Transportation Research Part F 69 (2020) 101–119

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

Pedestrians' road crossing behaviour in front of automated vehicles: Results from a pedestrian simulation experiment using agent-based modelling

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A R T I C L E I N F O

Article history:
Received 24 March 2019
Received in revised form 14 January 2020
Accepted 16 January 2020

Keywords:
Traffic safety
Automated vehicles
Pedestrian behaviour
Agent-based simulation

A B S T R A C T

The objective of this research is to explore the relation between personal characteristics of pedestrians and their crossing behaviour in front of an automated vehicle (AV). For this purpose, a simulation experiment was developed using Agent-Based Modelling (ABM) techniques. Sixty participants were asked to cross the road in a virtual environment displayed on a computer screen, allowing to record their crossing behaviour when in the presence of AVs and conventional vehicles (CVs). In some experimental configurations, the AVs communicated their intention to continue or not to continue their trajectories through the use of lights. The ABM allowed controlling the behaviour of the vehicles when interacting with the simulated avatar of the respondents. The subjects of the experiment were also asked to fill in a questionnaire about usual behaviour in traffic, as well as attitudes and risk perceptions toward crossing roads. The questionnaire data were used to estimate individual specific behavioural latent variables by means of principal component analysis which resulted in three main factors named: violations, lapses, and trust in AVs. The results of generalized linear mixed models applied to the data showed that besides the distance from the approaching vehicle and existence of a zebra crossing, pedestrians' crossing decisions are significantly affected by the participants' age, familiarity with AVs, the communication between the AV and the pedestrian, and whether the approaching vehicle is an AV. Moreover, the introduction of the latent factors as explanatory variables into the regression models indicated that individual specific characteristics like willingness to take risks and violate traffic rules, and trust in AVs can have additional explanatory power in the crossing decisions.

1. Introduction

1.1. Interaction of pedestrians with AVs

Automated vehicles (AVs) are expected to become commercially available between 2025 and 2045 (Milakis, Snelder, Arem, Wee, & Correia, 2015; Nieuwenhuijsen & de Correia, 2018), with promises to improve traffic flow efficiency and traffic safety. By eliminating the role of the human driver, it is foreseen that fully automated vehicles will be involved in fewer

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https://doi.org/10.1016/j.trf.2020.01.014
1369-8478/

collisions due to eliminating human error on the part of drivers (Fagnant & Kockelman, 2015; Petridou & Moustaki, 2000). However, pedestrians and other road users will have to interact with the AVs and this could lead to unsafe situations as AVs could, for example, behave differently than expected or be misunderstood by pedestrians and other road users (Mirnig, Perterer, Stollnberger, & Tscheligi, 2017; Vissers, van der Kint, van Schagen, & Hagenzieker, 2016).

Pedestrians can use the presence of a zebra crossing and the distance to the vehicle for their decision to cross the road as has been found in field studies involving traditional, manually driven cars (Havard & Willis, 2012; Schmidt & Färber, 2009). In a field study by Havard and Willis (2012), the effect of a zebra crossing in pedestrians' decision for crossing the road was investigated. The results showed that pedestrians' waiting time to cross the road and their walking speed during the crossing decreases in the presence of a zebra crossing. In another field study, by Schmidt and Färber (2009), it was found that the distance to the vehicle is an important criterion for crossing the road. Communication strategies also mediate the interaction between human drivers and pedestrians crossing the street which was investigated in a study by Šucha (2014). According to the results of a focus group, strategies like eye contact, waving the hand, and flashing with lights were considered important in making the decision to cross the road. In a small-scale field experiment pedestrians were less willing to cross the street if the driver of the approaching car was distracted; on the other hand, in the same experiment eye contact between the driver and the pedestrian led to a calmer interaction (Habibovic, Andersson, Nilsson, Lundgren, & Nilsson, 2016). Although the car was an AV in the study, participants were not informed about that and behaved as if the car was a conventional vehicle (CV).

Other studies have considered situations in which AVs will need to interact with other road users. Based on the results of a stated preference survey it was concluded that cyclists and pedestrians will prefer segregated facilities in the presence of AVs due to a lack of confidence in their behaviour (Blau, Akar, & Nasar, 2018). This supports the findings of a survey by Merat, Louw, Madigan, Wilbrink, and Schieben (2018). They asked 665 participants about their demographics, questions related to safety and priority in shared space, acceptance and use of technology, and also questions related to the type and mode of communication in interaction with AVs. The results indicate that pedestrians want to be informed about the behaviour of AVs and need to make sure they are detected by the AVs. Although they could not find a clear pattern about the form of external information to be communicated to the pedestrians, they found that conventional signals such as lights and beeps are more preferred than text messages or spoken words by AVs. On the other hand, Rothenbücher, Li, Sirkin, Mok, and Ju (2016) developed an experiment in which 67 pedestrians interacted with a vehicle that appeared not having a driver. Pedestrians believed that the car was fully-automated, yet they were actually able to have a "normal" reaction (Rothenbücher et al., 2016, p. 800). The pedestrians described the behaviour of the vehicles using words like "safe", "deliberate", and "smooth" in the interview after the interaction with the vehicle. Only when the vehicle behaved uncommonly, some pedestrians hesitated to cross. Similarly, in another field study by Rodríguez Palmeiro et al. (2018), no differences were found in pedestrians' critical gap acceptance and reported stress level when interacting with AVs. Twenty four participants encountered a vehicle with a fake driver who was inattentive in some scenarios. The vehicle was driven by a joystick and sometimes had a sign informing the participant that the vehicle was automated. Participants reported that the most important criteria for crossing the road were the speed of the vehicle and the distance from the vehicle. Although some participants who noticed the AV sign reported that they were more uncertain/doubtful about crossing the road, in general, there were no significant differences in the critical gap in terms of distance and time between the AV and joystick driven vehicle.

Results of these studies seem to imply that pedestrians are potentially more concerned with interacting with an AV as compared to a manually driven vehicle due to the absence/meaningless of eye contact with the driver or any type of body gesture by the driver that informs them about the vehicle's intention. However, Rothenbücher et al. (2016) and Rodríguez Palmeiro et al. (2018) did conclude in their study that the reaction of pedestrians, when confronted with the fake AV, was surprisingly 'normal' and identical to their reactions to conventional vehicles. Therefore, more research is needed to further understand crossing behaviour when in the presence of AVs.

It has been suggested that dedicated communication of AVs with pedestrians could help pedestrians overcome their fear of AVs (Keferböck & Riener, 2015; Mahadevan, Somanath, & Sharlin, 2018; Matthews, Chowdhary, & Kieson, 2017). However, only a few studies have been done toward defining which type of communication is most beneficial. Fridman et al. (2017) showed how various vehicle-to-pedestrian display concepts can illustrate the intention of the AV. In this experiment, 200 participants rated 30 external vehicle-to-pedestrian display concepts and came up with 4 designs that illustrate the intention of the vehicle best. Clamann, Aubert, and Cummings (2015) examined the influence of different messages shown on a forward facing display on an AV. However, in line with the results of the study by Rodríguez Palmeiro et al. (2018), the displays did not significantly influence the pedestrians' response time for making crossing decisions when interacting with the vehicles. In a different field experiment study (Lagström, Lundgren, & Lagström, 2015) nine participants encountered an AV that communicated its intentions to pedestrians using a LED-strip with different lighting patterns in the windshield. With the so-called AVIP-system (Automated Vehicle's Interaction with the Pedestrian system), more participants said they would cross the road before the vehicle stopped. However, the number of participants in this experiment was very small. In a video-based lab experiment by Petzoldt, Schleinitz, and Banse (2018), the use of a frontal brake light as a communication between the AV and pedestrians proved to be helpful in improving and speeding up the decision-making process of pedestrians.

Although the communication system seems to help pedestrians to cross the road with less response time, it also raises the question as to what extent pedestrians feel comfortable to cross the road before a vehicle stops. In a recent survey, it has been observed that pedestrians rated AVs as being significantly less risky than those being driven by humans (Hulse, Xie, & Galea, 2018). Millard-Ball has theorized, based on game theoretic reasoning, that pedestrians will exploit the caution of

AVs since they know that an AV is programmed to stop and will follow the law strictly (2017). Results consistent with this notion can be found in the outcome of the pedestrian receptivity questionnaire for fully automated vehicles created by Deb et al. (2017), which revealed that pedestrians with generally more risky behaviour in traffic will take advantage of the AV's detection system and cross the road with less attention. This shows that personal characteristics influence the decision to cross the road in front of an AV and need to be taken into account.

