Transportation Research Part F: Psychology and Behaviour 93 (2023) 34–54

Contents lists available at ScienceDirect

Transportation Research Part F: Psychology and Behaviour

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

Pedestrians’ perceived vulnerability and observed behaviours relating to crossing and passing interactions with autonomous vehicles

Lynn M. Hulse

FSEG, University of Greenwich, Old Royal Naval College, Park Row, London SE10 9LS, UK

ARTICLE INFO

Keywords:
Pedestrian-vehicle interaction
Autonomous
Safety
Mobility
Shared space
Cyclist

ABSTRACT

Researchers have predicted that “vulnerable road users” (VRUs) such as pedestrians will feel less vulnerable and thus take more risks around autonomous vehicles (AVs) than around human-operated vehicles (HOVs). However, data on the behaviours pedestrians are likely to display during passing as well as crossing interactions with AVs – particularly from naturalistic studies – are currently lacking. Such data could help inform AV system designers and authorities, as well as researchers. So, a novel study was conducted in London, UK. Perceived vulnerability was gauged via a survey on hypothetical pedestrian-vehicle interactions (N = 267). Behaviours were observed during real crossing and passing interactions with AV shuttle pods in a shared space (N = 330). While pedestrians were the main focus, joggers and cyclists were also frequenting the observation site and were included in the analysis of passing interactions. The survey results showed that pedestrians were not perceived to be less vulnerable around AVs. Diminishing initial boldness in the crossing interactions, and high yielding in the passing interactions, supported this, demonstrating that VRUs were not taking undue risks; rather, they appeared to be experiencing some uncertainty and discomfort. Further results showed other VRU behaviours (gap acceptance, inattention, hesitation, changes in speed, explicit communication, a side preference) may be relevant in AV interactions, but not necessarily to the same degree as when around HOVs or not in line with UK road rules. Positive conclusions were drawn for AV programming, and for safety, at least in the short term, but concerns regarding mobility need addressing.

1. Introduction

Pedestrians have a heightened risk of becoming a road casualty. For example, UK statistics show that, when accounting for distance travelled, pedestrians have a higher fatality rate than occupants of cars and other, larger motorised vehicles (Department for Transport, 2021b). This elevated risk means pedestrians are classed as “vulnerable road users” (VRUs), as are those on two wheels such as cyclists who have an even higher fatality rate. The vulnerability of these types of road user has also been observed globally (WHO, 2018).

One motivation behind the development of autonomous vehicles (AVs, or driverless vehicles) is that they are expected to make travelling safer (Department for Transport, 2017; European Parliament, 2019; NHTSA, 2021). This expectation rests on evidence that many road traffic collisions (RTCs) are attributable to the human operators of vehicles involved; for instance, a driver failing to look properly, failing to judge the other road user’s path or speed, or exceeding the speed limit (Department for Transport, 2021a). Thus, if

---

E-mail address: l.hulse@greenwich.ac.uk.

https://doi.org/10.1016/j.trf.2022.12.007
Received 5 April 2022; Received in revised form 8 November 2022; Accepted 18 December 2022

human operators were replaced with artificial intelligence systems, ones programmed to detect potential problems, make logical decisions swiftly, and act according to road rules, it should reduce the number of RTCs and associated casualties.

However, human operators of vehicles are not the only agent in RTCs. Pedestrians are too. Not only does their risky behaviour (e.g. failing to look properly) affect RTC occurrence (Department for Transport, 2021a), it can also affect RTC injury severity (Habibovic & Davidsson, 2012). It has been argued that risky pedestrian behaviours may occur more frequently around AVs, if pedestrians perceive themselves to be less vulnerable because they believe these vehicles will be more cautious and law-abiding than human drivers (Millard-Ball, 2018). This argument is similar to comments made by Peltzman (1975), among others, who stated that the intended benefits of introducing road safety measures can be offset by behavioural changes (e.g. an increase in risk-taking). This has been termed the "risk compensation theory". Wilde (cited in Wilde, 1998) extended this thinking with the "risk homeostasis theory", stating that individuals change their risk-taking behaviour with the aim of achieving equilibrium between the level of risk they currently perceive in the environment and the target level of risk they prefer (i.e. personal threshold). So, if new safety measures lower the cost of risk-taking (e.g. reduce the likelihood of an injurious collision), bringing the perceived risk to a level below that of the personal threshold, then individuals will seek to optimise the situation and engage in behaviours that are risky but potentially beneficial (e.g. crossing in front of an approaching vehicle if it means getting to one's destination quicker). There is contention as to whether these theories, particularly the latter, have any validity (O'Neill & Williams, 1998; Pless, 2016; Trimpop, 1996). Nevertheless, it remains important to identify and understand how pedestrians will behave around AVs during interactions – i.e. situations where the road users appear to be about to occupy the same spatial region at the same time, with consequences for perception and movement (cf. Markkula et al., 2020) – not least so AV system designers can program the vehicles to accurately predict and react to this (Camara et al., 2020).

A simple strategy, where AVs are programmed to always yield during interactions, would not be practical. Pedestrian safety would likely increase, but AV journey times would lengthen. This would decrease AVs' effectiveness and attractiveness in other areas, e.g. as a first-mile/last-mile mobility solution, helping those less able get to and from transport hubs such as train stations (Lau & Susilawati, 2021; Ruscher et al., 2019). Therefore, AVs cannot be programmed to be completely submissive. Consequently, pedestrian-AV interactions will involve conflicts requiring resolution. For a resolution to be satisfactory or at least tolerable for both parties, and for it to be safe, AVs will need to negotiate with pedestrians over who gets priority during an interaction. In turn, for negotiation to be effective, AVs will need to possess knowledge of possible pedestrian behaviours, identify the likelihood of those behaviours occurring in the given situation, and assess the associated risk of a RTC. AVs may opt to yield in situations where the risk is too high or there is large uncertainty (see Gupta et al., 2018, and Gupta et al., 2019, for promising research on negotiation models for crossing interactions between AVs and pedestrians). Available research findings on the various pedestrian behaviours displayed during interactions with human-operated vehicles (HOVs) could inform initial programming. Further research could then determine if behaviours around AVs differ from behaviours around HOVs, and whether any programming modifications might be required as a result.

Sections 1.1 and 1.2 that follow present relevant findings about pedestrian behaviours extracted from the existing literature on crossing and passing interactions with HOVs. The HOVs in these studies were typically motorised HOVs (mainly conventional cars), but some literature involving non-motorised HOVs (i.e. bicycles) has also been included, where appropriate, when studies with motorised HOVs were found to be lacking. As well as describing the types of pedestrian behaviours, these two sections present the reported frequencies of the behaviours. Section 1.3 then introduces relevant findings from the existing literature on pedestrians' perceived vulnerability and interactions with AVs. As will become clear, this research is still at a relatively early stage; there are several confounds and gaps in the methods employed and findings reported. Hence, this paper presents an original piece of research, utilising both a survey (to access people's internal thoughts or feelings surrounding vulnerability in hypothetical pedestrian-AV interactions) and observation (to capture visible behaviours in real pedestrian-AV interactions). Section 1.4 states the research questions that were addressed. The aim was to gain a clearer and more comprehensive insight into whether pedestrians' perceptions of and behaviour around AVs might be different, compared to previously reported responses towards HOVs, and whether this would have implications for AV system designers, as well as for other stakeholders (VRUs, authorities, researchers), regarding road safety primarily, but also mobility. An additional element was that observation took place in a shared space. Would the improved safety that these environments are designed to give VRUs result in pedestrians taking more risks around AVs, thereby neutralising the vehicles' potential for enhancing travel experiences?

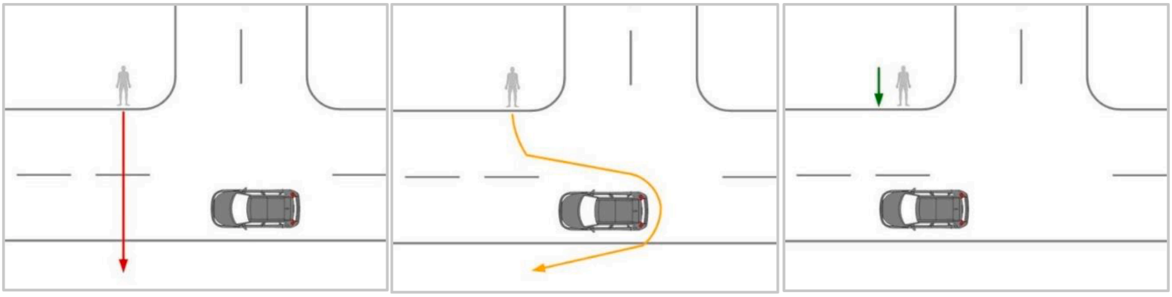


Fig. 1. Crossing choices: cross in front (high risk), cross behind (medium risk), or wait (low risk).

1.1. Pedestrian-vehicle interactions: Crossing

Pedestrians commonly interact with HOVs at crossing points. These can be designated (indicated by markings on the ground, traffic signals) or undesignated (unmarked, no signals, but where pedestrians tend to cross due to factors such as road width or the presence of a *T*-junction; Shurbutt & Do, 2013). This paper focuses on the latter. At undesignated crossing points, there is a greater onus on pedestrians to behave safely. For example, they could enter the road to cross in front or behind of an approaching HOV, but these would be riskier choices. Choosing to wait and let the approaching HOV pass first would pose least risk (Fig. 1). Yet, research suggests most pedestrians (60–65 %) do not wait to let motorised HOVs pass when at undesignated crossing points (Shaaban et al., 2018; Zhuang & Wu, 2011).

When making a crossing choice, pedestrians may look for gaps between their reference (crossing) point and approaching HOVs. If they think an available gap is sufficient for them to cross the road before the next vehicle arrives at the reference point, then they are likely to accept that gap and begin crossing; otherwise, they will reject the gap. Accepted gaps in interactions with motorised HOVs rarely seem to be shorter than 2 s and are more often at least 3 s long (Chandra et al., 2014). Some researchers argue that gaps are measured more in distance than time (Oxley et al., 2005; Yannis et al., 2013). Regardless, gaps may not feature in crossing choices at all if pedestrians are inattentive, e.g. distracted by their phones, which many may be (42 % in Zhuang & Wu, 2011).

When pedestrians do choose to cross, some may soon hesitate; that is, step out from the kerb then stop (41 %) or step backwards (11 %) (Zhuang & Wu, 2011). Once committed to going forwards, the travel speed is usually greater than normally observed for walking on pavements, although there are variations according to sociodemographic factors – e.g. studies of pedestrians crossing in areas with motorised HOVs have noted faster mean crossing speeds for relatively younger adults compared to older adults (1.32–1.57 m/s [c. 3–4 mph] versus 1.11–1.16 m/s [c. 2–3 mph], respectively, in the UK; Ishaque & Noland, 2008). Whether pedestrians' travel speeds will be sufficient to clear the crossing point in the gap available is dependent on the travel distance involved. Distance, in turn, depends on the number of lanes being crossed. If pedestrians begin to perceive that their current speed may not be sufficient when crossing in areas with motorised HOVs, some (21 %–32 %) may react by changing their speed, i.e. accelerate (Raghuram Kadali & Vedagiri, 2020; Zhuang & Wu, 2011). By that logic, if pedestrians perceive that their current speed is excessive, they might decelerate to a more comfortable walking pace.

Lastly, there may be attempts to communicate. At designated crossing points, there are often traffic signals present, which help convey who is expected to yield and when they are expected to yield, and the behavioural norms are defined by laws. Even at non-signalised designated crossing points, road markings help highlight the fact that any pedestrian approaching the kerb by the marked area is likely intending to cross the road, and thus HOVs are expected to slow and/or stop if necessary, with such a change in speed also acting as a means of communication (i.e. indicating to pedestrians that a HOV is yielding and it is safe for them to cross; Sucha et al., 2017). At undesignated crossing points, behavioural norms are even less well defined. Thus, if road users wish their expectations and behavioural intentions to be conveyed to the other party, their only means of communication is via unofficial cues, which may have a lower chance of being understood or obeyed (Chaloupka & Risser, 2020). For instance, pedestrians may try to make eye contact with or, more explicitly, direct hand gestures or verbal comments towards the motorised HOV operator to indicate that they expect them to yield. Such behaviour may only be observed in a small minority (3–4 %) of pedestrians (Dey & Terken, 2017; Lee et al., 2021). However, it has been reported that "pedestrians appear to consider the car as an entity, and do not distinguish between the car itself and the driver" (Dey & Terken, 2017, p. 110), so explicit communication attempts could occur even without sight of an operator. Additionally, it has been speculated that explicit communication may occur more frequently in interactions where motorised HOVs are travelling at lower speeds or where there is more need for negotiation over who gets priority, such as in a shared space (Lee et al., 2021).

