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Gap Acceptance Study of Pedestrians Crossing Between Platooning Autonomous Vehicles in a Virtual Environment

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Abstract

Autonomous vehicles (AVs) operating in shared urban environments, often referred to as "pods", will constantly have to interact with pedestrians. As a result, an effective strategy will be required for pods to continue operating, while in close proximity to people. This strategy could be in terms of active negotiation, where a pod identifies a person and gives way; or a more passive strategy, such as requiring pods to travel close together in platoons, in order to reduce the number of individual vehicle encounters. For this latter example, it is critical to understand how the spaces between pods and AVs in general are perceived by pedestrians, and what factors will persuade and dissuade crossing. Therefore, this paper seeks to understand this relationship, and presents results from a pedestrian gap acceptance study for platoons. To ensure the safety of participants, a virtual environment was used instead of real vehicles. The goal of the experiment described in this paper, is to understand the gap acceptance behaviour of participants, when presented with a platoon of pods in different environments. The experiment evaluated four vehicle speeds, from 1 km/h to 16 km/h, four temporal gaps, from 2 s to 5 s, and two environments. These environments were a typical road layout, with footpath and line markings, and a shared space, where all markings and separation between pod and pedestrian were removed. For each scenario, participants were asked if they would cross between the pods and how safe they felt about the situation, recorded as a Likert score. The results suggest that people are more likely to attempt to cross between a platoon of pods when they are travelling closer together in a shared space (no line markings or separation between vehicles and pedestrian), compared to a road environment (separated by raised pavement and road markings). However, it was also found that people's subjective rating of safeness was higher in the road environment, when presented with a platoon of pods, compared to the shared space.

Keywords: Autonomous vehicles, pedestrian gap acceptance, virtual reality, human factors

1. Introduction

Autonomous vehicles (AVs) have been heralded by many as a safer transport system, which will radically reduce vehicle crashes. However, as Fagnant and Kockelman (2015) states, while safety improvements may be greater than new safety risks, it is possible that new risks will be greater for some system users under certain circumstances, particularly at early technology stages. For AVs operating in urban areas, there remain significant challenges for ensuring the safety of pedestrians. This safety risk is increased further, when considering AVs, which operate in shared spaces or pedestrianised areas, often referred to as low-speed autonomous transport systems (L-SATS) or colloquially as "pods" in the literature. In these types of shared environment, it may not be possible or desirable to have separate paths and barriers for pods. Additionally, the main purpose of pedestrianisation has been to create places people can use, which are free of vehicles (Nieuwenhuijsen and Khreis, 2016). This has also led to a significant reduction in motor vehicle incidents involving pedestrians in city centres (Hamilton-Baillie and Jones, 2005). For shared spaces, where there are no road markings or pavements, drivers have been observed as more deferential and giving way more often to pedestrians compared to other road layouts (Amin, 2008). The challenge for developers, is to understand pedestrian behaviour and expectations, when presented with one or more AVs.

As AVs become common place in towns and cities, it is reasonable to predict that they will coalesce into platoons, for some or all of the journey. This would be due to routing pods towards designated vehicle paths to limit the impact on pedestrians (Woodman et al., 2019). This would be particularly likely for "last-mile" journeys, as pods, similar to taxis, will be at higher demand at popular locations, such as train stations and airports. Additionally, AV operators may want to keep their vehicles on "known paths", to minimise external risk and cause less disruption to pedestrians (Shay et al., 2018). This could be achieved by grouping vehicles into platoons separated by long time gaps, making crossing easier than if it was uniformly distributed (Baltes and Chu, 2002). Additionally, as Hexmoor and Yelasani (2018) reports, there could be benefits in travelling as a group, as it could reduce the amount of processing each vehicle needs to do, as each could share the path of the lead vehicle. For vehicles operating in shared spaces without a visible path, they will need to be able to operate with pedestrians passing closely to the vehicle and crossing in front of, between, and behind. This poses a challenge for multiple vehicles travelling as a platoon, as if one has to stop to prevent a collision with a pedestrian, then all vehicles must stop. One way of reducing this risk, which has been found to be effective, is for vehicle and pedestrian to communicate their intentions (Matthews et al., 2017; Rasouli and Tsotsos, 2019). Another potential solution to the issue of people crossing between vehicles, is to have them travel close enough to each other that it would not be physically possible for a person to walk between (Woodman et al., 2019). However, this solution has its own challenges. Firstly, the closer vehicles travel to each other, the less stopping distance if needed, also there will be reduced manoeuvrability due to the limited turning angle. Other technical challenges also exists such as reliable and resilient communications, as well as "hand-shake" protocols between the platoon of vehicles.

Pedestrian gap acceptance studies generally focus on three main aspects. (1) The reasons behind why pedestrians accept and reject gaps; (2) How to make crossing points more acceptable to pedestrians, in terms of trust and safety, and how to prevent / discourage crossing; (3) Understanding gap acceptance statistics of different spatial and temporal gaps. For this latter category, the key parameter under investigation is the critical gap (sometimes referred to as critical headway), and is generally defined as the gap size, below which a pedestrian will not attempt to begin crossing (Transportation Research Board, 2016). The gap size, which is often measured in seconds, can be described as the time to arrival (TTA) from one vehicle having finished passing the pedestrian to the next vehicle starting to pass the pedestrian (Schleinitz et al., 2016). Another term widely used is time-to-collision (TTC), which is measured as the time it would take for an approaching vehicle to collide with a pedestrian. For gap acceptance analysis, TTC at the point the pedestrian chooses to cross in front of a vehicle, can be considered an appropriate measure of gap acceptance (Rasouli et al., 2018).

