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# Understanding interactions between Automated Road Transport Systems and other road users: A video analysis

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## Abstract

If automated vehicles (AVs) are to move efficiently through the traffic environment, there is a need for them to interact and communicate with other road users in a comprehensible and predictable manner. For this reason, an understanding of the interaction requirements of other road users is needed. The current study investigated these requirements through an analysis of 22 hours of video footage of the CityMobil2 AV demonstrations in La Rochelle (France) and Trikala (Greece). Manual and automated video-analysis techniques were used to identify typical interactions patterns between AVs and other road users. Results indicate that road infrastructure and road user factors had a major impact on the type of interactions that arose between AVs and other road users. Road infrastructure features such as road width, and the presence or absence of zebra crossings had an impact on road users' trajectory decisions while approaching an AV. Where possible, pedestrians and cyclists appeared to leave as much space as possible between their trajectories and that of the AV. However, in situations where the infrastructure did not allow for the separation of traffic, risky behaviours were more likely to emerge, with cyclists, in particular, travelling closely alongside the AVs on narrow paths of the road, rather than waiting for the AV to pass. In addition, the types of interaction varied considerably across socio-demographic groups, with females and older users more likely to show cautionary behaviour around the AVs than males, or younger road users. Overall, the results highlight the importance of implementing the correct infrastructure to support the safe introduction of AVs, while also ensuring that the behaviour of the AV matches other road users' expectations as closely as possible in order to avoid traffic conflicts.

30 **1. Introduction**

31 The road traffic system is a highly interactive social system in which individuals, using different forms  
32 of transport, interact with one another to negotiate their movement through the traffic  
33 environment. These individuals must adapt to the prevailing traffic rules, interpret relevant  
34 information and react accordingly in order to avoid conflict (Svensson, 1998). The level of complexity  
35 in this constantly evolving system poses a particular challenge for automated vehicles (AVs), as they  
36 currently lack interaction capabilities, and are dependent on the application of collision avoidance  
37 principles to avoid critical conflicts with other road users (Rothenbücher, Li, Sirkin, Mok, & Ju, 2016).  
38 This lack of interaction and interpretation capability may make the traffic negotiation process more  
39 difficult for AVs, as other road users may have difficulties anticipating the AV's future actions (Eden,  
40 Nanchen, Ramseyer, & Évéquoz, 2017). The acceptance of AVs is likely to be closely linked to how  
41 safely and predictably they can move through the traffic environment, and this will depend on their  
42 ability to interact and communicate with other road users in a comprehensible and predictable  
43 manner (Fuest, Sorokin, Bellem, & Bengler, 2017). Thus, there is a need to understand the typical  
44 interaction patterns which may arise between AVs and other road users, so that appropriate  
45 interaction strategies and communication solutions can be designed for these vehicles.

46 There is an increasing level of interest in AVs as an alternative public transport solution, with  
47 vehicles such as the Lutz pathfinder (Transport Systems Catapult, 2016), Wepods (WePods, 2017),  
48 Olli (Local Motors, 2017), EZ10 (Easymile, 2019), and CityMobil2 Automated Road Transport Systems  
49 (ARTS, see Figure 1) being trialled across Europe, Asia, and the U.S (Stocker & Shaheen, 2017). These  
50 automated “pods” drive at low speeds in designated urban environments and do not contain a  
51 steering wheel or any other conventional driver controls (SAE Level 4; SAE, 2016). They operate  
52 along specified routes using simultaneous localisation and mapping (SLAM) along with laser and  
53 LiDAR technology (Roldão, Pérez, González & Milanés, 2015). It is likely that in the future these types  
54 of vehicles will share their environment with both motorised vehicles and vulnerable road users  
55 (VRUs), and will need to be able to interact effectively with all road user groups for successful traffic  
56 flow. One of the key elements for intelligent driving systems is the development of algorithms that  
57 predict the forthcoming actions of other road users (Rasouli & Tsotsos, 2019). The accurate  
58 identification of any interaction precursors is a vital element in enabling this prediction.



59

60

**Figure 1: CityMobil2 Shuttle in Trikala (left) and La Rochelle (right)**

## 61 **1.1. Factors that influence traffic interactions**

62 An important starting point for understanding the interaction requirements of AVs is to develop a  
63 framework which will enable us to specify the factors which are likely to influence these  
64 interactions. Habibovic et al. (2018) and Schieben, Wilbrink, Kettwich, Madigan, Louw, and Merat  
65 (2019) highlight the importance of context in enabling an understanding of individuals' cognition in  
66 AV interactions, pointing out that artefacts, such as AV or road design, shape road users' cognition  
67 and collaboration and may trigger new behaviours. The following sections provide an outline of the  
68 typical contextual factors, which might influence AVs' interactions with other road users, based on  
69 our current knowledge of driver-VRU communication strategies, and understanding of conflict  
70 resolution techniques. These contextual factors are grouped into three categories - road  
71 infrastructure characteristics, road user characteristics, and driver and vehicle characteristics. The  
72 contextual factors will be used to identify the features which affect the likelihood of an interaction  
73 occurring between an AV and another road user at two of the CityMobil2 demonstration locations –  
74 Trikala in Greece, and La Rochelle in France. Knowledge of common interaction patterns in these  
75 two locations will facilitate the development of communication and infrastructure  
76 recommendations, helping us to identify where specific AV infrastructure or communication tools  
77 might be required.

### 78 **1.1.1 Road infrastructure characteristics**

79 Numerous studies have highlighted important environmental factors which affect interactions  
80 between conventional motorised vehicles and VRUs. The majority of these studies have focused on  
81 accident risk, although some have investigated how environmental and situational factors influence  
82 the communication requirements of pedestrians and other VRUs.

83 Road infrastructure has been shown to have an impact on the risk of VRU accidents, with several  
84 studies pointing to an increased risk of pedestrians and cyclist collisions at intersections compared to  
85 non-intersections (Chen, Cao, & Logan, 2012; Kaplan & Giacomo Prato, 2015; Romanow,  
86 Couperthwaite, McCormack, Nettel-Aguirre, Rowe, & Hagel, 2012; Stone & Broughton, 2003; Wei &  
87 Lovegrove, 2013; Wessels, 1996; Moore, Schneider, Savolainen, & Farzaneh, 2011). The installation  
88 of specified pedestrian crossing locations such as zebra crossings has been found to have a positive  
89 impact on pedestrians' perceptions of safety, convenience and vulnerability (Harvard & Willis, 2012).  
90 Evidence, however, suggests that the willingness of drivers to give way to pedestrians at zebra  
91 crossings is actually low, with one Swedish study showing that drivers only gave way in 5% of  
92 situations in which a pedestrian was present (Várhelyi, 1998).

93 Other road infrastructure characteristics, such as road-width and lane markings, have also been  
94 shown to impact on the risk of traffic conflicts. For instance, it has been found that bridges without  
95 cycle facilities increased the risk of collisions (Vandenbulcke, Thomas, & Int Panis, 2014), while wider  
96 footpaths decreased the risk (Kim, Kim, Oh, & Jun, 2012), and the use of separate paths for cyclists  
97 has been identified as one of the main contributors to cycling safety in the Netherlands (Schepers,  
98 Twisk, Fishman, Fyhri, & Jensen, 2016). These studies point to safety benefits of separating traffic  
99 modes, an approach that was implemented for the Trikala CityMobil2 demonstration, where an AV  
100 operated in a dedicated lane (see Figure 1, left). In contrast, other research suggests that accidents  
101 are reduced in shared space areas (Hamilton-Baillie, 2008; Swinburne, 2006), as was the case in the  
102 La Rochelle CityMobil2 demonstration (Figure 1, right).

103 **1.1.2 Road user characteristics**

104 Studies also point to differences in behaviour across different groups of road users. For example,  
105 research has revealed gender differences in road crossing behaviour and accident risk, where female  
106 pedestrians were more aware of traffic hazards and more cautious when crossing the street than  
107 male pedestrians (Harrell, 1991). Male pedestrians tend to violate traffic rules more frequently, and  
108 were more likely to cross in risky situations (e.g., Rosenbloom, Nemrodov, & Barkan, 2004; Díaz,  
109 2002). In a study investigating pedestrian crossing decisions when observing the approach of a  
110 vehicle they had been told was an AV, Clamann, Aubert, and Cummings (2017) found that male  
111 pedestrians took less time to evaluate their environment prior to making a crossing decision  
112 compared to females. Similar gender differences also emerge for cyclist interactions with  
113 conventional vehicles (Bernhoft & Carstensen, 2008; Johnson, Newstead, Charlton, & Oxley, 2011).  
114 The potential safety implications of these gender differences in risk-taking behaviour become  
115 apparent when looking at U.S. crash data, where the fatality rate for male pedestrians is twice as  
116 large of that of female pedestrians (National Centre for Statistics and Analysis, 2018).