Also, other personal and road user characteristics play a role. Other bodies of research have, for example, suggested that older individuals are reluctant to use a new technology (Melenhorst, Rogers, & Caylor, 2001), but as the knowledge about the technology increases people are more likely to accept and use it (Nees, 2016). Older and female individuals are more hesitant to accept AVs (Schoettle Brandon, 2014). Furthermore, age and gender of the pedestrians play important roles in the probability of them showing risky behaviours (Mirzaei-Alavijeh et al., 2019; Rosenbloom, 2009; Rosenbloom, 2003; Holland & Hill, 2007). Given these results it is relevant to investigate the behaviour of different groups (age, gender, and familiarity with AVs) in interaction with AVs. While there are a few studies emphasizing the need for communication between AVs and vulnerable road users, the importance of that need and how personal characteristics such as age, gender, and familiarity with the technology affect the decision making of the pedestrians in response to the communication system is still scant, as becomes clear from the research studies described above.

1.2. Study aim

The focus of this paper is on pedestrian crossing behaviour in front of an AV, while explicitly considering a number of personal characteristics and background variables as potential determinants. More specifically, this research aims to develop models that explain the probability to cross a road as a function of the type of vehicle, type of communication with AV, pedestrians' familiarity with AVs, as well as their age, gender, and latent factors such as their attitudes and behaviour in crossing the road in front of AVs and CVs. It should be noted that, in this paper, AV refers to a fully automated vehicle without a human driver, which corresponds to SAE level 5 (Taxonomy, 2018).

Our main research questions are:

i. Will pedestrians' crossing behaviour be different when the approaching vehicle is demonstrably an AV as compared to a traditional, manually driven vehicle, and will this crossing behaviour be different for persons with different characteristics? Based on the literature described we expect that male pedestrians would be more risk-taking and less compliant with traffic rules related to the road crossing, that young pedestrians would be more likely to cross in front of AVs, and that people who are more familiar with AV technology would be more likely to trust an AV.
ii. Will pedestrians cross the road regardless of whether an AV stops or continues driving when approaching the crossing area? We expected that more compliant pedestrians with less rules-violating behaviour are less likely to cross if the AV does not slow down.
iii. How do different ways of communication by AVs informing pedestrians about their intention affect their crossing behaviour?
iv. What is the most important criterion for pedestrians to cross the road?

To answer the aforementioned questions, and given the difficulty in doing real-life experiments with AVs, a simulation experiment was developed using Agent-Based Modelling (ABM) techniques. Respondents were asked to fill the role of a pedestrian avatar who has to cross the street in front of a vehicle in several experiments. The ABM environment was used in order to control the vehicle that interacts with the digital avatar controlled by each subject, and the communication and appearance of the vehicles were varied. In addition, several questionnaires were administered to extract respondents' personal characteristics, attitudes and behaviour in crossing the road.

The paper is structured as follows. In Section 2 the method, the experimental setup and simulation details, and the analysis approach is described. Section 3 explains the analysis techniques that were applied and their results following the discussion in Section 4. Study limitations are presented in Section 5. Finally, Section 6 provides the main conclusions and formulates recommendations for further research.

2. Method

2.1. General design and set up

Two types of experiments for examining the pedestrian crossing behaviour have been created: (a) one using a mixed situation with AVs and CVs on the road and (b) a future situation where roads are used solely by AVs. In the first experiment, there were both AVs and CVs on the road and in the second experiment, only AVs using different signals to convey their intention (yield or not) to the pedestrian were present. The experiments are described in detail in Section 3. Two questionnaires were administered to the participants: one before and the other after the two experiments. The first questionnaire was used to obtain information about participants' personal background characteristics (age, gender, education level, familiarity with AV technology), attitudes and risk perceptions toward crossing roads, and the second one to determine

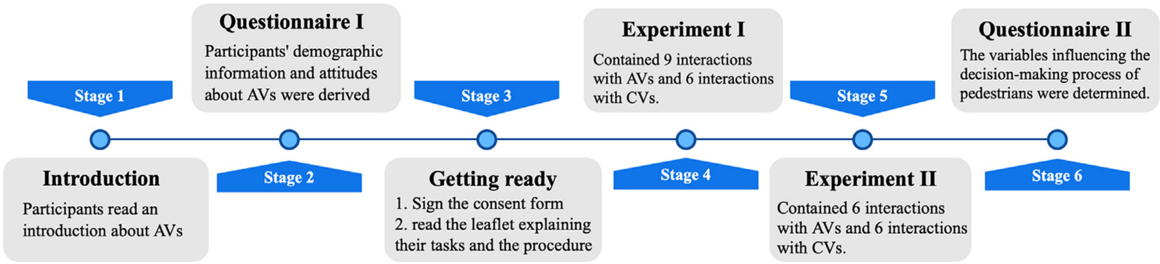

Fig. 1. Experimental procedure.

the variables influencing the decision-making process of participants during the simulation experiment. An overview of the study flowchart can be seen in Fig. 1.

2.2. Participants

In total 60 persons volunteered to participate in the experiment via an advertisement on the TU Delft campus (Delft, The Netherlands). The experiment was approved by the Human Research Ethics Committee of the Delft University of Technology. The participants (20 females and 40 males) who completed the experiment were between the age of 18 and 69 years old. Participation in this experiment was voluntarily, therefore no economic compensation was received by the subjects.

2.3. Materials

2.3.1. First questionnaire: background variables and self-reported behaviour

The first questionnaire contained a list of items to be rated on a 7-point Likert scale expressing: "always" (1 point)/" never" (7 points) or "strongly agree" (1 point)/ "strongly disagree" (7 points) behaviour scales. A short version of the behavioural questionnaire of Papadimitriou, Lassarre, and Yannis (2016) was used as a reference and modified for this study.

Based on the literature and having in mind the research questions stated in the introduction the questionnaire contained 3 main sections:

Section A: Demographics. This section contained demographic information and other personal characteristics to investigate research question i.
Section B: Stated behaviour of crossing, related to research question ii
Section C: Scenario-based questions, related to research questions iii and iv

The detailed questions can be seen in Table 1. In the questionnaire, the word "driverless vehicle" was used instead of "automated vehicle" to ensure that the participants knew that the focus of this study was on vehicles without any human driver.

2.3.2. Second questionnaire: participants' reported interactions with AVs

After the completion of the two experiments, the participants were required to fill out the second questionnaire. They answered questions about their opinion about interacting with AVs. They were also asked about which factors they considered to be more important when crossing the road and the meaning of the lights of AVs in the experiment. Table 2 illustrates the questions in more detail.

2.3.3. Simulation model & environment

The simulation model was developed using agent-based modelling (ABM) techniques and implemented in AnyLogic version 8.2.3. AnyLogic is a simulation tool that supports many simulation methodologies: system dynamics, discrete event, and ABM. ABM is a bottom-up technique in which the building blocks of the simulation are created and interact in a virtual environment given a set of rules. Agents are autonomous entities within the model that are capable of making decisions given an external stimulus. This type of simulation has proven to be successful in modelling different activities for vehicles and pedestrians, including pedestrian movement (Zhang, Luo, Chen, & Bao, 2009), pedestrian emergency evacuation (Jin & Chen, 2013), vehicle's schedules (Merkuryeva & Bolshakovs, 2010) or new urban transport modes (Martinez, Correia, & Viegas, 2015; Scheltes & de Almeida Correia, 2017; Vasconcelos, Martinez, Correia, Guimarães, & Farias, 2017). In the following sections, we describe the model components developed in this work.

A 3D environment was created in the model to illustrate the scenarios and allow the respondents to be embedded in the situation. In addition to the agents (vehicles), the environment contained a one-lane one-way road (3.5 m wide), a railroad and a train station (see Fig. 2). In this environment, the interaction takes place between the AVs and the user-controlled pedestrian avatar who has as an objective to cross the street to catch the train. The environment changed in some scenarios: there was a pedestrian zebra crossing in some scenarios and no zebra crossing in others.

Table 1
First survey questionnaire.

