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Research article

Interact or counteract? Behavioural observation of interactions between vulnerable road users and automated shuttles in Oslo, Norway

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Abstract: The current paper presents the results of behavioural observations in a field experiment with automated shuttles in Oslo, Norway. Video observations were conducted at five fixed locations along a challenging 1.2 km automated shuttle line with varying traffic conditions. Observed interactions between vulnerable road users and automated shuttles were coded using a predefined codebook, which allowed a structured quantitative analysis. The paper identified several potentially risky types of situations in which the automated shuttles did not always behave according to the traffic rules. Generally, the automated shuttles failed to give way to pedestrians at pedestrian crossings in 26%–50% of the interactions. Right-turning shuttles failed to yield to cyclists going straight in 38% of the interactions at observation Site 1 (the only location where the automated shuttle takes a right turn). In majority of same direction interactions between cyclists and automated shuttles, the interactions resulted in the cyclist overtaking the automated shuttle, usually on the left-hand side. Generally, the paper found little evidence of road users trying to bully or otherwise take advantage of the defensive driving style of the automated shuttles and identified only a limited number of interactions in which a vulnerable road user behaved ignorant or aggressive towards the automated shuttles. In addition, the paper found very little indication of temporal effects that suggest changes in the interaction patterns over time.

Keywords: automated shuttles, autonomous vehicles, driverless shuttles, road user interactions, vulnerable road users

1 Introduction

Recent innovations in sensor technology, computing power and Artificial Intelligence are leading to rapid advances in the performance of autonomous, or 'self-driving', vehicles.

Autonomous vehicles have the long term potential to fundamentally alter transportation systems by reducing the number of severe crashes and by providing improved mobility to those who are not capable of driving a motor vehicle (Kyriakidis *et al.* 2019). Complementary trends towards ride hauling and 'mobility as a service' may lead to a shift from private car ownership to on-demand services. These changes can in turn have major impacts on parking needs, land use patterns and trucking and other transportation activities (Fagnant & Kockelman 2015).

A promising niche within the field of autonomous driving is autonomous shuttles (Ainsalu *et al.* 2018). The absence of a human driver could reduce the operational costs of public transport services. Autonomous shuttles could therefore allow serving lower-volume connections that are not economically viable today. New opportunities include first- and last-mile public transport solutions (for instance feeder lines to main public transport nodes) and connections within campuses, business parks, etc. (Hagenzieker *et al.* 2021; Zubin *et al.* 2021).

However, before all road vehicles are fully automated, there will be a long transition period where fully autonomous vehicles, partly autonomous vehicles and manually driven vehicles will share the roads (Markkula *et al.* 2020). In addition, interactions with bicyclists, pedestrians and other types of vulnerable road users (VRUs) will likely continue to exist. For the introduction of autonomous vehicles into this traffic mix to be successful, safe and efficient, interactions with other road users are therefore critical (Domeyer *et al.* 2020). The decision making and behaviour of humans in interaction with autonomous vehicles has so far received little attention in the research community (Heikoop *et al.* 2020), despite being long called for by many experts in the field (Kyriakidis *et al.* 2019; Rasouli & Tsotsos 2018; Vissers *et al.* 2016).

While the performance of autonomous shuttles can (and should) to some extent be tested and optimized in laboratory conditions and using simulation, field experiments are of critical importance to investigate the performance of these shuttles in real traffic conditions, interacting with ordinary road users. The transport ecosystem is a complex environment that is governed by formal traffic rules, but that is also subject to informal traffic rules, negotiation between road users, human errors and violations, and infrastructural and conditional aspects that can affect road users' behaviour (De Ceunynck *et al.* 2013; Björklund & Åberg 2005; Reason *et al.* 1990). The interaction between road users is often a form of negotiation in which the parties involved have to coordinate their actions to accomplish their goal, e.g. crossing an intersection without getting involved in a crash (Rasouli & Tsotsos 2018). Interacting with other road users is, therefore, a challenging task for autonomous vehicles, especially in complex areas such as urban environments (Ackermann *et al.* 2019). Informal communication cues will normally not be perceived and acted upon by autonomous vehicles. It is impossible to foresee all situations that autonomous shuttles could encounter and to predefine the optimal decisions in these various challenging conditions. A thorough investigation of the performance of autonomous shuttles in real-world conditions is therefore needed.

Given the current state of the art, which usually involves vehicles that are not considered 'fully autonomous' (SAE level 4 or 5), we will use the term 'automated shuttles' for the remainder of the paper. In recent years, the number of field experiments with automated shuttles has increased exponentially, with 131 documented pilots and projects with automated shuttles by February 2021 (Hagenzieker *et al.* 2021). The results suggest a European lead on the number of experiments and manufacturers (Antonialli 2021). The majority of these pilots, however, were not investigated in-depth by independent researchers or authorities, and less than 10% led to published work in scientific journals (Hagenzieker *et al.* 2021). Earlier research on interactions with autonomous buses has largely focused on passengers, not on other road users.

The current paper presents the results of behavioural observations in a field experiment with automated shuttles in Oslo, Norway. Video observations were conducted at five fixed locations along a challenging 1.2 km automated shuttle line with varying traffic conditions. Observed interactions between vulnerable road users and automated shuttles were coded using a predefined codebook, which allowed a structured quantitative analysis.

2 Background

2.1 Game theory

When motor vehicles were first introduced in the early 1900s, poor communication and unsafe interactions between drivers and other road users generated resistance. Vehicle automation may lead to similar challenges when drivers are replaced by machines, potentially fundamentally changing or eliminating social behaviours that serve to smooth interactions between road users (Domeyer *et al.* 2020). Human road users typically communicate their intentions in traffic through lights (e.g. direction indicators), sounds (e.g. horn), eye contact and direction of gaze, bodily orientation, (change of) pace, gestures, etc. Some of these ways of communication can neither be generated nor easily interpreted by autonomous vehicles.

The studies on human response and interaction with self-driving vehicles that exist have until recently predominantly focused on trust and acceptance of such transport modes (Haque & Brakewood 2020; Kassens-Noor *et al.* 2020), often applying theories and models of trust in technology, such as the 'Unified theory of acceptance and use of technology' or the 'Technology Acceptance Model' (Nordhoff *et al.* 2018; Madigan *et al.* 2017; Vissers *et al.* 2016).

Game-theoretic approaches have gained more popularity in road transport research during recent years, particularly concerning interactions with autonomous vehicles (Heikoop *et al.* 2020; Thompson *et al.* 2020; Camara *et al.* 2018). Evolutionary game theory may be able to explain why certain patterns of interaction develop, are sustained or disappear (Bicchieri 2005). This has also been demonstrated in traffic situations, e.g. when road users meet at crossroads and must decide who will yield, i.e. give way to the other road user (Bjørnskau 2017). The mechanism behind the outcome predicted by game theory is that in interactions in road traffic, where road users are on crossing paths, it is assumed that road users generally prefer the opponent to yield and not to yield themselves. However, both actors also have a common interest to avoid a collision. Thus road traffic interactions are mixed-motive games where the actors both have common interests (no collision) and conflicting interests (best not to yield). Credible information about the other road user's intention is thus crucial. Game theory has been used to predict that over time self-driving vehicles will meet severe challenges in mixed traffic since other road users will eventually learn that self-driving vehicles are 'committed to' stop and give way in conflict situations, and hence might try to take advantage of that (Millard-Ball 2018). A temporal effect might be expected where road users more and more go first in an interaction with an self-driving vehicle, regardless of the yielding rules that apply (Bazilinskyy *et al.* 2021). This could result in a final outcome where automated shuttles are severely obstructed in traffic and not be able to operate properly (Markkula *et al.* 2020; Camara *et al.* 2018; Millard-Ball 2018). The problem has also been addressed in more general terms—that autonomous vehicles might be 'bullied' by other road users (Liu *et al.* 2020; Madigan *et al.* 2019).

When road user interactions are modelled as games, the preferences of the road users are highlighted as very important driving forces for the solutions reached. In general, we find it reasonable to assume that road users prefer to drive or ride without unnecessary stops. This is in a way the essence of travel—we want to get from A to B, and to avoid obstacles. Thus, we prefer green to red traffic lights, we prefer to speed up when the road is good, to avoid rush-hour traffic, if possible, etc.

Hence, at intersections, we believe the same motives apply, and that road users normally prefer not to stop, i.e. not to be the one giving way. However, to give way may not be very costly, and is of course preferred to having a collision. In our opinion, the preferences in traffic are in general explained according to what is known as a 'Leader game', i.e. to give way is preferred to a stalemate situation where the road users are unsure as to who shall drive and who shall yield. To yield and let the other drive first is in fact the second-best solution when interactions are modelled as a Leader game. This is not the case in the more famous 'game of Chicken' (out of pride, no one wants to yield) that has often been used to model road user interaction, e.g. between pedestrians and autonomous vehicles (Camara *et al.* 2018; Millard-Ball 2018).

Many studies of road user interactions do not highlight the motives, preferences or expectations of the road users involved, and focus mainly on the critical time gaps between road users on conflicting paths (Johnsson *et al.* 2018; Laureshyn *et al.* 2017a; Laureshyn *et al.* 2017b; Silvano *et al.* 2016; Räsänen & Summala 2000; Hydén 1987). Both Räsänen & Summala (2000) and Silvano *et al.* (2016) found that high speed of approaching cars contributed to the drivers not yielding to cyclists in roundabouts. These findings are consistent with Leader game preferences—when a bicyclist meets a car on a crossing path in a roundabout, and the car approaches in high speed, the bicyclist will be unsure to whether the driver will or can stop, and hence stop him/herself.