117 Age-related differences in pedestrian and cyclist behaviours have also been identified. Older  
118 pedestrians tend to be over-represented in serious injury and fatal crashes compared to younger  
119 adults (Oxley, Ihsen, Fildes, Charlton, & Day, 2005). Young adults and adolescent pedestrians are  
120 more likely to commit violations than older pedestrians (e.g., Díaz, 2002), and older road users  
121 express more appreciation for controlled pedestrian crossings and signalised intersections than  
122 younger pedestrians (Bernhoft and Carstensen, 2008). Clamann et al.'s (2017) study suggests that  
123 this tendency is unlikely to change in the presence of AVs, as they found that older participants  
124 generally made safer crossing decisions than younger participants, and were less likely to take risks.  
125 Young children have also been found to make poorer road crossing decisions than adults, being  
126 more likely not to look or stop before crossing (Rosenbloom, Beh-Eliyahu, & Nemrodov, 2008).

127 Numerous studies have also shown that pedestrians use cues from other pedestrians to help decide  
128 whether or not it is safe to cross at an intersection (Hamed, 2001; Marisamynathan & Vedagiri,  
129 2013; Wagner, 1981). For example, Hamed (2001) found that road-crossing wait times decreased as  
130 pedestrian flow increased, suggesting that pedestrians are more inclined to cross the road along  
131 with others (Zhou, Horrey, & Yu, 2009). In addition, Katz, Zaidel, & Elgrishi (1975) found that drivers  
132 gave the right of way more often for pedestrians crossing as a group, rather than as individuals.  
133 Interestingly, pedestrian gender is also likely to influence their interactions with other pedestrians.  
134 Research has shown that women are more likely to be influenced by the presence and behaviour of  
135 other pedestrians, whereas men are more concerned with the physical conditions of the setting, for  
136 example, traffic volume (Yagil, 2000).

137 **1.1.3 Vehicle characteristics**

138 Driver and vehicle behaviours can influence the perceptions and responses of VRUs in a variety of  
139 ways. Drivers can engage in explicit communication with other road users through the use of eye  
140 contact, hand gestures, flashing lights and indicator signals, or implicit communication strategies  
141 such as speed reduction (Fuest et al., 2017). A number of studies have suggested the importance of  
142 mutual eye-contact in facilitating safe interactions between vehicles and VRUs (see Schneemann &  
143 Gohl, 2016), with some studies suggesting that establishing eye contact with a driver increases the  
144 likelihood that the driver will yield to a pedestrian (Guéguen, Meineri, & Eyssartier, 2015).

145 At greater distances, drivers are more likely to use implicit communication strategies to convey their  
146 intent. For example, interview data collected by Sûcha (2014) showed that drivers make use of a  
147 variety of techniques to force pedestrians to yield, including refusing to decelerate, speeding up, and  
148 driving more in the centre of the road to avoid a pedestrian while not stopping for them. Clamann et  
149 al. (2017) suggest that this reliance on implicit modes of communication is unlikely to change with  
150 the introduction of AVs. In their study, the authors manipulated the information provided to  
151 pedestrians on the front display of a supposedly automated vehicle and found that the majority of  
152 participants still relied on the oncoming vehicle's distance and speed to inform their crossing  
153 decisions. However, it is important that the information conveyed through implicit cues does not  
154 contradict more explicit information. Lagström and Lundgren (2015) conducted a wizard-of-oz study,  
155 where they placed a fake steering wheel on the passenger side of a vehicle, and the real steering  
156 wheel was hidden from sight. The person sitting in the "driver" seat then engaged in a number of  
157 different behaviours, while the vehicle was actually controlled by the person sitting on the  
158 passenger side. Results showed that pedestrians were most uncomfortable and less willing to cross  
159 if a driver and a vehicle displayed mixed messages – for example if a vehicle slowed down, but the  
160 "driver" appeared to be reading a newspaper. Rothenbücher et al. (2016) used a "ghost-driver"  
161 methodology to study pedestrian and cyclist interactions with AVs. The "ghost-driver" was a human  
162 driver concealed in a car seat costume to create the appearance of a "driverless" vehicle.  
163 Pedestrians who encountered the car reported that they saw no driver, but were still able to  
164 manage interactions smoothly in most cases, provided the vehicle behaved predictably. This  
165 suggests that if pedestrians are not aware that a vehicle is automated they will be confused by any  
166 irregular behaviour by a person in the driving seat, or any vehicle behaviour which is inconsistent  
167 with their expectations, for example, a vehicle stopping and starting at an intersection  
168 (Rothenbücher et al., 2016). As there is no driver on board of the CityMobil2 pods, any unusual  
169 behaviour of the vehicles are also likely to cause confusion, and therefore, it is particularly important  
170 to understand where these confusing situations might arise.

171 Finally, vehicle manufacturers such as Mercedes and Volvo have expressed some concern that  
172 obvious indications that a vehicle is operating autonomously may lead to "bullying" or "malicious"  
173 behaviour by other road users (Connor, 2016; Mitchell, 2015; Rasouli & Tsotsos, 2019), such as  
174 failing to yield right of way to the AV or attempting to "take them on" (Connor, 2016). This type of  
175 behaviour may have a negative impact on safety by increasing the risk-taking behaviour of other  
176 road users, and could also negatively impact on traffic flow if the AV is forced to stop and start on a  
177 regular basis. Thus, in order to ensure that AVs bring the promised safety and efficiency benefits, it is  
178 important to gain an understanding of the regularity and nature of this type of behaviour.

## 179 **1.2. Aims and objectives**

180 The purpose of the current research was to analyse the video data collected during the CityMobil2  
181 demonstrations, to understand typical interactions between AVs and other road users. This study  
182 asked three key questions about the factors influencing the interactions between AVs and other  
183 road users:

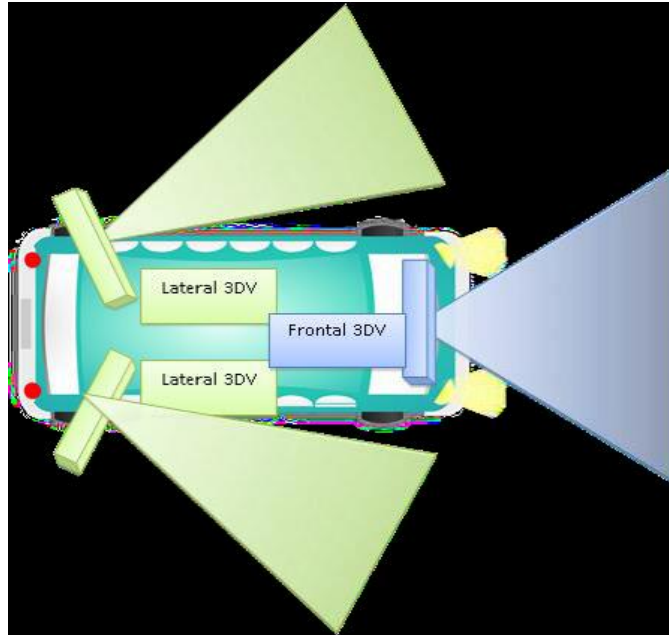
- 184 1. To what extent do road infrastructure factors impact on the types of interactions arising  
185 between AVs and other road users?
- 186 2. To what extent do the interaction requirements for AVs vary across different road user  
187 groups, e.g. pedestrians, cyclists, and other drivers?
- 188 3. To what extent do the interaction requirements for AVs vary across socio-demographic  
189 groups, e.g., age and gender?

190 Research has shown differences in risk attitudes, and pedestrian crossing behaviours across different  
191 cultures (Nordfjærn, Jørgensen, & Rundmo, 2011; Sueur, Class, Hamm, Meyer, & Pelé, 2013; Rasouli  
192 & Tsotsos, 2019). Thus, it is important to understand if it is likely that there will be some cross-  
193 cultural differences in the communication requirements between AVs and other road users? For that  
194 reason, an investigation of the similarities and differences that emerge between the two  
195 demonstration locations (in France and Greece) will be an overarching theme throughout the study.  
196 By gaining insights into how the structural differences between the two locations impact on the  
197 types of interactions observed, we will be able to gain a deeper understanding of which AV  
198 interaction requirements are likely to change according to location characteristics, and which are  
199 likely to be more stable across locations and cultures.

## 200 **2. Method**

### 201 **2.1 Video collection**

202 Videos used for the analysis in this paper were recorded at two of the CityMobil2 demonstration  
203 sites – Trikala, in Greece, and La Rochelle in France. Six Robosoft shuttles (see Figure 1) were used in  
204 both locations. One of the vehicles was fitted with three VisLab 3DV camera systems supplied by the  
205 University of Palma, which recorded images around the vehicle, as illustrated in Figure 2 and Figure  
206 3. Information from the cameras was stored in three different external Solid State Drives at a  
207 frequency of 2Hz in La Rochelle, and 3Hz in Trikala (see Merat, Louw, Madigan, Dziennus, &  
208 Schieben, 2016). Video data was only collected when the appropriate expert personnel and  
209 equipment were available, and all of the available data was included in the current analysis.



210

211

**Figure 2: Aerial view of the positioning and area covered by the three 3DV cameras**

212



213

214

**Figure 3: Example of road scene displayed by the three 3DV cameras in Trikala**

215 In La Rochelle, the CityMobil2 shuttles operated from November 2014 to April 2015, along a 1.7 km  
 216 route, which included seven station stops. Nine videos were recorded from La Rochelle between the  
 217 17<sup>th</sup> and 23<sup>rd</sup> March 2015, providing 10 hours and 45 minutes of footage in total.