1.2. Pedestrian-vehicle interactions: Shared space and passing

The concept of a shared space first gained popularity in the Netherlands and has spread to many other countries (Karndacharuk et al., 2014a). In these spaces, separation between pedestrians and HOVs is minimised, e.g. through the absence of features such as kerbs or demarcating road markings. The aim of this urban design is to reduce the dominance of HOVs, especially motorised vehicles, thereby making pedestrians feel safer and able to use more of the space (Department for Transport, 2011). The result is that pedestrians and HOVs may engage not only in crossing interactions at undesignated points but also in passing interactions where, instead of meeting orthogonally, they may meet head-on or with one approaching the other from behind.

Following criticism, particularly from groups representing persons with disabilities, the UK government withdrew its shared space guidance in 2018 in order to review and update it (Department for Transport, 2020). Plans for new schemes were paused, but existing shared spaces remained. Moreover, in response to the COVID-19 pandemic and social distancing requirements, many UK local authorities followed government advice to reallocate road space. While not shared space in name, some reallocated areas were akin to this in nature, e.g. streets turned into spaces for pedestrians and cyclists, but with motorised vehicles being granted access also during certain periods such as school drop-off/pick-up times (Department for Transport, 2021c). Reallocation of road space was also undertaken in other countries across the world (Combs & Pardo, 2021). Thus, the practice continues of pedestrians intermingling with HOVs in spaces designed to increase the former's safety and use of the space.

Findings from research on shared spaces have been somewhat mixed. In New Zealand, Karndacharuk et al. (2014b) compared video footage of interactions between pedestrians and motorised HOVs before and after a street was transformed into a shared space (although not specified, images in the paper suggest that interactions included passing as well as crossing). Previously, HOVs were usually given priority during interactions (91 % of the time), but in the two years following site redevelopment, pedestrians became marginally dominant (52 % then 53 % of the time). A similar study in London, UK (Kaparias et al., 2016) found that, in crossing interactions, pedestrians were now accepting smaller gaps (albeit not shorter than 3 s) and crossing at slower speeds, suggesting increased comfort and confidence. In Leeds, UK, Uttley et al. (2020) directly observed interactions in a different kind of shared space – a railway station car park. During interactions between pedestrians and motorised HOVs, pedestrians tended to dominate (they were given priority 65 % of the time), especially if in a group. Additionally, pedestrians were seen to explicitly communicate via hand gestures in 17 % of interactions, which supports Lee et al.'s (2021) speculation. However, not all research findings have been positive. Moody and Melia (2014) used video footage to track pedestrian movements in a more street-like shared space in Ashford, UK. They found that pedestrians would take diversions and skirt the periphery of the space rather than follow the more natural line through it, thereby avoiding some interactions with motorised HOVs. When paths did conflict, pedestrians tended to yield and wait for the motorised HOVs to pass (52 % of the time). Supplementary interviews conducted at the site revealed that 80 % of pedestrians felt safer when the space was not shared. So, while shared spaces do appear to reduce the major dominance of motorised HOVs, they do not necessarily reduce pedestrians' perceived vulnerability or increase their use of the space. Nor do they appear to encourage pedestrians to take excessive risks.

Further research on interactions in shared spaces – also using video observation, direct observation and/or surveys – has tended to focus on conflicts between pedestrians and non-motorised, two-wheeled HOVs. Findings have shown that the faster moving road user, the cyclist, tends to be the one to yield, at least in terms of changing path (67 %-90+% of the time; Hatfield & Prabhakharan, 2016; Liang et al., 2021). When a change in speed has also been observed, it is more often deceleration (Liang et al., 2021) but may sometimes be acceleration (Alsaleh et al., 2020). Additionally, pedestrians and cyclists tend to show a preference for a particular side during passing interactions. Liang et al. (2021) found that this was not associated with the direction of travel. More likely, the preference is influenced by local road rules. For instance, in Australia, where HOVs drive on the left and undertaking is discouraged, pedestrians were seen to keep left when approached from behind (82 %) or head-on (88 %), with cyclists passing to the right of them when approaching from behind (87 %) or head-on (84 %) (Hatfield & Prabhakharan, 2016). It is not known if a side preference or the type of approach might be important, along with a change of path and speed, in passing interactions between pedestrians and motorised vehicles in a shared space.

1.3. Pedestrian-vehicle interactions: AVs

To date, research on AVs and pedestrians or VRUs has often considered hypothetical interactions using surveys or virtual reality (VR). For example, Hulse et al.'s (2018) UK survey showed pedestrians were perceived to be safer around AVs than around motorised HOVs, although the general attitudes expressed indicated that non-drivers (and drivers) still had some reservations over the road safety capability of AVs. Survey data from VRUs in the USA (Penmetsa et al., 2019), gathered after AV trials had begun in that country, revealed a similar picture and with less uncertainty. Following their experiment in Canada, Farooq et al. (2018) argued that VR might be a better method of investigating pedestrian responses towards AVs than text-based surveys; the more realistic condition seemed to allow a preference for interacting with AVs over motorised HOVs to become apparent. However, their HOV scenario involved the opportunity to jaywalk at a designated crossing point (where pedestrians did not have priority), whereas the AV scenario involved crossing at an undesignated point (where participants were told they did have priority). So, the increased realism might have been highlighting the danger of taking risks when not having priority, rather than highlighting the safety potential of AVs.

VR data for undesignated crossing points was discernible in Nuñez Velasco et al.'s (2019) study in the Netherlands. Data visualisation showed most participants chose not to cross when the gap was 2 s – this was regardless of the approaching vehicle's type (AV, motorised HOV) or speed. When the gap was 4 s, most participants again chose not to cross but only in the AV scenario; more than half the participants chose to cross in the HOV scenario. Oddly, when the gap was still 4 s but the vehicle speed was faster (5.56 m/s [c. 12 mph] versus 2.78 m/s [c. 6 mph]), more participants chose to cross (75 %+ in the AV and HOV scenarios). Yet, when the data were analysed with logistic regression, Nuñez Velasco et al. found no interaction effects. Instead, the type of crossing point, the gap size, and vehicle speed were all significant predictors of crossing choices. Importantly, vehicle type was not. Moreover, when gap size was measured by distance, it again significantly predicted crossing choices, but vehicle speed was no longer significant.

Of the real-world research conducted so far, the prominent studies have utilised a "Wizard of Oz" method where the AV is artificial – i.e. a motorised HOV with the steering wheel and/or driver hidden from view (e.g. Lagström & Malmsten Lundgren, 2016; Rothenbücher et al., 2016). Few studies have progressed to using real AVs to study pedestrian behaviour, especially in shared spaces or passing interactions. Madigan et al. (2019) did. They analysed video of various VRUs plus motorised road users interacting with real AVs during trials in (sometimes shared) street spaces in France and Greece. No evidence was found to suggest that VRUs would either change path or stop to give priority to AVs. However, since these behaviours were recorded for both crossing (where they better resembled hesitation) and passing interactions and then merged in the analysis, and since some crossing points were designated, it is somewhat hard to interpret the results. In Löcken et al.'s (2019) small study in Germany, VRUs and real AVs interacted on roads that, based on images, lacked markings and were flanked by grass verges. Video observations revealed that, during passing interactions, VRUs tended to leave as much space between themselves and the AV as they would for a motorised HOV, but that "sometimes" VRUs moved onto the grass. Moreover, VRUs "sometimes" refused to yield and change path when approached by an AV from behind. Crossing interactions at undesignated points were rarely observed. However, three instances were noted of inattentive pedestrians crossing in front of the AV when the gap was less than 10 m, and two instances of pedestrian hesitation were noted.

1.4. *The current study and research questions*

To summarise the reviewed literature, there is a decent body of research defining pedestrian behaviours during interactions with motorised HOVs at undesignated crossing points. There is also some research on pedestrian-HOV passing interactions in shared spaces, although not always with motorised HOVs. The literature on pedestrian-AV interactions is still somewhat in its infancy. Moreover, there is a need for more naturalistic data collection methods to supplement surveys, and for further, clearer quantitative analysis. Thus, this paper describes a novel piece of original research that was designed to start addressing these issues. Along with an online survey, observation of pedestrian behaviours took place in a real-world setting where AVs were being trialled as part of a larger, ambitious project called GATEway (TRL, 2018). In a first-of-its-kind study for the UK, both crossing and passing interactions were observed, thereby providing insight into a broader range of scenarios in which pedestrians may mix with AVs. The crossing and passing data were analysed separately to avoid confounding findings. Behaviours were quantified as well as identified, allowing for a comparison of their frequency with that of behaviours reported in the existing literature on pedestrian-HOV interactions.

Via the survey, which was conducted in the same part of the UK as the observations, this study sought to answer the following question:

(a) Will pedestrians be perceived to be vulnerable around AVs?

Ratings would reveal firstly whether participants had a realistic perception of the risk of becoming a road casualty for pedestrians when around motorised HOVs (cyclist risk > pedestrian risk > car passenger risk). Second, they would reveal whether participants still perceived pedestrians to face a greater risk than passengers when around AVs as compared to when around motorised HOVs. The results would indicate whether the first part of Millard-Ball's (2018) prediction is supported or not – i.e. that pedestrians will perceive themselves to be less vulnerable around AVs due to a belief that these vehicles will be more cautious and law-abiding than human drivers. Next, via the observations, the current study sought to answer three further questions:

(b) Will pedestrians display typical crossing behaviours during interactions with AVs?
(c) Will one party dominate passing interactions between pedestrians and AVs?
(d) Will passing manoeuvres involving AVs reflect UK road rules?

The frequency of observed behaviours at an undesignated crossing point would reveal whether pedestrians were taking greater risks around AVs, as compared to when around motorised HOVs, using a comparison with the existing literature. In so doing, this study would help test the second part of Millard-Ball's (2018) prediction, which echoes the risk compensation or homeostasis theories, i.e. that risky pedestrian behaviours will increase around AVs because these vehicles are seemingly safer. The observed behaviours when passing in a shared space would reveal whether one party was more likely to yield to the other by changing path and speed, and whether a normative side preference exists. Also, sociodemographic factors (e.g. gender, age, group size) that might modify responses were considered. Altogether, this would provide insights relevant to road safety and mobility – ones to help inform those involved in programming AV systems, as well as those involved in launching, managing, and researching the use of AVs in public spaces where they can intermingle with VRUs.

1.5. *Structure of the paper*

Section 2 that follows describes the data collection and analysis methods employed in this study. Section 3 presents the results about perceived vulnerability from the survey, then it presents the results from the observations of crossing interactions, before lastly

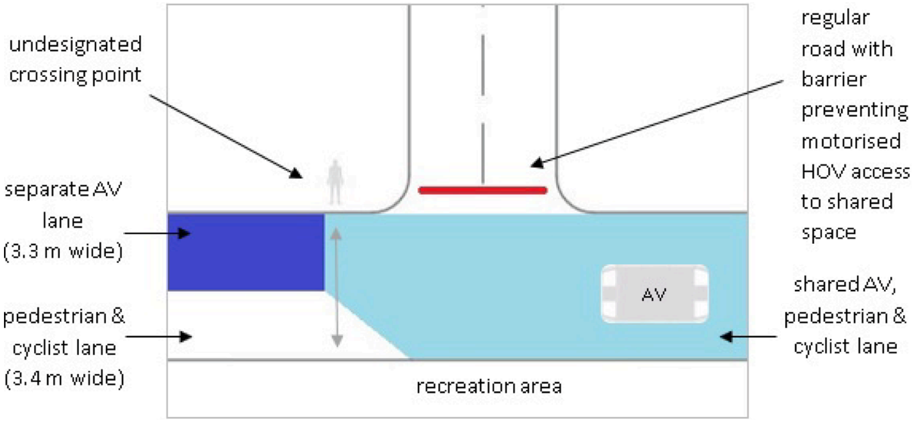


Fig. 2. *T*-junction where crossing interactions were observed.

presenting the results from the observations of passing interactions. In section 4, the results are compared with findings from the existing literature described in section 1, and then the study is discussed with respect to (a) the implications of its findings for various stakeholders and (b) its limitations. Finally, section 5 concludes the paper by summarising this study's innovations, contributions, and limitations, and by providing direction for future studies.