	Questions	Possible answers
A	**Personal characteristics**	
A_i.	Gender	(female/male)
A_ii.	Age group	(18–24, 25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70 or older)
A_iii	What is your education level?	Lower vocational/secondary education; Higher vocational education; Bachelor degree; Master's degree; Ph.D. or medical degree
A_iv	How familiar are you with the concept of the driverless vehicle?	I have never heard of driverless vehicles; I have heard about driverless vehicles once or twice; I am fairly familiar with the idea of driverless vehicles; I follow the development of driverless vehicles; I work in a field directly related to driverless vehicles.
B1	**In the "CURRENT SITUATION WITH NO DRIVERLESS VEHICLES ON THE ROAD", how much would you agree with each one of the following statements:**	Strongly disagree = 1 to strongly agree = 7
B1_i.	Crossing roads outside specific crossing areas (eg. zebra crossing) saves time	
B1_ii.	I am willing to make a detour to find a protected crossing	
B1_iii.	I am willing to take any opportunity to cross	
B1_iv.	I am willing to take dangerous actions as a pedestrian to save time if I am in a hurry	
B2	**As a pedestrian, how often do you CURRENTLY adopt each one of the following behaviours:**	Never = 1 to always = 7
B2_i.	I cross diagonally	
B2_ii.	I cross roads with no zebra crossing when I am in a hurry	
B2_iii.	I cross roads with no zebra crossing if no vehicle is approaching	
B2_iv.	I cross even though the pedestrian light is red	
B2_v.	I have crossed the road without paying attention to traffic	
B2_vi.	I am absent-minded while walking	
C	**Place yourself in a situation where DRIVERLESS VEHICLES ARE ON THE ROAD, MIXED WITH CONVENTIONAL CARS. As a pedestrian, how much would you agree with each one of the following statements?**	Strongly disagree = 1 to strongly agree = 7
C_i.	I feel comfortable to cross the road in front of a vehicle which is in automated mode.	
C_ii.	I expect the driverless vehicles to be better at identifying me than a human driver.	
C_ii.	I cross the road if the driver is not paying attention to the road (reading newspaper or sleeping) because it may be in automated mode.	

Table 2
Second survey questionnaire.

	Questions	Possible answers
1	In which places do you think a driverless vehicle should stop for you to cross the road? (you may choose more than one option)	Everywhere; Pedestrian zebra crossing; No zebra crossing; Un-signalized junctions; Signalized junctions even during pedestrian red signal
2	In the first experiment, did you realize, BEFORE MAKING THE DECISION, that in some scenarios the vehicle was equipped with specific lights?	Yes/No
3	In the second experiment, did you realize, the differences between red and green lights? Could you explain that?	Open answer
4	What was the most important criterion to consider for making your decision to cross or not to cross?	Open answer
5	I think it is important for the automated vehicles to be distinguishable to me, as a pedestrian.	Strongly disagree = 1 to strongly agree = 7
6	There is a need to have a communication way between the automated vehicles and me, as a pedestrian.	Strongly disagree = 1 to strongly agree = 7

2.3.4. Vehicles and pedestrians

The AnyLogic "road traffic library" was used to create the vehicles as agents. In general, the cars from the traffic library supplied with the software are able to detect each other and avoid a crash, however, they are not able to detect pedestrians. Therefore, cars would maintain their speed and simply run over the pedestrians in the simulated environment. In order to make the cars able to detect the pedestrian and stop for him/her under the desired experimental conditions, three virtual fields of view were defined for pedestrian detection as well as another field that defines a physical boundary that once it

Fig. 2. The simulation environment.

was touched immediately resulted in a crash. During the experiment runs, none of these fields was visible for the participants. The fields can be seen in Fig. 3.

i. Crash Avoidance Field of View (yielding car): is a polygon attached to the front part of the car. If any point of the pedestrian's body lies inside the polygon, the car will brake. In case the car is going to yield to the pedestrian, the orange polygon shown in Fig. 3 is active. The dimensions of this polygon are defined in a way that the vehicle is able to stop for the pedestrians slightly before reaching the zebra crossing and the polygon covers the area where the pedestrian is waiting. It should be noted that the pedestrian avatar could only cross the road laterally and participants did not have any control in changing the position of the pedestrian avatar longitudinally to the road. Given that the pedestrian was the only obstacle for the vehicles, it was enough to define a static polygon which is always able to detect the pedestrian on the same lateral line (crossing path).
ii. Crash Avoidance Field of View (not yielding car): if the car is not yielding to the pedestrian, the green polygon in Fig. 3 is active. The polygon is exactly the same as the orange polygon except that it just covers the area on the road and not the roadside where the pedestrian is waiting. Therefore the car is not able to detect the pedestrian at the roadside and will not stop unless the pedestrian starts crossing the road.
iii. Lights field of view: is defined to turn on the AV's lights when a pedestrian is inside this polygon (illustrated as the blue polygon in Fig. 3). This field of view is active only for AVs and not for conventional cars (CVs). The dimensions of this polygon were defined so that the AV could detect the pedestrian and turn on the lights 30 m before his/her waiting area.
iv. Crash boundary: covers the shape of the car (the yellow polygon shown in Fig. 3), meaning that if any point of the pedestrian is inside this boundary, a crash will occur and the screen turns to red and notifies the participant that a crash has happened (see Fig. 4).

The state chart in Fig. 5 illustrates the behaviour of the vehicle agent. The vehicle state is changed through transitions. Variables are used to define specific attributes of the vehicle or of the relation of the vehicle to the environment, changing over time. Transitions are triggered by a timeout to change the state of the vehicle according to the variables.

The following states are defined in the state chart: *Driving* and *StopForPed.* At the first stage, when the vehicle is generated, it is in driving state starting at a pre-defined point of the road. Every 0.1 ms, *checkforped* transition checks for a change in the variables with the objective of checking for pedestrians. If no pedestrian is found inside the crash avoidance field of view, the vehicle continues in driving state. However, if a pedestrian is inside the crash avoidance field of view, the variable "*PedInDanger*" takes the Boolean "true" value. As soon as *PedInDanger* is true, *checkforped* changes the state of the vehicle to *StopForPed* which is setting the variable *PreferredSpeed* to 0, leading to reduce the speed of the vehicle to 0 km per hour, letting the pedestrian pass. The vehicle resumes speed afterward and continues its trajectory. It is important mentioning that the default deceleration rate of the vehicles in AnyLogic is set to 4.2 m/s^2. As it was indicated in the pilot study, it was not obvious from the participant's perspective that the vehicle was braking until the last second. Therefore, the deceleration rate was increased to 10 m/s^2 to ensure that the participant was able to detect it.

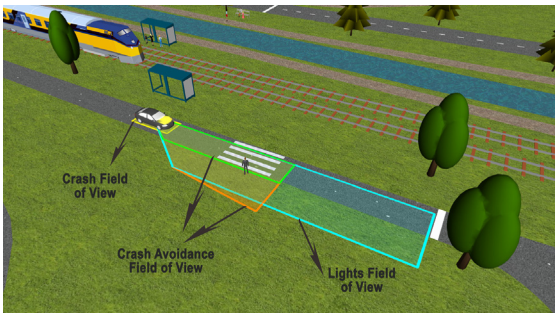

Fig. 3. Fields of view of the vehicles.

Fig. 4. Crash notification.

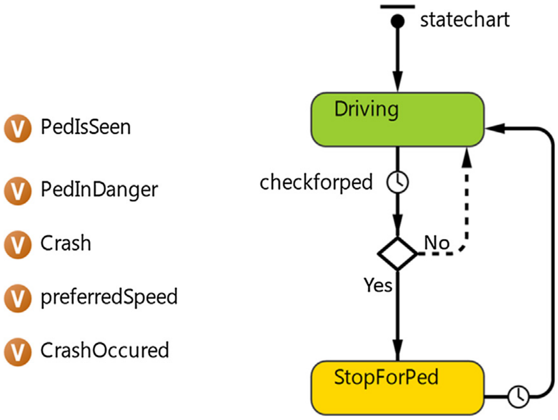

Fig. 5. State chart of vehicle behaviour.