218 In Trikala, the shuttles ran from September 2015 to February 2016, along a 2.5 km route including  
 219 eight station stops. 24 videos were recorded in Trikala between 21 January and 21 February 2016. In  
 220 total there was 12 hours and 33 minutes of footage from this location.

## 221 **2.2 Description of locations**

222 The characteristics of the road infrastructure differed across the two CityMobil2 demonstration  
 223 sites. In Trikala, the “normal route” used by the AV (see Table 1) consisted of a demarcated,  
 224 dedicated lane, segregated from the rest of the vehicular, cyclist, and pedestrian traffic. Much of this  
 225 area had previously been allocated as 800 parking spaces, and there were times when the AV had to  
 226 move around a parked vehicle. The trial involved the installation of a control centre, road  
 227 segregation equipment, road signage, and new traffic lights (Raptis, 2016). There were two areas  
 228 where the AV travelled in a shared space; one where it moved through an off-road area with  
 229 pedestrians and cyclists, and another area where it entered the same stream as vehicular traffic on  
 230 the approach to a set of traffic lights. In a number of areas, the traffic alongside the AV was moving



231 on a one-way street, and there was not much space between the AV and other vehicles. The AV was  
232 given priority at all intersections, and did not have to obey traffic lights. The majority of the route  
233 (see Figure 6) was located in a busy town centre, in an area surrounded by shops and offices.

234 In La Rochelle the “normal route” consisted of a wide shared space, in which other vehicles,  
235 pedestrians and cyclists were also moving freely. The trial involved the installation of new traffic  
236 lights, which were designed to change upon the approach of the AV, along with new signage  
237 highlighting the AV route (Graindorge et al., 2013). There were two narrow parts to the route, one  
238 along a one-way street, and one crossing a one-way bridge which had a segregated lane for  
239 pedestrians and cyclists. The route encountered 2 small roundabouts, with the AV taking the first  
240 exit in each case. The route used was not a circular loop (see Figure 7), which meant that the AV  
241 travelled in both directions, and on some occasions encountered a manually controlled vehicle on  
242 the one-way section of the route. The majority of the La Rochelle route was located in a busy town  
243 centre area, surrounded by tourist attractions and restaurants.

## 244 **2.3 Video coding and analysis**

245 Computer vision scientists have made use of numerous automated tracking techniques to analyse  
246 and code videos of traffic movement, using techniques such as multiple object tracking (Luo, Xing,  
247 Zhang, Zhao, & Kim, 2014). The tracking of pedestrians and other vulnerable road users can cause  
248 particular challenges due to their varied appearance, intertwined movement paths, and less  
249 organised traffic structure (Gerónimo, López, Sappa, & Graf, 2010). Therefore, the current research  
250 made use of both manual and automated video analysis techniques to identify the road  
251 infrastructure and road user factors which influence AV interactions with other road users. The main  
252 objective of the manual video coding analysis was to derive the most commonly occurring factors  
253 influencing the interaction between the AVs and other traffic participants. The focus of the analysis  
254 was on providing qualitative descriptions of the typical interactions of these AVs, to ensure that all  
255 potential interaction scenarios were captured from the data. This analysis can aid the development  
256 of computer-based algorithms, by defining the types of interaction which need to be captured. The  
257 automated video analysis was used to provide some additional quantitative metrics (i.e. vehicle  
258 speed, pedestrian density, and time to collision measurements) to complement the observations  
259 from the manual analysis.

### 260 **2.3.1 Manual video coding procedure**

261 The first two videos in both La Rochelle and Trikala were selected for the initial identification of  
262 video coding categories. These two videos were initially watched separately by three human factors  
263 specialists, who coded every situation they believed constituted an interaction. For the analysis, an  
264 interaction scenario was defined as *situations where road users adapt their behaviour ahead of a*  
265 *“conflicting zone”, leaving time and space for fluid movement with other users* (Cloutier, Lachapelle,  
266 Amours-Ouellet, Bergeron, Lord, and Torres, 2017, p.37). This was operationalised as any situation in  
267 which another road user entered the AV’s path at a distance of no greater than 5 metres, or changed  
268 their behaviour in relation to the AV by altering their movement trajectory or coming to a stop. The  
269 5 metres distance was subjectively rated by the coders, which meant that there was some margin of  
270 error. Previous research using the Swedish Traffic Conflict Technique has shown that observers can  
271 make satisfactory estimates of speed and time variables (incorporating distance) (Svensson, 1998).  
272 The criticality of each interaction was also subjectively evaluated by the coder, based on the

273 potential for a collision to occur. Incidents defined as highly critical involved near-miss events, where  
 274 a collision was narrowly avoided.

275 The coders then watched the videos as a group, discussing each of the categorised interactions in  
 276 detail to ensure that there was agreement on the types of situations which qualified as interaction  
 277 scenarios. From this discussion, six main interaction scenarios were identified, with 25  
 278 subcategories. The features of each of these interaction scenarios were categorised using a  
 279 comprehensive list of environmental and road user factors, including information about the road  
 280 infrastructure, the surrounding environment, the prevailing weather, time of day variables, and road  
 281 user characteristics. The current paper focuses on road infrastructure, road user type, and  
 282 pedestrian demographic information. The specific sub-categories for these variables are shown in  
 283 Table 1. Vehicle speed and pedestrian density were objectively measured using the automated video  
 284 analysis techniques described in Section 2.3.2.

285 **Table 1: Contextual factors influencing the interactions of AVs and other Road Users**

<b>Contextual Factors</b>	<b>Categories</b>
Road Infrastructure	Normal route Intersection Zebra crossing Traffic Lights Curve / bend At or near an AV stop Narrow road Roundabout Pedestrian area (Trikala only) 2-lanes / 2-directions (La Rochelle only)
Type of road user	Pedestrian Cyclist Car Driver Powered 2 Wheeler Van /Truck / Bus
Gender	Male Female Unknown
Age Group	Child (<13 years) Teenager (13 – 18 years) Young Adult (18 – 35 years) Middle-aged adult (35 – 55 years) Older adult (>55 years) Unknown
Presence of other road users	Group (>1) Individual (1)

286  
 287 The remaining videos were then divided between two trained coders, who were given a detailed  
 288 description and examples of each of the interaction categories. These coders watched each video in  
 289 its entirety, pausing the video when any interaction scenario was identified, noting the type of  
 290 interaction scenario, and categorising the contextual factors (road, user, and vehicle factors) which  
 291 contributed to the scenario. In some cases, this required the creation of additional interaction  
 292 categories to describe newly identified situations. These new categories were shared between the

293 coders, and all coding was independently checked by a third coder to ensure inter-rater reliability  
 294 and coding consistency. As more videos were watched and a deeper understanding of typical  
 295 interactions emerged, some of the initial coding categories were amalgamated, and some new  
 296 overarching categories were created. This led to a total of five overarching interaction types, with 15  
 297 subcategories (see Table 2). Where disagreements or uncertainty in coding arose, the interactions  
 298 were discussed by all three coders until a consensus was reached.

299 **Table 2: Description of interaction scenarios and sub-categories**

Interaction type	Sub-categories
<b>1. Traffic participant crosses in front of the AV</b>	(i) Another road user increases his/her speed to cross in front of the AV (looks at AV). (ii) Another road user increases his/her speed to cross in front of the AV (does not look at AV). (iii) Another road user maintains constant speed while crossing in front of the AV (looks at AV). (iv) Another road user maintains constant speed while crossing in front of the AV (does not look at AV).
<b>2. Traffic participant passes alongside of the AV</b>	(i) Another road user travels in the same lane as the AV, moving in the same direction (right side). (ii) Another road user travels in the same lane as the AV, moving in the opposite direction (right side). (iii) Another road travels in the same lane as the AV, moving in the same direction (left side). (iv) Another road travels in the same lane as the AV, moving in the opposite direction (left side).
<b>3. Traffic participant changes trajectory of movement</b>	(i) Another road user changes the trajectory of their movement by stepping into and then back out of AV path. (ii) Another road user changes the trajectory of their movement by swerving to move out of the AV path.
<b>4. Traffic participant stops to let AV pass (or cross)</b>	(i) Another road user stops in order to let the AV pass, although the road user had priority. (ii) Another road user stops in order to let the AV pass in a situation where the AV had priority. (iii) Another road user stops in order to let the AV pass in a situation of unclear priority.
<b>5. Traffic participant “tests” the AV</b>	(i) Another road user tests the AV by stepping into its path. (ii) Another road user tests the AV by stepping out of its path at the last moment.

300

301 Due to the small number of cases falling into some of the subcategories, only the five overarching  
 302 interaction categories were included in the analyses. In addition, some of the road infrastructure  
 303 characteristics were coded in too few scenarios to enable interpretation and therefore only the main

304 factors outlined in Table 1 were included in the analysis (e.g. one interaction took place at a taxi  
305 stand).