2. Methods

2.1. Study area

The entire study was conducted in a metropolitan area, London's Royal Borough of Greenwich. This was one of the first places to trial AVs around members of the UK public. Observation occurred within two separate sections of a longer shared space in North Greenwich. While not the main urban centre of the borough, North Greenwich (also known as the Greenwich Peninsula) nevertheless is an urban area that attracts a flow of people due to it containing a major hospitality venue, several transport hubs, as well as offices, high-rise residences, and a river with recreation areas built in alongside; all of these features surrounded the shared space. Prior to the AV trials, the space was shared by pedestrians and cyclists. For the trials in 2018 it was developed into a space to be shared by VRUs and AVs. This required minimal change to the current infrastructure of the shared space (Saeed, Alabi, & Labi, 2021); the main modification was the addition of some painted lines on the ground to occasionally separate pedestrians and cyclists into a different lane from the AVs at points where the latter would be stopping to drop off/pick up passengers. Separation only slightly encroached into the section where observations of crossing interactions took place (see Fig. 2). Separation was completely absent from the section where observations of passing interactions took place (see Fig. 3).

Crossing interactions were observed within a 20 m long section at a location where a regular road met the shared space, creating a *T*-junction (Fig. 2). A kerb on the side with the regular road dropped away there, encouraging crossing at this point. Crossing behaviour was recorded if participants arrived at the point when an AV was already approaching at a constant speed.

VRUs would arrive at the undesignated crossing point from either the side with the regular road (which connected them to several transport hubs, office blocks, and car parks) or from the side with the recreation area (which provided a place to have a seat or stroll by the river's edge). Travelling along the recreation area in a northward direction eventually took VRUs to another transport hub, while travelling along the recreation area in a southward direction eventually took VRUs to a children's play area and residences opposite. The occasional vegetation, seating, and steps in the recreation area, and the boards and railings by transport hubs, sometimes presented an obstacle to VRUs and so it tended to be easier and quicker to reach destinations by travelling in the shared space's lane(s) instead.

Passing interactions were observed inside a straight 30 m long section of the shared space, flanked by no kerb. This section was located further along from the crossing point, in a northward direction, close to one of the transport hubs. Some of the residences lining this section were still under construction at the time of the study, hence hoarding on one side (Fig. 3). Passing behaviour was recorded if participants entered this section and encountered an AV travelling at a constant speed.

2.2. Participants

Survey participants aged 18 + years were recruited via advertisements placed on websites and social media targeting diverse demographics. Advertisements were also circulated within the University of Greenwich (which provided ethical approval for the study). Interested parties were informed that they would be taking part in a short online survey, lasting fewer than 10 min. The survey

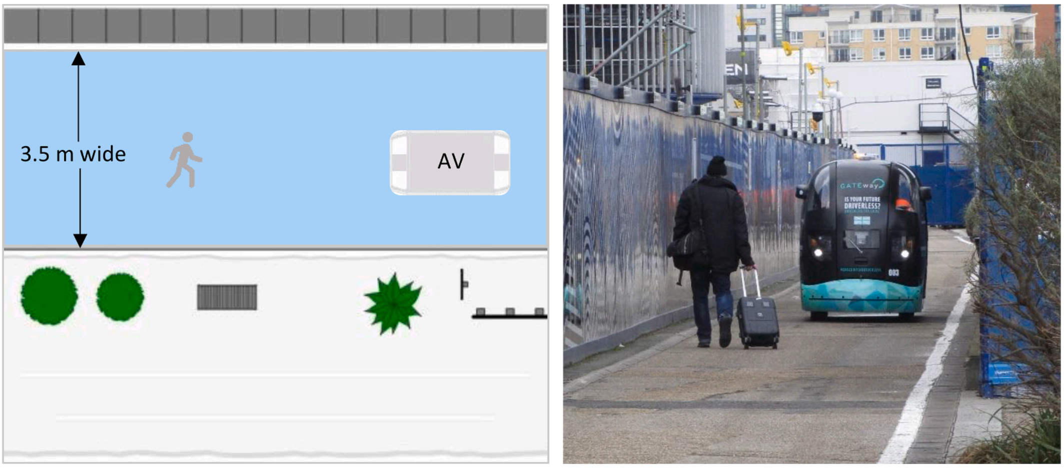


Fig. 3. (Left) Shared AV, pedestrian, and cyclist lane where passing interactions were observed – hoarding at the top of the illustration, recreation area at the bottom; (Right) an AV and a pedestrian during a passing interaction – hoarding on the left, recreation area on the right.

would ask about AVs from the perspective of road users including pedestrians. No financial incentives were offered. Data collection occurred prior to the start of the AV trials. A total of 267 participants who completed the survey and who lived and/or worked in Greenwich were included in the survey analysis.

Observation participants were not recruited; they were members of the public who happened to be in the shared space at the time of the trials. Their familiarity with the shared space is unknown. However, given the nature of the buildings and amenities connected to the shared space (see section 2.1), and given the timing of data collection (see section 2.4), participants were believed to be mostly regular commuters and/or local residents and workers. They were directly observed by researchers who operated discreetly to ensure that they did not influence behaviour. A total of 530 participants were included in the observation analysis.

2.3. *Survey materials and procedure*

The survey inquired about personal variables relevant to road user behaviour: i.e. participants' gender, age (in years), and driver status (whether or not they had a driving license). It was discovered that females and older adults were under-represented in this sample compared to in the borough's population, thus weighting was applied to the data. Consequently, the gender ratio of the sample matched that of the population (49 % males, 51 % females), while the percentage of older adults in the sample also now matched the percentage in the population (14 % 65 + years old) (Table 1). The survey also measured participants' tendency for risk-taking using the five-item instrument created by Hulse et al. (2018). It asked participants to rate the likelihood of them engaging in risky behaviours related to road users including pedestrians, cyclists, car drivers, and car passengers (e.g. "crossing the road when the 'don't walk' sign is indicated"). Likelihood was rated on a seven-point scale (where 1 = extremely unlikely, 2 = moderately unlikely, 3 = somewhat unlikely, 4 = not sure, 5 = somewhat likely, 6 = moderately likely, and 7 = extremely likely). The ratings for the five items were then summed to provide a risk-taking score (possible range = 5 to 35, with a higher score indicating a greater tendency to take risks).

The survey also included Hulse et al.'s (2018) materials for measuring the perceived risk of becoming a road casualty. Participants were asked to rate the risk they associated with being (i) a pedestrian and (ii) a car passenger in an area with traffic. In one scenario, the traffic (and the passenger's own vehicle) comprised motorised HOVs and, in the other scenario, it comprised AVs. Note, in the HOV scenario, participants were also asked about being (iii) a cyclist. Risk ratings were made using a seven-point scale (where 1 = extremely low, 2 = moderately low, 3 = somewhat low, 4 = not sure, 5 = somewhat high, 6 = moderately high, and 7 = extremely high).

2.4. *Observation materials and procedure*

The researchers visited and familiarised themselves with the shared space prior to the AV trials commencing. Suitable locations to observe crossing and passing without visual obstruction were identified and relevant spatial dimensions and features were recorded. Also recorded was people's use of the shared space without AVs; behaviours during passing interactions with AVs were compared with this baseline data.

The baseline and trial observations took place during peak footfall hours on weekdays (typically between 12:00 and 14:00). Although winter, the weather was consistent during observation periods (most frequently cloudy, visibility good, temperature 8 °C, wind speed 11 mph, road surface dry). The researchers, dressed inconspicuously, took turns to visit the shared space over a period of five weeks. They positioned themselves either in the recreation area or by the regular road, ensuring they had a good vantage point. Observed behaviours were recorded on a checklist, which had boxes that could be ticked or filled with letters or symbols for fast and easy coding (see Appendix for category codes used with this checklist, their definitions, and further procedural notes). Both researchers had experience of coding data from observations. To ensure they could adequately estimate different genders and age categories based

Table 1
Descriptive statistics for the survey sample and borough population.

	Sample: unweighted (N = 267)	**Population (N = 193,185)**	**Sample: weighted (N = 267)**
Gender:			
- Male	62 %	49 %	49 %
- Female	38 %	51 %	51 %
Age:			
– 18–29	20 %	25 %	25 %
– 30–64	76 %	61 %	61 %
– 65+	4 %	14 %	14 %
Age:			
- Minimum to maximum	19–85 years		19–85 years
- Mean (standard deviation)	42.26 years (12.96)		43.95 years (15.44)
Driver status:			
- No	17 %		17 %
- Yes	83 %		83 %
Risk-taking			
- Minimum to maximum	5–35		5–35
- Mean (standard deviation)	18.77 (6.65)		17.99 (6.70)
- Cronbach's alpha	0.68		0.70

Note: Borough population data for males and females aged 18 and over were derived from the last census (Office for National Statistics, 2013).

on a person's physical appearance, they also undertook training and testing using stimuli from the 10 k US Adult Faces Database (Bainbridge, Isola, & Oliva, 2013). The final test comprised a sample of 90 stimuli showing individuals from various ethnic groups; the researchers each achieved overall accuracy scores of more than 88 %. Additionally, during a test run of the AV fleet on the eve of the trials, the researchers practised observing and recording the behaviours of a number of passerbys ($N = 25$) interacting with the vehicles. The same passersby were observed by each researcher, who were stood in close proximity yet separate from one another, thus making independent records. These records were then compared to check if the researchers were coding consistently. They were, to a high degree (inter-rater reliability scores: Cohen's kappa for the age variable = 0.78, $p < .001$; for all other variables coded, Cohen's kappa greater than 0.90, ps less than 0.001).

While pedestrians were the main focus, the presence of joggers and cyclists was noted during site familiarisation visits. Since they too constitute VRUs, albeit ones moving at a faster average speed than walking pedestrians (in shared spaces, 2.87–3.34 m/s [c. 6–7 mph] for jogging and 5.76–5.95 m/s [c. 13 mph] for cycling; Virkler & Balasubramanian, 1998), they were also included in the baseline and passing interaction observations (Table 2).

Two joggers were observed during crossing interactions but, since they stopped running before reaching the crossing point and did not start again until after having crossed, they were re-classified as pedestrians. Group membership was determined by displays of physical or social contact (e.g. holding hands, engaged in conversation) or by proximity (i.e. travelling closely together and moving in the same direction). Researchers only recorded the behaviour of one member per group. The procedure was to select the individual who differed most from the previously observed participant (e.g. choose a male if the previous participant was female). If it was not possible to select on this basis, then researchers recorded the behaviour of the individual who was most visible to them. The only exception was if this was a child; then, the behaviour of an accompanying adult was coded instead. Children travelling on their own were not subject to observation. Participants with dogs, using mobility aids, or wheeling an item such as a pushchair or suitcase were not excluded from the sample, but these characteristics were noted (six, one, and 26 cases, respectively, with none in the crossing interactions except two wheeling an item). Also, researchers watched for any RTCs; there were none.

2.5. AVs in the interactions

The AVs were a fleet of four driverless electric pods; the word "driverless" appeared on the body of each vehicle (Fig. 3). They used a combination of cameras, radar, lidar, and GPS to sense and navigate through the environment. Their purpose was a shuttle service; each pod (3.7 m long, 1.7 m wide, 2.1 m high) transported passengers – maximum of three plus one steward – between drop-off/pick-up points along a 3.4 km route that included the shared space. The steward was also the person designated to take over control of the AV in the event of a critical situation arising (with an internal button control panel and a screen showing real-time camera footage at their disposal), as per the legal requirements for AV trials in the UK (Department for transport, 2015). Vehicle speed (4.17 m/s [c. 9 mph]) was low, in line with shared space guidance (Department for Transport, 2011). Vehicle density was also low, since the number of pods was small. Due to the reflective quality of the pod windows, and the inward-facing seating configuration, VRUs were not able to see the faces of AV occupants.

2.6. Statistical analysis

The software package IBM SPSS Statistics 26 was used. Survey analysis was conducted with the paired samples *t*-test, the independent samples *t*-test, and Pearson's correlation (r). Results were produced first using the unweighted survey data. These were then compared with the results when the survey data were weighted. No meaningful differences in findings were detected, hence only the results using the weighted survey data are reported in this paper. Observation analysis was conducted with the chi-square test (X^2). Post hoc tests were also run, where appropriate. Results with p-values less than 0.050 were deemed to be statistically significant.

Table 2
Descriptive statistics for the crossing, passing, and baseline samples.