A number of empirical studies have been presented on pedestrian gap acceptance (Petzoldt, 2014; Yannis et al., 2013; Asaithambi et al., 2016). However, to the best of our knowledge, no papers have been published specifically looking at temporal or spatial gap acceptance in relation to AVs. Although it is likely that gap acceptance will be similar to that of traditional vehicles, several studies have found that pedestrians are likely to act more assertively with AVs (Dey and Terken, 2017; Fox et al., 2018). It is also important to note that analysis of real world crossing behaviours, shows that gap acceptance is not universal between countries. For example, a study by Kadali and Vedagiri (2013) has shown that the gap acceptance for developing countries, is much smaller than that for developed countries for both spatial and temporal gaps. A recent study by Pawar and Patil (2016) looked at pedestrian crossing behaviours at uncontrolled mid-block crossing areas using video data. In their study they used a number of methods to determine gap acceptance, and found a critical gap of between 3.6-4.3 s and 60-73 m, with a mean vehicle speed of 62 km/h. Their analysis revealed that both temporal and spatial gaps follow lognormal distributions. However, they concluded that the speed of the conflicting vehicle has a significant effect on spatial gap acceptance. A similar study by Petzoldt (2014) looked at gap acceptance for vehicles travelling at 30 and 50 km/h. They found a mean gap acceptance of 3.57 s and 29.71 m for the vehicle approaching at 30 km/h, and 2.98 s and 41.33 m at 50 km/h. Their results showed that the mean time gap accepted was smaller when the approaching vehicle was moving faster. Beggiato et al. (2017) compared gap acceptance for vehicles of different sizes (trucks vs. cars). They found that for vehicles travelling below 20 km/h, there was no difference in gap acceptance between the vehicle sizes. However, for speeds over 25 km/h, a smaller gap for the larger vehicles was accepted, which was not predicted. Their findings also revealed that at speeds of between 10 km/h and 25 km/h, there was a declining temporal gap acceptance from 6.10 s to 5.50 s. Finally, their results showed that for the age groups <30 and >45 years, there was an approximately 0.5 s difference in gap acceptance for speeds between 10 km/h and 30 km/h, with the <30 years group choosing a lower gap. However, they found that for speeds over 35 km/h the probability of gap acceptance of the two groups converged, a finding which is supported by a number of other studies (Petzoldt, 2014; Pawar and Patil, 2016).

This paper presents a gap acceptance study of autonomous platooning pods, conducted in a Virtual Reality (VR) en ronment. The VR testing method was chosen to mitigate risk and to allow for precise repeatability of the experiment. VR also has the advantage of making people focus on the task presented to them, as it is harder to look away or escape the task. However, it is understood that people may behave differently in VR than they would in the real world, due to knowledge that their actions would not put them at risk. To help reduce this issue, it is essential that the VR simulation behaves like the real world, and the participant is not required to move in a way that is not reflected in the simulation (Blascovich et al., 2002). Additionally, it is important to note than a number of similar research studies have confirmed the efficacy of using VR in pedestrian safety research (Burns et al., 2019; Deb et al., 2017; Azam et al., 2017; Schwebel et al., 2008).

The aim of this research study is to understand how pedestrians behave in different environments, particularly in terms of crossing behaviour, when presented with a platoon of pods. The study uses the pod design currently under development by RDM in Coventry, UK. To the best of the authors' knowledge, this is the first pedestrian gap acceptance study conducted for platoons of AVs. The scope of this research was limited to investigating platoons with constant speed and gap distances.

The study is concerned with investigating how different temporal gaps between pods travelling in a platoon, as well as the platoon speed, effect pedestrian's decision to accept or reject a gap. As the gap between pods create a corridor, through which the pedestrians can choose to cross, we cannot use TTC to identify the appropriate headway between pods. This is due to both the passing pod and approaching pod having an effect on the pedestrian crossing decision. The aim is to both understand pedestrian's attitudes to different temporal gaps and to establish what the largest gap between pods that pedestrians will not cross between.

The paper makes a contribution to the literature by presenting findings from a pedestrian gap acceptance behaviour study, conducted in multiple environments, with a platoon of pods travelling at low speeds. This is an important area of research, as it is essential that the effect of AVs on pedestrian behaviour is understood, before their deployment. The findings from this paper, and further planned studies, will be used to influence the design decisions of the RDM pod system (and other AV transport systems). It is argued that by involving users and other stakeholders at an early design stage, will result in a system that can deliver a useful service with greater user acceptability. Additionally, findings of this study have meaningful implications for researchers that apply VR technology as an experimental tool to study AV pods interactions with pedestrians. Finally, we outline our future research plan and discuss how our findings will be used to manage pod platooning behaviour.

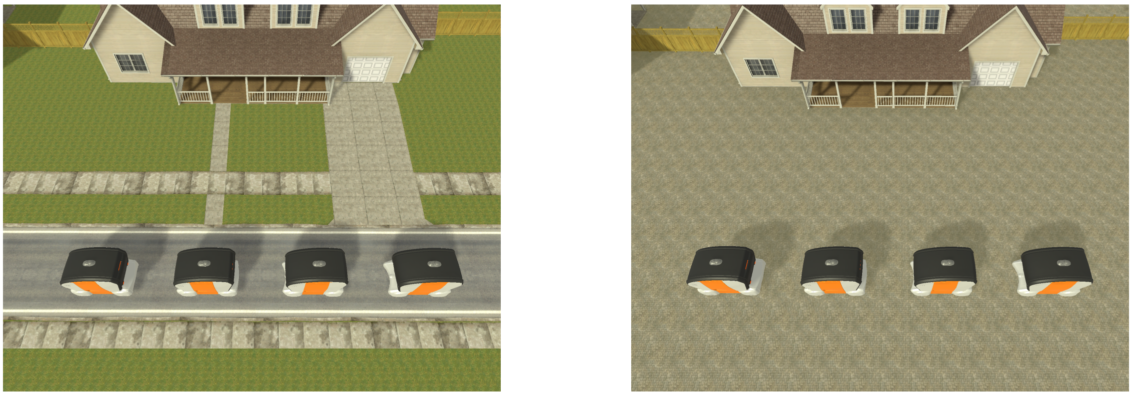
2. Methodology

To determine pedestrian gap acceptance behaviour, it is reasonable to predict that the most reliable method would be to use a physical environment with real vehicles. However, this poses several challenges, most importantly of which is how to mitigate risk of injury to the participant. Another challenge is repeatability, as at this stage of development there are technical challenges of having four pods travelling close together at speed. Therefore, the study uses a VR headset to allow participants to experience a computer simulated environment. This environment simulates an urban environment and a platoon of autonomous pods. Although the experiment setup was not similar, part of the experimental design was inspired by a VR study carried out by Azam et al. (2017).

VR was chosen over a simulation presented on a computer screen or projector, as it allowed for an immersive experience. This was achieved by making the pods and other environmental structures appear the same size as the real world. Although, it should be noted that with a non VR setup, we would have had better control over the participants head position, the sense of presence within the simulation would have been lost. To help mitigate the head position issue, the participants were required to look at a question menu within the simulation, which was placed in a fixed position in the location the participant were required to look. The participants were required to answer questions about what they were seeing, before and after each platoon past their position. This was found to reposition the participant's head location, and maintain focus on the observation tasks.