306 In Trikala, 331 interactions were coded across over 12 hours of footage. Of these, a total of 271  
307 interactions fitted into one of the categories outlined in Table 2, and contained some of the  
308 contextual factors outlined in Table 1. In La Rochelle, 302 interaction scenarios were coded across  
309 over 10 hours of video, with 245 fitting into the categories outlined in Table 1 and Table 2. Examples  
310 of the types of rare or one-off situations which did not fit the categories include situations where  
311 another road user interacted with a static AV; situations where another road user, e.g. a parked car,  
312 blocked the AV path; situations where the AV stopped unnecessarily or for no apparent reason; and  
313 situations where another road user was approaching the AV to talk to somebody (most likely the  
314 operator) on board.

### 315 **2.3.1.1 Data analysis**

316 Evaluations of the associations between the road infrastructure and road user factors (Table 1) and  
317 the interaction categories (Table 2) were conducted using Chi-Square analyses, which measure the  
318 divergence of the observed data points from the values expected under the null hypothesis of no  
319 association, and Fisher's exact tests (for small samples), which allow an examination of the  
320 significance of an association between two categorical variables. Adjusted Standardized Residuals  
321 (ASR) were used to test the strength of the difference between observed and expected values in  
322 situations when a cross-tabulation result is larger than a  $2 \times 2$  contingency table. This analysis  
323 enabled us to take account of the fact that the numbers in each group may not have been equal.  
324 ASR values of 2 or greater indicated a lack of fit of the null hypothesis in a given cell (Sharpe, 2015).  
325 Statistical analyses were completed using IBM SPSS v21.

### 326 **2.3.2 Automated video coding**

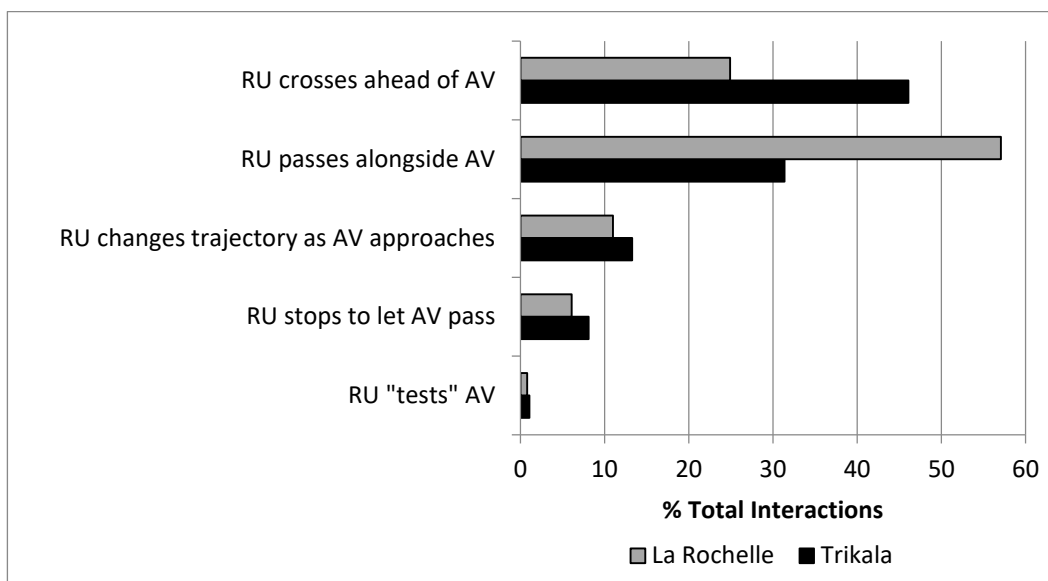
327 The second part of the data-analysis focused on the use of automated video analysis techniques to  
328 provide quantitative support for the manual observations, by examining the travelling speed of the  
329 AV, the pedestrian density along the route, and time to collision values for critical events. Videos  
330 from the centre cameras (see Figure 3) were post-processed offline. The vehicle's location and  
331 heading at each frame was inferred using a Dynamic Time Warp algorithm, which measures the  
332 similarity between two time-based sequences which may vary in speed (e.g. allowing a comparison  
333 of vehicles which may not have been travelling at the same speed), to align Scale Invariant Feature  
334 Transform (SIFT), or features detected within each frame of the video (Rao, Gritai, & Shah, 2003). In  
335 other words, the descriptive features of each frame in the reference video were compared to each  
336 new video to establish the frame location it was most similar to. Vehicle speed was computed at  
337 each video frame, using the location estimates obtained from the video alignment. The route was  
338 then reduced to a 1m square grid, and the mean speed in each box of the grid was computed for a  
339 sample of one in ten frames (to save on computation). These tools were selected as they provide  
340 standardised and easy to implement methods for general sequence alignment. A visual inspection of  
341 the data provided by the Dynamic Time Warp suggested that it provided similar accuracy and detail  
342 to more complicated models.

343 **3. Results**

344 **3.1 Manual analysis: Overall pattern of interaction scenarios**

345 The total number of interactions falling into each overarching interaction category across the two  
346 locations was calculated from the manual video coding (see Figure 4). The top three interaction  
347 types were almost the same in both locations, although there were some differences. The most  
348 commonly occurring category in Trikala was a road user crossing ahead of the AV (N=125). Although  
349 this type of interaction happened significantly more often in Trikala than La Rochelle ( $\chi^2=25.15$ ,  
350  $df=1$ ,  $p<0.001$ ), it still represented almost 25% of the interactions identified in La Rochelle (N=61).  
351 The most commonly occurring interaction category in La Rochelle was a road user passing alongside  
352 the AV (N=140). This type of interaction arose significantly more often in La Rochelle than in Trikala  
353 ( $\chi^2=34.77$ ,  $df=1$ ,  $p<0.001$ ), but was also one of the most commonly identified interactions in Trikala  
354 (N=85).

355 To understand whether the presence of an AV had any effect on how other road users moved  
356 through the environment, an analysis of changes in other road users' trajectories was conducted.  
357 This category was identified 36 times in Trikala, and 27 times in La Rochelle, with no significant  
358 differences between the two locations ( $\chi^2=0.62$ ,  $df=1$ ,  $p=0.43$ ). Finally, there was no significant  
359 difference between the two locations in terms of the number of observations of other road users  
360 stopping to give priority to the AV ( $\chi^2=0.77$ ,  $df=1$ ,  $p=0.38$ ), with this category occurring 22 times in  
361 Trikala and 15 times in La Rochelle. It is interesting to note that, across the two locations, only 5  
362 interactions involved a pedestrian or cyclist "testing" the vehicle.

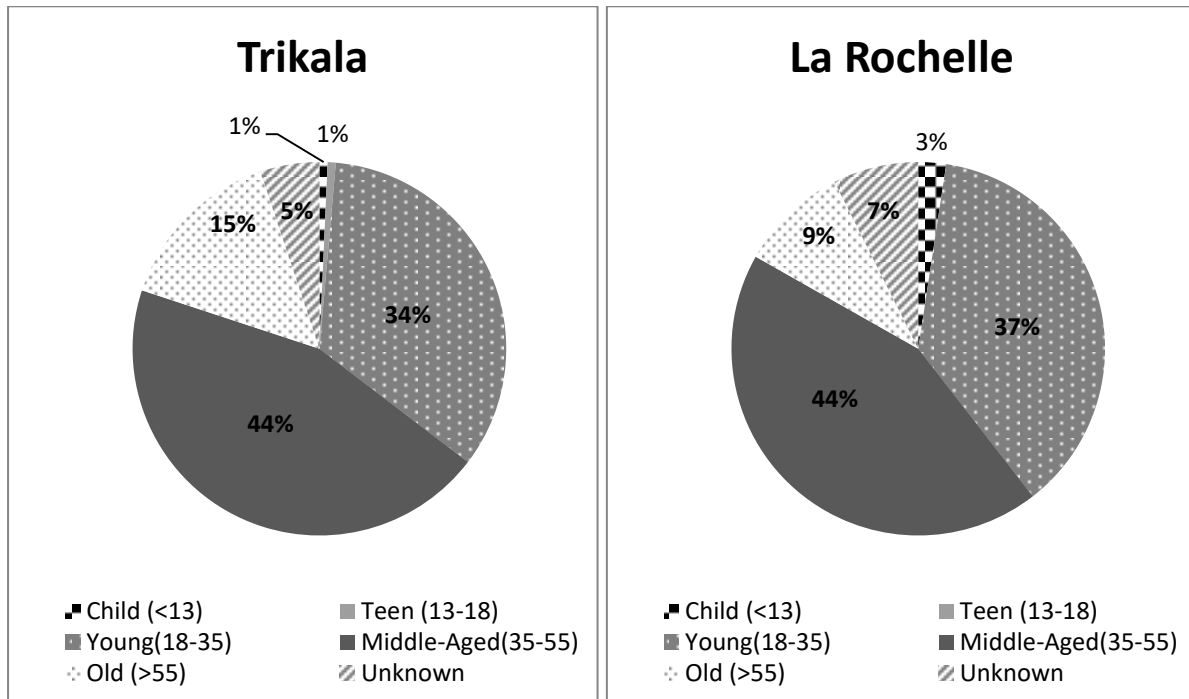


363

364 **Figure 4: Percentage of interactions falling into each of the categories in Trikala and La Rochelle**

365 Figure 5 shows the age range of the individuals involved in interactions with the AV, for both La  
366 Rochelle and Trikala. The evaluation of age was based on subjective judgement (e.g. Harrell, 1991;  
367 Harvard & Willis, 2012). Although there may be flaws in this method regarding differentiating  
368 between people who are close in age, it enables a descriptive overview of differences arising  
369 between younger and older age groups. Across both locations, the majority of interactions involved  
370 young adults (aged 18-35 years) and middle-aged adults (aged 35-55 years). Overall, more males

371 were identified as having interactions with the AVs in both Trikala (69.7% Male, 26.9% Female) and  
 372 La Rochelle (62.4% Male, 34.7% Female). However, it was not possible to identify gender and age in  
 373 every interaction.