The AnyLogic "pedestrian library" was used to create the pedestrian agent. The Pedestrian library supports 3D animation (Borshchev, 2013). In every scenario, one pedestrian is injected into the model, which represents the avatar of the participant. The time of injection in the environment was set to obtain the exact time to collision (TTC) for each scenario (knowing where the vehicle is injected and when). TTC is thus the exact time in seconds until a collision would occur between the vehicle and the pedestrian if the vehicle did not stop and the participant clicked the button to cross immediately after the pedestrian avatar arrived at the road side. Once the pedestrian was inserted, it walked automatically to the roadside and waited for the participant to press a button to cross the road. Pushing an array key on the keyboard let the subject give an order for the pedestrian to cross.

2.4. Experimental procedure and design

Participants were presented with the scenario of crossing a road in their neighbourhood to a train station and being late to catch the train. The train arrived a few seconds after the pedestrian reached the roadside and waited for 15 s before leaving the station. The participants were asked to cross the road when they felt it was safe to do so. Participants were further informed that they would be interacting with vehicles passing by. Black vehicles are in automated mode with no driver and vehicles in other colours are the conventional ones with a human driver. The objective that was given to each participant was reaching the train on time so that he/she would have an incentive to cross as soon as he/she felt it was safe rather than waiting for all the cars to pass. AnyLogic notified the participants if they were able to board on time or if otherwise they missed the train (Fig. 6).

In total each participant had to cross the street 28 times, including a practice trial, which was crossing the road with no vehicle in order for the respondent to see the environment and to learn how to get to the train station using the keyboard.

When the experiment started, before administering the first questionnaire, participants read an introduction about AVs in order to become familiar with this technology. The explanation was according to the definition of self-driving cars on Wikipedia (2019) since we found this to be a simple yet complete definition to give to the participants: *"An automated vehicle (also known as a driverless car or self-driving car) is a vehicle that is capable of sensing its environment and navigating without human input. Automated cars use a variety of techniques to detect their surroundings, such as radar, laser light, GPS, odometer, and computer vision. Advanced control systems interpret sensory information to identify appropriate navigation paths, as well as obstacles and relevant signage."* Subsequently, participants' understanding and attitudes about AVs were derived through question-

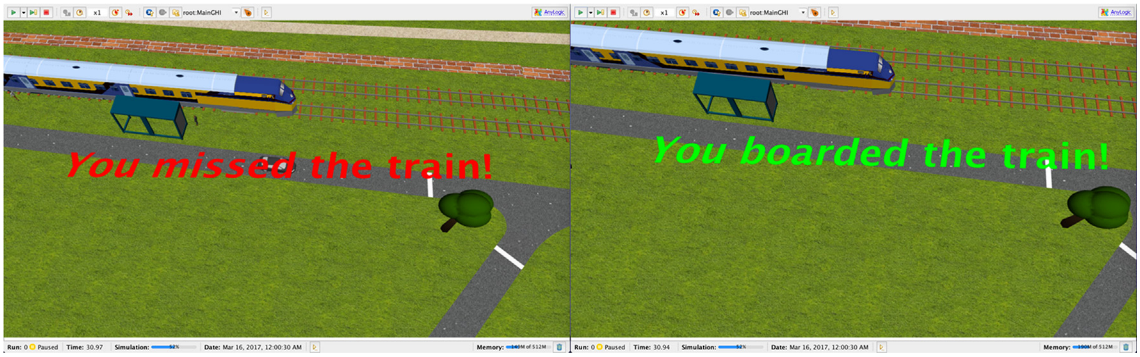

Fig. 6. Notification of boarding the train.

naire 1. Then, they were presented with a leaflet explaining their task and the procedure of the simulation experiment. The leaflet also mentioned that they should act as much as possible as they would normally do. They were also advised to stop the experiment if they felt any discomfort. Next, participants signed a consent form to allow the usage of their data for research and started with the practice trial.

2.4.1. Experiment I (AVs and CVs on the road)

The participant reached the crossing area at a specific TTC (3 s, 5 s, and 7 s) from an approaching vehicle as it is shown in Fig. 7. In this experiment, all cars moved at a constant speed of 40 km per hour and the participants were informed about it. The vehicles were able to detect the pedestrians around 30 m before the crossing area, utilizing the lights field of view (the blue polygon). As soon as a pedestrian had been detected in the lights field of view of an AV, the variable *PedIsSeen* became true and triggered the function to turn on the lights (see Fig. 5) to inform the pedestrian that he/she had been seen. In this experiment, a yellow light was used as a signal to only inform the pedestrians about being detected and no information was given about the vehicle's decision to stop or not. As the vehicle drove closer, the pedestrian could be detected in the crash avoidance field of view (the orange polygon to cover the pedestrian's waiting area) and caused the vehicle to brake based on the State chart of vehicle behaviour. The participant had to decide to trust the AV and cross the road when he/she saw the lights or wait until the AV stopped completely.

According to the traffic rules in the Netherlands, drivers need to stop for pedestrians at zebra crossings and pedestrians are also allowed to cross in the absence of zebra crossing after they have made sure they can see the traffic clearly and are seen well (Ministerie van Verkeer en Waterstaat, 2019). Assuming that AVs always obey the traffic rules, they always stopped for the pedestrians if there was a zebra crossing in their path. If there was no zebra crossing, they only stopped while their lights were on, informing the pedestrian that he/she is detected. However, in some scenarios without zebra crossing the AVs did not turn on their light and continued driving. The experimental design can be seen in detail in Fig. 8. If the AV was not yielding to the pedestrian, it passed by the pedestrian or it reduced speed in order to avoid an accident in case the pedestrian started to cross. However, if the stopping distance was not enough a crash would occur. The CVs did not have these special lights and randomly yielded to the pedestrians when there was no zebra crossing. In case of zebra crossings, CVs always yielded to the pedestrians except for one scenario per experiment which is meant to be representative of human drivers who violate the rules. Considering the 3 different TTCs (3 s, 5 s, and 7 s) and two types of crossing area (zebra and no zebra), there were six scenarios where the participants interacted with CVs (first six scenarios in Fig. 8). Six other interactions happened between the participants and AVs which had lights with the same settings for TTC and crossing area (second six scenarios in Fig. 8). It should be noted that AVs with lights always yielded to the pedestrians regardless of the type of

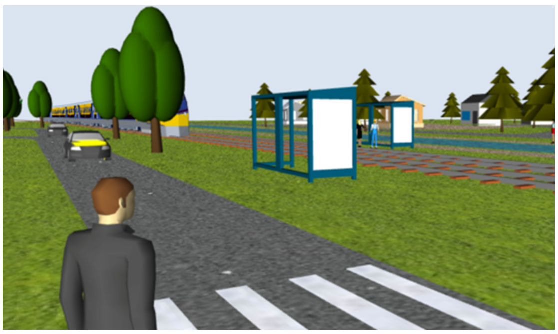

Fig. 7. The view of the participant with an AV with its yellow lights on. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

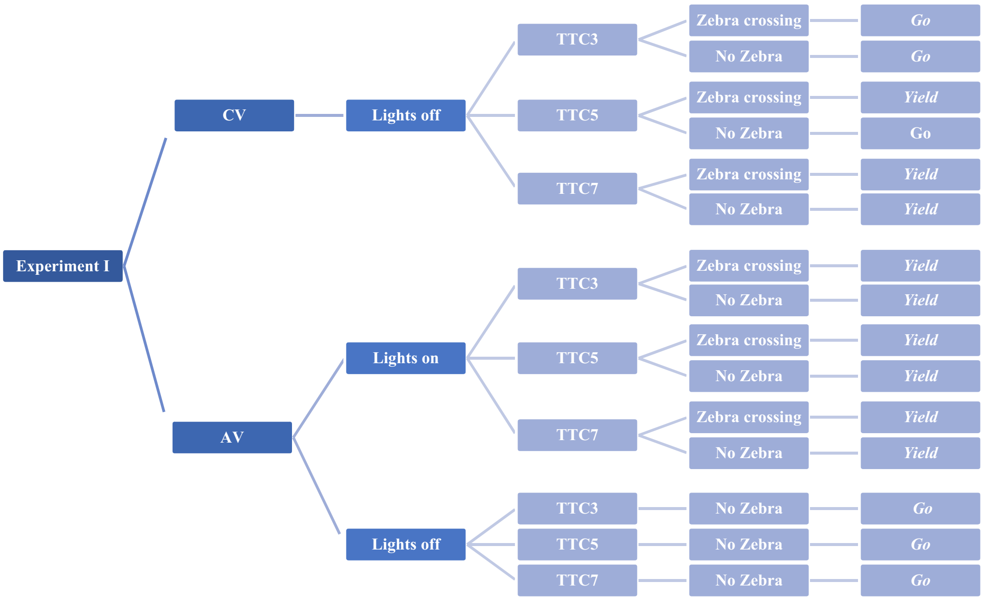

Fig. 8. Summary of experimental design of experiment I.