2.1. Participants

Participants were recruited from the University of Warwick, Coventry University, and Jaguar Land Rover. To comply with University of Warwick's Biomedical & Scientific Research Ethics Committee (BSREC) ethics policy, participants had to be over 18 years of age. In total, 28 people participated in the study, of which 14 identified as females and 14 as males. The sample size was based on data sat ration being reached, which is a method to determine



(a) (b)

Figure 1: Screenshots of the VR simulated environment used for the experiment; (a) A single lane road and pavement is used to show a clear separation between vehicle and pedestrian; (b) Block paving is used to simulate a shared space for vehicles and pedestrians

the point at which gathering more data will not lead to more information for a given research aim (Birks and Mills, 2015). The stopping criterion for saturation was determined to be the point at which no new themes were found from the semi-structured interviews. The participants consisted of a mixed age, M = 34.08, SD = 10.79. The occupation breakdown was 32.1% Student, 42.9% Professional, and 25.0% Clerical. Participant's prior exposure to AVs was 10.7% none, 25.0% low, 35.7% medium, 28.6% high. There were no exclusion criteria for participants, although during recruitment, it was made clear that there was a risk of motion sickness from the VR equipment. However, no participants were excluded, and no issues were caused due to motion sickness during the study. Participants received no compensation for taking part in the study.

2.2. Materials

To perform the experiment, a virtual environment was developed at WMG using the Unity 5 game engine. This allowed us to create 360-degree 3D rendered computer images in real-time, of platooning pods. To simplify this description, we refer to these computer renderings as scenarios. This virtual environment, and the scenarios generated within it, simulated four pods travelling in a platoon. An XML configuration file was used for each simulation scenario. This configuration file allowed the following parameters to be changed: gap between pods; pod speed; pod starting position; and scenery. Other parameters, such as the number of pods and user position could be set via the configuration file. However, these parameters were fixed for all scenarios. The scenery parameter was used to set the ground surface to either a single lane road with pavement and grass verge, or a shared space with a block paving effect (see Figure 1). A road with a single lane was used, over a two-lane carriageway, as it was important that the participants felt they were crossing from one area of safety to another. Additionally, it was thought important that there was no space for oncoming vehicles, which could distract participants.

Several VR headsets were evaluated for the experiment, including the HTC Vive and the Oculus Rift. The Oculus Go was ultimately chosen for the experiment, due to it not requiring any cables and the increased display resolution. Although the Oculus Go has limited onboard computing power, compared to the other headsets (which require tethering to a high-powered computer), it was able to render the environment at 60 fps with minimal tearing or artefacts. The Oculus Go is also limited to three degrees of freedom (3DoF), which meant the participant would not be able to physically move around the scene. However, this was not considered an issue, as standing in a fixed position was preferred, as it reduced the exposure of risk to the participant. The Oculus Go also has a lower processing capacity, compared to the other models tested, which means a reduction of real-time lighting effects and shading. However, during the pilot study, it was made clear that the freedom of head movement offered by the Oculus Go, was far more important than additional lighting effects, which were not noticed by participants.

Audio was also used to enhance the simulation and make sure the participant faced the correct way when required. This was achieved using the Oculus Go's 3D audio spatialization system, which allowed binaural vehicle sounds to be attached to each vehicle asset in the scene, providing realistic vehicle sounds, which changed based on the distance

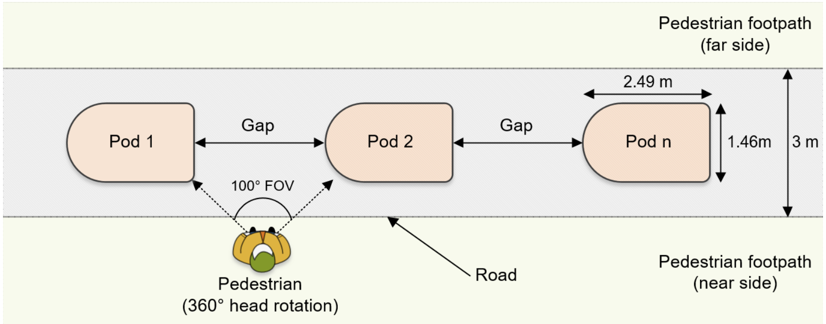


Figure 2: Experimental setup for pedestrian's crossing decision in relation to a platoon of pods

and angle of the vehicle in relation to the participant. Additionally, ambient sounds were used to make the environment more realistic.

2.3. *Experimental Procedure*

Each participant was given a brief introduction to the project and asked to fill in a demographic questionnaire. This was followed by the VR part of the experiment, where the participants were asked to view a series of simulation scenarios of platooning pods. After completing this, the participant was asked to complete a VR immersion questionnaire. Finally, a short semi-structured interview was conducted. During the experiment the participant was encouraged to talk about what they were experiencing and their decision-making processes.

For the VR part of the experiment, the participant was asked to stand while wearing the VR headset. The simulation was started, and the participant was presented with a dialogue box, overlaid on the world scene, which explained what they were going to see and what they were required to do. This was done to make sure the participant had fitted the headset correctly, had a clear view of the simulation, and was looking in the correct direction. They were then presented with 32 short (between 10 and 40 seconds) VR scenarios, each followed by two questions. It was shown from the pilot study that participants preferred a break half-way through the experiment (on average between 6 to 8 minutes), which coincided with the change of scene, from road layout to shared space. The first question asked after each scenario was, "Would you cross between the pods?", with a dichotomous variable as the answer, with the levels "yes" or "no". An answer of yes would mean the participant "accepts" the gap, and would cross between the pod, and an answer of no means the participant rejects the gap and would not cross. The second question asked, was "Do you feel safe with the pods passing at this speed and distance?". The answers were represented in a five-level Likert scale (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree). For both questions, the participant was told to treat the simulated situation as they would in the real world. Although, the participant's position was fixed in the scene, they were told to imagine they could walk around. Therefore, they may choose to accept a gap, if they would cross between the pods, or reject the gap, if they would wait for the pods to pass, or walk towards them and cross behind the platoon. One restriction was they were not allowed to cross before the first pod arrived in front of them. This was required, as for the scenarios where the pod travels at 1 km/h, it took approximately 20 seconds for the first pod to cross the path of the participant. A diagram showing the simulation setup is provided in Figure 2. As this diagram shows, the pedestrian had a field of view (FOV) of 100°, but was able to rotate their head 360°, in order to view the full scene.

