACT Automated Vehicles*. https://www.interact-roadautomation.eu/wp-content/uploads/interACT_WP4_D4.2_Final_Human_Vehicle_Interaction_Strategies_v1.1_uploadWebsiteApproved.pdf

Werner, A. (2018). New colors for autonomous driving: An evaluation of chromaticities for the external lighting equipment of autonomous vehicles. *Colour Turn*, *1*, 1–15. https://doi.org/10.25538/tct.v0i1.692

Appendix A

Pre-Study Questionnaire

Name in block letters	
Age	
Gender	
Nationality	
How long have you been living in the UK?	(___ years)
Do you have a driving license?	Y / N
Which country is your driving license from?	
How many years of active driving experience do you have?	
What is your annual mileage (miles)?	
Do you use glasses (or other instruments to improve your vision) in everyday life?	Y/N

Post-Study Questionnaire

1. What information from the vehicle, if any, do you think was important to help with your decision to cross/not cross? Rate how important each of the factors were, leaving the factor blank if you did not use the information:	**Unimportant/Slightly unimportant/Neutral/Slightly important/Important**
A) Speed	
B) Distance	
C) Braking	
D) Vehicle positioning	
E) Light band	
F) Zebra Crossing	
G) None	
2a. Did you notice the Pulsing Light Band around the vehicle?	**Y/N**
2b. If so, did this light influence your crossing decisions? if yes, in what way? - Yes - Text	Free Text
3a. Do you think that the pulsing light band was conveying a particular message?	**Y/N**
3b. If so, please describe what information the pulsing light-band was conveying?	Free Text
4. Do you think the Pulsing Light Band is useful in helping you with your crossing decision?	**Y/N**
5a. Are you familiar with the concept of self-driving/driverless cars?	**Y/N**
5b. Do you think the Pulsing Light Band would be useful if implemented in future in self-driving (driverless) cars?	Y/N
5c. Please explain in your own words, why you think the Pulsing Light Band will (will not) be useful.	Free Text
6. Do you have any other thoughts / comments on the experiment?	**Free Text**
7. Short Sensation Seeking Questionnaire (20 items, see Arnett, 1994)	**Does not describe me at all / Does not describe me very well / Describes me**

	somewhat / Describes me very well
7a. I can see how it would be interesting to marry someone from a foreign country	
7b. When the water is very cold, I prefer not to swim even if it is a hot day	
7c. If I have to wait in a long line, I'm usually patient about it	
7d. When I listen to music, I like it to be loud	
7e. When taking a trip, I think it is best to make as few plans as possible and just take it as it comes	
7f. I stay away from movies that are said to be frightening or highly suspenseful	
7g. I think it's fun and exciting to perform or speak before a group	
7h. If I were to go to an amusement park, I would prefer to ride the rollercoaster or other fast rides	
7i. I would like to travel to places that are strange and far away	
7j. I would never like to gamble with money, even if I could afford it	
7k. I would have enjoyed being one of the first explorers of an unknown land	
7l. I like a movie where there are a lot of explosions and car chases	
7m. I don't like extremely hot and spicy foods	
7n. In general, I work better when I'm under pressure	
7o. I often like to have the radio or TV on while I'm doing something else, such as reading or cleaning up	
7p. It would be interesting to see a car accident happen	
7q. I think it's best to order something familiar when eating in a restaurant	
7r. I like the feeling of standing next to the edge on a high place and looking down.	
7s. If it were possible to visit another planet or the moon for free, I would be among the first in line to sign up	
7t. I can see how it must be exciting to be in a battle during a war	