crossing area and TTCs. This could be representative of AVs which are not in a rush and give the priority to the pedestrians as it currently happens with CVs as well. However, some AVs which did not yield to the pedestrians had no lights and continued their trajectory regardless of TTC. This happened only when there was no zebra crossing (the last three scenarios in Fig. 8). The reason was that it was assumed that at zebra crossings pedestrians would expect AVs to yield. It could lead to confusion by participants if the AV did not yield to the participants without indicating its intention, and this combination was therefore left out. So, in this experiment, a total of 15 scenarios were presented to the participants as illustrated in Fig. 8 to assess:

i. whether the pedestrian's intention to cross changes, as the approaching vehicle is demonstrably an AV as compared to when it is a CV; and
ii. whether the pedestrian's intention to cross varies according to personal characteristics (age, gender, education level, and familiarity with AVs).

Interactions happened on the same road and traffic properties while the order of the scenarios was randomized to prevent an order effect. The TTC of 3–7 s is within the critical TTC-limits regarding the gap acceptance of pedestrians found in the literature (Schmidt & Färber, 2009).

2.4.2. Experiment II (only AVs on the road)

In this experiment all vehicles were automated, however, participants were not informed directly about that. In every interaction, the AV turned on the lights to indicate the pedestrian whether it was going to yield (green headlight) or continue its trajectory (red headlight) (see Fig. 9).

Fig. 9. The communication system: (a) AV is yielding and (b) AV is not yielding.

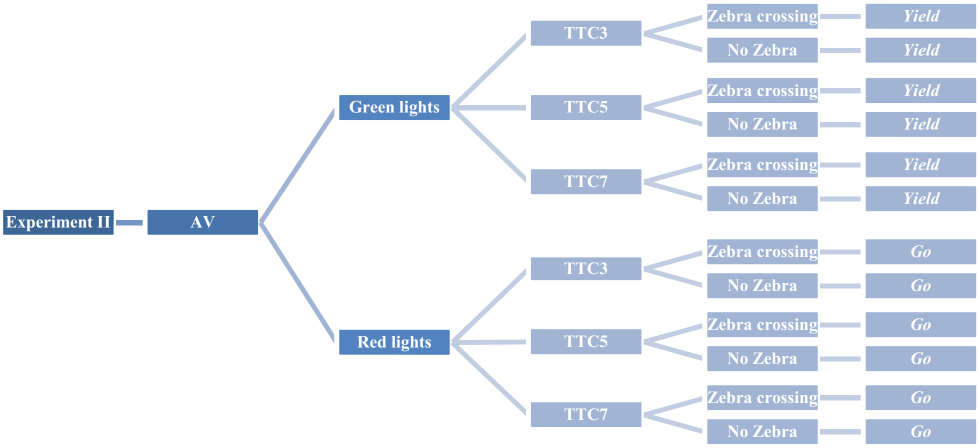

Fig. 10. Summary of experimental design of experiment II.

The participant should decide to cross the road or not. It must be noted that he/she was probably aware (based on what he/she had experienced during experiment I) that the AV would stop anyway if he/she stepped on the road. The purpose of this experiment was to assess:

i. if the **red** or **green signal** helps the participants to understand the AV's intention; and
ii. if participants cross the road regardless of whether the AV continuous driving near the zebra crossing and signals with the red light (meaning not to cross).

In total the participants had to respond to 12 interactions (3 TTCs $\times$ 2 types of crossing area $\times$ 2 types of lights) in random order in experiment II (see Fig. 10):

For each scenario, in both experiments, according to the time participant started to cross and the time the vehicle (AV or CV) stopped at the crossing area it was calculated:

- *Whether the participant crossed before the approaching vehicle stopped (0 = no, 1 = yes).*

In experiment II, only when the AV signalled with the red light also:

- *Whether the participant made the AV stop by stepping on the road (0 = no, 1 = yes).*

2.5. Analysis approach

A two-step analysis approach was implemented to analyse the questionnaire data in this study. First, a principal component analysis (PCA) was conducted on the answers to the 13 questions (sections B1, B2, and C) from the questionnaire. The purpose was to determine the latent attitudinal or behavioural components relevant to the crossing behaviour. Secondly, a Generalized Linear Mixed Model (GLMM) with repeated measures estimated the importance of several predictors on the road crossing behaviour. All analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 24.0. The level of statistical significance was set to be lower than 5%.

Prior to conducting the GLMM analysis, bivariate comparisons were first used to evaluate statistical significance of the independent variables in participants' decision in crossing the road in each experiment.

The main results of these bivariate comparisons are as follows (for more details see Tables A.1–A.3 in the Appendix A)

In experiment I, independently of the type of vehicle and crosswalk, with an increase in TTC, the participants' tendency to cross before the first vehicle passes increased significantly. Participants were more inclined to cross the road if the approaching vehicle was automated and when there was a zebra crossing. Considering the participant's level of knowledge about the AVs, those participants who follow the development of the AVs technology and study about the AVs were most likely to cross the road before the vehicle stopped.

Similar to Experiment I, TTC, type of crosswalk and level of knowledge about AVs turned out to be significant for participants to make their decision to cross before the first vehicle in Experiment II. In this experiment, AVs signaled their intention with green and red light meaning to yield and not to yield to the pedestrians respectively. This communication method improved the vehicle intention recognition by the participants in a significant way. More participants were willing to wait when the AV signaled not to cross compared to the first experiment. In the first experiment, the communication method (yellow light when the AV detected the pedestrian and stopped) was not significantly helpful in understanding the intention of the AVs by participants.

Another comparison was done for those interactions where the AV signaled with the red light, to investigate if the participant stops for the AV or if he/she crosses despite the AV's signal. As far as TTC is concerned, participants interrupted the AV in TTCs of 5 s the most. Regarding the type of crosswalk, participants interrupted the AV more often on a zebra crossing.

During this experiment, participants were involved in a total of 17 accidents out of 720 interactions. Participants had 14 crashes with the AVs on zebra crossing and TTC of 3 s. In fact, they would not expect the AV to maintain its speed on a zebra crossing since they believed the pedestrian has the priority on a zebra crossing. Due to the fact that the AV was quite close to the zebra at the moment when the participant decided to cross, the stopping distance was not enough for the AV to stop completely and therefore the crashes happened.

3. Results

3.1. First questionnaire

The PCA was conducted with orthogonal rotation (varimax) and based on eigenvalues greater than 1. Table 3 illustrates the results of the estimated latent variable model. After checking communalities between indicators, a simple structure was obtained resulting in three components, which cumulatively accounted for 58.89% of the total variance. Indicators with a communality lower than 0.4 were excluded from the exploratory factor analysis. The Kaiser-Meyer-Olkin measure of sampling adequacy was satisfactory (0.79) and Bartlett's test of sphericity was significant ($p < 0.0001$) which means that the data was suitable for the proposed statistical procedure of factor analysis (Williams, Onsman, & Brown, 2010).

In conclusion, 12 out of the 13 indicators were part of the final 3-component solution. The latent variable Component 1 can best be described as "willingness to take risks and violate rules", representing the extent to which participants take the risk in crossing the road. Component 2 reflects the attitude of travellers with regards to "trust in automated vehicles", and finally, Component 3 refers to "lapses", describing faults and mistakes which pedestrians make in crossing the road.