As argued by several authors (Bjørnskau 2017; Goffman 2010; Sugden 2005; Schelling 1960), in Leader (and similar) games commitment to a specific action, by for instance entering an intersection in high speed, can be seen as a strategic move in the game resulting in being the one not having to stop.

2.2 Studies about automated vehicle interactions

Human responses to automated vehicles are complex and not straightforward (Rovira *et al.* 2019). Little is known yet about how VRU behave around automated shuttles (Pelikan 2021). Therefore, there is a strong need for more research into the results of pilot projects and field experiments involving automated shuttles. The few available studies primarily focus on the interaction with pedestrians rather than cyclists (Ezzati Amini *et al.* 2021; Haque & Brakewood 2020; Heikoop *et al.* 2020; Rehrl & Zankl 2018). Nuñez Velasco *et al.* (2020) and Vlakveld *et al.* (2020) are exceptions, but these studies investigate cyclist interactions with automated passenger cars, not shuttles, and in virtual and animated environments rather than in real life. Other studies target the design and evaluation of eHMIs for communication between VRU and automated shuttles (Berge *et al.* 2022; Merat *et al.* 2018). Few real-life behavioural observation studies have been reported so far, with a few exceptions that are included in the next subsection (Beauchamp *et al.* 2022; Pelikan 2021; Pokorny *et al.* 2021; Madigan *et al.* 2019).

Thompson *et al.* (2020) used two experimental conditions to explore how autonomous vehicles, human-operated vehicles and cyclists might interact based on the introduction of flawlessly performing autonomous vehicles. The results showed that, although flawlessly performing autonomous vehicles might initially reduce total conflicts, human adjustment to the behaviour and risk presented by autonomous vehicles could create new sources of error that offset some of the autonomous vehicles' assumed safety benefits.

A significant body of research has investigated communication between autonomous vehicles and other road users. Results indicate that advanced communication interfaces, using sound or signs to indicate what to expect, can provide helpful cues for other road users when interacting with autonomous vehicles (Hagenzieker *et al.* 2021; Lee *et al.* 2020; Kyriakidis *et al.* 2019; Merat *et al.* 2018). A lot of research on interactions between autonomous vehicles and other road users took place in controlled environments (Thompson *et al.* 2020; Hagenzieker *et al.* 2019). In understanding how humans might adjust to new technologies in transport, not only controlled experiments, but real-world studies are necessary (Thompson *et al.* 2020).

2.3 Previous empirical observation studies about interactions between VRU and automated shuttles

Madigan *et al.* (2019) analysed 22 hours of video footage from two automated shuttle demonstrations in France and Greece. Results indicated that road infrastructure and road user factors had a major impact on the type of interactions that arose between automated shuttles and other road users. Where possible, pedestrians and cyclists appeared to leave as much space as possible between their trajectories and that of the automated shuttle. However, in situations where the infrastructure did not allow for the separation of traffic, risky behaviours were more likely to emerge. In particular, cyclists appeared to ride closely alongside the automated shuttles. The types of interaction varied considerably across socio-demographic groups.

Pelikan (2021) reports on initial findings from a demonstration project in Linköping, Sweden, in which self-driving shuttles by two different manufacturers were tested on the university campus and its surroundings. The paper highlights the complexity of interaction and coordination between self-driving shuttles and other road users. The author states that automated shuttles face difficulties when interacting with other road users, both on the regular road and in the mixed-traffic campus environment. This is particularly the case when the shuttles are overtaken by cars and cyclists, often resulting in an unnecessary sudden brake when a car or cyclist pulls in in front of the shuttle. Such situations continued to take place during the full duration of the experiment.

Pokorny *et al.* (2021) explore encounters between automated shuttles approaching a T-intersection and other road users in Norway. Videos of 83 encounters were analysed using video analysis software. Several types of risk and behavioural patterns were identified, such as road users misusing the defensive driving style of the automated shuttles or cyclists riding in the bicycle lane not being sure about the automated vehicle's intention. Frequent hard stops of the shuttles were identified in interactions with a right-turning automated shuttle and a cyclist in the adjacent bicycle lane going straight through. None of these hard stops were necessary to prevent a crash. This could be a safety risk to vehicle occupants and might increase the risk of rear end crashes as well.

Beauchamp *et al.* (2022) used surrogate measures of safety to analyse the interactions between road users and automated shuttles in Canada during two pilot projects in 2019. The results indicate that these automated shuttles behave generally more safely than regular motorized vehicles following similar paths: their speeds and accelerations are lower and their interactions are characterized by higher (i.e. safer) Time-to-Collision and Post-Encroachment Time values, and lower speed differences.

2.4 Related publications

The current study builds on an earlier study within the same research project (Bjørnskau *et al.* forthcoming). The paper investigated whether game-theoretic predictions of ordinary road users' interaction with automated shuttles are supported by real-life experience, making use of field interviews. According to the game-theoretic reasoning, it was expected that after some time, other road users would be aware of the defensive driving style and take advantage of this. Consequently, they would be increasingly assertive in their behaviour towards the shuttle, infringing upon the shuttle's right of way, and perhaps even showing 'bullying' behaviour. The interview results provided mixed evidence related to this hypothesis. In Oslo, cyclists self-reported a tendency towards more ignorant behaviour towards automated shuttles. However, no such tendency was present in the responses of pedestrians, nor among pedestrians or cyclists at another research site (the city of Kongsberg). In general, road users reported behaving considerately towards automated shuttles. Results show that pedestrians and bicyclists generally are positive to automated shuttles. The latter finding is in line with research by Rahman *et al.* (2021).

The current paper focuses on interactions between VRU and automated shuttles. Interactions between automated shuttles and other motorized vehicles were collected and analysed as well, but these are the focus of a separate paper (Johnsson *et al.* forthcoming).

3 Research questions and hypotheses

This study investigates how vulnerable road users interact with automated shuttles in different traffic environments, and whether the way these road users interact changes over time. Research questions include the following:

- What types of interactions between automated shuttles and VRU are frequently observed in different road environments?
- How does the yielding process between VRU and automated shuttles take place? And does it differ from that between VRU and other motor vehicles?
- Is ignorant/aggressive behaviour by VRU towards automated shuttles observed?
- Can any changes over time be observed?

4 Methodology

4.1 Vehicles and research site

This study analyses interactions between vulnerable road users and automated shuttles in real-world traffic conditions. Two Navya automated shuttles operated on a 1.2 km stretch of road in the city of Oslo, Norway (approx. 1 million inhabitants).

Some of the technical parameters and technological equipment of the automated shuttles are the following:

- Capacity: 8 passengers
- SAE level: 3
- Max speed: 18 km/h
- Dimensions: 4.75 m long, 2.11 m wide and 2.65 m tall
- LIDAR (4 front and 4 back sensors) for detecting objects, obstacles and landmarks within and established security radius around the shuttle
- Global Navigation Satellite System (GNSS) providing positioning, navigation and timing
- Odometer for measuring distance travelled
- An inertial measurement unit which measures acceleration, orientation, angular rates and other gravitational forces

Data from the various sensors are merged and interpreted by deep learning programs. This way, the autopilot of the vehicle interprets its surroundings, the road users within it, and their anticipated actions. In addition to these interpretations, a security radius around the shuttle is guarded, i.e. there must always be a minimal clear area around the vehicle. Should the autopilot detect a potential risk of a collision, either because of interpretations of the surroundings or the anticipated actions of other road users, or because of a breach of the security radius around the vehicle, the vehicle takes an evasive action to mitigate the hazard. In this project, the shuttle could only slow down or stop (controlled or emergency braking) as an evasive action; swerving or deviations from the programmed path were not allowed.

A safety steward was on board the shuttles to assist passengers and to take over control of the vehicle if necessary. The route ran along Akershusstranda (waterfront) in the city centre from bus stop Vippetangen to the town hall (Kontraskjæret). The route operated in both directions, resulting in a total route length of 2.4 km. The route consisted of different traffic environments. Video footage was collected at five points along the route. The shuttle route and observation points are shown in Figure 1. The 'beaks' indicate the camera direction. The camera views of the five observation sites are shown in Table 1.

Figure 1 Shuttle route with video recording sites indicated. *Source*: GoogleMaps image with own additions

4.2 Video observations

Data were collected from 20 May 2019, immediately when the automated shuttles started to operate, till 1 November 2019. Video footage was collected by temporary cameras (Miovision Scout) installed at a height of approximately 6 m to allow a good overview. Recordings have a low resolution (720 x 480 pixels) and a speed of 30 frames per second. The low resolution in combination with the height ensure that persons cannot be identified, nor licence plates be read. Information signs were installed near the cameras to inform passers-by about the recordings and where they can find additional information and contact details. This approach has been cleared with the Norwegian Data Protection Authority. Recordings took place with the permission of the Oslo Harbour Authority (Oslo Havn AS) and Ruter, the transport agency operating the autonomous shuttles.