	Crossing (N = 66)	**Passing (N = 264)**	**Baseline (N = 200)**
Road user:			
- Pedestrian	100 %	83 %	82 %
- Jogger	–	9 %	10 %
- Cyclist	–	9 %	9 %
Gender:			
- Male	68 %	69 %	67 %
- Female	32 %	31 %	34 %
Age:			
- Younger adult	21 %	20 %	20 %
- Adult	73 %	72 %	71 %
- Older adult	6 %	8 %	9 %
Group size:			
- Alone	73 %	61 %	46 %
– 2	20 %	21 %	36 %
– 3+	8 %	18 %	18 %

3. Results

3.1. Survey: Perceived vulnerability

Fig. 4 displays the mean risk ratings given overall, by gender, and by driver status. Overall, around HOVs, pedestrians were perceived to face a different level of risk compared to other road users. This level of risk was significantly lower than for cyclists ($t(266) = -20.33$, $p < .001$) but significantly higher than for car passengers ($t(266) = 7.67$, $p < .001$). When imagining a scenario with AVs, participants' perception of risk did change but not with regards to pedestrians. That is, the perceived risk for pedestrians around AVs was similar to that for AV passengers ($t(266) = 0.43$, $p = .666$), as well as to that for pedestrians in the HOV scenario ($t(266) = -0.61$, $p = .541$). Instead, it was passengers who were perceived to face a changed (i.e. significantly increased) level of risk when imagining a scenario involving AVs as opposed to HOVs ($t(266) = -4.98$, $p < .001$).

There were gender differences. Females perceived significantly greater risk than did males for all road users in both the HOV and AV scenarios ($t(265)_{Cyc(1)} = -3.90$, $p < .001$; $t(265)_{Ped(1)} = -2.41$, $p = .017$; $t(265)_{CarP(1)} = -2.63$, $p = .009$; $t(265)_{Ped(2)} = -5.62$, $p < .001$; $t(265)_{AVP(2)} = -5.84$, $p < .001$). In contrast, driver status was unrelated to perceived risk in either scenario ($t(265)_{Cyc(1)} = -0.17$, $p = .862$; $t(265)_{Ped(1)} = 1.05$, $p = .294$; $t(265)_{CarP(1)} = -0.12$, $p = .901$; $t(265)_{Ped(2)} = -0.70$, $p = .483$; $t(265)_{AVP(2)} = -0.88$, $p = .378$). Age was typically negatively correlated with perceived risk but only significantly so in the HOV scenario ($r_{Cyc(1)} = -0.15$, $p = .016$; $r_{Ped(1)} = -0.34$, $p < .001$; $r_{CarP(1)} = -0.23$, $p < .001$; $r_{Ped(2)} = -0.03$, $p = .570$; $r_{AVP(2)} = 0.01$, $p = .906$). Risk-taking was also typically negatively correlated with perceived risk but never significantly so ($r_{Cyc(1)} = 0.01$, $p = .913$; $r_{Ped(1)} = -0.09$, $p = .124$; $r_{CarP(1)} = -0.09$, $p = .138$; $r_{Ped(2)} = -0.06$, $p = .307$; $r_{AVP(2)} = -0.07$, $p = .274$).

3.2. Observation: Crossing interactions

Most participants (89 %) did not wait before crossing. In fact, the majority chose the riskiest option – crossing in front of an AV (Table 3). The majority also accepted gaps that were objectively unsafe (i.e. a distance of less than or equal to 10 m; see notes in Appendix), although significantly fewer did this when crossing in front compared to behind ($X^2(1) = 13.81$, $p < .001$). Those who crossed in front showed less caution – displaying most inattention and least hesitation – while those who waited were always attentive and hesitated more when stepping out once the AV had passed. However, inattention and hesitation were only ever displayed by a minority and were not significantly associated with crossing choice ($X^2(2)_{Inatt} = 2.09$, $p = .351$; $X^2(2)_{Hesit} = 2.05$, $p = .359$). There was also no significant association between the number of lanes crossed and crossing choice ($X^2(2) = 1.36$, $p = .506$) or change in speed ($X^2(2) = 4.90$, $p = .086$). Nonetheless, around three-tenths of participants did change their travel speed while crossing, including those who waited for the AV to pass first. Acceleration occurred significantly more often when crossing in front of the AV, and deceleration when crossing behind it ($X^2(4) = 9.74$, $p = .045$). Regarding explicit communication with the AV, no attempts were observed.

Crossing choice was then examined in relation to sociodemographic factors (Fig. 5). Males and females were both unlikely to wait before crossing and, although more males opted for the riskiest option, gender was not significantly associated with crossing choice ($X^2(1) = 3.48$, $p = .176$). Nor was age, with all categories making the riskiest choice most often ($X^2(4) = 3.91$, $p = .418$). While

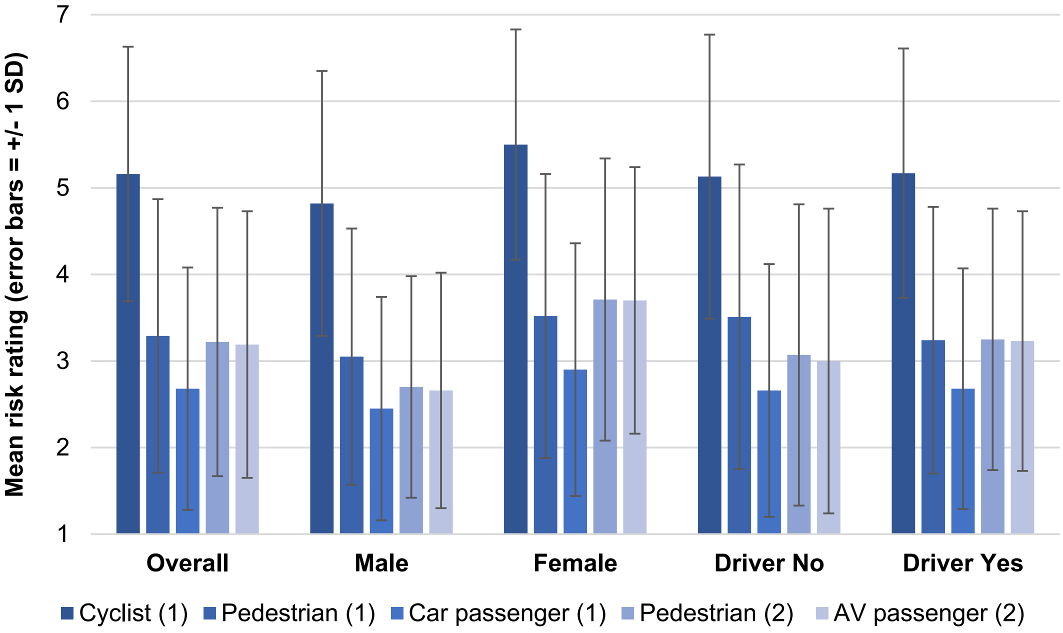


Fig. 4. Perceived risk for each type of road user in the HOV scenario (1) and AV scenario (2).

Table 3
Behaviours observed during pedestrian-AV crossing interactions.

	Accepted gap ≤ 10 m	Inattentive	Hesitated	Crossed both lanes	Changed speed	
					Acc.	Dec.
Overall	74 %	17 %	15 %	53 %	9 %	20 %
Crossing choice:						
- Cross in front (48 %)	53 %	22 %	9 %	59 %	19 %	9 %
- Cross behind (41 %)	96 %	15 %	19 %	44 %	0 %	30 %
- Wait (11 %)	–	0 %	29 %	57 %	0 %	29 %

Note: Acc. = accelerated, Dec. = decelerated.

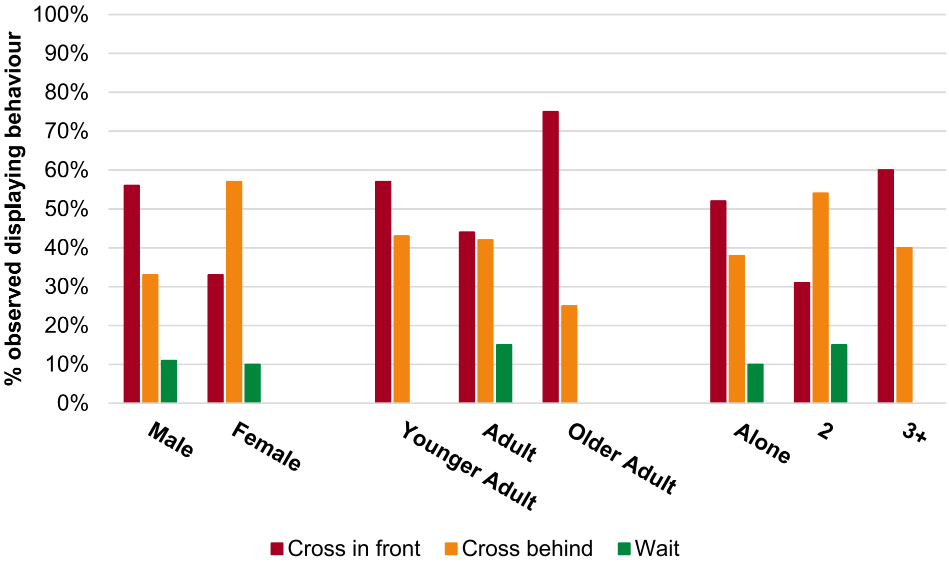


Fig. 5. Crossing choice by gender, age, and group size.

participants in groups of three or more appeared to take slightly greater risks than those with less company, there was no significant association between group size and crossing choice either ($X^2(4) = 2.59$, $p = .629$).

Gender, age, and group size were also examined in relation to the further behaviours of those who crossed in front, i.e. made the riskiest choice (Table 4). But the numbers in some categories were not sufficient to perform inferential statistical analysis. So, while it seemed that e.g. older adults might make this choice less frequently than others when the gap is smaller but slow down on the crossing point when they do, or that individuals in groups might behave differently depending on the size of the group, it is not possible to tell whether these patterns can be generalised beyond this sample.

Table 4
Further behaviours of pedestrians who crossed in front, by gender, age, and group size.

	Accepted gap ≤ 10 m	Inattentive	Hesitated	Crossed both lanes	Changed speed	
					Acc.	Dec.
Gender:						
- Male (n = 25)	56 %	28 %	12 %	60 %	16 %	8 %
- Female (n = 7)	43 %	0 %	0 %	57 %	29 %	14 %
Age:						
- Younger adult (n = 8)	63 %	25 %	0 %	37 %	13 %	0 %
- Adult (n = 21)	52 %	24 %	14 %	62 %	24 %	5 %
- Older adult (n = 3)	33 %	0 %	0 %	100 %	0 %	67 %
Group size:						
- Alone (n = 25)	56 %	28 %	12 %	60 %	16 %	4 %
− 2 (n = 4)	0 %	0 %	0 %	100 %	50 %	50 %
− 3+ (n = 3)	100 %	0 %	0 %	0 %	0 %	0 %

Note: Acc. = accelerated, Dec. = decelerated.

3.3. Observation: Passing interactions

In around two-thirds (66 %) of passing interactions, the AV approached the participant head-on. In a further 20 % of interactions, the AV approached from behind. In the remaining interactions (14 %), the participant approached and passed the AV from behind. This third group are examined later.

Of participants who were approached head-on or from behind, most yielded to the AV. However, the yielding rate and direction differed significantly depending on the type of approach ($X^2(2) = 21.27$, $p < .001$). That is, 95 % of those approached head-on moved over – 30 % to the left, 65 % to the right – to let the AV pass, while the remaining 5 % did not change path. In contrast, 73 % of those approached from behind moved over – now 9 % to the left, 64 % to the right – while 27 % did not change path.

As Fig. 6 shows, the pattern of yielding by sociodemographic factors reflected that observed overall, i.e. the majority yielded and tended to move over to the right rather than the left. There was no significant association with road user ($X^2(4) = 2.50$, $p = .644$), gender ($X^2(2) = 4.36$, $p = .113$), or age ($X^2(4) = 0.62$, $p = .960$). But there was a significant association with group size ($X^2(4) = 21.64$, $p < .001$). That is, participants in the largest groups (3 +) were less likely to move over to the left, participants in pairs were less likely to move over to the right unlike lone participants who were more likely to do this, and participants in a group of any size were less likely to yield, unlike participants who were alone.

For some participants – those travelling northwards along the shared space – moving over to the left meant moving toward the hoarding. In contrast, for those travelling southwards along the shared space, moving over to the right meant moving toward the hoarding, while moving over to the left meant moving toward the more open recreation area. Thus, an adjustment was made for the direction of travel. Overall, only the yielding rate differed significantly now according to the type of approach ($X^2(2) = 19.76$, $p < .001$). That is, most participants clearly preferred to move toward the recreation area rather than the hoarding, regardless of whether they were approached head-on (82 % versus 14 %) or from behind (70 % versus 3 %).