374

375 **Figure 5: Proportion of people from each age group involved in interactions in Trikala (left) and La Rochelle**  
 376 **(right)**

377 **3.2 Manual Analysis: Impact of contextual variables on interaction**  
 378 **scenarios**

379 The following sections contain analyses which attempt to understand how road user behaviour and  
 380 interaction with the AV was influenced by the road infrastructure, or user demographic factors. This  
 381 analysis is based on the manual coding of the videos. For variables with two categories, chi square  
 382 tests of associations were conducted, while for variables with three or more categories, Fisher's  
 383 exact tests were used to provide more stringent criteria, given the small cell-count sizes for some of  
 384 the variables (Sharpe, 2015).

385 **3.2.1 Impact of Road Infrastructure**

386 Table 3 provides a breakdown of the number of observed interactions in each type of road  
 387 infrastructure, for the two locations. Due to the nature of the coding process, some road  
 388 infrastructure categories were difficult to identify. Therefore, the analyses outlined below are based  
 389 on 248 observations of a possible 271 in Trikala, and 217 of a possible 245 in La Rochelle.

390 **Table 3: Results of chi-square analyses examining associations between road infrastructure present and**  
 391 **observed road users' behaviours in Trikala (Tr) and La Rochelle (LR). (Numbers marked in bold represent**  
 392 **cases where the ASR value was greater than 2).**

Location		RU crossing ahead of AV			RU Passing Alongside the AV			RU Changes Trajectory in Presence of the AV			RU Stops to Give Priority to AV		
		Observed	Expected	ASR	Observed	Expected	ASR	Observed	Expected	ASR	Observed	Expected	ASR
<b>Normal Route</b>	Tr	39	47.9	<b>-2.3</b>	38	34.9	0.8	24	13.8	<b>3.9</b>	3	9.1	<b>-2.8</b>
	LR	21	19	0.7	40	41.5	-0.4	8	8.6	-0.3	5	5.2	-0.1
<b>Intersection</b>	Tr	46	34	<b>3.3</b>	20	24.8	-1.4	2	9.8	<b>-3.2</b>	8	6.4	0.8
	LR	12	8.9	1.3	14	19.4	<b>-2.0</b>	2	4	-1.2	7	2.4	<b>3.3</b>
<b>Zebra Crossing</b>	Tr	22	15.7	<b>2.3</b>	2	11.4	<b>-3.7</b>	2	4.5	-1.4	9	3	<b>4.0</b>
	LR	0	0	0	0	0	0.0	0	0	0.0	0	0	0.0
<b>At or near AV stop</b>	Tr	3	4	-0.7	5	2.9	1.5	1	1.2	-0.2	0	0.8	-0.9
	LR	5	2	<b>2.5</b>	3	4.4	-1.0	0	0.9	-1.0	0	0.6	-0.8
<b>Narrow path</b>	Tr	1	9.4	<b>-3.9</b>	16	6.9	<b>4.4</b>	3	2.7	0.2	1	1.8	-0.6
	LR	13	20.8	<b>-2.5</b>	56	45.3	<b>3.0</b>	11	9.4	0.7	2	5.7	<b>-2.0</b>
<b>Roundabout</b>	Tr	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	LR	1	1.8	-0.7	6	3.9	1.6	0	0.8	-1.0	0	0.5	-0.7
<b>Wide Road: 2-lanes</b>	Tr	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	LR	3	2.5	0.3	1	5.5	<b>-2.9</b>	4	1.2	<b>2.9</b>	1	0.7	0.4

393

394 As outlined in Table 3, the impact of road infrastructure on road users' behaviours was quite similar  
 395 across the two locations. In both locations there was a significant association between the type of  
 396 road infrastructure present, and the likelihood of a road user passing alongside the AV (Trikala:  
 397 Fisher's exact = 34.39, df = 4, p<0.001; La Rochelle: Fisher's exact = 20.87, df = 5, p<0.001). Road  
 398 users travelled closely alongside the AV significantly more often when the path was narrow, while  
 399 they were significantly less likely to do so near road crossing infrastructure such as zebra crossings or  
 400 intersections.

401 Similarly, there was a significant relationship between the type of road infrastructure, and the  
 402 likelihood of a road user crossing ahead of the AV in both locations (Trikala: Fisher's Exact = 31.35, df  
 403 = 4, p<0.001; La Rochelle: Fisher's Exact = 11.59, df = 5, p = 0.03). This type of interaction happened  
 404 significantly more often than expected in Trikala when there was supporting road infrastructure, for  
 405 example at an intersection or a zebra crossing. It was more likely to occur at, or near, an AV stop in  
 406 La Rochelle, where the AV was likely to be travelling particularly slowly. For both locations, this  
 407 behaviour was significantly less likely to occur on a narrow part of the route.

408 For both locations, a significant association also emerged between road infrastructure and the  
 409 interaction category of a road user stopping to give priority to an AV (Trikala: Fisher's exact=15.70, p  
 410 = 0.002; La Rochelle: Fisher's Exact = 10.32, df = 5, p = 0.04). In Trikala, this happened significantly  
 411 more often than expected at a zebra crossing, where the pedestrian should have had priority,  
 412 whereas in La Rochelle this behaviour happened significantly more often than expected at an  
 413 intersection.

414 While there was a significant association between the road infrastructure present and observations  
 415 of road users changing trajectory in Trikala (Fisher's Exact = 18.06, df = 4, p = 0.001), there was no  
 416 significant association in La Rochelle (Fisher's Exact = 8.00, df = 5, p = 0.11). This type of interaction  
 417 arose more often than expected on a normal part of the route in Trikala. An examination of the  
 418 adjusted residuals suggests that road users were somewhat more likely to change their trajectory on  
 419 the wide part of the road compared to other areas in La Rochelle, suggesting that when there is  
 420 space to do so, other road users will move away from the AV.

421 **3.2.2 Impact of type of Road User**

422 Table 4 provides a breakdown of the road users involved in specific interactions for the two  
 423 locations. As with the previous analyses, there were some missing data points, thus the analyses  
 424 below are based on 270 observations of a possible 271 in Trikala, and 243 of a possible 245 in La  
 425 Rochelle.

426 **Table 4: Results of tests of association between type of road user and observed road user behaviours in**  
 427 **Trikala (Tr) and La Rochelle (LR). (Numbers marked in bold represent cases where the ASR value was greater**  
 428 **than 2).**

Location		RU crossing ahead of AV			RU Passing Alongside the AV			RU Changes Trajectory in Presence of the AV			RU Stops to Give Priority to AV		
		Observed	Expected	ASR	Observed	Expected	ASR	Observed	Expected	ASR	Observed	Expected	ASR
Pedestrian	Tr	94	75.3	<b>4.7</b>	27	51.6	<b>-6.6</b>	23	21.9	0.4	17	13.4	1.7
	LR	49	46.2	1.0	100	107	<b>-2.1</b>	23	20.8	1.1	13	11.5	0.9
Cyclist	Tr	21	38.1	<b>-4.5</b>	48	26.1	<b>6.2</b>	10	11.1	-0.4	4	6.8	-1.3
	LR	10	12.1	-0.8	37	28	<b>2.9</b>	1	5.4	<b>-2.3</b>	1	3	-1.3
Car Driver	Tr	2	1.8	0.2	1	1.3	-0.3	1	0.5	0.7	0	0.3	-0.6
	LR	0	0.7	-1.0	0	1.7	<b>-2.0</b>	3	0.3	<b>4.9</b>	0	0.2	-0.4
Powered 2-wheeler	Tr	6	7.8	-0.9	8	5.4	1.4	2	2.3	-0.2	1	1.4	-0.4
	LR	0	0.5	-0.8	2	1.1	1.2	0	0.2	-0.5	0	0.1	-0.4
Van/Truck/Bus	Tr	1	0.9	0.1	1	0.6	0.6	0	0.3	-0.6	0	0.2	-0.4
	LR	1	5	0.8	0	1.1	-1.6	0	0.2	-0.5	1	0.1	2.6

429

430 In both Trikala (Fisher’s Exact=46.14, df=4, p<0.001) and La Rochelle (Fisher’s Exact=14.90, df=4, p =  
 431 0.001), cyclists travelled alongside the AV significantly more often than expected, compared to other  
 432 road user groups, while car drivers and pedestrians were significantly less likely to portray this  
 433 behaviour (see Table 4).