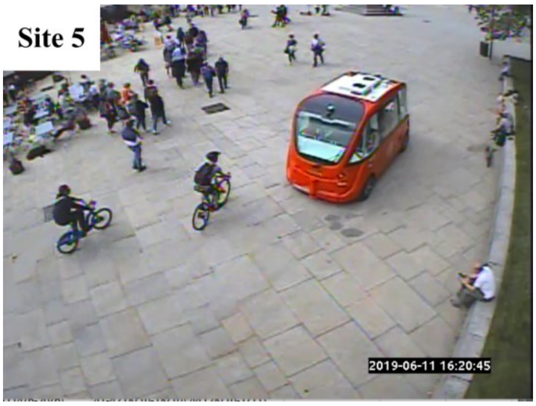
Table 1 Camera views and description of the observation sites

Site 1 is a right-hand priority intersection. The departure (Vippetangen) of the route is located in the side road on the left side of the picture. The automated shuttles turn left onto Akershusstranda. The left turn manoeuvre is not fully automated but needs a confirmation from the on-board safety steward and is therefore not analysed. The right-turn manoeuvre on the way back, however, is fully automated. Akershusstranda is an ordinary two-way street with cycle lanes and sidewalks. The intersection has crossings for pedestrians (who have priority when crossing) and for cyclists. The volume of motorised traffic is relatively low. Since Akershusstranda is one of the busiest cycle commuting routes to the city centre, the volume of cyclists is high.

Site 2 is another right-hand priority intersection, between Akershusstranda and Kongens gate. The shuttle drives straight through on Akershusstranda, but it needs to yield to vehicles from the side road when driving towards Site 3 (away from the camera) (priority to the right). On the way back, the shuttle has priority over vehicles merging in from the side road. The bicycle lanes stop at the intersection. After the intersection, cyclists merge with motor vehicles. The volume of motorized traffic that continues to follow Akershusstranda after this site is limited. The maximum speed of the automated shuttle is 18km/h here.

Site 3 is located at the cruise terminal. Although the infrastructure still looks like an environment for motorized traffic, the volumes of motorized traffic are low and the volumes of vulnerable road users (cyclists, e-scooterists and pedestrians) are high. A pedestrian crossing is present at the entrance of the terminal. The shuttles have a bus stop in both directions. In the direction of Site 4, the stop is near the end of the visible area of the camera (downstream); in the direction of Site 2, the stop is immediately after the pedestrian crossing. The maximum speed of the automated shuttle is 18 km/h here.

Table 1 *cont.*

At **Site 4**, the road environment is starting to look like a shared space environment, although the direction of movement is mostly linear for all road users (resulting in mostly same direction and face-to-face interactions with the automated shuttle). The volumes of motorized traffic are very low, given the fact that access to the square further down is blocked by extendable bollards. The volumes of VRUs are high. At this site, the maximum speed of the automated shuttle is 10 km/h.	
Site 5 is a true shared space environment, dominated by VRU (cyclists, pedestrians and e-scooterists). It is located at the waterfront close to the town hall and attracts a lot of tourists. No motorized traffic is allowed here except for the autonomous shuttles. The path of the shuttle is near the edge of the square. At this site, the maximum speed of the automated shuttle is 7 km/h.	

All interactions between automated shuttles and other road users were registered by trained coders using a predefined codebook, leading to a data set of several thousand interactions. The codebook consisted of several variables that describe the interaction, such as involved road users, type of interaction, driving direction and action of the involved road users, the location and time of the interaction, and (if applicable) whether the yielding process took place according to the traffic rules. The work was divided between two coders. Each interaction was coded by one coder. Regular consistency checks as well as discussions of edge cases and deviant situations between the two coders ensured the consistency and reliability of the dataset. In order to limit the margin for error, all variables were categorical with a limited number of choice options.

The possibility to apply traffic conflict (near-crash) indicators to assess the safety of automated shuttles was considered. The use of traffic conflict indicators from video data is a valid surrogate safety approach, with near-crash events being much more common than actual crashes, yet with similar characteristics, allowing to investigate the possible causes of crashes without having to observe actual crashes (Johnsson *et al.* 2018; De Ceunynck 2017; Laureshyn 2010; Hydén 1987). However, due to the low speed and conservative settings of the automated shuttles, the occurrence of situations with critical indicator values was very rare and therefore did not allow further investigation.

Due to numerous arrangements and construction work along the route, the route was sometimes shortened, and the autonomous shuttles were not continuously operating due to technical issues and maintenance. The dates of video footage collection differed between locations due to limitations based on available material and resources. While all interactions between VRUs and automated shuttles were registered, the results will zoom in on the types of interactions that took place frequently enough to draw meaningful conclusions.

5 Results

5.1 Interactions with pedestrians

5.1.1 Interactions between pedestrians crossing at the pedestrian crossing and automated shuttles (Site 1 and Site 3)

At Site 1, pedestrian crossings are present at the intersection, both on the main road (Akershusstranda) and the side road. The automated shuttle is, as all motor vehicles, required to yield to crossing pedestrians at pedestrian crossings.

Seventy-eight interactions with crossing pedestrians have been observed (see Figure 2). The majority of the interactions (N = 63) involved yielding to pedestrians that were crossing the side road while the automated shuttle was turning right. The other interactions (N = 15) were yielding situations at the pedestrian crossing of the main road. In 58 interactions the shuttle yielded correctly (74%), in 20 interactions the shuttle did not yield (26%). The results were very similar for both crossings and are therefore only shown combined. The yielding rate does not differ significantly between the three periods [χ^2 (2, 78) = 0.483; p = 0.785].

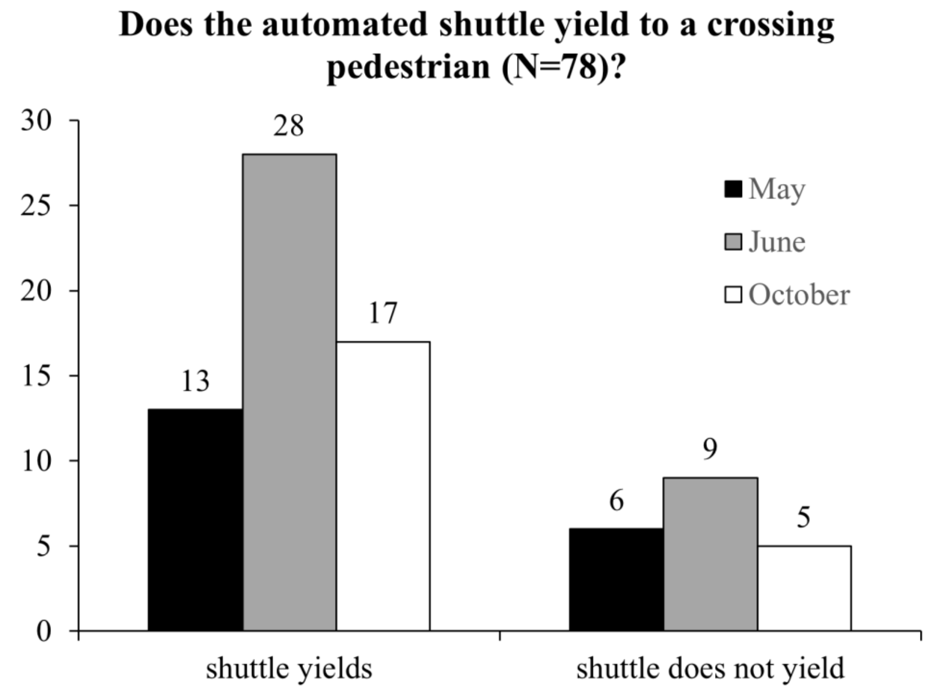


Figure 2 Interactions between automated shuttles and crossing pedestrians (Site 1)

At Site 3, a pedestrian crossing is present on the road section near the entrance of the cruise terminal. The number of interactions is relatively low (N = 32), and the results should therefore be interpreted with caution (see Figure 3). It is, nevertheless, noteworthy that the shuttle only yields to pedestrians in 50% of the situations at this crossing. The yielding rate is significantly worse at Site 3 compared to Site 1 [χ^2 (1, 110) = 6.115; p = 0.013]. The yielding rate at Site 3 does not differ significantly between the periods May and June (Fisher's Exact test: p = 0.433).

An additional analysis was done to compare the yielding rate of automated vehicles with regular motor vehicle drivers. For both sites, a random sample of 8h of video data was selected, and all interactions between regular motor vehicles and crossing pedestrians were analysed. For both sites, the conclusion is that the rate of yielding to crossing pedestrians did not statistically significantly differ between automated shuttles and regular motor vehicle drivers[1].

[1] Site 1: N = 81; driver yields = 56 (69%), driver does not yield = 25 (31%); χ^2 (1, 159) = 0.534; p = 0.465

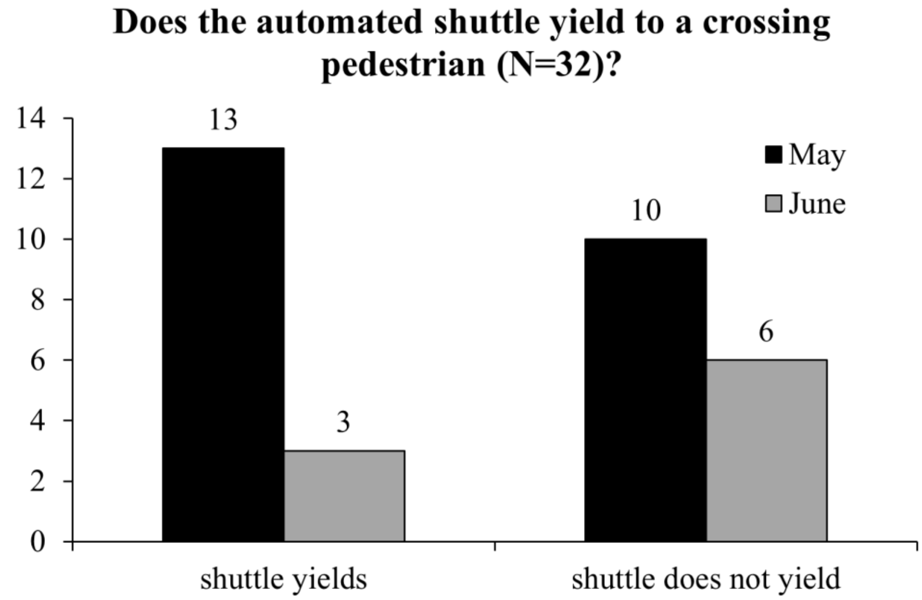


Figure 3 Interactions between autonomous shuttles and pedestrians crossing (Site 3)

5.1.2 Face-to-face interactions between pedestrians and automated shuttles

At the shared space Sites 4 and 5, approximately 200 face-to-face interactions between pedestrians and automated shuttles could be observed. In more than 90% of the interactions, the pedestrian moved out of the way of the shuttle. In other words, pedestrians behaved cooperatively to handle the interaction. However, in quite some cases, pedestrians reacted slowly. Consequently, the automated shuttle slowed down or stopped in around 40% of these interactions.