This adjustment was also applied to the analysis involving the sociodemographic factors. Again, it was apparent that there was a side preference among those yielding (Fig. 7), regardless of road user ($X^2(4) = 5.48$, $p = .241$), gender ($X^2(2) = 2.86$, $p = .239$), or age ($X^2(4) = 2.54$, $p = .637$). Group size was still significantly associated with yielding ($X^2(4) = 18.88$, $p < .001$), but the overriding preference for moving toward the recreation area removed the effect of yielding direction; in other words, participants in any size of group were simply significantly less likely to yield than participants who were alone.

The baseline data were then examined to see if a preference to keep to the right side or keep close to the recreation area was apparent when the AVs were not present. This examination revealed that, overall, participants did not really seem to favour the right (25 %) over the left side (21 %), and there was a less prominent preference for keeping close to the recreation area (33 %) as opposed to the hoarding (13 %). Instead, most participants (54 %) kept in the middle or spread across the shared space when travelling through the section in question, free of motorised vehicles.

Nevertheless, there were variations within the baseline data when looking deeper (Fig. 8). While the use of space was not significantly associated with gender ($X^2(2) = 2.79$, $p = .248$), it was with road user ($X^2(4) = 15.98$, $p = .003$), i.e. pedestrians were less likely to keep to the left, joggers less likely to keep in the middle/spread across the space, and cyclists less likely to keep to the right. Use of space was also significantly associated with age ($X^2(4) = 10.24$, $p = .036$); younger adults were less likely to keep to the left and more likely to keep to the right. A further significant association was found with group size ($X^2(4) = 96.71$, $p < .001$). That is, lone participants were more likely to keep to the left, while those in groups were more likely to travel in the middle/spread across the space, and less likely to keep to the right, as the size of the group increased.

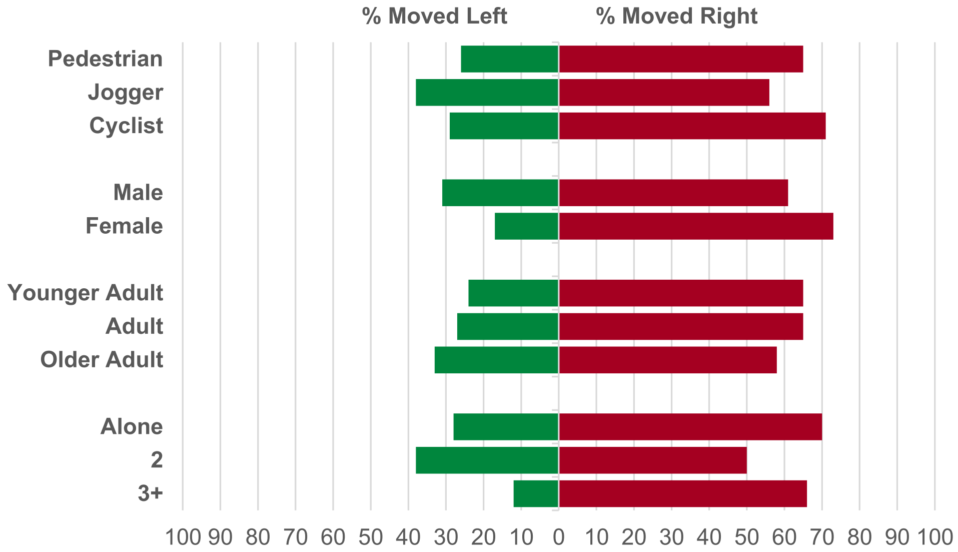


Fig. 6. Direction of yielding by road user, gender, age, and group size.

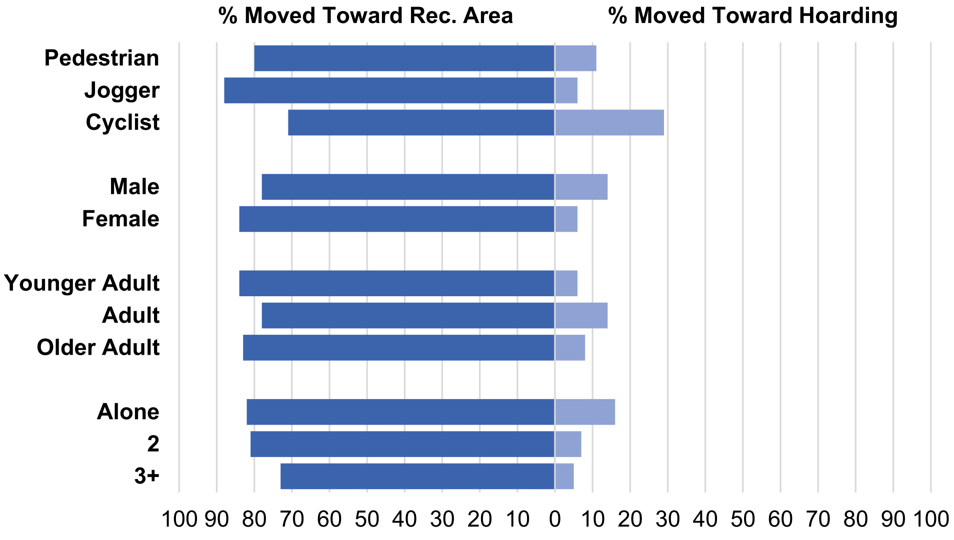


Fig. 7. Adjusted direction of yielding by road user, gender, age, and group size.

Fig. 8. Baseline use of shared space by road user, gender, age, and group size.

When adjusting for the direction of travel (Fig. 9), the baseline use of space remained unrelated to gender ($X^2(2) = 3.43$, $p = .180$). There was still a significant association between the use of space and road user ($X^2(4) = 15.79$, $p = .003$), but no group had a clear preference for keeping close to the recreation area; instead, pedestrians were least likely to travel close to the hoarding, while joggers were most likely to do so. The use of space was no longer significantly associated with age ($X^2(4) = 1.75$, $p = .781$) but it still was with group size ($X^2(4) = 97.31$, $p < .001$); i.e. those travelling alone were more likely than those in groups to keep close to the hoarding, while the likelihood of keeping close to the recreation area reduced with increasing group size.

Returning to the passing interaction data, participant behaviour was examined next for a change in speed. Most often (68 %), participants did not visibly change speed during passing interactions with the AVs. When a change was observed, it tended to be deceleration (30 %) rather than acceleration (2 %). This pattern was not significantly associated with whether participants yielded or not ($X^2(2) = 2.13$, $p = .344$), but was significantly associated with the type of approach ($X^2(2) = 12.44$, $p = .002$). That is, when the AV approached head-on, participants more often made no change in speed (74 %) and decelerated less frequently (25 %) than when it approached from behind (50 % and 44 %, respectively).

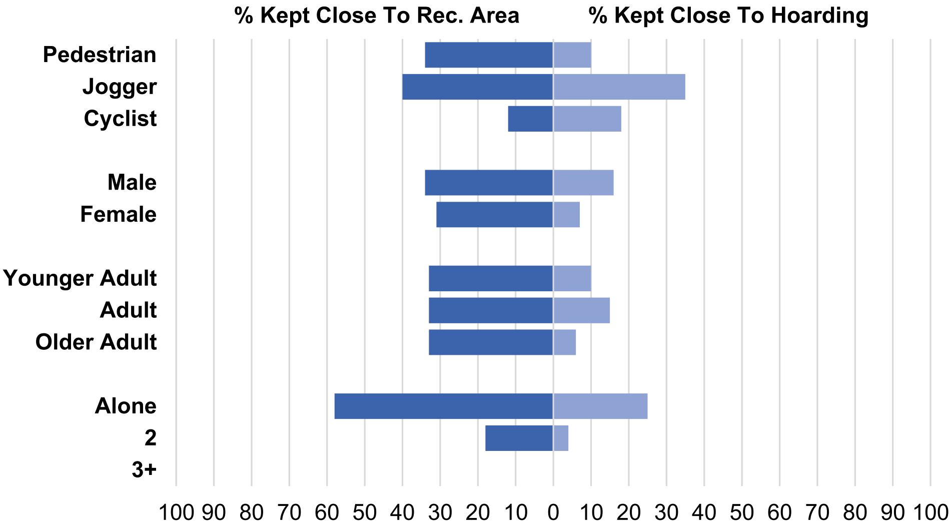


Fig. 9. Adjusted baseline use of shared space by road user, gender, age, and group size.

Table 5
Speed-related behaviours of participants who were approached head-on or from behind.

	No change	Accelerated	Decelerated
Road user:			
- Pedestrian	64 %	3 %	33 %
- Jogger	94 %	0 %	6 %
- Cyclist	93 %	0 %	7 %
Gender:			
- Male	70 %	2 %	28 %
- Female	65 %	3 %	32 %
Age:			
- Younger adult	55 %	4 %	41 %
- Adult	75 %	2 %	24 %
- Older adult	47 %	0 %	53 %
Group size:			
- Alone	89 %	2 %	9 %
− 2	48 %	2 %	50 %
− 3+	33 %	4 %	63 %

A change in speed was also significantly associated with road user ($X^2(4) = 10.62$, p =.031). As Table 5 shows, pedestrians were more likely to change speed, and more likely to decelerate, than were joggers and cyclists. Gender was not significantly associated with a change of speed ($X^2(2) = 0.51$, p =.775) but age ($X^2(4) = 11.72$, p =.020) and group size ($X^2(4) = 63.91$, p <.001) were. That is, adults were less likely to change their speed, and less likely to decelerate, than were younger and older adults. Plus, participants travelling alone were less likely to change their speed, and less likely to decelerate, than those travelling in groups.

As mentioned earlier in section 3.3, there was a third group of passing interactions. Here, the AV was approached and passed from behind by either a faster moving participant or a slower participant who had caught up with it when the AV, which had initially been travelling at a constant speed, now decelerated in response to some event up ahead. Most participants in this third group passed on the right (84 %) instead of the left (16 %); this was irrespective of road user ($X^2(2) = 0.58$, p =.748), gender ($X^2(1) = 0.23$, p =.633), age ($X^2(2) = 1.06$, p =.589), or group size ($X^2(2) = 1.12$, p =.572). When adjusting for the direction of travel, it was found that most passed on the side with the recreation area (89 %) rather than the hoarding (11 %); this was still irrespective of road user ($X^2(2) = 2.59$, p =.274), gender ($X^2(1) = 0.00$, p =.973), age ($X^2(2) = 1.22$, p =.544), or group size ($X^2(2) = 0.70$, p =.704).

Lastly, only two attempts at explicit communication were observed during passing interactions involving any type of approach. First, a lone younger adult male pedestrian was approached from behind by an AV, became aware of its presence, and deliberately remained in front. He forced the AV to give up its attempt to pass and instead continue slowly behind him. Eventually, he directed an aggressive verbal comment and hand gesture at the AV and let it through. Second, a lone adult male pedestrian approached an AV from behind and, when alongside, practically pressed his face against the door's window. This forced the AV to stop. The pedestrian then continued to stare and gesture into the pod in a rather delighted fashion. It could not be seen if the AV occupants shared his delight.

4. Discussion

4.1. Findings regarding the research questions

The survey participants had a realistic perception of pedestrians' vulnerability compared to other road users when around motorised HOVs and imagined that pedestrians would be no less vulnerable around AVs. Instead, they imagined that passengers would face a greater risk of becoming a road casualty when interacting with AVs as compared to motorised HOVs. So, at this pre-trial juncture, participants were not convinced that AVs would make travel safer for VRUs or other road users. Responses could reflect awareness of the "moral dilemma" discussed extensively in the media, using sensational headlines such as "Will your driverless car be willing to kill you to save the lives of others?" (Sample, 2016). Alternatively, it could reflect security concerns (e.g. whether AVs might be vulnerable to hacking; Hulse et al., 2018).

Conversely, some of the observed behaviours at the undesignated crossing point indicated that pedestrians might be bolder in real interactions with AVs, at least at first. Although participants displayed the same types of behaviours that are typical in crossing interactions with motorised HOVs, the frequency of those behaviours differed from the frequencies reported in the HOV literature (see section 1.1). For example, the majority who did not wait before crossing was much larger here. However, it should be noted that close to half of those not waiting refrained from making the riskiest choice, i.e. they entered the crossing point as the AV was approaching but then changed path and moved around the back of the vehicle. A further example is the high proportion of participants who accepted an objectively unsafe gap of 10 m or less (which, based on calculations, would leave just under 3 s available to clear the crossing). But again, it should be noted that the proportion was lower among those who crossed in front of the AV. Being distracted by phones and so forth played a part in this risky behaviour. However, since the observed frequency of inattention was not very high, that did not appear to be the only factor. Hesitation was also not very common and less frequent than previously observed around motorised HOVs. Thus, it appears that most of those not waiting stepped out confidently, in the knowledge that the AV was there. That confidence did not always remain though. A similar proportion of participants as compared to in HOV studies changed speed while crossing. For those who crossed in front, that was most often a quickening of pace. However, not all changes in crossing speed were acceleration. For those who chose to cross behind the AV, only deceleration was observed. So, despite any initial boldness, participants appeared to be paying attention to the AV while they crossed and sensibly adapting their behaviour as it got closer. Those who waited also paid attention to the AV, and perhaps felt some lingering uncertainty and/or curiosity about it, based on the hesitation and deceleration observed among this group when they did cross.