In total, 32 scenarios were presented to the participants, each with four pods travelling at a constant speed in a platoon, with a fixed gap size between each. The decision to use four pods was made to reduce the time the participants would spend in VR, while making sure there was enough time available to make a decision. With a platoon of four pods, participants had three gaps in which to make a crossing decision. Temporal gaps were used over spatial gaps, as this is the most often used approach in the literature. Time gaps were between 2 and 5 seconds with 1 second increments. A minimum 2 second gap was, as it was found to be the smallest gap acceptance time reported in the literature. For example, findings by Rasouli et al. (2018), who examined pedestrian gap acceptance in terms of TTC, found pedestrians on average cross the street between the TTC of 3 to 7 seconds. They also found no instances of pedestrians attempting to cross when the TTC is below 3s. A similar study by the Indian Statistical Institute analysed

Figure 3: Participant's view of the simulated environment, showing a single lane road and platoon of pods

data from traffic in New Delhi, found critical gaps between 2 and 8 s TTC minimum for pedestrians (Das et al., 2005). The speed of the pods were 1 km/h, 4 km/h, 8 km/h, and 16 km/h, and were chosen to allow a comparison of slow, medium and high speeds, without burdening the participant with too much exposure to the VR equipment. The pods travelled from the right of the participant, as the study was conducted in the UK. A screenshot showing the participant's view of the simulated environment is provide in Figure 3.

2.4. Pilot Study

Prior to running the study, it was important to first run a pilot to make sure that the VR simulation, VR equipment, and task design, were acceptable for the participants. This initial pilot identified several interesting issues, which were used to shape the design of the study. Therefore, they are given here as they were beneficial in informing the final design of the experiment.

It was found during the pilot study that setting the eye-level of the participant in VR was of critical importance. For example, if the participant has a height of 160 cm, and the simulated view is set at 180 cm, it was shown that gap acceptance would increase significantly. Therefore, it was important for the eye-level in the simulation to match that of the participant. Another important factor in making the simulation seem more real, was sound. The vehicle sound proved an important factor in gap acceptance, with participants reporting that without sound, the simulation was very difficult to relate to the real world. This is supported by research by (Kerber, 2006) who identifies sound as important factor for people to localise and determine the speed of vehicles. The pilot study also revealed that removing the headset after each scenario (i.e. once every 10 to 40 seconds) to answer questions, made it difficult for participants to give accurate answers to questions about their experience. The purpose of doing this was to give the participants a break from the simulation. Similarly, people preferred to answer questions in the simulation on a "virtual question page", than being asked to respond to questions verbally, and having to give a response without being able to see the researcher. Finally, it was found that people became frustrated with more than two questions, as by the time they got to the third question, they had often forgotten what they were thinking during the scenario. Furthermore, with two consistent questions, participants were able to remember what they were going to answer at the end of each scenario, i.e. "would I cross?" and "do I feel safe?".

2.5. Semi-structured Interviews

Participant interview and discussion data was collated and analysed to help inform the gap acceptance results. During the semi-structured interviews, and throughout the VR experiment, extensive notes were taken of the participants' responses, as well as details of how people responded to each scenario. All notes were captured in a Microsoft

Excel spreadsheet, where data could be cleaned and analysed. This process involved refining responses into short sentences, without removing any of the meaning. To derive our findings, we used thematic analysis, which is a process to identify patterns within the responses. This iterative process starts with understanding the data, before codes and sub-codes can be generated. This coding process assigns one or two words to the response, which identify its core meaning. These codes are then grouped into categories, which can be analysed to identify the main themes and concepts (Guest et al., 2012).

2.6. Limitations

As with all research studies, there are a number of important limitations worth discussing. Many of these limitations, which have been discussed in previous sections, are associated with using VR, such as the fidelity of the simulated environment. However, the majority of limitations would also be present if the study was performed in the real world. Furthermore, as the data gathered in the experiment is obtained by questioning, many of the results and conclusions made are based on the subjective assessment of participants.

Establishing an appropriate level of motivation for participants, in terms of crossing between pods, proved difficult. What we found worked best for our study, was for participants to cross as fast as possible without putting themselves in danger. There was no motivation for participants to cross between the pods, and they were told that rejecting the gap and walking around was an equally valid decision. However, it must be acknowledged that pedestrian behaviour would likely be influenced by the presence of other pedestrians crossing between vehicles (Harrell, 1991; Wang et al., 2010) which would happen often in an urban environment. Furthermore, crossing behaviour could be affected by how important it was to a reach a location i.e. being late for work, or travelling to an airport.

3. Results and Discussion

This section presents both the preliminary testing, which helped in designing the study, and the results of the VR experiment. The results are divided in to analysis of the gap acceptance behaviour, and findings from the semi-structured interviews. All statistical analysis is conducted using the statistical analysis software SPSS v25.

3.0.1. VR Immersion Questionnaire

At the end of each session, participants were asked to fill in a VR immersion questionnaire. This used a similar structure, to a questionnaire presented by Schwebel et al. (2008). The results, which are used to support the findings of the participant interview, are shown in Table 1. These results indicate that the participants were only slightly affected by the task being conducted in VR (question 5), with a median score of 4 being recorded. This is supported by questions 1 to 4, which received a median score of between 4 and 5. For question 4 (N = 28, M = 4.13, SD = 0.93), a number of participants reported that their score was based on not being able to move around in the virtual world and not due to the simulation itself.

Table 1: Summary of responses from VR immersion questionnaire. The answers were represented in a five-level Likert scale (1 = not at all, 2 = slightly, 3 = somewhat, 4 = moderately, 5 = a lot)

Id	**Question**	**Median score**	**Mean score (SD)**
1	To what extent did the simulation hold your attention?	5	4.54 (0.58)
2	To what extent did you feel you were focused on the simulation tasks?	4	4.17 (0.47)
3	To what extent did you feel the simulation task was something you were actively doing, rather than passively experiencing?	4	4.17 (0.80)
4	To what extent did the simulated world behave like the physical world?	4	4.13 (0.93)
5	To what extent do you feel your decision matched what you would do in the real world outside of the simulation?	4	3.92 (0.70)

As each question item in the questionnaire related to the same underlying variable, which was the effect of the simulation on the gap acceptance task compared to the real world, it is possible to measure how closely related each question is as a set. To calculate this internal consistency, Cronbach's alpha was used, which produced a value of α = 0.72, which indicates an acceptable internal consistency. Therefore, by evaluating all response as a set (*Mdn* = 4), it can be suggested that participant's gap acceptances responses were only moderately affected by the experiment being conducted in simulation. This affect will likely result in participant's accepting smaller gaps, and reporting a higher perceived level of safety. This is due to evidence that people often take more risks in a simulated environment, as they are aware that their actions will not result in harm (Simpson et al., 2003).