3.2. Experiments

To explore the predictive factors of pedestrian crossing behaviour, a GLMM was estimated with the road crossing decision (Yes/No) as a function of the predictors: TTC, vehicle type, the existence of a zebra crossing, communication way, familiarity with AV, age, gender, education level, and latent variables. GLMM is able to consider these changes. Let D_{ijk} represent the decision of participant i to cross the road, at scenario j, with k level of familiarity with AVs (considering the potential changes in participants' level of familiarity with AV during the experiment). Then the model structure of the GLMM for the crossing decision can be expressed as follows:

$$D_{ij} = \beta_0 + T_k + P_{ki} + \beta_f Fixed_{ij} + \varepsilon_{ijk} \tag{1}$$

where T_k is the effect of getting familiar with AVs during the experiment which is classified as a random effect. P_{ki} is the person effect with k level of familiarity, and $Fixed_{ij}$ is the effect of fixed effects on participant i in scenario j. $\beta_0 + T_k + P_{ki}$ would be an intercept specific to participant i with k level of familiarity with AV, allowing individuals to start at different values. The ε_{ijk} is the error term with mean 0.

3.2.1. Experiment I (both AVs and CVs on the road)

The repeated measures GLMM was estimated to identify significant predictors of pedestrians' road crossing behaviour. Participants' decision to cross the road before the first vehicle was used as the dependent variable. In addition to TTC, type

Table 3
Estimation results of latent variable model (factor loads < 0.40 are not shown).

		Component		
		1	2	3
B1_i.	Crossing roads outside specific crossing areas (e.g. zebra crossing) saves time	0.679		
B1_ii.	I am willing to make a detour to find a protected crossing	No communality		
B1_iii.	I am willing to take any opportunity to cross	0.659		
B1_iv.	I am willing to take dangerous actions as a pedestrian to save time if I am in a hurry	0.684		
B2_i.	I cross diagonally	0.730		
B2_ii.	I cross roads with no zebra crossing when I am in a hurry	0.801		
B2_iii.	I cross roads with no zebra crossing if no vehicle is approaching	0.799		
B2_iv.	I cross even though the pedestrian light is red	0.811		
B2_v.	I have crossed the road without paying attention to traffic			0.781
B2_vi.	I am absent-minded while walking			0.774
C_i.	I feel comfortable to cross the road in front of a vehicle, which is in automated mode.		0.806	
C_ii.	I expect the driverless car to be better at identifying me than a human driver.		0.668	
C_ii.	I cross the road if the driver is not paying attention to the road (reading newspaper or sleeping) because it may be in automated mode.		0.651	

Table 4
Results of the GLMM estimation for crossing before the vehicle stops completely.

	Model (a)			Model (b)		
Parameters	**Coefficient**	**t-statistics**	**P-value**	**Coefficient**	**t-statistic**	**P-value**
Fixed effects						
Intercept	4.418	9.757	0.000	4.047	10.609	0.000
TTC=3	-3.854	-14.419	0.000	-3.557	-12.464	0.000
TTC=5	-1.402	-5.540	0.000	-1.299	-4. 692	0.000
TTC=7	_a	_a	_a	_a	_a	_a
No zebra	-1.724	-8.294	0.000	-1.565	-7.497	0.000
Zebra	_a	_a	_a	_a	_a	_a
Conventional vehicle	-0.793	-4.454	0.000	-0.751	-3.665	0.000
Automated vehicle	_a	_a	_a	_a	_a	_a
Less familiar	-0.978	-1.818	0.069	-0.811	-2.372	0.018
Fairly familiar	-0.228	-0.535	0.593	-0.143	-0.514	0.607
Follow AV developments	0.346	0.770	0.441	0.285	0.972	0.331
Work on AV	_a	_a	_a	_a	_a	_a
Violation	Not significant in the model			0.218	2.140	0.033
Trust in AV	Not significant in the model			0.209	2.066	0.039
Random effects				Not included in the model		
Intercept	1.009	Z = 3.492	0.000	Not included in the model		
Number of observations	886			886		
Overall Percent Correct	84.8%			80,2%		
AIC	4584.512			4562.563		
BIC	4598.817			4572.100		

Probability distribution: Binomial
Link function: Logit
a. Reference category

of vehicle, communication way, and type of crosswalk, the latent variables identified by the PCA and pedestrians' personal characteristics such as age, gender, education level, and familiarity with AVs were used as predictors of crossing the road in the model as well. The Results of the GLMM estimation for experiment I can be seen in Table 4.

The GLMM was performed in two ways: (a) GLMM including random intercept for *subjects* and *familiarity with AVs* to control for individual differences and possible improvement in familiarity with AVs respectively; and, (b) GLMM excluding random effects and considering only fixed effects. The reason was the fact that the first model with random effects (model (a) in Table 4) had a higher percentage of correctly predicted crossing behaviour (85%) whilst the latent variables like violation and trust in AVs were not significant. With excluding the random effects in the second GLMM (model (b) in Table 4), there was a slight improvement in the Akaike Information Criterion (AIC) and Schwarz's Bayesian Criterion (SBC) and the latent variables turned out to be statistically significant, however, the model could explain only 80% of the variance. It is worth mentioning that the level of knowledge as a random effect was not significant since the experiment might be too short for the subjects to get familiar with AVs, so the presented model (a) in Table 4 includes only the random intercept for subjects.

The results from both models (Table 4) revealed that the age, gender, education level, and communication way (yellow lights) are not significant predictors for crossing the road, while the TTC, familiarity with AVs, type of crosswalk, and type of vehicle are significant in the GLMM. In the GLMM excluding random effects, participants who reported having more violating

Table 5
Results of the GLMM estimation for crossing before the vehicle stops completely.

	Model (a)			Model (b)		
Parameters	**Coefficient**	**t-statistics**	**P-value**	**Coefficient**	**t-statistic**	**P-value**
Fixed effects						
Intercept	7.160	11.186	0.000	5.848	10.391	0.000
TTC=3	-5.730	-13.032	0.000	-4.894	-10.343	0.000
TTC=5	-2.574	-6.200	0.000	-2.235	-4.817	0.000
TTC=7	_a	_a	_a	_a	_a	_a
No zebra	-2.055	-9.665	0.000	-1.756	-8.299	0.000
Zebra	_a	_a	_a	_a	_a	_a
Red light	-1.567	-7.541	0.000	-1.326	-5.569	0.000
Green light	_a	_a	_a	_a	_a	_a
Less familiar	-1.658	-2.464	0.014	-1.328	-3.398	0.001
Fairly familiar	0.138	0.261	0.794	0.394	1.240	0.215
Follow AV development	0.605	1.081	0.280	0.572	1.707	0.088
Work on AV	_a	_a	_a	_a	_a	_a
Age (18-40)	Not significant in the model			0.711	2.366	0.018
Age > 40	Not significant in the model			_a	_a	_a
Violation	Not significant in the model			0.230	1.934	0.053
Trust in AV	Not significant in the model			0.198	1.677	0.094
Random effects				Not included in the model		
Intercept	1.699	Z = 3.585	0.000	Not included in the model		
Number of observations	717			717		
Overall Percent Correct	90.1%			85.8%		
AIC	4253.607			4066.419		
BIC	4271.806			4075.521		

Probability distribution: Binomial
Link function: Logit
a. Reference category

behaviour in road crossing and those who trust in AV (based on questionnaire results) tend to cross before the vehicle stops more significantly compared to others.

3.2.2. Experiment II (only AVs on the road)

To investigate the predictor variables that influence the crossing of the road in the second experiment, two GLMMs were conducted: (a) with a random intercept for subjects and level of knowledge about AVs, and (b) without random effects and including just the fixed effects. The results can be seen in Table 5.

In both models, participants' decision to cross the road before the first AV was used as the dependent variable in the GLMM. In addition, TTC, type of crosswalk, the communication way (red or green light), the latent variables identified by the PCA, pedestrians' personal characteristics such as age, gender, education level, and familiarity level with AVs were used as predictors of crossing the road in the GLMM. Similar to the results of the first experiment, the familiarity with AV as a random effect was not significant, so the presented model (a) in Table 5 includes only the random intercept for subjects. It is worth mentioning that in this experiment we defined a new variable representing the participant's learning effect from interacting with AVs. This variable was named E and counted as E^{th} interaction of the participant during the experiment. For example, if a specific scenario happened as 4^{th} interaction, then E is equal to 4. It is obvious that a larger E represents more experience and possibly greater learning effects. However, such learning effect turned out not to be significant in the crossing decisions.

In both models, distance to the approaching vehicle, type of crosswalk, the communication way and the familiarity with the AV technology were significant predictors of crossing behaviour. In the model without random effects, it was further

Table 6
Results of the GLMM estimation for interrupting the AV excluding random effects.