Boldness was not apparent in the behaviours observed during passing interactions. Participants usually yielded to the AV (with a still high but lower amount of around three-quarters doing so when approached from behind, most likely due to challenges in perceiving a quiet electric vehicle not in their visual field). This contrasts with previous findings where pedestrians dominated interactions with HOVs – motorised or non-motorised – in shared spaces (see section 1.2) and is more pronounced than the one exception (Moody & Melia, 2014) where pedestrians yielded to HOVs in just over half the interactions. A lack of familiarity may have evoked the greater incidence of yielding seen here. Prior to the AV trials, only pedestrians and cyclists used the shared space, so they would have been unfamiliar with how a motorised vehicle – let alone a driverless one – would behave around them. According to the "uncertainty reduction theory" (Berger & Calabrese, 1975), when there is uncertainty in an initial interaction with an entity, people's behaviour will be determined to an extent by norms or rules, which may be implicit or explicit. So, faced with an unfamiliar motorised vehicle, participants might have automatically reacted as VRUs would in a standard situation where a motorised vehicle approaches, i.e. by keeping or moving in to one side, allowing the vehicle to pass. Taking this further, participants might have been expected to show a preference for the left-hand side, reflecting UK road rules. However, the majority moved over to the right. Only those participants who were the ones overtaking showed typical rule-based behaviour by moving right. But, when the direction of travel was considered, it became apparent that participants – whether passing or being passed – in fact preferred the side that was less restrictive spatially, i.e. the recreation area rather than the side with the hoarding. The baseline data revealed that this preference only really emerged when interacting with the AVs; at other times, VRUs tended to stay in the middle of or spread across the shared space. All combined, these findings suggest that many participants were uncomfortable around AVs during passing interactions and thus keen to have some distance. This may also be why some VRUs were seen to move onto the grass during passing interactions with AVs in Löcken et al.'s (2019) study (see section 1.3).

Participants tended not to change speed during passing interactions. When they did, they usually decelerated. Stopping/slowing can reduce the likelihood or severity of an injurious collision. However, it can also allow time to gather more information – another means of reducing uncertainty (Berger & Calabrese, 1975). Thus, the fact that participants usually did not try to end the interaction quickly, especially when approached from behind, suggests that they may have been attempting to learn more about the AV during passing to help predict its behaviour in the present or future interactions.

4.2. Implications

Since participants displayed typical types of behaviours when interacting with AVs, then the pedestrian-HOV interaction literature would appear to provide a decent foundation for programming AV systems. Even so, caution should be applied regarding the frequency of behaviours reported in that literature. Additionally, as Camara et al. (2020) highlight, further work is required to translate knowledge about pedestrian behaviour in vehicle interactions into optimal algorithmic strategies for AVs. However, given that naturalistic studies of pedestrian-AV interactions are currently limited in ways including volume, scope, and/or sample sizes, it would be unfortunate if the HOV literature was not a resource that could be utilised meanwhile.

The survey results, the diminishing boldness observed in crossing interactions, the yielding observed in passing interactions, and the absence of RTCs during the AV trials, indicated that pedestrians were not perceived to be less vulnerable and did not take more risks around AVs. Consequently, Millard-Ball's (2018) prediction à la the risk compensation or homeostasis theories was not borne out. Of course, it could be argued that the unchanged perception of vulnerability among people in the borough was precisely why participants did not take more risks around the AVs. Moreover, AVs are still novel. Their safety record is yet to be established. As such, isolated but widely publicised incidents such as the 2018 RTC in Arizona, USA, where a pedestrian was fatally injured by an AV, can cause safety concerns in the short term (Tapiro et al., 2022). However, in the long term, pedestrians' perceptions and behaviours might change as they accumulate experiences with AVs. According to the constructivist "experiential learning theory" (Kolb et al., 2001), learning is a continuously cyclical process involving concrete experiences, reflection, conceptualisation, and active experimentation. So, initially, pedestrians might not feel safer around AVs and therefore might behave cautiously in early interactions. But, as their knowledge and understanding of AVs is refined with each personal experience and observations of others' experiences, they might choose to start acting differently around AVs to see if this results in a more preferential practical or emotional outcome for themselves. If that turns out to be the case, then a change in perceived vulnerability and, in turn, a negative change in behaviour could potentially manifest. There are already early indications that vicarious experiences related to AVs can positively influence cyclists' perceptions of vulnerability (Pyrialakou et al., 2020) and that, once provided with positive information about AVs, conventional car drivers may display more trust in AVs but also more risky behaviours during interactions with the vehicles (Soni et al., 2022). If taking such risks provides immediate pleasing outcomes, and if habits or even norms are allowed to form, through repetition and reinforcement, then a negative change in VRU behaviour could become more permanent (Kwasnicka et al., 2016).

Regarding mobility, the crossing interactions suggested that pedestrians and AVs could interact without either party being unduly hindered in their travel. In contrast, the passing interactions suggested that AV journeys would generally be unhindered, but that pedestrians and other VRUs would change path or, less often, decelerate. If only a single encounter, then such behaviours would have a negligible impact on the VRUs' journey. But if they were to encounter multiple AVs along the way, and react in this manner each time, it could become a noticeable inconvenience. Consequently, AV use might increase, with VRUs riding as passengers in order to gain priority. This would mean pedestrians would reach their destinations quicker than on foot (depending on the number of drop-off/pick-up stops), but they would lose the health benefits of walking (or running). For cyclists, they would also lose the health benefits of physical activity and could be frustrated by the difference in speed between pods and bicycles. Additionally, increased passenger numbers could mean less space on AVs for those less able to walk or cycle, while increased pod numbers could result in greater traffic congestion. Other unintended outcomes could include VRUs opting to entirely avoid areas where AVs operate, restricting their use of space.

If VRU uncertainty and discomfort in passing interactions can be reduced, this might result in less deceleration and more moving in toward the nearside rather than the most open side, thereby minimising delays to VRU journeys. Researchers have already speculated about VRU uncertainty and discomfort, albeit in relation to crossing interactions. The solution typically proposed is for the AV to have some means of explicitly communicating with VRUs (Rasouli & Tsotsos, 2020). However, this is problematic. First, any such communication would have to be perceptible from all angles and preferably by multiple modalities, since VRUs could approach or move around the vehicle on any side and some might have sensory impairments. Second, it would need to have broad applicability and be quickly perceived and comprehended, given there are multiple VRU types, some of whom travel faster than others. Third, the communicated message would need to be universally understood, which is unlikely in urban environments such as the study area used here, where people of various nationalities and cultures reside, work, and visit. Fourth, the observation results showed that participants rarely attempted to explicitly communicate with the AVs, a finding reflected in studies with HOVs (but at a lower frequency than in Uttley et al.'s 2020 shared space study). So, it is not clear if explicit communication is expected and necessary, or whether experience of the vehicles will provide sufficient information for VRUs to predict AV behaviour and be more comfortable around them.

A partial solution might be for local authorities to ensure that AV routes have adequate space available on both sides – not only objectively adequate but also subjectively adequate (i.e. no solid tall structures such as hoarding present). For even if a passenger AV is non-threatening in its general appearance and behaviour, it is still larger than any VRU, and so it may be intimidating for VRUs to pass between two larger objects. Research has shown that when in a group of any size rather than alone, individuals will perceive adversaries to be smaller in size and mass, i.e. less physically formidable (Fessler & Holbrook, 2013). This may explain why participants in groups in this study were less likely to yield during passing interactions. Group size was not associated with crossing choices, but participants were crossing to and from open spaces. Indeed, sociodemographic factors were rarely associated with behaviour. The greater perceived vulnerability reported by females in the survey was not supported by any gender differences in the observation data.

The only significant age difference was seen during passing interactions, where younger and older adults – as well as pedestrians and participants in groups – were more likely to change speed and decelerate than other categories. It is possible that adults, joggers, cyclists, and lone participants were in more of a hurry to reach their destination (i.e. travelling for commuting or competitive reasons rather than for leisure), and thus less willing to slow or stop. Therefore, when deciding upon AV routes, local authorities should consider VRUs' use of space not only in terms of movement but also purpose.

4.3. Limitations

It must be acknowledged that studying complex interactions via a naturalistic method, i.e. direct observation as opposed to via an experiment conducted under strictly controlled laboratory conditions, means that the behaviours displayed may be influenced by more variables than just the ones under investigation. While extra variables were taken into account to mitigate the problem of "unobserved heterogeneity" (Mannering et al., 2016; Saeed et al., 2019) – e.g. by recording the weather conditions during data collection and by adjusting the analysis of left/right movements due to the hoarding – it is possible that further influential variables were missed.

Direct observation may not afford the ability to capture some details (e.g. speed) as precisely as via video observation. Nonetheless, steps were taken wherever possible to ensure coding accuracy and reliability, and research has demonstrated the benefits of direct observation as a tool for studying pedestrian-vehicle interactions (Madigan et al., 2021). Although the researchers were vigilant for any eccentric or otherwise notable behaviour displayed by the AVs, resource restrictions meant they were not able to systematically record or deeply analyse AV behaviour. Thus, this paper only reports the VRU's behaviour in each interaction. The reported behaviours may not be generalisable beyond interactions at undesignated crossing points or in shared spaces where the presence of motorised vehicles is uncommon.

Additionally, the timing of the AV trials (during winter) was beyond the author's control. This timing meant a lower volume of VRU traffic in the shared space. When combined with the small number of AVs, this resulted in fewer opportunities for the occurrence of interactions, especially crossing interactions. Consequently, this limited the depth of statistical analysis that could be conducted in this study. Furthermore, it likely limits the reported behaviours to areas with low density traffic. Thus, it is recommended that, in future studies, AV trials take place in seasons where the temperature, weather, and amount of sunlight are likely to seem more favourable to walking, cycling, and running, thereby increasing VRU traffic.

In summer, there are also more large events scheduled at the major hospitality venue in the vicinity of the shared space. So, that season would have again increased pedestrian traffic and data collection opportunities, with the possibility of observing audience members arriving en masse during the early (and still naturally lit) evenings. On the other hand, this would have meant a sample containing a high proportion of new visitors to the area. Moreover, it would have raised the potential for pedestrians to have consumed alcohol before arrival. As such, the behaviour of participants during AV interactions could have been confounded by unfamiliarity with the area and/or intoxication.

5. Conclusions

This novel study extends and strengthens the existing literature on interactions with AVs. By supplementing a survey with direct observation in the field, this meant that real as well as hypothetical interactions between AVs and VRUs, mainly pedestrians, could be examined. Observed VRU behaviours included those displayed during crossing interactions but also those displayed during passing interactions. Although rarely studied, passing interactions are no less important given that AVs are likely to be initially deployed in spaces where they will variously intermingle with VRUs while AV system designers grapple with the complexities involved in driving on higher-density, higher-speed, multi-lane public highways with motorised HOVs.

Previous predictions that pedestrians would be perceived to be less vulnerable around AVs, and therefore would take greater risks during interactions with these vehicles, were not supported by the data. Thus, this study did not find any evidence for safety concerns, at least not in the short term. The results may therefore provide some encouragement to stakeholders such as authorities in charge of launching and managing the use of AVs in public spaces. Nonetheless, it is important that they note the limitations of this study, which include a smaller-than-desired sample size for the observation part of the study and no knowledge yet of whether the findings can be generalised beyond interactions at undesignated crossing points or in shared spaces. The stakeholders should also consider safety in the long term. Learning theory suggests that pedestrians' perceptions and behaviours could change over time, as personal and vicarious experiences of interacting with AVs accumulate. Consequently, the outcomes of interactions will need to be recorded and monitored as more AV trials are rolled out and these vehicles become a more frequently encountered road user. It is vital to note that outcomes will not only include those visible to observers, such as RTCs or near misses, but also those experienced internally, such as emotions. So, data will need to be periodically collected from various sources (e.g. AV sensors and cameras, surveys of VRUs).