434 For the other interaction categories, the road user behaviour patterns were somewhat different in  
 435 the two locations. In La Rochelle, car drivers were more likely than expected to change their  
 436 trajectory for an AV, when compared to other road users, while cyclists were significantly less likely  
 437 to do so (Fisher’s Exact=17.92, df = 4, p = 0.001). However, there was no significant association  
 438 between road user type and changing trajectory in Trikala (Fisher’s Exact = 1.43, df = 4, p = 0.81). On  
 439 the other hand, pedestrians in Trikala crossed the road ahead of the AV significantly more often than  
 440 expected, while cyclists were significantly less likely than expected to engage in this behaviour  
 441 (Fisher’s exact=24.44, df=4, p<0.001). There were no significant associations for this behaviour in La  
 442 Rochelle (Fisher’s exact = 2.52, df = 4, p = 0.58).

443 There were also no significant associations between the type of road user present and the likelihood  
 444 of stopping to give priority to the AV in either location (Trikala: Fisher’s Exact = 2.63, df = 4, p = 0.58;  
 445 La Rochelle: Fisher’s Exact = 6.82, df = 4, p = 0.14).

446 **3.2.3 Impact of pedestrian demographics and group size**

447 In order to understand whether pedestrian interactions with AVs are influenced by their gender or  
 448 age-group, tests of association were conducted between each of the road user behaviour categories  
 449 and observed categorisation of their age and gender, as well as whether they were travelling in a  
 450 group (group status). Table 5 provides a breakdown of the results of the Fishers exact and chi-square  
 451 tests of association, examining the relationships between age, gender and group status, and each of  
 452 the road user interaction categories. It was not always possible for the coders to identify the  
 453 pedestrians’ gender or estimate their age. Therefore, the analyses for gender are based on 262



454 observations of a possible 271 in Trikala, and 238 of a possible 245 in La Rochelle; while the analyses  
 455 for age are based on 257 observations in Trikala, and 227 in La Rochelle.

456 **Table 5: Results of tests of association between age, gender, and group status, and the road user interaction**  
 457 **categories (significant associations marked in bold)**

		Location		Age		Gender		Group Status	
		Tr	LR	Fisher's Exact	p	$\chi^2$	p	$\chi^2$	p
<b>RU crossing ahead of AV</b>	Tr			4.56	0.29	0.04	0.89	0.30	0.60
	LR			3.92	0.26	0.09	0.88	5.59	<b>0.02</b>
<b>RU passing alongside AV</b>	Tr			8.08	0.06	0.002	1.00	1.32	0.25
	LR			9.54	<b>0.02</b>	3.32	0.07	3.18	0.09
<b>RU changes trajectory</b>	Tr			5.12	0.28	2.03	0.22	1.12	0.29
	LR			2.6	0.46	3.94	<b>0.05</b>	0.04	1.00
<b>RU stops to give priority to AV</b>	Tr			3.15	0.53	3.70	<b>0.05</b>	0.51	0.48
	LR			7.64	<b>0.04</b>	1.32	0.25	0.09	0.79

458

459 The effects of gender differed across the two locations. In La Rochelle, there was a significant  
 460 association between gender and road users changing their trajectory ( $\chi^2 = 3.94$ ,  $df = 1$ ,  $p = 0.05$ ), with  
 461 female traffic participants (Observed = 13, Expected = 8.6, ASR = 2.0) significantly more likely than  
 462 expected to change direction, compared to males (Observed = 11, Expected = 15.4). In Trikala, the  
 463 only significant association which emerged with gender was that, when compared to males, female  
 464 pedestrians (Observed = 10, Expected = 6.1, ASR = 1.9) stopped to give way to the AV significantly  
 465 more than expected (Observed = 12, Expected = 15.9;  $\chi^2 = 3.70$ ,  $df = 1$ ,  $p = 0.05$ ).

466 Finally, in La Rochelle, the only significant association with road users' crossing ahead of the AV, was  
 467 whether the road user was moving as an individual or as part of a group ( $\chi^2 = 5.59$ ,  $df = 1$ ,  $p = 0.02$ ),  
 468 with people walking alone (Observed = 39, Expected = 31.2, ASR = 2.4) crossing ahead of the AV  
 469 significantly more often than when in a group (Observed = 19, Expected = 26.8).

470 Table 6 provides a breakdown of the number of observed interactions around each age group for  
 471 the two locations. It should be noted that the teenager category was never selected for observations  
 472 of La Rochelle, perhaps suggesting the difficulty in distinguishing this age group from other  
 473 categories.

474 In La Rochelle (Fisher's Exact = 9.54,  $df = 3$ ,  $p = 0.02$ ), there was a significant association between  
 475 pedestrian age group and the likelihood of a road user passing alongside the AV, with children  
 476 (under 13 years of age) significantly more likely than expected to engage in this type of interaction,  
 477 and older pedestrians significantly less likely (see Table 6). There was also a significant effect for  
 478 road users stopping to give priority to the AV (Fisher's Exact=7.64,  $df = 3$ ,  $p = 0.04$ ), with older road  
 479 users stopping significantly more often than expected. There were no significant associations  
 480 between age and road users' behaviours around the AV in Trikala. However, an examination of the  
 481 adjusted standardised residuals suggests older pedestrians were slightly less likely to pass alongside  
 482 the AV, while young adults were slightly more likely to.

483 **Table 6: Results of tests of association between age-group of road users and observed road user behaviours**  
 484 **in Trikala (Tr) and La Rochelle (LR). (Numbers marked in bold represent cases where the ASR value was**  
 485 **greater than 2).**

	Location	RU crossing ahead of AV			RU Passing Alongside the AV			RU Changes Trajectory in Presence of the AV			RU Stops to Give Priority to AV		
		Observed	Expected	ASR	Observed	Expected	ASR	Observed	Expected	ASR	Observed	Expected	ASR
<b>Child (&lt;13)</b>	Tr	1	0.9	0.1	0	0.6	-1.0	1	0.3	1.6	0	0.2	-0.4
	LR	0	1.5	-1.5	6	3.5	<b>2.1</b>	0	0.6	-0.8	0	0.4	-0.6
<b>Teen (13-18)</b>	Tr	0	0.9	-1.3	0	0.6	-1.0	1	0.3	1.6	0	0.2	-0.4
	LR	0	0	0.0	0	0	0.0	0	0	0	0	0	0
<b>Young Adult (18 - 34)</b>	Tr	38	42.6	-1.2	37	28.6	<b>2.3</b>	12	11.8	0.1	5	7.9	-1.3
	LR	23	23.3	-0.1	55	52.9	0.6	7	8.4	-0.7	4	5.6	-0.9
<b>Middle-aged (35 - 55)</b>	Tr	57	56	0.2	36	37.7	-0.4	14	15.5	-0.6	12	10.4	0.7
	LR	26	27.3	-0.4	63	62.2	0.2	13	9.9	1.4	5	6.6	-0.9
<b>Older (&gt;55 )</b>	Tr	23	18.5	1.5	7	12.5	<b>-2.0</b>	5	5.1	-0.1	5	3.4	1
	LR	9	5.9	1.6	8	13.4	<b>-2.4</b>	1	2.1	-0.9	5	1.4	<b>3.3</b>

486

### 487 3.2.4 Road user “tests” AV

488 Across the two locations, only 5 cases of road users testing the AVs were identified. There were not  
 489 enough cases to run any statistical analyses on this data. However, a qualitative exploration of the  
 490 cases provides some interesting insights. In Trikala, this situation arose three times. The first case  
 491 occurred when a teenage girl, walking as part of a group, stuck out her leg while the AV was  
 492 approaching. The other two incidents involved two separate middle-aged men, both of whom  
 493 jumped out in front of the AV to test if it would stop. The two cases in La Rochelle were quite similar,  
 494 with one incident involving two teenage boys who ran backwards and forwards ahead of the AV, and  
 495 another incident involving a middle-aged man who appeared to be communicating with the AV’s  
 496 operator.

### 497 3.3 Automated analysis: Speed profiles and pedestrian locations

498 Thus far, the focus of the analysis has been on the subjective coding of the video material. To  
 499 provide a more objective overview of the interaction between AVs and pedestrians, automated  
 500 analyses of the videos (as described in Section 2.3.2) were conducted, to provide an overview of the  
 501 speed profiles of the AV, and information about the density of pedestrians in each location, for the  
 502 two sites. Figure 6(a) and Figure 7(a) shows the vehicles average speed along the routes in the two  
 503 cities, as indexed by the speed bars in the lower left corners. In both locations, the vehicles travelled  
 504 between 7 and 14 km/h, with some variance along the routes. Figure 6(b) and Figure 7(b) show all  
 505 the pedestrian detections encountered during the trials, for both La Rochelle and Trikala. Each  
 506 detection is represented using a black dot, giving an indication of the density of pedestrians in  
 507 different regions. Pedestrians are shown in absolute space, including their horizontal distance into  
 508 the road or pavement. In Trikala, there was a similar level of pedestrian density across the whole  
 509 route, whereas in La Rochelle, there appeared to be a higher number of pedestrians towards the  
 510 beginning / end of the route (depending on travel direction).