Parameter	Coefficient	t-statistic	P-value
Fixed effects			
Intercept	−1.262	−3.373	0.001
TTC = 3	0.276	0.878	0.381
TTC = 5	2.811	7.946	0.000
TTC = 7	_a	_a	_a
No Zebra	−1.000	−3.871	,000
Zebra	_a	_a	_a
Less Familiar	−0.122	−0.245	0.806
Fairly familiar	0.926	2.432	0.016
Follow AV development	0.862	2.187	0.029
Work on AV	_a	_a	_a
Violation	0.394	2.762	0.006
Number of observations	356		
Overall Percent Correct	75.3%		
AIC	1682.153		
BIC	1689.823		

Probability distribution: Binomial.
Link function: Logit.
a. Reference category.

revealed that pedestrians younger than 40 years old tend to cross around twice as much as those older than 40 years old. Besides, pedestrians with more violating behaviour (high factor loadings on component 1) in road crossing and those who trust in AV technology (high factor loadings on component 2) are more inclined to cross before the approaching vehicle.

The second objective of Experiment II was to investigate if the participants cross the road despite the red signal from the AV. In order to find an answer to this question, a GLMM analysis including random intercept for subjects and familiarity with AVs was performed with the data on the interactions where the AV signalled with the red light, meaning that it is not going to stop for the pedestrian. Since the random effects were not significant in the model, another GLMM without random effects was done and the results are presented in Table 6. Participants interrupted the AV most frequently with a TTC of 5 s. They tended to stop the vehicle more on a zebra crossing as they apparently believed that they had the right to cross. As far as the level of knowledge about AV is concerned, participants who reported to be fairly familiar with the AV technology interrupted the AV more often when compared to other groups. Finally, participants with a higher value of component 1 (violation) stopped the AV significantly more often than others.

3.3. Second questionnaire

After completing the experiments, another questionnaire was filled in by the participants. They were asked about where they expect AVs to stop for them to cross the road. They could choose answers such as "1. Everywhere, 2. Zebra crossing, 3. No zebra crossing, 4. Un-signalized junctions, and 5. Signalized junctions even during pedestrian red signal". Based on the results, zebra crossing and un-signalized junctions were chosen more frequently than other options: 49 (81.7%) and 27 (45%) times respectively. On the other hand, 15 (25%) expected AVs to stop for them everywhere and 8 (13.3%) participants chose no zebra crossings in addition to other options. Surprisingly, 4 (6.7%) participants expected AVs to stop for them at signalized junctions even when the pedestrian signal is red. It should be noted that participants could choose more than one answer. That is why the sum of answers and percentages are more than the number of participants (more than 100% of the sample respondents).

Participants were further asked whether AVs should be distinguishable and whether they need communication with AVs (strongly disagree = 1 to strongly agree = 7). Participants strongly agreed (M = 6.0, SD = 1.4) that the AV should be distinguishable to them and they emphasized the need for a communication way that allows them to recognize the AVs intention (M = 5.7, SD = 1.6). Participants who were less familiar with AVs felt more strongly about having a communication way between the pedestrian and the AV when compared with those who were more familiar (Spearman's correlation r_s = -0.232, p = 0.038). However, no significant correlation was found between participants' reported familiarity with AVs and their opinion on whether AVs should be distinguishable.

Participants were asked about the meaning of the red and green light in Experiment II as well. Their answers could be categorized in three groups: (a) 33 out of 60 (55%) persons reported to realize the meaning of the coloured lights and explained it correctly; (b) 14 persons (23%) reported to realize the meaning but they interpreted it wrongly; (c) 13 persons (22%) reported not to understand the meaning. Out of the 14 persons who misunderstood the meaning of the lights, 7 subjects interpreted the lights as a sign for detection. One participant answered: "*I Feel safe with the green light and unsafe with red light. The green light might refer to the car that recognises me and the red light may mean that the automated vehicle does not see me.*" 7 other subjects misinterpreted the meaning of the lights answering: "*Green stopped everywhere, red only at zebra* *crossings.*" In fact, participants were more likely to cross the road when there was a zebra crossing leading to interrupting the AV. Therefore, they assumed that the AV was stopping for them because of the zebra crossing while it actually was stopping to avoid a crash. However, the AV with green light stopped always no matter if there was a zebra crossing or not.

Additionally, when the participants were asked what was the most important criterion to cross the road, distance to the approaching vehicle, zebra crossing, the communication way and the vehicle being automated were the most important criteria respectively. This was evaluated according to the frequency of these words or their synonyms (i.e. pedestrian crossing instead of zebra crossing) in the open answers. In total, distance to the vehicle was mentioned 42 times and zebra crossing 22 times. The terms communication and automated vehicles were mentioned 9 and 6 times, respectively. The reason for open answers was to prevent possible bias by providing options to participants to choose from. In that case they might report what they should choose according to certain assumed norms instead of what they really had in mind when crossing the road.

4. Discussion

In this section, the results are summarized and discussed according to the research questions proposed in the beginning of the paper.

The first research question was to investigate how the type of vehicle (AV or CV) can influence the road crossing behaviour of pedestrians given their personal characteristics, attitudes, and perceptions. In the first experiment, participants' crossing decisions were compared in function of the type of approaching vehicle. It was revealed that participants are more likely to cross the road when the approaching vehicle is an automated one. This confirms the results obtained in past survey studies where respondents rated AVs as being less risky and causing fewer crashes (Begg, 2014; Hulse et al., 2018; Underwood, 2014). On the other hand, our results are in contrast to those of other studies reporting that there were no differences between the crossing behaviour in front of an AV compared to a CV (Rodríguez Palmeiro et al., 2018; Rothenbücher et al., 2016).

Gender was not a significant predictor of pedestrians' road crossing behaviour (rejecting hypothesis 1.1), despite the findings of previous studies (Mirzaei-Alavijeh et al., 2019; Rodríguez Palmeiro et al. (2018)). On the other hand, the effect of age was found to be significant for the interaction with an AV. The younger group (age < 40) were more willing to cross the road in the second experiment when all vehicles were automated which confirms hypothesis 1.2. In general, young people are more inclined to experience new technologies while older people seem to be more reluctant to adopt those new technologies, especially when the benefits and reliability have not been proved yet (Melenhorst et al., 2001). Regarding automated vehicles, previous literature showed that the intention to use AVs decreases as the age increase (Schoettle Brandon, 2014). Therefore, as it was shown in the current study, older people are more hesitant about interacting with new, unproven technology. However, we must recognize that in this experiment the sample was dominated by younger male participants (only 14/60 were older than 40 and 20/60 were female). Thus, further analysis in terms of gender and age is suggested.

The effect of being familiar with AVs was a significant parameter in road crossings in the presence of AVs (hypothesis 1.3). Individuals less familiar with AVs were not so willing to cross in front of an AV and vice versa. The pedestrians who follow the development of this novel technology were most likely to cross while the group who reported to be fairly familiar with AVs made them stop most frequently. In fact, as the knowledge about a new technology increases, individuals accept it easier (Nees, 2016), so people should feel more confident when crossing in front of AVs (Blau et al., 2018).

This study investigated three aspects of current pedestrian behaviour - violations, lapses, trust in AV - and their influence on their decisions in the experiment. Lapses were not influencing pedestrian road crossing decision, while trust in AVs and violation were found to be significant for making the decision to cross the road. Pedestrians who trusted the AV technology were more willing to cross before the approaching car stopped completely. Individuals who show rule-abiding behaviour having less violating behaviour while sharing the road with other road-users, were more likely to yield to AVs and made road crossings according to the signal emitted from the AVs, which is in line with the second hypothesis. These results are supported by a previous survey study which predicted that pedestrians with positive behaviour (behaviour that seeks to avoid violation or error and/or seeks to ensure traffic rule compliance) would comply with necessary traffic rules in the presence of AVs (Deb et al., 2017). In our experiment, pedestrians who reported more violating behaviour made the AV stop more frequently by stepping on the road, especially in the presence of a zebra crossing. This is in line with the findings of Papadimitriou et al. (2016) which suggested more risk taking pedestrians accept less delay when crossing the road. Also supports the prediction of Millard-Ball (2017) who says that pedestrians will want to exploit the caution of AVs. This answers the second research question in which we were asking if pedestrians still cross the road even if the AV is not willing to yield and continues its trajectory when approaching the crossing area.