A further note of caution must be offered here: the yielding of VRUs during passing interactions with the AV shuttle pods did raise concerns about VRUs' travel experiences. That is, there were signs of uncertainty and discomfort, which if not suitably resolved could conceivably have unintended consequences for mobility (including inconveniencing VRUs, lowering their health benefits and use of space, excluding target AV passengers, and increasing traffic congestion). Therefore, researchers and local authorities need to carefully consider ways to reduce VRU uncertainty and discomfort. This could involve more careful selection of the environments to be used for AV trials and deployment. It could also be worthwhile if, in future, researchers direct more efforts to modelling negotiations. If it is clear to VRUs that no party need always yield, and that passing interactions will instead involve give and take on a case-by-case basis, then their discomfort may lessen. However, negotiation needs each party to understand the other's possible behaviours and the consequences of those, which in turn will require communication. It remains to be seen whether VRUs can ascertain sufficient understanding simply from what is communicated through the AVs' behaviours (e.g., their speed) or whether a means of explicit communication will be needed – this is an area that is currently receiving much research attention but clearly has multiple issues to solve, which will take time. On a more positive note, it would appear that AV programmers can proceed cautiously with utilising the existing, larger body of pedestrian-HOV interaction literature while awaiting advancements in AV research.

CRediT authorship contribution statement

Lynn M. Hulse: Conceptualization, Methodology, Resources, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by Innovate UK, the Centre for Connected and Autonomous Vehicles, and industry as part of GATEway – Greenwich Automated Transport Environment (project no. 102200). GATEway comprised the following partners: Commonplace, Digital Greenwich, Fusion Processing, GOBOTiX, Heathrow Enterprises, Imperial College, Oxbotica, Royal Borough of Greenwich, Royal College of Art, RSA, Shell, Telefonica, TRL, University of Greenwich, and Westfield Sportscars. The views and opinions expressed in this article are those of the author and do not necessarily reflect the official position of FSEG-University of Greenwich, GATEway partners, or funders. The author would like to thank: Ed Galea (FSEG) regarding funding acquisition and original conceptualisation; Hui Xie (then FSEG) regarding assistance with investigation; plus Kristen Fernández Medina, Simon Tong, and Amy Woodward (then TRL) regarding project administration and resources.

Appendix

Category codes used with observer checklist, their definition, and additional notesNotes:

🟩 = Variable relevant to both crossing and passing interactions
🟨 = Variable relevant to only crossing interactions
🟦 = Variable relevant to only passing interactions

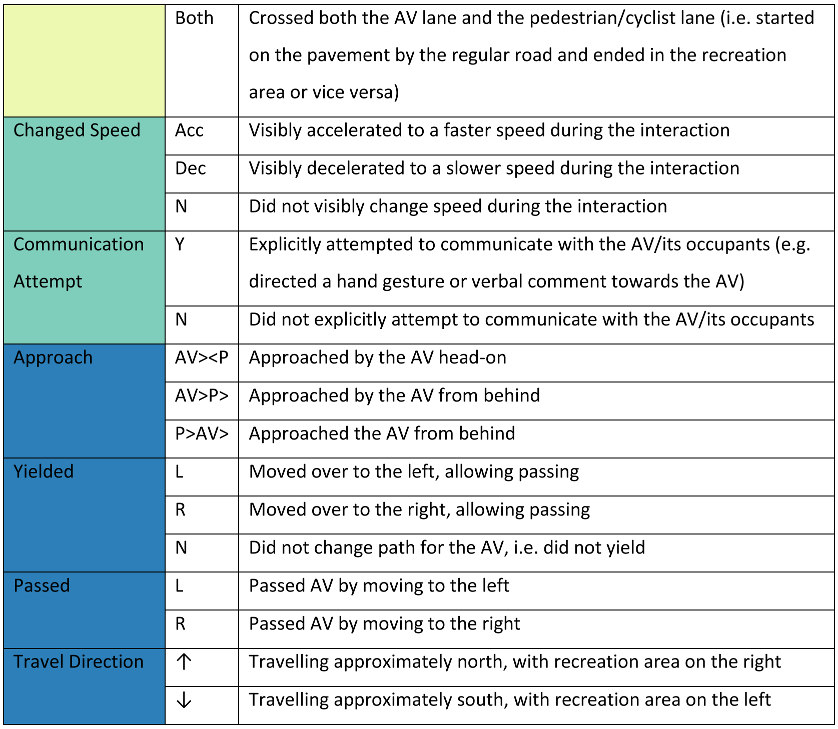
[1] Less than or equal to 10 m was considered to be an unsafe gap. This conclusion was based on the following calculations using the equation **speed = distance / time**:

- Minimum distance to cross (AV lane only) = 3.3 m
- Younger UK adult crossing speed = 1.32–1.57 m/s
- Older UK adult crossing speed = 1.11–1.16 m/s
- Time for average UK adult to cross minimum distance = (3.3 / 1.32 + 3.3 / 1.57 + 3.3 / 1.11 + 3.3 / 1.16) / 4 = 2.6 s
- AV speed = 4.17 m/s

Variable	Code	Definition
Road user	P	Pedestrian (travelling on foot)
	J	Jogger (travelling on foot but running, wearing sports gear)
	C	Cyclist (travelling on a bicycle)
Gender	M	Male
	F	Female
Age	YA	Younger adult (18-29 years old)
	A	Adult (30-64 years old)
	OA	Older adult (65+ years old)
Group size	Alone	Unaccompanied
	2	Together with one other person
	3+	Together with two or more other persons
Pet	Y	Walking a dog
	N	Not walking a dog
Physically Impaired	Y	Using a mobility aid (e.g. crutches, walking frame)
	N	Not using a mobility aid
Wheeling Item	Y	Pushing or pulling a wheeled item (e.g. pushchair, bicycle, suitcase)
	N	Not pushing or pulling a wheeled item
Crossing Choice	F	Crossed in front of approaching AV
	B	Crossed behind approaching AV
	W	Waited for approaching AV to pass first, then crossed
Accepted gap ≤ 10m	Y	Accepted gap of less than or equal to 10 m when started crossing [1, 2, 3]
	N	Rejected gap of less than or equal to 10 m, crossed with larger gap
Inattentive	Y	Did not pay attention to approaching AV (e.g. engrossed in phone or conversation with group members; did not look at AV)
	N	Visibly directed attention towards approaching AV
Hesitated	Y	Hesitated (i.e. started to step out then stopped or retreated)
	N	Did not hesitate (e.g. stepped out and proceeded confidently)
Lanes Crossed	AV	Crossed the AV lane only (i.e. started on the pavement by the regular road and ended in the pedestrian/cyclist lane or vice versa)

(*continued on next page*)

(*continued*)



	Both	Crossed both the AV lane and the pedestrian/cyclist lane (i.e. started on the pavement by the regular road and ended in the recreation area or vice versa)
Changed Speed	Acc	Visibly accelerated to a faster speed during the interaction
	Dec	Visibly decelerated to a slower speed during the interaction
	N	Did not visibly change speed during the interaction
Communication Attempt	Y	Explicitly attempted to communicate with the AV/its occupants (e.g. directed a hand gesture or verbal comment towards the AV)
	N	Did not explicitly attempt to communicate with the AV/its occupants
Approach	AV><P	Approached by the AV head-on
	AV>P>	Approached by the AV from behind
	P>AV>	Approached the AV from behind
Yielded	L	Moved over to the left, allowing passing
	R	Moved over to the right, allowing passing
	N	Did not change path for the AV, i.e. did not yield
Passed	L	Passed AV by moving to the left
	R	Passed AV by moving to the right
Travel Direction	↑	Travelling approximately north, with recreation area on the right
	↓	Travelling approximately south, with recreation area on the left

- Distance an approaching AV could cover in the time it would take an average UK adult to cross $= 4.17 \times 2.6 = 10.8$ m

[2] Researchers had previously measured the area and identified the location of features (e.g. street sign, sign post) against which the AV's location could be visually compared to determine if the AV was more than 10 m away from the crossing point at the time the pedestrian started crossing.

[3] A pedestrian was deemed to have started crossing when their leading foot left either:

- the edge of the pavement next to the regular road (crossed the AV lane only or both lanes);
- the edge of the paved recreation area (crossed both lanes); or
- the edge of the painted line separating the AV and the pedestrian/cyclist lanes (crossed the AV lane only).

References

Alsaleh, R., Hussein, M., & Sayed, T. (2020). Microscopic behavioural analysis of cyclist and pedestrian interactions in shared spaces. *Canadian Journal of Civil Engineering, 47*, 50–62. https://doi.org/10.1139/cjce-2018-0777

Bainbridge, W. A., Isola, P., & Oliva, A. (2013). The intrinsic memorability of face images. *Journal of Experimental Psychology: General, 142*, 1323–1334. https://doi.org/10.1037/a0033872

Berger, C. R., & Calabrese, R. J. (1975). Some explorations in initial interaction and beyond: Toward a developmental theory of interpersonal communication. *Human Communication Research, 1*, 99–112. https://doi.org/10.1111/j.1468-2958.1975.tb00258.x

Camara, F., Bellotto, N., Cosar, S., Weber, F., Nathanael, D., Althoff, M., … Fox, C. (2020). Pedestrian models for autonomous driving Part II: High-level models of human behavior. *IEEE Transactions on Intelligent Transportation Systems, 22*, 5453–5472. https://doi.org/10.1109/TITS.2020.3006767

Chaloupka, C., & Risser, R. (2020). Communication between road users and the influence of increased car automation. *Transactions on Transport Sciences, 10*, 5–17. https://doi.org/10.5507/tots.2019.014

Chandra, S., Rastogi, R., & Das, V. R. (2014). Descriptive and parametric analysis of pedestrian gap acceptance in mixed traffic conditions. *KSCE Journal of Civil Engineering, 18*, 284–293. https://doi.org/10.1007/s12205-014-0363-z

Combs, T. S., & Pardo, C. F. (2021). Shifting streets COVID-19 mobility data: Findings from a global dataset and a research agenda for transport planning and policy. *Transportation Research Interdisciplinary Perspectives, 9*, Article 100322. https://doi.org/10.1016/j.trip.2021.100322

Department for Transport. (2011). *Local Transport Note 1/11: Shared space*. Norwich: TSO.

Department for Transport. (2015). *The pathway to driverless cars: A code of practice for testing*. London: Crown.

Department for Transport. (2017). *Pathway to driverless cars: Consultation on proposals to support Advanced Driver Assistance Systems and Automated Vehicles – Government Response*. London: Crown.

Department for Transport. (2020). The inclusive transport strategy: Achieving equal access for disabled people. Retrieved from: Https://www.gov.uk/government/publications/inclusive-transport-strategy/the-inclusive-transport-strategy-achieving-equal-access-for-disabled-people. Accessed March 31, 2022.

Department for Transport. (2021a). RAS50002: Contributory factors allocated to vehicles or pedestrians in reported accidents, Great Britain, 2016–2020. Retrieved from: https://www.gov.uk/government/statistical-data-sets/reported-road-accidents-vehicles-and-casualties-tables-for-great-britain#contributory-factors-for-reported-road-accidents-ras50 Accessed March 31.

Department for Transport. (2021b). *Reported road casualties Great Britain: Road user risk, 2020 data*. London: Office for National Statistics.

Department for Transport. (2021c). Traffic Management Act 2004: Network management in response to COVID-19. Retrieved from: Https://www.gov.uk/government/publications/reallocating-road-space-in-response-to-covid-19-statutory-guidance-for-local-authorities/traffic-management-act-2004-network-management-in-response-to-covid-19. Accessed March 31, 2022.

Dey, D., & Terken, J. (2017). Pedestrian interaction with vehicles: roles of explicit and implicit communication. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '17)*, (pp. 109-113). https://doi.org/10.1145/3122986.3123009.

European Parliament. (2019). Self-driving cars in the EU: From science fiction to reality. Retrieved from: Https://www.europarl.europa.eu/news/en/headlines/economy/20190110STO23102/self-driving-cars-in-the-eu-from-science-fiction-to-reality. Accessed March 31, 2022.