5.1.3 Same direction interactions between pedestrians and shuttles

At the shared space Sites 4 and 5, a total of 53 interactions were observed in which the shuttle approaches one or more pedestrians from behind. In 45 of these interactions (85%), the pedestrian moved out of the way to allow the shuttle to pass them, while in 8 (15%) of the interactions, the pedestrian took no action.

5.2 Interactions with cyclists

5.2.1 Interactions between right-turning shuttles and cyclists going straight through (Site 1)

When returning to the Vippetangen bus stop (Site 1), the automated shuttle turns right at the intersection. While doing so, the shuttles are required to yield to cyclists going straight. The results are shown in Figure 4. In total, 61 interactions between a right-turning shuttle and a cyclist going straight through were observed. Of these interactions, in 38 cases (62%) the automated shuttle yielded correctly to the cyclist. In 23 interactions (38%), the shuttle did not yield and cut in front of the straight going cyclist.

Looking at the different periods, the shuttles yielded better to cyclists in the first period (May) than in the second (June) and third period (October). The period effect is statistically significant at the 95% confidence level [χ^2 (2, 61) = 6.101; p = 0.047].

Based on a sample of 8 hours of video footage, an additional analysis was performed again to compare the rate of yielding towards cyclists going straight through of automated shuttles with regular motor vehicle drivers. The difference between automated shuttles and regular motor

Site 3: N = 82; driver yields = 41 (50%), driver does not yield = 41 (50%); χ^2 (1, 114) = 0.000; p = 1.000

vehicle drivers is not statistically significant, but the number of interactions with regular motor vehicle drivers was low (N = 9)[2].

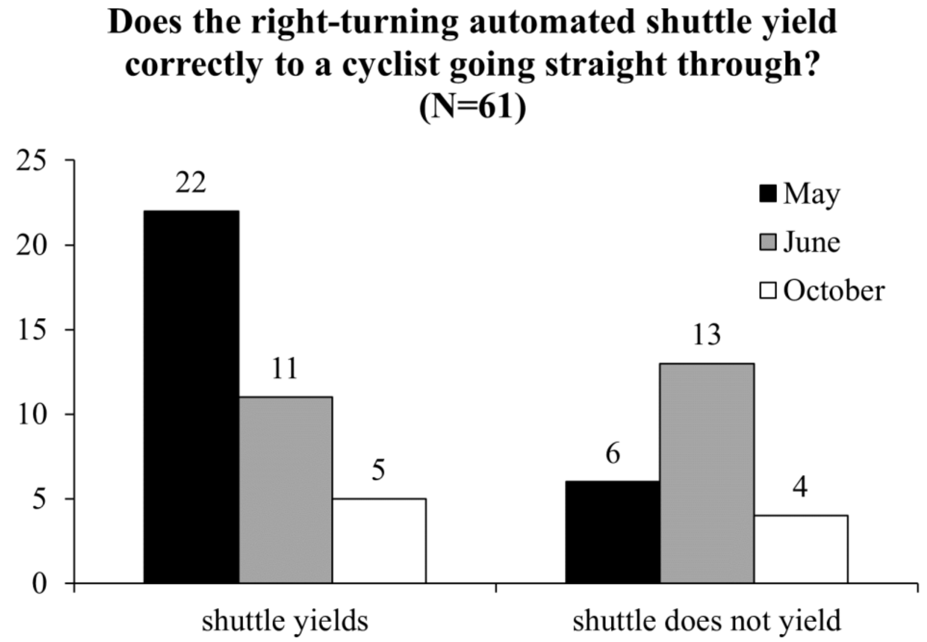


Figure 4 Interactions between right-turning autonomous shuttles and cyclists going straight through

5.2.2 *Cyclists riding in the same direction as automated shuttles*

Since the automated shuttles are driving relatively slowly (maximum speed of 18 km/h, but considerably slower at Sites 4 and 5), many cyclists were observed to ride faster than the automated shuttles. The vast majority of same direction interactions between cyclists and automated shuttles involve a cyclist catching up with and/or overtaking an automated shuttle. The number of interactions where an automated shuttle catches up with a cyclist is very low and will therefore not be analysed.

At Site 1 and at the southern part before the intersection at Site 2, cycle lanes are present. Situations involving a cyclist and an automated shuttle are not included here, since both road users are using separate infrastructure and are therefore not interacting. As a result, the analyses include same direction interactions between shuttles and bicycles at Site 2 (the northern part without cycle lanes) and Sites 3, 4 and 5. The results are shown in Figure 5. Note that for Site 3 (cruise terminal), an additional analysis is made of a similar type of interaction where the shuttle is blocking the cyclist's path by stopping (usually at the bus stops on the road that are visible within the camera view).

Very similar results are found at Sites 2, 3 and 4. At all sites, a clear majority of the cyclists overtake the automated shuttle. A low number of situations is observed where the cyclists only follow the shuttle but do not overtake it (21%, 5% and 6% of the interactions, respectively). In the vast majority of the interactions, the cyclists overtake the automated shuttle on the left side (64%–77% of the interactions), usually immediately (i.e. without riding behind the shuttle for a while first before overtaking). The share of overtaking manoeuvres on the right-hand side is limited (15%–30%). The findings for the interactions at Site 3 where the shuttle is blocking the cyclist's path are in line with (and even slightly more pronounced than) the regular same direction interactions.

[2] N = 9, driver yields = 7 (78%), driver does not yield = 2 (22%); χ^2 (1, 70) = 0.819; p = 0.366