Although there were justifications for using the VR method proposed in this paper, which were primarily there to ensure the safety of participants, it clearly introduced some limitations. However, every effort was made to establish a protocol, which modelled the real world, considering the limitations of the hardware / software and its effect on participants responses.

To establish the validity of this computer-based experiment, a future experiment is planned, which will perform gap acceptance as part of a real-world study. This work will be carried out when the potential hazards from exposing participants to live vehicle trials, can be fully mitigated for speeds and gaps that would not normally be run.

3.1. Gap Acceptance Analysis

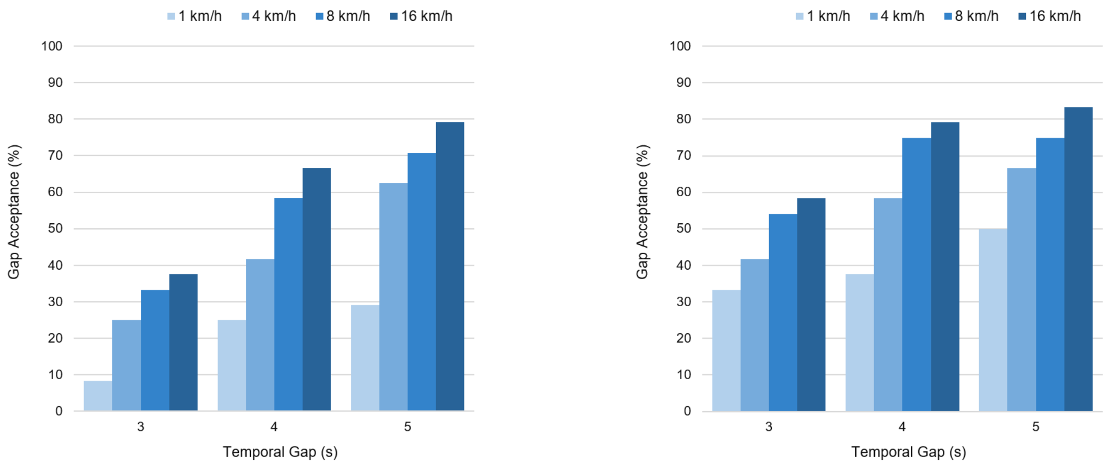
In total, 896 gap acceptance results were collected across 28 participants. These results have been collated to allow frequency comparisons of gap acceptance for road and shared environments, and the effect of temporal gaps and approach speed. From an initial analysis of the results, it was found that all 2 s gaps were rejected by all participants, meaning there was a 0% gap acceptance for this temporal gap across both tested environments. The gap acceptance results for each participant was compared for both the road and shared environments, to produce a contingency table (Table 2). This table captures 448 matched pair observations for each participant across the 16 scenarios. As the results show, only once did a participant reject a gap in the shared environment that they accepted in the road environment (out of a total of 153). To analyse the data further, statistical analysis was used in the form of a McNemar's test, to compare the total gap acceptance score for all participants, for both road and shared environments. This found evidence to suggest that participants had statistically significantly greater gap acceptance when presented with a platoon of pods in a shared environment compared to a road environment (χ^2 = 44.18, p <0.001, odds ratio = 0.02).

Table 2: Frequency distribution of pedestrian gap acceptance, for both the road and shared environment

Road	**Shared space**	
	Accept gap	Reject gap
Accept gap	152	1
Reject gap	49	246

In Figure 4 the results for gap acceptance in relation to the temporal gap are presented, for both the road and shared environments. As these graphs show, there is a higher gap acceptance for shared spaces compared to the road environment, across all three temporal gap times, with the highest difference for the 3 s gap. This is confirmed by calculating the observation frequency difference for each participant across both environments (Table 3a). From this we can observe that as the temporal gap value increases, the difference between gap acceptance scores for the two tested environments decreases. This suggests that pedestrians are more willing to accept smaller temporal gaps in the shared environment, but as the time gap increases, the difference between environments converge.

In Figure 5 the results for gap acceptance in relation to the pod approach speed are presented, for both the road and shared environments. As with the temporal gap results, these graphs show there is a higher gap acceptance for shared spaces compared to the road environment, across all four speeds, with the highest difference for the 1 km/h vehicle speed. This is confirmed by calculating the observation frequency difference for each participant across both environments (Table 3b). From this we can observe that for an approach speed of 1 km/h there was a large difference between gap acceptance scores for the two tested environments decreases. However, for speeds over 1 km/h the difference decreases significantly and continues to decrease as the approach speed increases. This result suggests that as the pod speed increases, participants are less concerned with environmental factors, and are more concerned with the speed of the approaching vehicle. It could be reasonably concluded that at higher speeds, the gap acceptance



(a) (b)

Figure 4: Participants gap acceptance for different temporal gap sizes (2 s gap is omitted as all gaps were rejected) at 1 km/h, 4 km/h, 8 km/h, and 16 km/h approach speed; (a) Road environment; (b) Shared environment

for the two environments will eventually converge. It also indicates that pedestrians may behave differently around vehicles travelling slowly, compared to faster vehicles.