Considering the effectiveness of the way to communicate between the AV and the pedestrians, which corresponds to the third research question, this is in line with past research outcomes (Petzoldt, Schleinitz, & Banse, 2018; Lagström et al., 2015; Mahadevan et al., 2018; Matthews et al., 2017), the current study shows that in general, the communication system helps pedestrians to recognize the intention of the AV and that they are willing to cross the road according to that information.

However, there are some misunderstandings about the meaning of the signals from the AVs. In larger TTCs, pedestrians do not wait for the signal from the AV since they believe they have enough time to cross. As a result, they start crossing the road, and the AV -which is not going to yield to the pedestrian and signals with the red light- has to stop for the pedestrian to avoid a crash. Thus, the pedestrian concludes the red light means that the AV will stop. In order to avoid confusion in such situations, it may be an option that the AV changes the light colour from red to green when it is forced to change its intention by the pedestrians. However, if the AV changes the colour to green and stops for every pedestrian who interrupts it, pedestrians may always claim priority expecting that AVs will automatically stop or slow down in the interest of safety which could lead to disturbing the traffic flow. On the other hand, the AV cannot start signalling from a far distance to inform the pedestrians earlier, due to the fact that it could be the wrong advice to another pedestrian who is waiting at a nearer distance. So, the distance where the AV starts communicating with the pedestrian should be researched.

The 'most important' criterion for pedestrians to either cross or not to cross the road, the last research question, was the TTC. This is based on the generalized linear mixed models that were estimated for both experiments, and also the subjects' comments in the questionnaire. No matter the type of vehicle, type of crossing area, or the signal from the AV, as the TTC increased pedestrians were more likely to cross. Although crossing behaviour was assessed based on TTC, since the speed was constant in all scenarios, TTC and distance to the vehicle are totally correlated, which means that as the distance increases, participants are more likely to cross. This corroborates the results from the literature which reveal a positive correlation between the distance to the vehicle and road crossing probability (Oxley, Ihsen, Fildes, Charlton, & Day, 2005; Schmidt & Färber, 2009). Furthermore, speed and distance to the vehicle were recorded as the main factors to consider in crossing the road in the study by Rodríguez et al. as well (2018).

It has been concluded from previous studies that people feel safer, less vulnerable to traffic and more confident when crossing at zebra crossings (Havard & Willis, 2012). Similarly, in this study, it appears that the existence of zebra crossings is the second most important criterion to cross the road. This is in line with findings of Clamann et al. (2015) which showed that people were more willing to wait for AVs and CVs to pass in the absence of a zebra crossing.

5. Study limitations

It would not have been possible to create a real-life setting for this experiment, due to both technical and ethical reasons. We therefore chose a virtual environment for conducting the experiment. This made it possible to systematically vary the variables of interest but brings along questions concerning realism and whether such an environment can induce a form of risk perception. Participants' perceived realism and perception of presence and immersion have however not been measured. Furthermore, participants' sense of danger of (approaching) AVs could, for example, influence their trust in AVs and, consequently, their interaction with AVs (e.g. Lee & See, 2004; Basu & Singhal, 2016), such as their crossing behaviour in front of AVs. This was however not studied in the present experiment.

Another limitation which must be noted is that in this experiment the drivers in the vehicles were not visible, also not in the CVs. So, it was not possible for participants to use e.g. eye contact or look for a waving hand. These strategies could be effective in pedestrians' crossing behaviour in the real world (Habibovic et al., 2016; Šucha, 2014). Other contextual elements such as perceived time pressure by the participants to reach the train, their perceived behavioural control (see e.g. Evans & Norman, 1998), and the absence of other pedestrian(s) may also influence the decision of the participants. Such factors would be interesting to take into account in future research.

6. Conclusions and future work

This study investigated the influence of pedestrians' personal characteristics in crossing the road in front of AVs. Pedestrians with different personal characteristics behaved differently when confronted with an AV which leads to the conclusion that the whole system (AV interacting with pedestrian) cannot be perceived as accident free.

This study further gave insights into pedestrian road crossing behaviour in response to the communication system of the AVs with the pedestrians. Although the communication between pedestrians and AVs is significantly effective in vehicle intention recognition, existing crossing strategies like relying on "TTC" and "pedestrian zebra crossing" are still playing a more effective role in the decision to cross (at least in the short-term). Accidents were observed during the experiment due to the misinterpretation of the signals of the AVs and late decision making of the pedestrians and consequently, lack of enough stopping distance between the pedestrian and the AV. We have also observed that people with higher knowledge about the AV technology behave significantly different in interacting with them. They trust more the capabilities of the vehicles to detect them and are more likely to behave according to the communication signal.

Thus future research is needed on the long term effects of the communication system especially after it starts to be understood correctly by the pedestrians. It would also be important to find whether people still take advantage of AVs after they are educated about the rules and communication with these vehicles. If this is the case and education is effective in understanding the communication, it will be even more effective if this communication style is consistent across manufacturers. Moreover, considering the time it takes for the pedestrian to make the decision to cross the road, and the stopping distance of the AV, there is the need for studies that better explore the distance in which the AV should start communicating with the pedestrian if that communication is going to be possible. Moreover, depending on the distance where the AV starts communicating with the pedestrian, it might be indicative for one pedestrian and deceptive for another one at a closer distance to the vehicle which we did not have in our study. Therefore, future research should study how this communication system would work.

CRediT authorship contribution statement

Solmaz Razmi Rad: Conceptualization, Methodology, Software, Investigation, Formal analysis, Writing - original draft. **Gonçalo Homem de Almeida Correia:** Methodology, Software, Supervision, Writing - review & editing. **Marjan Hagenzieker:** Supervision, Writing - review & editing.

Acknowledgements

The authors thank all the volunteers who dedicated their time to participate in the experiment. In addition, the first author would like to thank the department of Transport and Planning at the Delft University of technology for hosting her as a guest researcher.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A

See Tables A1–A3.

Table A1
Bivariate Comparisons for crossing before the first vehicle stops (Experiment I).

		Crossed before the first vehicle stops.		Total
		Wait	Cross	
Time To Collision	3 s	66. 7%	33.3%**	300
	5 s	23.7%	76.3%**	300
	7 s	8.3%	91.7%**	300
Type of Vehicle	Conventional Car	37.2%	62.8%*	360
	Automated Vehicle	30.0%	70.0%*	540
Type of Crosswalk	No Zebra	40.7%	59.3%**	540
	Zebra	21.1%	78.9%**	360
How familiar are you with an AV?	I have heard about driverless vehicles once or twice	44.2%	55.8%**	120
	I am fairly familiar with the idea of driverless vehicles	34.5%	65.5%**	330
	I follow the development of driverless vehicles	26.7%	73.3%**	255
	I work in a field directly related to driverless vehicles	30.0%	70.0%**	180
Total		296	604	900
		32.9%	67.1%	100.0%

* $p < .05$.
** $p < .01$.

Table A2
Bivariate Comparisons for crossing before the first vehicle stops (Experiment II).

		If they crossed before the first vehicle stops		Total
		Wait	Cross	
Time To Collision	3	55.4%	44.6%*	240
	5	13.9%	86.1%*	237
	7	2.1%	97.9%*	240
Type of Crosswalk	No Zebra	32.8%	67.2%*	360
	Zebra	14.8%	85.2%*	357
Lights color	Red	30.8%	69.2%*	357
	Green	16.9%	83.1%*	360
How familiar are you with an AV?	I have heard about driverless vehicles once or twice	39.6%	60.4%*	96
	I am fairly familiar with the idea of driverless vehicles	22.6%	77.4%*	261
	I follow the development of driverless vehicles	18.1%	81.9%*	204
	I work in a field directly related to driverless vehicles	23.7%	76.3%*	156
Total		23.8%	76.2%*	717

* $p < .01$.

Table A3
Bivariate Comparisons for interrupting the AV (Experiment II).

		Did the participant interrupt the AV?		Total
		No	Yes	
Time To Collision	3	69.2%	30.8%*	120
	5	19.7%	80.3%*	117
	7	73.9%	26.1%*	119
Type of Crosswalk	No Zebra	62.6%	37.4%*	179
	Zebra	46.3%	53.7%*	177
Total		54.5%	45.5%*	356

* $p < .01$.

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2020.01.014.

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