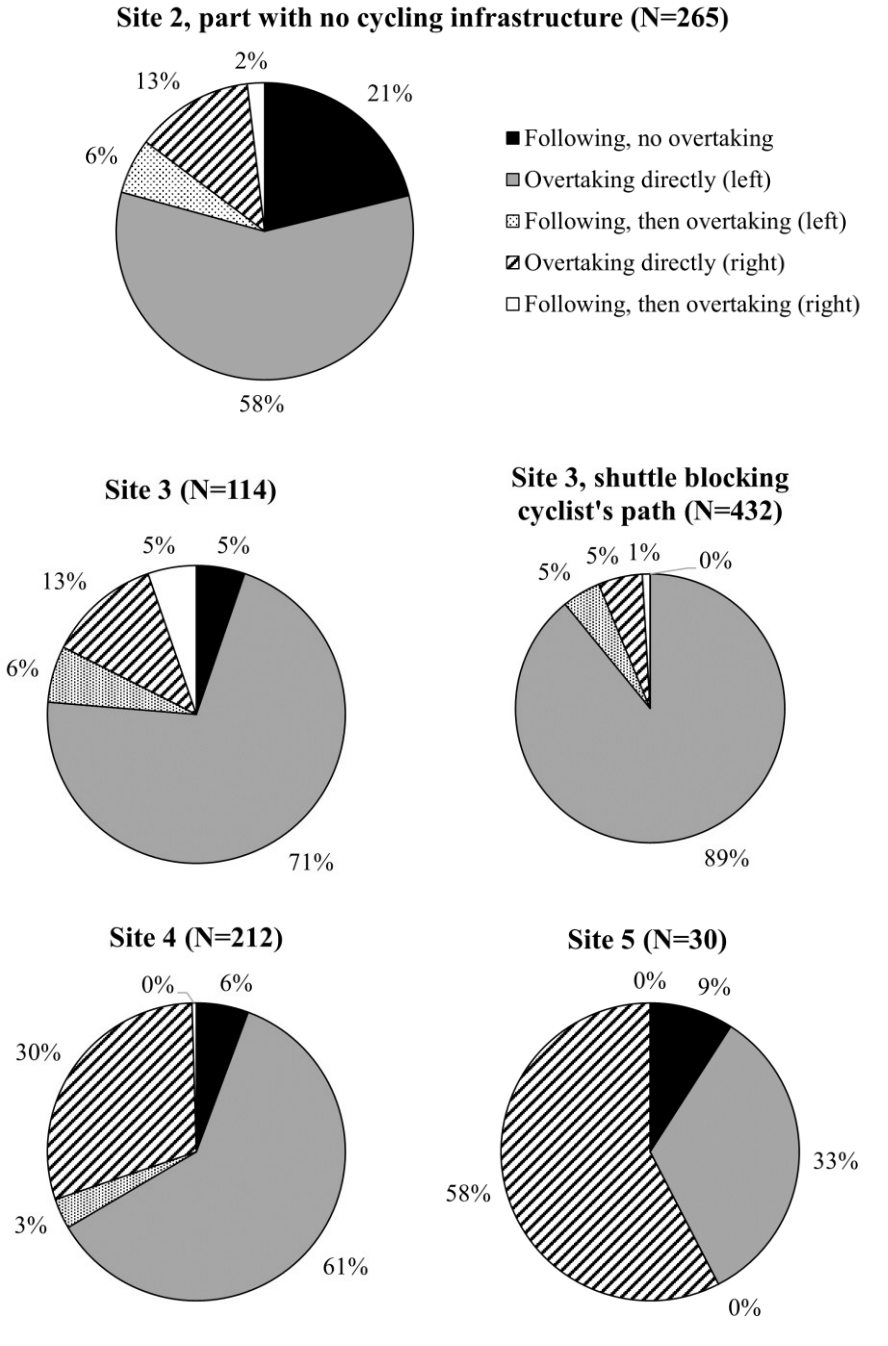


Figure 5 Same direction interactions between automated shuttles and cyclists

The findings at Site 5 show a slightly different picture, with only 33% of interactions leading to an overtaking manoeuvre on the left side of the shuttle, compared to 58% of interactions leading to an overtaking manoeuvre on the right side of the shuttle. This is a shared space area, and consequently, the interaction patterns are in general less structured than at other observation sites. It should be noted, however, that the number of observations at Site 5 is low (N = 30), and these results, therefore, need to be interpreted with caution.

For each site, a significance test is performed to see if any statistically significant seasonal effects can be found. The results are the following:

- Site 2, same direction interactions: $\chi^2\,(8, 265) = 17.347$; $p = 0.027$. The test shows that there are statistically significant differences between the different observation periods.

However, the variations do not show any systematic trend. No conclusions can be drawn.

- Site 3, same direction interactions: $\chi^2\,(2, 114) = 1.068$; $p = 0.586$. The test shows that there are no statistically significant differences between the different observation periods.
- Site 3, shuttle blocking cyclist’s path interactions: $\chi^2\,(1, 432) = 0.328$; $p = 0.567$. The test shows that there are no statistically significant differences between the different observation periods.
- Site 4, same direction interactions: $\chi^2\,(4, 212) = 7.268$; $p = 0.122$. The test shows that there are no statistically significant differences between the different observation periods.
- Site 5, same direction interactions: not tested due to low sample size.

5.3 Interactions with e-scooters

The number of interactions between e-scooters and automated shuttles was substantially lower than the number of interactions with pedestrians and cyclists. The following types of situations were frequent enough for quantitative analysis (see Figure 6). At Site 3, the number of interactions where an automated shuttle blocked the e-scooter’s path (usually by stopping at the bus stop) was sufficiently high to analyse (N = 52). At Site 4 and Site 5, same direction interactions between automated shuttles and e-scooters where the e-scooter was riding behind the automated shuttle could also be analysed (N = 30 and N = 29, respectively).

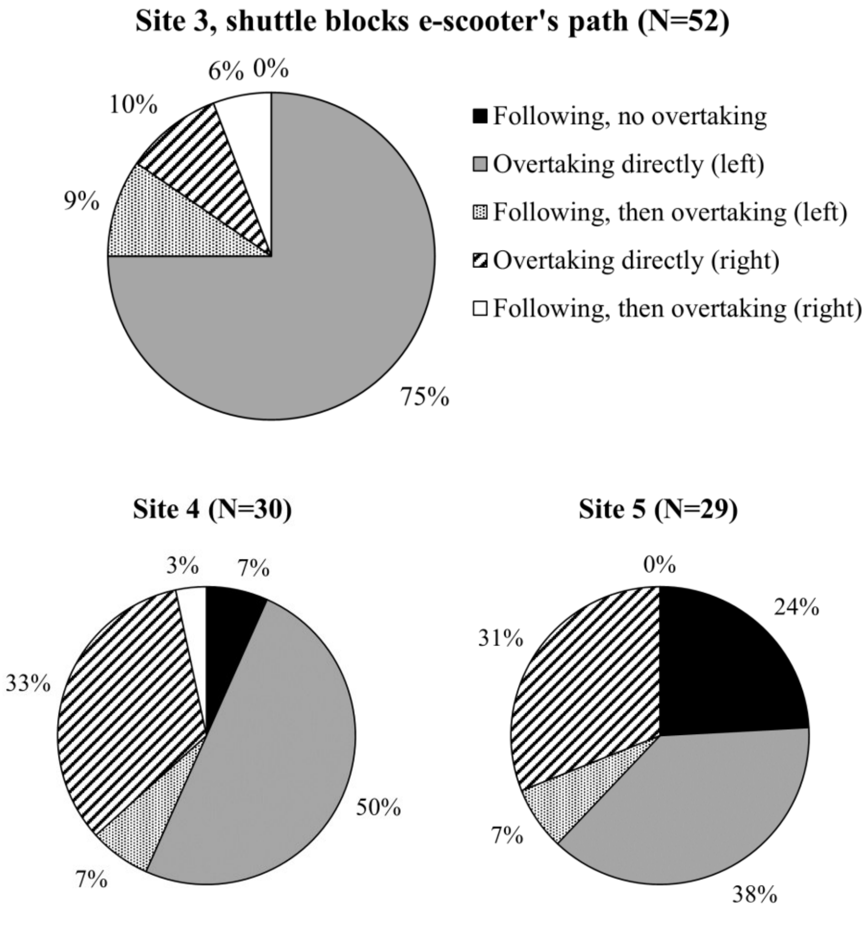


Figure 6 Same direction interactions between e-scooter riders and automated shuttles

The results at Site 3 show that an automated shuttle that is blocking an e-scooter's path is always overtaken. In the majority of cases, the overtaking takes place immediately (without following the shuttle first), and on the left of the vehicle. We see a somewhat different picture for same direction interactions at Sites 4 and 5, though overtaking on the left is still more common.

Next, we checked whether the overtaking behaviour of e-scooter riders in these interactions differs from the behaviour of cyclists in the same interactions. This was tested by use of chi-square tests and we tested the distributions of three types of behaviour: no overtaking, overtaking on the left, and overtaking on the right. The significance tests gave the following results:

- Shuttle blocking the path at Site 3 (cyclist vs. e-scooter): χ^2 (1, 484) = 5.773; p = 0.016. It can be observed that, at Site 3, e-scooter riders that are confronted with an automated shuttle blocking their path have a relatively higher probability of overtaking the shuttle on the right-hand side compared to cyclists. The blocking situations mostly occur because the automated shuttle stops at a bus stop at this site. This is potentially safety-relevant behaviour since shuttle passengers access and egress the shuttles on the right-hand side and they might therefore have an increased risk of getting involved in a crash with an e-scooter rider compared to a cyclist.
- Same direction interaction at Site 4 (cyclist vs. e-scooter): χ^2 (2, 242) = 0.635; p = 0.728
- Same direction interaction at Site 5 (cyclist vs. e-scooter): χ^2 (2, 62) = 5.101; p = 0.078

5.4 Ignorant and aggressive behaviour of VRUs towards the automated shuttles

The codebook included a checkbox to mark 'ignorant or aggressive behaviour' of the VRU towards the automated shuttles. These are remarkable forms of behaviour that could not be well delineated in advance, but that suggest that the defensive driving style and/or the novel nature of the automated shuttle could lead to abnormal behaviour of VRUs. This involves amongst others taking advantage of the defensive driving style, for instance by stepping/riding in front of a shuttle that is already very close and that possibly has the right of way, deliberately trying to provoke an emergency stop of the automated shuttle or other forms of bullying or abuse.

Over all observation sites and all periods combined, only 21 instances of ignorant or aggressive behaviour were registered. The highest number of instances is observed at Site 5, which is a shared space environment with a high number of interactions with VRU.

Some observed examples of ignorant and aggressive behaviour included pedestrians who deliberately took a step in front of the automated shuttle, cyclists who aggressively approach the shuttle head-on and swerve late, and an e-scooter rider who rode a circle around the bus. The operator of the shuttle reported that for some time one particular cyclist repeatedly 'bullied' the shuttle by intentionally riding closely past it almost every day, forcing the shuttle to stop. This anecdotal situation took place outside the observed periods and is therefore not shown in the data.

It can be concluded that ignorant and aggressive behaviour of VRU towards autonomous shuttles is quite uncommon. The low numbers do not allow us to make an inference on the temporal effect.

6 Discussion

6.1 Discussion of results

Generally, the automated shuttles fail to yield to pedestrians at pedestrian crossings quite often, i.e. the automated shuttles do not stop to let a pedestrian cross while they are required to do so.

At Site 1, they fail to yield in 26% of all interactions according to our annotation. At Site 3, the yielding is significantly worse and automated shuttles fail to yield to pedestrians 50% of the time. While it could not be confirmed whether this level of yielding is worse than for regular motor vehicle drivers, for automated shuttles we should expect that they violate traffic rules rarely if ever. Not yielding to pedestrians waiting at, or even already walking on, a pedestrian crossing is a clear violation of the traffic rules. This is an important issue to address for automated shuttle manufacturers.