Table 3: Gap acceptance observation frequencies for the road / pavement and shared space environments; (a) Temporal gaps (b) Approach speed

(a)

Duration	**Road**	**Shared**	**Difference**
2 s	0	0	0
3 s	28	52	24
4 s	55	70	15
5 s	70	79	9

(b)

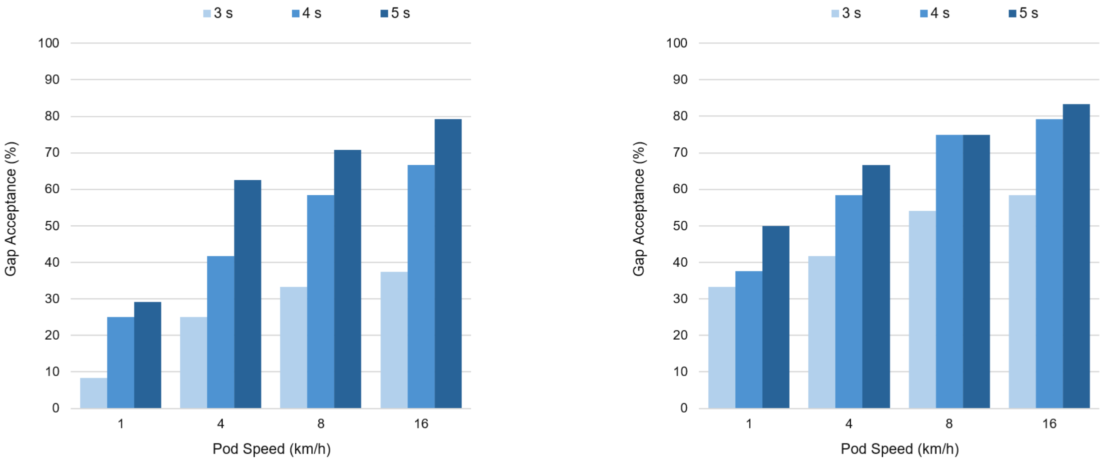
Speed	**Road**	**Shared**	**Difference**
1 km/h	17	33	16
4 km/h	37	48	11
8 km/h	48	58	10
16 km/h	53	61	8

Finally, by dividing pod speed by temporal gap size, it is possible to calculate the spatial gap size. Based on this calculation, we have found that the maximum distance between pods that had no gap acceptance from participants, often referred to as the critical gap value, was 0.56 metres (1 km/h, 2 s gap). Although, for this research study our intention was not to measure the effect of differing spatial gap size, it does provide a starting reference value for future studies. This result is consistent with a survey of different gap acceptance studies by Rasouli and Tsotsos (2019) that found critical gap acceptance results ranged from 2 s to 8 s. However, it must be acknowledged that for gap acceptance studies that look at the intention of the pedestrian, and not the actual action of crossing in front of a vehicle, the result may be subject to error. As discussed by Schmidt and Frber (2009), pedestrians may start walking and suddenly change direction or stop.

The question of how much the results are affected by using a simulated environment, is still to be determined. However, as identified by Simpson et al. (2003), pedestrians can exhibit greater risk taking behaviour in a safe virtual environment. This may have resulted in gap acceptance, which is higher than what we may find for the real world. This is somewhat beneficial for our study though, as the aim is to identify the largest gap that pedestrians will not pass through. Further testing will be required to identify the level of discrepancy.

3.1.1. Safety and Acceptability

To establish a measure of safety in relation to gap acceptance, the participants were asked about their perception of safety for each pass of the pod platoon. In total, 896 results were collected for the question, “Do you feel safe with

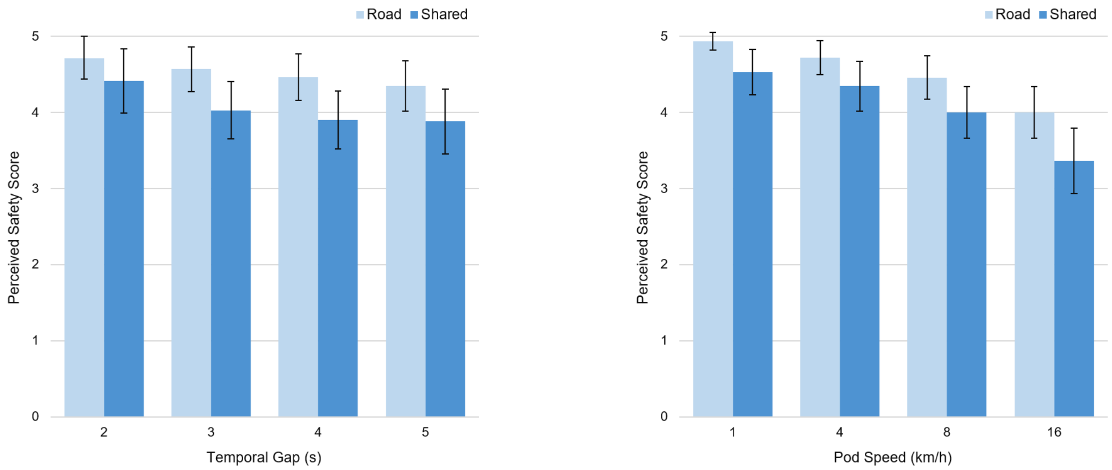


(a) (b)

Figure 5: Participants gap acceptance for different approach speeds with 3 s, 4 s, and 5 s gap size (2 s gap is omitted as all gaps were rejected); (a) Road environment; (b) Shared environment

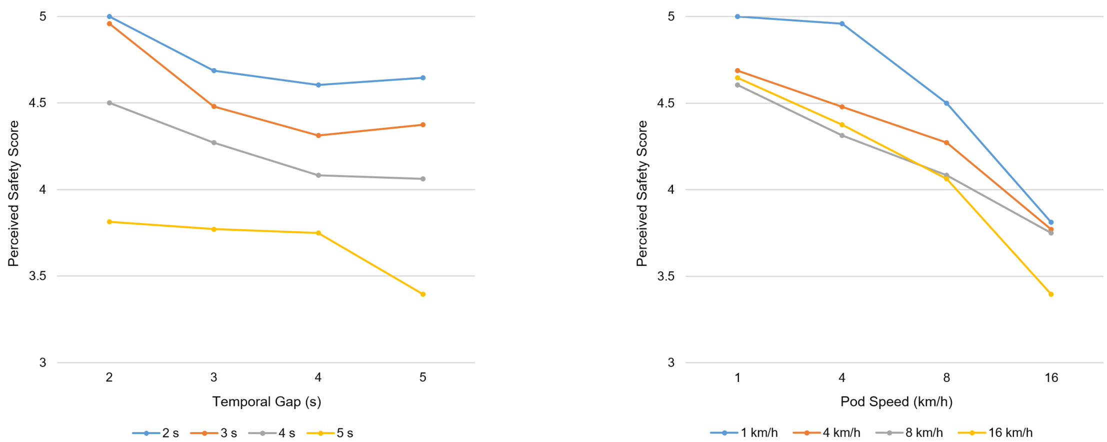
the pod passing at this speed and distance?". These results are presented in Figure 6 as two graphs, to show the effect of changing the temporal gap and pod approach speed, for both road and shared environments. As these graphs show, for all starting conditions, participants on average reported a lower perceived safety score for the shared environment, for all speed and gap conditions. A Wilcoxon signed-rank test indicates the median perceived safety level for the road environment test (*Mdn* = 5) is statistically significantly higher than the median shared space environment test (*Mdn* = 4, *MD* = 0.92, *z* = -3.62, *p* <0.05). This suggests that participant's subjective perception of safety is reduced in our virtual representation of the shared space environment. This is in contrast to the gap acceptance results, which found that people have higher gap acceptance in shared environments. Taking both these results into consideration, it could be concluded that participant's perception of safety is an influencing factor for gap acceptance. Furthermore, it could also be concluded that participants are less likely to reject a gap, if they perceive that in their current position their safety is compromised. This latter point is supported by interviews conducted after the experiment, which found several participants reporting that removing the pavement from the environment, meant they had no boundary between themselves and the pod. Therefore, they felt less safe in the position they were standing in and thought that crossing between the pods and moving to the opposite side would put them in a safer position. One participant offered a comparison with their real-world decision process, which would mean they would rarely step-backwards to put themselves in a safer position but would instead move either forward or laterally. Further outcomes of the interview part of the experiment are discussed in the next section.