Farooq, B., Cherchi, E., & Sobhani, A. (2018). Virtual immersive reality for stated preference travel behavior experiments: A case study of autonomous vehicles on urban roads. *Transportation Research Record, 2672*, 35–45. https://doi.org/10.1177/0361198118776810

Fessler, D. M. T., & Holbrook, C. (2013). Friends shrink foes: The presence of comrades decreases the envisioned physical formidability of an opponent. *Psychological Science, 24*, 797–802. https://doi.org/10.1177/0956797612461508

Gupta, S., Vasardani, M., Lohani, B., & Winter, S. (2019). Pedestrian's risk-based negotiation model for self-driving vehicles to get the right of way. *Accident Analysis & Prevention, 124*, 163–173. https://doi.org/10.1016/j.aap.2019.01.003

Gupta, S., Vasardani, M., & Winter, S. (2018). Negotiation between vehicles and pedestrians for the right of way at intersections. *IEEE Transactions on Intelligent Transportation Systems, 20*, 1–12. https://doi.org/10.1109/TITS.2018.2836957

Habibovic, A., & Davidsson, J. (2012). Causation mechanisms in car-to-vulnerable road user crashes: Implications for active safety systems. *Accident Analysis & Prevention, 49*, 493–500. https://doi.org/10.1016/j.aap.2012.03.022

Hatfield, J., & Prabhakharan, P. (2016). An investigation of behaviour and attitudes relevant to the user safety of pedestrian/cyclist shared paths. *Transportation Research Part F: Traffic Psychology and Behaviour, 40*, 35–47. https://doi.org/10.1016/j.trf.2016.04.005

Hulse, L. M., Xie, H., & Galea, E. R. (2018). Perceptions of autonomous vehicles: Relationships with road users, risk, gender and age. *Safety Science, 102*, 1–13. https://doi.org/10.1016/j.ssci.2017.10.001

Ishaque, M. M., & Noland, R. B. (2008). Behavioural issues in pedestrian speed choice and street crossing behaviour: A review. *Transport Reviews, 28*(1), 61–85. https://doi.org/10.1080/01441640701365239

Kaparias, I., Hirani, J., Bell, M. G. H., & Mount, B. (2016). Pedestrian gap acceptance behavior in street designs with elements of shared space. *Transportation Research Record, 2586*, 17–27. https://doi.org/10.3141/2586-03

Karndacharuk, A., Wilson, D. J., & Dunn, R. (2014a). A review of the evolution of shared (street) space concepts in urban environments. *Transport Reviews, 34*, 190–220. https://doi.org/10.1080/01441647.2014.893038

Karndacharuk, A. A., Wilson, D. J., & Dunn, R. C. M. (2014b). Safety performance study of shared pedestrian and vehicle space in New Zealand. *Transportation Research Record, 2464*, 1–10. https://doi.org/10.3141/2464-01

Kolb, D. A., Boyatzis, R. E., & Mainemelis, C. (2001). Experiential learning theory: Previous research and new directions. In R. J. Sternberg, & L. F. Zhang (Eds.), *Perspectives on Cognitive, Learning, and Thinking Styles* (pp. 228–247). Mahwah, NJ: Erlbaum.

Kwasnicka, D., Dombrowski, S. U., White, M., & Sniehotta, F. (2016). Theoretical explanations for maintenance of behaviour change: A systematic review of behaviour theories. *Health Psychology Review, 10*, 277–296. https://doi.org/10.1080/17437199.2016.1151372

Lagström, T., & Malmsten Lundgren, V. (2016). *AVIP – autonomous vehicles' interaction with pedestrians – an investigation of pedestrian-driver communication and development of a vehicle external interface* [Master's thesis, Chalmers University of Technology]. *Chalmers Open Digital Repository*. https://hdl.handle.net/20.500.12380/238401.

Lau, S. T., & Susilawati, S. (2021). Shared autonomous vehicles implementation for the first and last-mile services. *Transportation Research Interdisciplinary Perspectives, 11*, Article 100440. https://doi.org/10.1016/j.trip.2021.100440

Lee, Y. M., Madigan, R., Giles, O., Garach-Morcillo, L., Markkula, G., Fox, C., … Merat, N. (2021). Road users rarely use explicit communication when interacting in today's traffic: Implications for automated vehicles. *Cognition, Technology & Work, 23*, 367–380. https://doi.org/10.1007/s10111-020-00635-y

Liang, X., Meng, X., & Zheng, L. (2021). Investigating conflict behaviours and characteristics in shared space for pedestrians, conventional bicycles and e-bikes. *Accident Analysis & Prevention, 158*, Article 106167. https://doi.org/10.1016/j.aap.2021.106167

Löcken, A., Wintersberger, P., Frison, A.-K., & Riener, A. (2019). Investigating user requirements for communication between automated vehicles and vulnerable road users. In *In Proceedings of the 2019 IEEE Intelligent Vehicles Symposium (IV)* (pp. 879–884). https://doi.org/10.1109/IVS.2019.8814027

Madigan, R., Nordhoff, S., Fox, C., Ezzati Amini, R., Louw, T., Wilbrink, M., … Merat, N. (2019). Understanding interactions between Automated Road Transport Systems and other road users: A video analysis. *Transportation Research Part F: Traffic Psychology and Behaviour, 66*, 196–213. https://doi.org/10.1016/j.trf.2019.09.006

Madigan, R., Lee, Y. M., & Merat, N. (2021). Validating a methodology for understanding pedestrian-vehicle interactions: A comparison of video and field observations. *Transportation Research Part F: Traffic Psychology and Behaviour, 81*, 101–114. https://doi.org/10.1016/j.trf.2021.05.006

Mannering, F. L., Shankar, V., & Bhat, C. R. (2016). Unobserved heterogeneity and the statistical analysis of highway accident data. *Analytic Methods in Accident Research, 11*, 1–16. https://doi.org/10.1016/j.amar.2016.04.001

Markkula, G., Madigan, R., Nathanael, D., Portouli, E., Lee, Y. M., Dietrich, A., … Merat, N. (2020). Defining interactions: A conceptual framework for understanding interactive behaviour in human and automated road traffic. *Theoretical Issues in Ergonomics Science, 21*, 728–752. https://doi.org/10.1080/1463922X.2020.1736686

Millard-Ball, A. (2018). Pedestrians, autonomous vehicles, and cities. *Journal of Planning Education and Research, 38*, 6–12. https://doi.org/10.1177/0739456X16675674

Moody, S., & Melia, S. (2014). Shared space: research, policy and problems. *Proceedings of the ICE – Transport, 167*, 384–392. https://doi.org/10.1680/tran.12.00047

NHTSA. (2021). Automated vehicles for safety. Retrieved from: https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety. Accessed March 31, 2022.

Nuñez Velasco, J. P., Haneen, F., van Arem, B., & Hagenzeiker, M. P. (2019). Studying pedestrians' crossing behavior when interacting with automated vehicles using virtual reality. *Transportation Research Part F: Traffic Psychology and Behaviour, 66*, 1–14. https://doi.org/10.1016/j.trf.2019.08.015

Office for National Statistics (2013). DC2101EW: Ethnic group by sex by age. Retrieved from: https://www.nomisweb.co.uk/census/2011/dc2101ew. Accessed March 31, 2022.

O'Neill, B., & Williams, A. (1998). Risk homeostasis hypothesis: A rebuttal. *Injury Prevention, 4*, 92–93. https://doi.org/10.1136/ip.4.2.92

Oxley, J. A., Ihsen, E., Fildes, B. N., Charlton, J. L., & Day, R. H. (2005). Crossing roads safely: An experimental study of age differences in gap selection by pedestrians. *Accident Analysis & Prevention, 37*, 962–971. https://doi.org/10.1016/j.aap.2005.04.017

Peltzman, S. (1975). The effects of automobile safety regulation. *Journal of Political Economy, 83*(4), 677–726. https://www.jstor.org/stable/1830396.

Penmetsa, P., Kofi Adanu, E., Wood, D., Wang, T., & Jones, S. L. (2019). Perceptions and expectations of autonomous vehicles – a snapshot of vulnerable road user opinion. *Technological Forecasting and Social Change, 143*, 9–13. https://doi.org/10.1016/j.techfore.2019.02.010

Pless, B. (2016). *Risk compensation: revisited and rebutted. Safety, 2*, 16. https://doi.org/10.3390/safety2030016

Pyrialakou, V. D., Gkartzonikas, C., Gatlin, J. D., & Gkritza, K. (2020). Perceptions of safety on a shared road: Driving, cycling, or walking near an autonomous vehicle. *Journal of Safety Research, 72*, 249–258. https://doi.org/10.1016/j.jsr.2019.12.017

Raghuram Kadali, B., & Vedagiri, P. (2020). Evaluation of pedestrian crossing speed change patterns at unprotected mid-block crosswalks in India. *Journal of Traffic and Transportation Engineering, 7*(6), 832–842. https://doi.org/10.1016/j.jtte.2018.10.010

Rasouli, A., & Tsotsos, J. K. (2020). Autonomous vehicles that interact with pedestrians: A survey of theory and practice. *IEEE Transactions on Intelligent Transportation Systems, 21*, 900–918. https://doi.org/10.1109/TITS.2019.2901817

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

Ruscher, S. H., Kofler, A. C., Neumayer, V., & Renat, J. (2019). Moving ahead: Elaboration on cumulative effects on urban and suburban transport ecosystems by enhancing last mile mobility of older adults and persons with disabilities. In P. D. Bamidis, M. Ziefle, & L. Maciaszek (Eds.), *Information and Communication Technologies for Ageing Well and e-Health* (ICT4AWE 2018, pp. 180–195). Springer. https://doi.org/10.1007/978-3-030-15736-4_10.

Saeed, T. U., Alabi, B. N. T., & Labi, S. (2021). Preparing road infrastructure to accommodate connected and automated vehicles: System-level perspective. *Journal of Infrastructure Systems, 27*, 06020003. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000593

Saeed, T. U., Hall, T., Baroud, H., & Volovski, M. J. (2019). Analyzing road crash frequencies with uncorrelated and correlated random-parameters count models: An empirical assessment of multilane highways. *Analytic Methods in Accident Research, 23*, Article 100101. https://doi.org/10.1016/j.amar.2019.100101

Sample, I. (2016, June 23). Will your driverless car be willing to kill you to save the lives of others? *The Guardian*. Retrieved from: https://www.theguardian.com/science/2016/jun/23/will-your-driverless-car-be-willing-to-kill-you-to-save-the-lives-of-others. Accessed March 31, 2022.

Shaaban, K., Muley, D., & Mohammed, A. (2018). Analysis of illegal pedestrian crossing behavior on a major divided arterial road. *Transportation Research Part F: Traffic Psychology and Behaviour, 54*, 124–137. https://doi.org/10.1016/j.trf.2018.01.012

Shurbutt, J., & Do, A. (2013). Where pedestrians cross the roadway (Publication No. FHWA-HRT-13-099). *U.S. Department of Transportation Federal Highway Administration*. Retrieved from: https://www.fhwa.dot.gov/publications/research/safety/13099/index.cfm. Accessed March 31, 2022.

Soni, S., Reddy, N., Tsapi, A., van Arem, B., & Farah, H. (2022). Behavioral adaptations of human drivers interacting with automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour, 86*, 48–64. https://doi.org/10.1016/j.trf.2022.02.002

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

Tapiro, H., Wyman, A., Borowsky, A., Petzoldt, T., Wang, X., & Hurwitz, D. S. (2022). Automated vehicle failure: The first pedestrian fatality and public perception. *Transportation Research Record.*. https://doi.org/10.1177/03611981221083297

Trimpop, R. M. (1996). Risk homeostasis theory: Problems of the past and promises for the future. *Safety Science, 22*, 119–130. https://doi.org/10.1016/0925-7535(96)00010-0

TRL (2018). *GATEway: Greenwich Automated Transport Environment - this is just the beginning, positioning the UK at the forefront of automated mobility (D 1.3: GATEway Project Final Report).* Retrieved from: https://trl.co.uk/projects/gateway-project. Accessed November 7, 2022.

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

Virkler, M. R., & Balasubramanian, R. (1998). Flow characteristics on shared hiking/biking/jogging trails. *Transportation Research Record, 1636*, 43–46. https://doi.org/10.3141/1636-07

WHO. (2018). Global status report on road safety 2018. Retrieved from: https://www.who.int/publications/i/item/9789241565684. Accessed March 31, 2022.

Wilde, G. J. S. (1998). Risk homeostasis theory: An overview. *Injury Prevention, 4*, 89–91. https://doi.org/10.1136/ip.4.2.89

Yannis, G., Papadimitriou, E., & Theofilatos, A. (2013). Pedestrian gap acceptance for mid-block street crossing. *Transportation Planning and Technology, 36*(5), 450–462. https://doi.org/10.1080/03081060.2013.818274

Zhuang, X., & Wu, C. (2011). Pedestrians' crossing behaviors and safety at unmarked roadway in China. *Accident Analysis & Prevention, 43*, 1927–1936. https://doi.org/10.1016/j.aap.2011.05.005