In face-to-face interactions between pedestrians and automated shuttles in shared space environments (Sites 4 and 5), in more than 90% of the interactions, the pedestrian moved out of the shuttle's way. Similarly, in same direction interactions where the automated shuttle approaches one or more pedestrians from behind, the pedestrian(s) move out of the way in 85% of the interactions. This was to be expected since the automated shuttles are programmed to drive a fixed path and they can therefore not swerve in an interaction. It seemed like most pedestrians that did not move out of the way in face-to-face interactions, did not understand this limitation to the behaviour of the automated shuttle. In most same direction interactions, it seemed that the pedestrian(s) did not notice or hear the (electric) shuttle approaching.

Right-turning shuttles often failed to yield to cyclists going straight at observation Site 1. More specifically, in 38% of the interactions, the automated shuttle did not yield and cut in front of the straight going cyclist. In other words, automated shuttles seemed prone to miss cyclists in the 'classic' blind spot at the right-hand side behind the vehicle. This, too, is a violation of the traffic rules. Given the low driving speed of the automated shuttle, many of these situations involved either a faster cyclist 'undercutting' the automated shuttle or a cyclist riding at a similar speed and therefore 'hovering' in this blind spot. Automated shuttles' detection of cyclists in the blind spot when turning right should be improved. The analysis of this right-turn manoeuvre was one of the few that showed a statistically significant temporal effect. The results suggest that the shuttles yielded better to cyclists in the first period (May) than in the second (June) and third period (October). It is unclear why this is the case.

The recent paper by Pokorny *et al.* (2021) looked more closely into a sample of interactions between automated shuttles and cyclists in the bicycle lane going straight, using the same automated shuttles at the same site (Site 1, Vippetangen) one year after the recordings discussed in the current paper (i.e. in 2020 instead of in 2019). The results of the study suggest that the automated shuttle yielded correctly more often in 2020 than in 2019, which could be the result of improvements to the self-driving functionalities of the automated shuttle in general or because of a finetuning of parameters specifically for this location. However, the shuttle often yielded by conducting hard stops, which could result in an increased risk of injuries for passengers inside the shuttle as well as rear-end crashes. Indeed, earlier research has indicated that automated vehicles are more likely to be struck from behind than conventional motor vehicles (Goodall 2021). Pokorny *et al.* (2021) also report several situations where both the shuttle and the cyclist stopped to yield to one another, which could indicate a lack of trust from the perspective of the cyclists, possibly because of experiences with the shuttles in 2019. The study did not find improvements in the automated shuttles' yielding towards pedestrians at the pedestrian crossings, but the number of recorded interactions of this type was low.

In the vast majority of same direction interactions between cyclists and automated shuttles, the interaction results in the cyclist overtaking the automated shuttle. Usually, the cyclists overtake the shuttle on the left side (64%–77% of the interactions, depending on the observation site at Sites 2, 3 and 4). Only at Site 5, which is a shared space environment, the number of cyclists overtaking the automated shuttle on the right-hand side is higher than the number of cyclists overtaking the automated shuttle on the left-hand side.

The number of interactions between e-scooters and automated shuttles was substantially lower than for other types of VRU, so not all possible types of interactions could be studied in sufficient detail. At Site 3, in situations where an automated shuttle blocks the path of an e-scooter rider, the e-scooter rider is more likely to overtake the stopped shuttle on the right-hand side compared to a cyclist that is confronted with an automated shuttle blocking their path. At Sites 4 and 5, no statistically significant difference was found between e-scooters and cyclists in terms of overtaking behaviour.

In other words, the low speed of the automated shuttle triggers a high number of overtaking manoeuvres from cyclists and e-scooterists that could indirectly lead to secondary (potentially hazardous) interactions, for example with oncoming traffic. This finding is in line with Pelikan (2021), and also with Johnsson *et al.* (forthcoming), who found a similar result for interactions between automated shuttles and regular motor vehicles.

In summary, the current study identified several potentially risky types of situations in which the automated shuttles did not always behave according to the traffic rules. This suggests that the automated shuttles do not always behave as defensively as is generally assumed. While the paper by Pokorny *et al.* (2021) suggests some improvements over time, as can be expected from rapidly developing technology, many issues (most of which are reported in other empirical studies on automated shuttles as well) remain unsolved, and some new issues emerge as well.

Although the findings could not always confirm whether this issue is more substantial for automated shuttles than for similar interactions involving regular (human-driven) motor vehicles and although it is uncertain whether the identified issues apply to automated shuttles from all manufacturers, it suggests that work is needed to improve the behaviour of automated shuttles when interacting with VRU. It is not acceptable that automated shuttles violate the traffic rules at such a high frequency as was observed in this study. However, it may also suggest that it is to be recommended that in future pilot projects, road users are informed about the fact that caution is needed when interacting with automated shuttles since they could (for the time being) make judgment errors and incorrect decisions just like regular drivers. These findings are in line with recent work by Pelikan (2021), whose initial findings in an observational study on self-driving shuttles in traffic suggest that the shuttles currently do not comply with cyclists' expectations of social coordination in traffic.

It can be concluded that the low speed of the automated shuttles triggers a high number of overtaking manoeuvres from cyclists and e-scooterists that could lead to secondary conflicts and might therefore be a safety risk. This finding is in line with Johnsson *et al.* (forthcoming), who analysed interactions between automated shuttles and motor vehicle drivers. They also found that motor vehicles drivers very often overtake the automated shuttles because of their low speed. It could be stated that the slow speed of the automated shuttles introduces turbulence into the traffic situation, which might lead to unexpected manoeuvres from road users and therefore might lead to secondary conflicts.

From a safety point of view, it is logical to use conservative settings and start operations with lower driving speeds and with very defensive interaction behaviour (e.g. slowing down or stopping often, unnecessary hard stops, etc.). However, it is unclear whether automated shuttles will (or should) maintain such conservative settings. At some point, it may be considered to make the settings of automated shuttles less conservative to more closely match the speed profile of the traffic they are operating in, and possibly to make the automated shuttles more 'assertive' in their interactions, claiming their right-of-way and avoiding unnecessary stops and delays. This could lead to safety issues that are very different from the ones observed with todays' automated shuttles. For example, higher driving speeds could lead to a higher crash risk and a higher probability of injury (Lubbe *et al.* 2022; Kröyer *et al.* 2014). It should be noted that higher speeds of automated shuttles might also pose a safety risk to the occupants in non-crash events. In case of emergency stops at higher speeds (be it justified emergency stops or false detections), there is an increasing risk of injury for shuttle occupants due to for instance a fall, loss of balance or being propelled from their seat. The importance of non-crash injuries should not be ignored, given the fact that research into injury events of traditional bus and coach occupants showed that non-crash injuries are an important share of all injuries of bus and coach occupants, and sudden stops are one of the main contributors (Björnstig *et al.* 2005).

Generally, the paper found little evidence of road users trying to bully or take advantage of the defensive driving style of the automated shuttles and identified only a limited number of interactions in which the VRU behaved ignorant/aggressive towards the automated shuttles. In addition, the paper found very few indications of temporal effects. Important preconditions for these effects to emerge, in line with game theory, are that (*a*) the automated shuttle acts defensively, and (*b*) other road users learn this over time and therefore become more assertive. Based on the empirical findings of this study, we could argue that condition (*a*) is not fulfilled since the automated shuttles do not always behave defensively and that consequently condition (*b*) cannot be fulfilled either. This might explain why no evidence was found to support the hypothesis that road users will try to take advantage of the automated shuttles.

6.2 Strengths, limitations and further research

The main strength of the study is that it involves observed behaviour in real-world traffic conditions. This is a rather unique future in current research on automated vehicles since most research around human behaviour around automated shuttles makes use of stated preferences or takes place in highly controlled (laboratory) conditions.

The size of the data collection is both a strength and a limitation of this study. The data collection was extensive, with weeks of video footage that have been analysed, including hundreds of interactions between automated shuttles and VRU at five observation sites. However, the observed interactions were very diverse, and when zooming into specific types of interactions, the data sizes often became small, limiting the possibilities to infer conclusions from them. This is also the case when analysing the different observation periods to look for temporal effects. This paper found very few indications of such effects. Consequently, the occurrence of behavioural changes over time in line with game-theoretic theory could not be confirmed. This is, however, a topic deserving further research, using larger sample sizes and longer observation periods to allow for longer-term behavioural adaptations. Additionally, future research could focus more strongly on specific situations in which other road users can have a stronger gain from taking advantage of the way automated shuttles behave, such as locations where many VRU are in a hurry.

This paper made use of the observation of road user interactions. Some behavioural elements that were found could indicate potential safety hazards for VRU, such as the poor yielding behaviour of automated shuttles turning right towards cyclists going straight through and to pedestrians crossing at zebra crossings. Research suggests that even normal traffic events contain information that can be applied to make road safety assessments (Saunier & Sayed 2007; Svensson 1998). However, to better assess the true impact on road safety, metrics that are more closely linked to crashes should be used (Johnsson *et al.* 2018; De Ceunynck 2017; Laureshyn 2010). Further research based on surrogate measures of safety (near-crashes, traffic conflicts) is therefore recommended.

The use of an 'external perspective' in the form of site-based observations allows to collect some parameters of both the automated shuttles and the other involved road user in interactions. However, no vehicle data is used in this study, limiting for instance the possibilities to analyse detailed behavioural adaptations to traffic situations and also limiting the possibilities to infer the reason behind some of the observed behaviour. For example, while this paper has identified some interaction situations where the automated shuttles do not yield to VRU sufficiently well, based on our data we cannot infer why this is the case nor how this can be improved.