To determine how participant's response to the safety question, was affected by between-subjects' factors (temporal gap and vehicle speed) and within-subjects factor (environment type), a two-way repeated measures ANOVA was conducted. This statistical analysis was used to examine the effect of temporal gap and speed, on gap acceptance, for the two environment types. The results showed there was a statistically significant interaction between the effects of temporal gap and speed on participant's responses, F (9, 414) = 2.76, p <0.001. The results also showed that there was a main effect of temporal gap, F (3, 138) = 33.55, p <0.001, a main effect of speed F (3, 138) = 100.90, p <0.001, and a main effect of environment type F (1, 46) = 9216.95, p <0.001. To illustrate the effect difference of temporal gap compared to speed, plots of the results are provided in Figure 7. As these plots show, there is a statistically significant difference between each speed on the participant's responses to the safety question. Whereas for temporal gap, there is a minor difference between participant's responses between each gap size. These results suggests that speed has a greater effect on participants perception of safety than temporal gap size. Additionally, it can be seen that as approach speed increases, participants safety score decreases. Finally, results for the road environment group, which is a combination of all scores for that environment, received a higher mean score, M = 4.53 with a 95% confidence interval of (4.40, 4.66), compared to the shared environment, M = 4.06 with a 95% confidence interval of (3.93, 4.19). This



(a) (b)

Figure 6: Mean responses to the question "Do you feel safe with the pod passing at this speed and distance?" captured as a level of perceived safety. For each result, standard deviation error bars are given; (a) Results grouped by time (b) Results grouped by pod speed



(a) (b)

Figure 7: Mean responses to the question "Do you feel safe with the pod passing at this speed and distance?" captured as a level of perceived safety. Responses for road and shared environments are combined; (a) Results grouped by time (b) Results grouped by pod speed

suggests that participants generally had a greater perceived safety when exposed to the pods in the road environment.

3.2. Interview and Participant Feedback

As part of the study, each participant took part in a semi-structured interview, to gain understanding about their experiences during the study. This was in the form of a series of open and closed questions, about both the gap acceptance task and the VR simulation. Each question was accompanied with follow-up "why" and "how" questions, in order to fully understand the participant's response. The output from the interviews and participant feedback was captured as 448 separate and individually identifiable rows in a spreadsheet. Thematic analysis was applied to identify themes in the data. The first stage of this process involved assigning each row one or more descriptive codes, which explained the core meaning of the response. These codes were subsequently analysed and grouped, from which six themes emerged. These themes, ranked by frequency of responses, are as follows: pod design; environment; safety; pod speed; task requirements; VR efficacy. A summary of participant responses or each theme is provided in Table 4.

Table 4: Summary of responses from semi-structured interviews. Responses in quotation marks signify direct quotes

Theme	**Summary of participants' responses**
Pod design	• The height of pods was seen as a limiting factor for gap acceptance. A number of participants reported that the height of pods was comparable to a van and that it greatly restricted the view of the other side of the path. Therefore, it was hard to determine if crossing between the pods would put the person in the path of an oncoming object, such as another pod, cyclists, jogger, etc. • "As the pods are both tall and box shaped, it made the gap between the pods seem more imposing than the gap between cars would be" • There are no external indicators on the pod, therefore there is no way of understanding the pod's intention
Environment	• For the shared space it was not clear where the pods would go. It was much easier to understand in the road environment, as this is generally what you encounter in the real world • Several participants reported feeling uncomfortable with the pods approaching in the shared space, as there were no barriers or raised area to move to • "I would feel more confident where the pod was going, if there were painted lines on the ground for the shared space"
Safety	• "As the pods didn't slow down as they got closer to me, I didn't think they would stop if I stepped out" • "I wouldn't feel comfortable with pods travelling at the highest speed in a shared space" • Several participants reported that because they were told the pods were automated, they were more confident the pods would detect them and prevent a collision
Pod speed	• "I Would just wait for the platoon to pass, especially if the pods were going fast" • "Constant speed made it easier to judge. Maybe if the pods were accelerating, it would change my opinion" • Participants reported that as the pod speed didn't vary, it was not possible to judge the vehicles intentions. It also felt unusual, as in the real world, drivers rarely keep a constant speed
Task requirement	• For scenarios where the pods were closer together, several participants said they would walk quickly or run between, which is what they would do with normal traffic • Participants liked that they could answer the questions in VR, without removing the headset • The task was repetitive, with some participants reporting that they would liked more variety
VR efficacy	• "The VR environment was surprisingly realistic. It felt like I could reach out and touch the pods" • "The background sounds and pod noise was appropriate and it was good how it changed as I rotated my head" • "The simulation is set on a sunny day, i'm not sure if different weather conditions would work so well e.g. raining"

By performing thematic analysis on the data, we were able to identify the key issues and areas of interest, which we could explore further. The remainder of this section looks in more detail at participant responses and how they relate to the literature.

Participants were asked about what influenced their decision in accepting or rejecting a gap. Several participants reported that for each scenario, as four pods were passing, there decision changed between viewing each of the three gaps. Interestingly, there was a trend in the discussions, which revealed that participants were increasingly likely to cross between the final pod, even though they only had to wait a few more seconds for the vehicle to pass. However, they still thought they would cross and not wait for all pods to pass, which they said reflects what they would do in the real world. This finding was supported by further statements, which showed that participants trust in the pods increased, once the first pod had passed. This raises a number of interesting questions, for example, if we exposed participants to a longer platoon, would the gap acceptance rate have increased? and would this in turn have affected responses to the safety question?