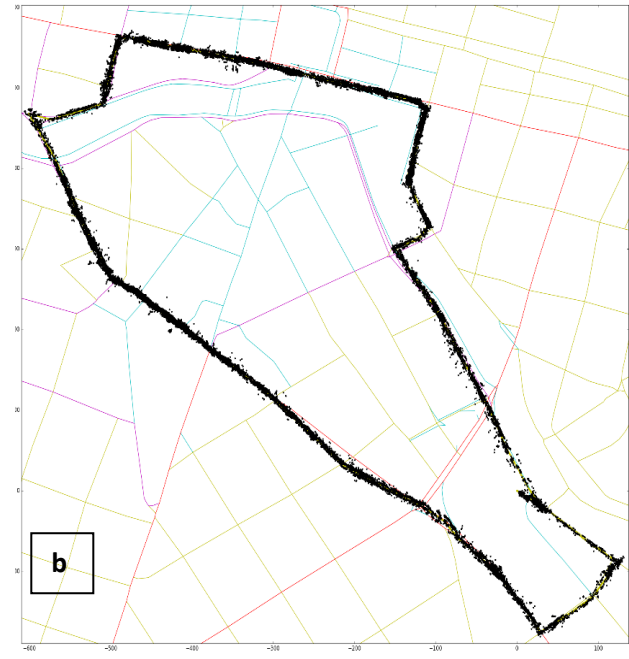
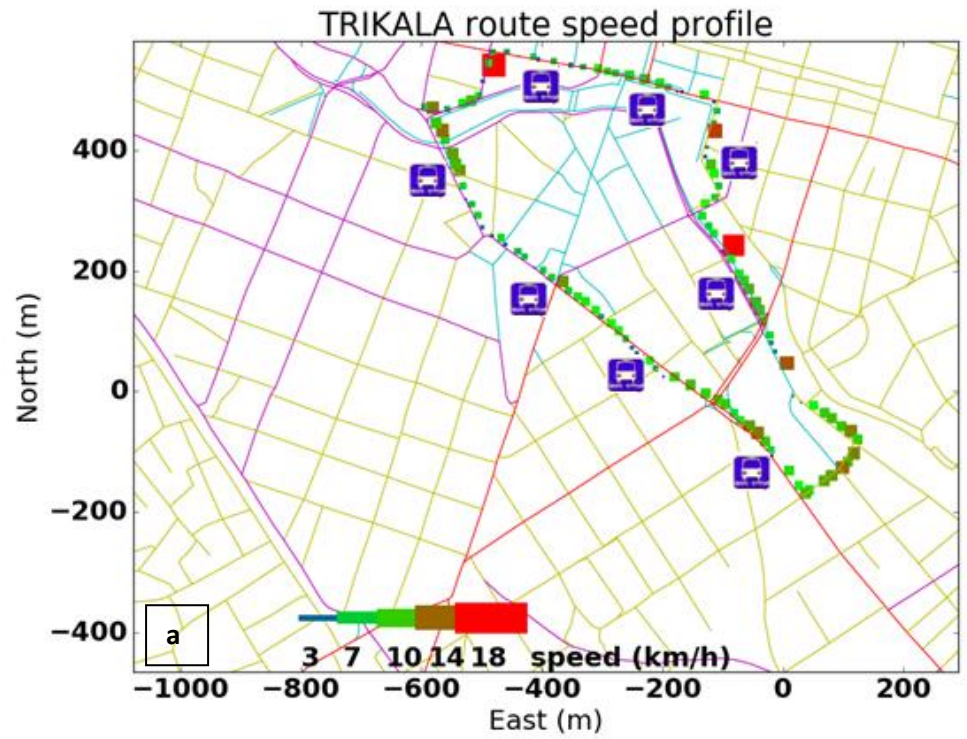
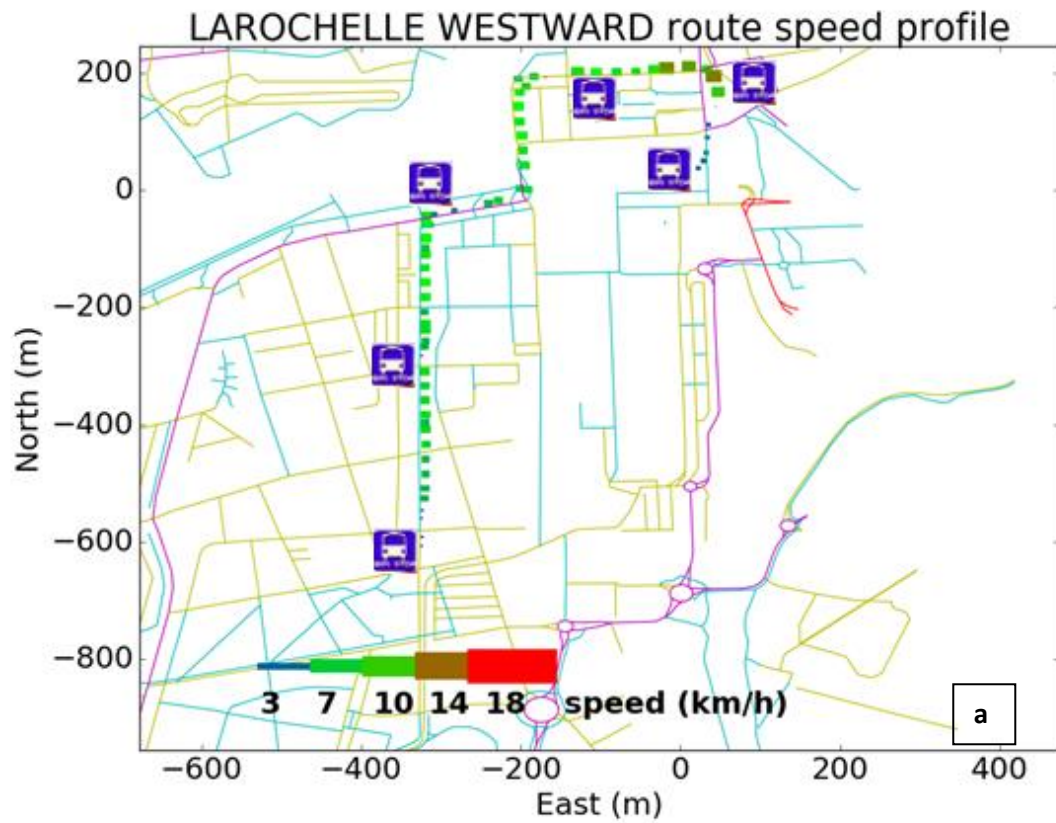


Figure 6: Average speed profile (a) and pedestrian densities (b) across the route in Trikala

511  
512  
513



514  
515

Figure 7: Average speed profile (a) and pedestrian densities (b) across the AV route in La Rochelle

### 516 **3.4 Video analysis: Critical events**

517 During the manual video analysis, the criticality of each interaction was subjectively evaluated by the  
518 coder, based on the potential for a collision to occur. Incidents defined as highly critical involved  
519 near miss events, where the coder believed that a collision had been narrowly avoided. Across the  
520 analyses, the coders identified 14 interactions which were deemed to have safety-critical  
521 implications (Trikala, N = 9, La Rochelle, N = 5). In order to get a more objective measure of criticality  
522 for these situations, automated video analysis tools were used to calculate the distance between the  
523 two road users involved, and the minimum time to collision (TTC, Green, 2013) for each of the  
524 situations.

525 **Table 7: Speed, distance, minimum TTC, and text description of all manually coded critical incidents**

No.	Location	Distance to AV (m)	AV Speed (m/s)	Minimum TTC (s)	Description
1.	La Rochelle	2.81	3.27	0.86	Cyclist crosses a very short distance ahead of the AV, moving from left to right.
2.	La Rochelle	3.23	3.48	0.93	A group of people are sitting on the kerb to the right of an AV. One woman steps out in front of the AV while standing up but quickly moves out of the way again.
3.	La Rochelle	2.40	3.06	0.79	A number of groups are walking on the road with their backs to the AV near café's/restaurants and sea-front. They move out of the way once they notice the AV. The closest person was a woman with a pram who took longer to move.
4.	La Rochelle	2.43	3.07	0.79	A group of young adults/teenagers are walking towards the AV near the café's/restaurants and sea-front (same location as incident 3), and move to the left out of its way, but are remain quite close to the left-hand side of the AV.
5.	La Rochelle	2.223	3.34	0.67	A group of young adults/teenagers are congregating at a right turn corner, and are slow to move out of the way of the AV.
6.	Trikala	3.24	3.14	1.03	At pedestrian crossing, a male & female pedestrian (travelling separately) cross a very short distance ahead of the AV. A number of pedestrians and cyclists cross in each direction during AV approach.
7.	Trikala	4.07	3.23	1.26	A female pedestrian is standing in the AV lane with her back to the AV. Once she becomes aware of the AV approach she jumps out of the way.
8.	Trikala	5.38	2.96	1.82	At dusk, the AV is turning left at an intersection and a cyclist crosses a very short distance ahead (video image unclear)
9.	Trikala	2.23	2.86	0.78	At dusk, a male pedestrian approaches from the left & jumps out suddenly in front of the AV.
10.	Trikala	2.23	3.15	0.71	At a pedestrian crossing (same location as incident 6), an older man approaching from the left changes speed to run across ahead of the AV. On AV approach there are numerous other pedestrians crossing from both the left & right.
11.	Trikala	3.06	3.23	0.95	On a corner with a pedestrian crossing, a man and boy cross from the left a short distance ahead from the AV and have to run to get past.
12.	Trikala	2.23	2.51	0.89	The AV passes very closely alongside a vehicle reversing out of garage on the right.
13.	Trikala	3.03	2.95	1.03	On a corner with a pedestrian crossing (same location as incident 11), a female pedestrian crosses from the right a very short distance ahead of the AV.
14.	Trikala	2.23	3.08	0.73	On a corner with a pedestrian crossing (same location as incident 11 & 13), a pedestrian crosses the street from the left very closely ahead of the vehicle.