Furthermore, the technical specifications of the vehicle, the overall performance of the autopilot as well as the site/project-specific parameters are constantly under development. This complicates comparisons between different projects, but also comparisons at different points in time within a project. The fact that the study by Pokorny *et al.* (2021), who observed one of our research sites one year later, found an improvement in yielding to cyclists in the adjacent bicycle lane when turning right (but at the expense of a high number of hard stops) illustrates this limitation. Additionally, automated shuttles from different manufacturers use different hardware set-ups and parameters and therefore findings related to the behaviour of the automated shuttles of one manufacturer cannot necessarily be transferred to vehicles from other manufacturers. This shows in our view that more empirical studies like the one at hand are needed in order to come to more generalizable conclusions. Longer-term projects can also benefit from analyses that are regularly repeated.

This paper presents observations at one test route in Oslo, Norway. The effects are likely at least to some extent to be context-specific (i.e. affected by local factors related to the road infrastructure design and traffic culture). Further research about interactions between VRU and automated shuttles in real-world traffic conditions at other sites and in other countries is needed.

7 Conclusions

This paper identified several potentially risky types of situations in which the automated shuttles did not always behave according to the traffic rules. Generally, the automated shuttles fail to yield to pedestrians at pedestrian crossings quite often (26%–50% of the interactions). Right-turning shuttles failed to yield to cyclists going straight in 38% of the interactions at observation Site 1 (the only location where the automated shuttle takes a right turn). While it could not be confirmed whether these levels of yielding are worse than for regular motor vehicle drivers, for automated shuttles we should expect that they violate traffic rules rarely if ever. Therefore, these levels of yielding violations are not acceptable.

In the vast majority of same direction interactions between cyclists and automated shuttles, the interaction results in the cyclist overtaking the automated shuttle, usually on the left-hand side. These overtaking manoeuvres often lead to unnecessary braking or stopping of the automated shuttle.

Generally, the paper found little evidence of road users trying to bully or take advantage of the defensive driving style of the automated shuttles and identified only a limited number of interactions in which a vulnerable road user behaved ignorant/aggressive towards the shuttles. The paper also found very few indications of temporal effects that suggest changes in the interaction behaviour over time.

CRediT contribution statement

Tim De Ceunynck: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Writing—original draft. **Brecht Pelssers:** Data curation, Investigation, Writing—review & editing. **Torkel Bjørnskau:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing—review & editing. **Ole Aasvik:** Resources, Writing—review & editing. **Aslak Fyhri:** Resources, Writing—review & editing. **Aliaksei Laureshyn:** Funding acquisition, Investigation, Methodology, Software, Supervision, Writing—review & editing. **Carl Johnsson:** Investigation, Methodology, Software, Writing—review & editing. **Marjan Hagenzieker:** Funding acquisition, Supervision, Writing—review & editing. **Heike Martensen:** Supervision, Writing—review & editing.

Declaration of competing interests

The authors report no competing interests.

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References

Ackermann, C., M. Beggiato, L.-F. Bluhm, *et al.* (2019), 'Deceleration parameters and their applicability as informal communication signal between pedestrians and automated vehicles', *Transportation Research Part F: Traffic Psychology and Behaviour*, 62, 757-768, https://doi.org/10.1016/j.trf.2019.03.006.

Ainsalu, J., V. Arffman, M. Bellone, *et al.* (2018), 'State of the Art of Automated Buses', *Sustainability*, 10 (9), 3118, https://dx.doi.org/10.3390/su10093118.

Antonialli, F. (2021), 'Autonomous shuttles for collective transport: a worldwide benchmark', *International Journal of Automotive Technology and Management*, 21 (1/2), 5, https://doi.org/10.1504/ijatm.2021.113349.

Bazilinskyy, P., T. Sakuma, J. de Winter (2021), 'What driving style makes pedestrians think a passing vehicle is driving automatically?', *Applied Ergonomics*, 95, 103428, https://doi.org/10.1016/j.apergo.2021.103428.

Beauchamp, É., N. Saunier, M.-S. Cloutier (2022), 'Study of automated shuttle interactions in city traffic using surrogate measures of safety', *Transportation Research Part C: Emerging Technologies*, 135, 103465, https://doi.org/10.1016/j.trc.2021.103465.

Berge, S. H., M. Hagenzieker, H. Farah, J. de Winter (2022), 'Do cyclists need HMIs in future automated traffic? An interview study', *Transportation Research Part F: Traffic Psychology and Behaviour*, 84, 33-52, https://doi.org/10.1016/j.trf.2021.11.013.

Bicchieri, C. (2005), *The Grammar of Society: The Nature and Dynamics of Social Norms* (Cambridge: Cambridge University Press), https://doi.org/10.1017/CBO9780511616037.

Björklund, G. M., L. Åberg (2005), 'Driver behaviour in intersections: Formal and informal traffic rules', *Transportation Research Part F: Traffic Psychology and Behaviour*, 8 (3), 239-253, https://doi.org/10.1016/j.trf.2005.04.006.

Bjørnskau, T. (2017), 'The Zebra Crossing Game – Using game theory to explain a discrepancy between road user behaviour and traffic rules', *Safety Science*, 92, 298-301, https://doi.org/10.1016/j.ssci.2015.10.007.

Bjørnskau, T., T. De Ceunynck, A. Fyhri, *et al.* (forthcoming), 'Game over for AV shuttles? Are game theoretic predictions of ordinary road users' interaction with AV shuttles supported by real-life experience?', *Transportation Research Interdisciplinary Perspectives* (in review).

Björnstig, U., P.-O. Bylund, P. Albertsson, *et al.* (2005), 'Injury Events Among Bus and Coach Occupants: Non-crash Injuries as Important as Crash Injuries', *IATSS Research*, 29 (1), 79–87, https://doi.org/10.1016/S0386-1112(14)60121-7.

Camara, F., R. Romano, G. Markkula, *et al.* (2018), 'Empirical game theory of pedestrian interaction for autonomous vehicles', in Grant, R., T. Allen, A. Spink, M. Sullivan (eds.), *Proceedings of Measuring Behavior 2018: 11th International Conference on Methods and Techniques in Behavioral Research, 6-8 June 2018, Manchester, UK* (Manchester: Manchester Metropolitan University), 238-244, https://eprints.whiterose.ac.uk/129303, accessed 31 July 2022.

De Ceunynck, T., E. Polders, S. Daniels, *et al.* (2013), 'Road Safety Differences between Priority-Controlled Intersections and Right-Hand Priority Intersections', *Transportation Research Record: Journal of the Transportation Research Board*, 2365 (1), 39-48, https://doi.org/10.3141/2365-06.

De Ceunynck, T. (2017), 'Defining and applying surrogate safety measures and behavioural indicators through site-based observations', PhD thesis (double degree), Hasselt University, Belgium, and Lund University, Sweden, https://portal.research.lu.se/en/publications/7f7f7952-2b51-40ca-bb33-a551427ed6e8, accessed 31 July 2022.

Domeyer, J. E., J. D. Lee, H. Toyoda (2020), 'Vehicle Automation–Other Road User Communication and Coordination: Theory and Mechanisms', *IEEE Access*, 8, 19860-19872, https://doi.org/10.1109/access.2020.2969233.

Ezzati Amini, R., C. Katrakazas, A. Riener, C. Antoniou (2021), 'Interaction of automated driving systems with pedestrians: challenges, current solutions, and recommendations for eHMIs', *Transport Reviews*, 41 (6), 788-813, https://doi.org/10.1080/01441647.2021.1914771.

Fagnant, D. J., K. Kockelman (2015), 'Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations', *Transportation Research Part A: Policy and Practice*, 77, 167-181, https://doi.org/10.1016/j.tra.2015.04.003.

Goffman, E. (2010), *Relations in Public: Microstudies of the Public Order* (New York: Routledge), https://doi.org/10.4324/9781315128337.

Goodall, N. J. (2021), 'Comparison of automated vehicle struck-from-behind crash rates with national rates using naturalistic data', *Accident Analysis & Prevention*, 154, 106056, https://doi.org/10.1016/j.aap.2021.106056.

Hagenzieker, M., R. Boersma, P. Nunez Velasco, *et al.* (2021), 'Automated Buses in Europe: an Inventory of Pilots' (Delft: Delft University of Technology), Version 1.0 ed., https://research.tudelft.nl/en/publications/automated-buses-in-europe-an-inventory-of-pilots-version-10, accessed 31 July 2022.

Hagenzieker, M. P., S. van der Kint, L. Vissers, *et al.* (2019), 'Interactions between cyclists and automated vehicles: Results of a photo experiment', *Journal of Transportation Safety & Security*, 12 (1), 94-115, https://doi.org/10.1080/19439962.2019.1591556.

Haque, A. M., C. Brakewood (2020), 'A synthesis and comparison of American automated shuttle pilot projects', *Case Studies on Transport Policy*, 8 (3), 928-937, https://doi.org/10.1016/j.cstp.2020.05.005.

Heikoop, D. D., J. P. Nuñez Velasco, R. Boersma, *et al.* (2020), 'Automated bus systems in Europe: A systematic review of passenger experience and road user interaction', *Advances in Transport Policy and Planning*, 5, 51-71, https://doi.org/10.1016/bs.atpp.2020.02.001.

Hydén, C. (1987), 'The development of a method for traffic safety evaluation: The Swedish Traffic Conflicts Technique', PhD thesis, Lund University, Sweden, https://www.ictct.net/wp-content/uploads/SMoS_Library/LIB_Hyden_1987.pdf, accessed 31 July 2022.

Johnsson, C., A. Laureshyn, T. De Ceunynck (2018), 'In search of surrogate safety indicators for vulnerable road users: a review of surrogate safety indicators', *Transport Reviews*, 38 (6), 765-785, https://doi.org/10.1080/01441647.2018.1442888.