The size and design of the pods was a commonly discussed topic, with a number of participants stating that they were reluctant to cross as the pods were both tall and box shaped, which made gaps seem more imposing than the gap between cars would be. This is consistent with analysis of pedestrian behaviour at crossings, which have found that pedestrians cross faster in front of passenger vehicles (Hamed, 2001).

Participants were asked about how they felt about the number of pods in the platoon and the gap sizes. The majority (79%) of participants preferred to have a few pods travelling closely together, with no place to walk between, and a minority (21%) preferred pods to be travelling far apart, with space to walk between. Although in general, everyone thought the four pod platoon, at the speeds and gaps tested, was acceptable. However, it was pointed out that for a long platoon of pods, if the gap was too small to pass through, then people would become frustrated if they were required to wait more than a minute for all the vehicles to cross their path. It is clear that this point at which the number of pods in a platoon become an annoyance, is important for this technology to be accepted in public spaces.

To understand each participants propensity to risk, they were asked how they made their decision to cross between the pods, and whether they deemed their choice to put them at risk. From these responses, it was found that 22 % of people would consider themselves risk-takers, 39 % were risk-adverse, and 39 % believed they were neither. Interestingly, none of the participants considered their crossing decision would put them at any undue risk. This suggests that each participant was making a crossing decision based on their own acceptability of risk, and are not being influenced by the task to take more risk than they are comfortable with.

Finally, when asked if the pods being autonomous affected participants crossing decision, 27% said it made them more likely to cross, 15% said it made them less likely to cross, and 58% reported that it didn't influence their decision. As this study was investigating small gap sizes, it was expected that the majority of participants would not be influenced by the autonomous mode, as the stopping distance would be small. Additionally, several participants stated that they would never consider making a vehicle stop or slow down when crossing in front of any vehicle. When questioned further about the autonomous nature of the pods, all of the participants that said they would be less likely to cross, reported that the reason was due to the technology being unproven and that they trusted a human driver more. However, conversely the participants that reported they would be more likely to cross, said that they trusted the pod to stop, more than if a driver was operating it. These findings are consistent with a number of studies (Sucha et al., 2017; Ren et al., 2016; Rothenbcher et al., 2016) that looked at the effect of the driver on pedestrian behaviour. It was found that eye-contact played an important role, as well as other subtle movements, such as head nodding and hand gestures. Also related, is the effect of a vehicle's change in speed, with pedestrians often interpreting acceleration as a sign the vehicle will not yield, and deceleration a sign the driver will allow the pedestrian to cross (Rasouli et al., 2017). This is consistent with our findings, as a number of participants reported that as the pods maintained a consistent speed, there was no indication that the pods would stop if attempting to cross.

4. Conclusions

As autonomous vehicles are introduced to urban areas, it seems likely that they will be required to operate in platoons. The work presented in this paper is a first look at pedestrian crossing behaviour, in relation to the gaps between platooning pods. The primary aim of the research is to understand how different size gaps between pods effect pedestrians willingness to cross. This meant not measuring the pedestrians actual chosen time gap, but instead recording whether they would choose to walk between the pods. A secondary goal was to determine how the environment can affect gap acceptance for different temporal gaps. A computer-based VR simulation was used for the experiment, as exposing people to pods was deemed too risky and impractical, for the distances we required.

To understand how using VR affected participants, an immersion questionnaire was applied. The results from this indicated that participants were only slightly affected by the task being conducted in VR. This was reinforced by interviews, which found that participants were surprised at how immersed they felt in the simulation and how they thought the pods moved like real vehicles. However, the degree to which the results were affected by using a simulated environment, is still to be determined, as the literature shows, pedestrians can exhibit greater risk taking behaviour in a safe virtual environment. This may have resulted in gap acceptance, which is higher than what we may find for the real world. This is somewhat beneficial for our study though, as the aim is to identify the largest gap that pedestrians will not pass through. Further testing will be required to identify the level of discrepancy. A further influencing factor on the results is the design of the pod. Participants commented on the vehicles being tall and restricting the view of the path. It could be suggested that vehicles that were lower to the ground or were designed to provide more external viability, would result in participants rejecting fewer gaps.

Results from statistical analysis found that there was a significant increase of gap acceptance for shared spaces, which had no ground markings, compared to the road environment, which had a clear separation between vehicle and pedestrian. However, as the speed was increased, the difference in gap acceptance for the two environments converged. The findings suggest that people are more willing to walk between a platoon of pods in a shared space (accept a gap), compared to the same gap size in a road environment. This finding was unexpected and not what we had hoped to have found, as pedestrians crossing between the platoon will increase the likelihood vehicles will have to stop suddenly. This could mean gaps between pods will need to be reduced to prevent an acceptable crossing gap, or increased to allow safe crossing space for the pedestrians. Alternatively, ground markings could be used to add a visual separation between the pedestrian and pods. These finding have potential policy implications for urban design, as the layout of pedestrianised areas will need to provide enough space for vehicles to operate. Additionally, if ground markings are used, they will need to form a guide for people and not as a visual barrier, limiting the pedestrianised area. This is due to interview feedback, which showed that for a pod system to be accepted, it must not unduly disrupt the movement of pedestrians.

Results also found that although people were more likely to accept gaps in a shared environment, participants reported lower safety scores. To understand this result, interviews were conducted, which revealed that most participants felt safer in the road environment, as there was a clear path that they believed the vehicle would follow. In contrast, for the shared environment, there was a perception that they were at greater risk, as they could not determine where the vehicles would go. Therefore, in general people felt that they would be safer if they crossed between the pods and moved away in order to distance themselves. This result shows that one way to reduce pedestrian's safety perception of pods, is to make it clear what the vehicles direction of travel is. Interestingly, none of the participants reported that they would step backwards or walk away from the vehicles until they had passed.

Finally, the responses obtained from the interviews revealed that peoples gap acceptance and safety judgement of the pods changed as each pod passed. In particular, it was found that participants were more comfortable after the first pod had crossed their position, as it gave them confidence on the precise path of the vehicle and helped make a judgement on speed. To understand this finding, further research is needed to record pedestrian gap acceptance and safety scores, as each pod passes, without pausing the simulation.

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