Johnsson, C., T. De Ceunynck, B. Pelssers, *et al.* (forthcoming), 'Behavioural observation of interactions between cars and autonomous shuttles in Oslo and Kongsberg, Norway', *Traffic Safety Research* (in review).

Kassens-Noor, E., Z. Kotval-Karamchandani, M. Cai (2020), 'Willingness to ride and perceptions of autonomous public transit', *Transportation Research Part A: Policy and Practice*, 138, 92-104, https://doi.org/10.1016/j.tra.2020.05.010.

Kröyer, H. R. G., T. Jonsson, A. Várhelyi (2014), 'Relative fatality risk curve to describe the effect of change in the impact speed on fatality risk of pedestrians struck by a motor vehicle', *Accident Analysis & Prevention*, 62, 143-152, https://doi.org/10.1016/j.aap.2013.09.007.

Kyriakidis, M., J. C. F. de Winter, N. Stanton, *et al.* (2019), 'A human factors perspective on automated driving', *Theoretical Issues in Ergonomics Science*, 20 (3), 223-249, https://doi.org/10.1080/1463922x.2017.1293187.

Laureshyn, A. (2010), 'Application of automated video analysis to road user behaviour', PhD thesis, Lund University, Department of Technology and Society, Bulletin 253, https://lucris.lub.lu.se/ws/portalfiles/portal/5337337/1522970.pdf, accessed 31 July 2022.

Laureshyn, A., T. De Ceunynck, C. Karlsson, *et al.* (2017a), 'In search of the severity dimension of traffic events: Extended Delta-V as a traffic conflict indicator', *Accident Analysis & Prevention*, 98, 46-56, https://doi.org/10.1016/j.aap.2016.09.026.

Laureshyn, A., M. de Goede, N. Saunier, A. Fyhri (2017b), 'Cross-comparison of three surrogate safety methods to diagnose cyclist safety problems at intersections in Norway', *Accident Analysis & Prevention*, 105, 11-20, https://doi.org/10.1016/j.aap.2016.04.035.

Lee, Y. M., R. Madigan, O. Giles, *et al.* (2020), 'Road users rarely use explicit communication when interacting in today's traffic: implications for automated vehicles', *Cognition, Technology & Work*, 23 (2), 367-380, https://doi.org/10.1007/s10111-020-00635-y.

Liu, P., Y. Du, L. Wang, J. Da Young (2020), 'Ready to bully automated vehicles on public roads?', *Accident Analysis & Prevention*, 137, 105457, https://doi.org/10.1016/j.aap.2020.105457.

Lubbe, N., Y. Wu, H. Jeppsson (2022), ‘Safe speeds: fatality and injury risks of pedestrians, cyclists, motorcyclists, and car drivers impacting the front of another passenger car as a function of closing speed and age’, *Traffic Safety Research*, 2, 000006, https://doi.org/10.55329/vfma7555.
Madigan, R., T. Louw, M. Wilbrink, *et al.* (2017), ‘What influences the decision to use automated public transport? Using UTAUT to understand public acceptance of automated road transport systems’, *Transportation Research Part F: Traffic Psychology and Behaviour*, 50, 55-64, https://doi.org/10.1016/j.trf.2017.07.007.
Madigan, R., S. Nordhoff, C. Fox, *et al.* (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.
Markkula, G., R. Madigan, D. Nathanael, *et al.* (2020), ‘Defining interactions: a conceptual framework for understanding interactive behaviour in human and automated road traffic’, *Theoretical Issues in Ergonomics Science*, 21 (6), 728-752, https://doi.org/10.1080/1463922x.2020.1736686.
Merat, N., T. Louw, R. Madigan, *et al.* (2018), ‘What externally presented information do VRUs require when interacting with fully Automated Road Transport Systems in shared space?’, *Accident Analysis & Prevention*, 118, 244-252, https://doi.org/10.1016/j.aap.2018.03.018.
Millard-Ball, A. (2018), ‘Pedestrians, Autonomous Vehicles, and Cities’, *Journal of Planning Education and Research*, 38 (1), 6-12, https://doi.org/10.1177/0739456x16675674.
Nordhoff, S., J. de Winter, R. Madigan, *et al.* (2018), ‘User acceptance of automated shuttles in Berlin-Schöneberg: A questionnaire study’, *Transportation Research Part F: Traffic Psychology and Behaviour*, 58, 843-854, https://doi.org/10.1016/j.trf.2018.06.024.
Nuñez Velasco, J. P., A. de Vries, H. Farah, *et al.* (2020), ‘Cyclists’ Crossing Intentions When Interacting with Automated Vehicles: A Virtual Reality Study’, *Information*, 12 (1), 7, https://doi.org/10.3390/info12010007.
Pelikan, H. R. M. (2021), ‘Why Autonomous Driving Is So Hard: The Social Dimension of Traffic’, presented at *Companion of the 2021 ACM/IEEE International Conference on Human-Robot Interaction* (Boulder, CO, USA: 8-11 March 2021), https://doi.org/10.1145/3434074.3447133.
Pokorny, P., B. Skender, T. Bjørnskau, M. P. Hagenzieker (2021), ‘Video observation of encounters between the automated shuttles and other traffic participants along an approach to right-hand priority T-intersection’, *European Transport Research Review*, 13 (1), https://doi.org/10.1186/s12544-021-00518-x.
Rahman, M. T., K. Dey, S. Das, M. Sherfinski (2021), ‘Sharing the road with autonomous vehicles: A qualitative analysis of the perceptions of pedestrians and bicyclists’, *Transportation Research Part F: Traffic Psychology and Behaviour*, 78, 433-445, https://doi.org/10.1016/j.trf.2021.03.008.
Rasouli, A., J. K. Tsotsos (2018), ‘Joint Attention in Driver-Pedestrian Interaction: from Theory to Practice’, *arXiv*, 1802.02522, https://doi.org/10.48550/arXiv.1802.02522.
Reason, J., A. Manstead, S. Stradling, *et al.* (1990), ‘Errors and violations on the roads: a real distinction?’, *Ergonomics*, 33 (10-11), 1315-1332, https://doi.org/10.1080/00140139008925335.
Rehrl, K., C. Zankl (2018), ‘Digibus©: results from the first self-driving shuttle trial on a public road in Austria’, *European Transport Research Review*, 10, 51, https://doi.org/10.1186/s12544-018-0326-4.
Rovira, E., A. C. McLaughlin, R. Pak, L. High (2019), ‘Looking for Age Differences in Self-Driving Vehicles: Examining the Effects of Automation Reliability, Driving Risk, and Physical Impairment on Trust’, *Frontiers in Psychology*, 10, 800, https://doi.org/10.3389/fpsyg.2019.00800.
Räsänen, M., H. Summala (2000), ‘Car Drivers' Adjustments to Cyclists at Roundabouts’, *Transportation Human Factors*, 2 (1), 1-17, https://doi.org/10.1207/sthf0201_1.
Saunier, N., T. Sayed (2007), ‘Automated Analysis of Road Safety with Video Data’, *Transportation Research Record: Journal of the Transportation Research Board*, 2019 (1), 57-64, https://doi.org/10.3141/2019-08.
Schelling, T. C. (1960), *The Strategy of Conflict* (Cambridge, MA: Harvard University Press).
Silvano, A. P., H. N. Koutsopoulos, X. Ma (2016), ‘Analysis of vehicle-bicycle interactions at unsignalized crossings: A probabilistic approach and application’, *Accident Analysis & Prevention*, 97, 38-48, https://doi.org/10.1016/j.aap.2016.08.016.
Sugden, R. (2005), *The Economics of Rights, Co-operation and Welfare* (London: Palgrave Macmillan), https://doi.org/10.1057/9780230536791.
Svensson, Å. (1998), ‘A method for analysing the traffic process in a safety perspective’, PhD thesis, Lund University, Department of Traffic Planning & Engineering, Bulletin 166, https://portal.research.lu.se/files/4456913/1653512.pdf, accessed 31 July 2022.
Thompson, J., G. J. M. Read, J. S. Wijnands, P. M. Salmon (2020), ‘The perils of perfect performance; considering the effects of introducing autonomous vehicles on rates of car vs cyclist conflict’, *Ergonomics*, 63 (8), 981-996, https://doi.org/10.1080/00140139.2020.1739326.
Vissers, L., S. van der Kint, I. van Schagen, M. Hagenzieker (2016), ‘Safe interaction between cyclists, pedestrians and automated vehicles. What do we know and what do we need to know?’ (The Hague: SWOV

Institute for Road Safety Research), R-2016-16, https://swov.nl/sites/default/files/publicaties/rapport/r-2016-16.pdf, accessed 31 July 2022.

Vlakveld, W., S. van der Kint, M. P. Hagenzieker (2020), 'Cyclists' intentions to yield for automated cars at intersections when they have right of way: Results of an experiment using high-quality video animations', *Transportation Research Part F: Traffic Psychology and Behaviour*, 71, 288-307, https://doi.org/10.1016/j.trf.2020.04.012.

Zubin, I., N. Van Oort, A. Van Binsbergen, B. Van Arem (2021), 'Deployment Scenarios for First/Last-Mile Operations With Driverless Shuttles Based on Literature Review and Stakeholder Survey', *IEEE Open Journal of Intelligent Transportation Systems*, 2, 322-337, https://doi.org/10.1109/ojits.2021.3106164.

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