527 As shown in Table 7, there were some locations at which critical incidents appeared more often. For  
528 example in both La Rochelle and Trikala, there were four close incidents at corners, where the AV  
529 was required to make a right turn, and visibility of pedestrians may have been low. In addition, in La  
530 Rochelle, the busy area surrounded by restaurants and cafés appeared to lead to pedestrians acting  
531 in a more relaxed manner around the AV, getting quite close to it. In Trikala, two of the critical  
532 incidents arose at one particular pedestrian crossing, where pedestrians obviously believed they  
533 should have right of way. The AV did not appear to come to a complete stop at this crossing, which  
534 may have led to increased uncertainty from the pedestrians' point of view.

535 According to the automated video analysis, the manual coding process captured all of the  
536 encounters with a minimum TTC of less than or equal to 1 s, confirming that these were indeed  
537 near-miss events. An examination of the distances suggest that any TP passing up to 3.25 m ahead of  
538 an AV travelling at an average speed of 3.10 m/s is likely to be of high risk.

## 539 **4. Discussion**

540 The main purpose of this study was to gain an understanding of the types of interactions occurring  
541 between AVs and other road users. This was achieved via analysis of video footage which focused on  
542 actual interactions between AVs and other road users, during the CityMobil2 demonstrations in  
543 Trikala in Greece, and La Rochelle in France. This in-depth evaluation allows us to understand the  
544 types of interaction which are likely to arise with the introduction of AVs into mixed traffic  
545 environments in urban areas, and enables us to develop an understanding of whether contextual  
546 artefacts are likely to lead to changes in road users' behaviour around these vehicles. Knowledge of  
547 typical AV interaction scenarios and linked contextual factors will ensure that policy, planning, and  
548 communication implications can be identified to maximise road users' perceptions of safety and  
549 convenience, and thus their acceptance of these AVs (Fuest et al., 2017).

### 550 **4.1 Road infrastructure factors: Findings & implications**

551 Road infrastructure factors had a major impact on the types of interaction which occurred in both of  
552 the CityMobil2 demonstration locations. Although road users in Trikala were more likely to cross the  
553 road a short distance ahead of the AV at intersections or zebra crossings, for both locations, they  
554 were also more likely to stop to let an AV pass in this type of environment. This suggests that there  
555 may have been some uncertainty as to whether the AV would obey the right-of-way rules of the  
556 road. A particular issue in Trikala was that the AVs were not obliged to obey the traffic lights at  
557 certain junctions, and this appeared to cause some confusion for other road users. In addition, the  
558 analysis of critical incidents showed that there was some hesitation at zebra crossings, which may  
559 indicate that pedestrians believed they should have right-of-way and were endangered when the AV  
560 did not behave in line with this expectation. Clearly, further technological developments of AVs will  
561 allow better connection with its surrounding environment, allowing it to adhere to current road  
562 regulations, reducing uncertainty for other road users.

563 One of the most common techniques used by VRUs to establish whether a vehicle will yield, is its  
564 travelling speed (Bertulis & Dulaski, 2014; Clamann et al., 2017). Therefore, pedestrians and cyclists  
565 interacting with the slow-moving AVs during the CityMobil2 trials may have expected the vehicle to  
566 adhere to conventional traffic behaviour, and give way. This disparity between the behaviour of the  
567 AV and the implicit expectations of the pedestrian/cyclist may have increased the riskiness of these

568 situations. Indeed, previous research with AVs has highlighted the importance of ensuring that the  
569 signals given both explicitly (e.g. through external human-machine interfaces) and implicitly (e.g.  
570 through speed or braking behaviour) are consistent (Lagström and Lundgren, 2015). In La Rochelle,  
571 this was likely to have been less of an issue due to the shared nature of the space, where other road  
572 users could adjust their route from a distance away, to avoid having to cross directly ahead of the  
573 AV.

574 Road users in both locations were more likely to pass closely alongside the AV in narrow areas, with  
575 this type of event occurring particularly often at a one-way bridge in La Rochelle, and areas where  
576 the lane alongside the AV was narrow in Trikala. Interestingly, users in both locations were less likely  
577 to cross ahead of the AV in areas where the road was narrow. In addition, road users were more  
578 likely to change their trajectory to accommodate the AV along the normal route, which consisted of  
579 a dedicated lane alongside other traffic in Trikala. There was also a trend for this type of behaviour  
580 to be observed in the wide road sections of La Rochelle, where it was possible for two vehicles to  
581 pass each other. These findings show the importance of understanding the context in which the AV  
582 operates, as it seems that the width of the road influenced the level of risk VRUs were likely to  
583 accept when interacting with AVs. Previous research with conventional vehicles has shown that the  
584 separation of road users can lead to a decrease in accident risk (Vandenbuckle et al., 2014; Kim et  
585 al., 2012). In addition, a questionnaire study conducted at the CityMobil2 demonstration sites found  
586 that pedestrians had a clearer understanding of their priority, and felt safer when AVs operated in a  
587 dedicated lane (Merat, Louw, Madigan, Dziennus, & Schieben, 2018). Therefore, the current results  
588 suggest that risk-taking behaviour around AVs will be reduced if sufficient space is provided for both  
589 modes of traffic, allowing them to adopt separate trajectories.

## 590 **4.2 Road user factors: Findings and implications**

591 The types of interaction portrayed by the different road user groups varied considerably. In both  
592 locations, cyclists were most likely to travel closely alongside the AV, and as mentioned in the  
593 previous section, this was most likely to occur on narrow parts of the road. Cyclists were also  
594 significantly less likely than expected to change their trajectory when approaching the AV in La  
595 Rochelle, and were less likely to cross ahead of the AV in Trikala, compared to the other road user  
596 groups. These results suggest that cyclists in both locations were not overly concerned about  
597 proximity to the AV. This type of behaviour may cause problems in the future, because of the  
598 increased risk of collisions when cyclists and vehicles share the same space (Vandenbulcke et al.,  
599 2014).

600 In terms of giving way to the AVs, the pattern of road user behaviours was slightly different for the  
601 two locations. In La Rochelle, car drivers were more likely than other road users to change their  
602 trajectory for the AV, a behaviour that was not apparent in Trikala. On the other hand, pedestrians  
603 in Trikala crossed ahead of the AV more often than expected, whereas this was not the case in La  
604 Rochelle. Once again, these differences in road user behaviours may be a reflection of the difference  
605 in the infrastructure provided in Trikala and La Rochelle. For the majority of the route in La Rochelle,  
606 the AVs operated in a shared space, where pedestrians could adjust their route from a distance  
607 away to avoid having to closely interact with the AVs. However, some parts of the route were quite  
608 narrow, where there was not enough space for two vehicles to travel, and this led to a change in  
609 trajectory by car drivers, to move out of the AV's path. In Trikala, the pedestrian crossing options  
610 were more limited, and there were a number of intersections and zebra crossing areas, which may



611 have led to the increased likelihood of pedestrians crossing a short distance ahead of the AV. These  
612 results once again highlight the importance of taking context into account when investigating AV  
613 interaction behaviours, as requirements for vehicle communications are likely to vary depending on  
614 the environmental design in a given location.

615 A number of gender differences emerged across interaction categories, with females seeming to  
616 show more cautionary behaviour in their interactions with the AVs than males. For example, in La  
617 Rochelle, female road users were more likely to change their trajectory to give themselves more  
618 space when moving ahead of, or beside the AVs - where there was the space to do so. They were  
619 also more likely to stop to give priority to the AV in Trikala - where they had fewer options for  
620 getting out of the way. These results show that the inherent gender-based differences observed in  
621 interactions with conventional vehicles (Bernhoft & Carstensen, 2008; Harrell, 1991) are unlikely to  
622 change when interacting with AVs.

623 Age-related interaction patterns also emerged within the analysis. In La Rochelle, the older age  
624 group (>55 years) were more likely to stop and give priority to the AV, and less likely to pass closely  
625 alongside the AV. Children (<13 years), were the group most likely to pass closely alongside the AV. A  
626 similar pattern of results emerged in Trikala, although it did not reach significance. These findings  
627 suggest that, similar to current traffic patterns (Bernhoft & Carstensen, 2008; Oxley et al., 2005),  
628 older pedestrians may show cautious behaviour around even slow-moving AVs. However, the fact  
629 that these links to demographics was not consistent across the two locations emphasises the  
630 importance of surrounding infrastructure in this context. Further research is, therefore, required to  
631 gain an understanding of the specific ways in which infrastructure design might facilitate, or hinder,  
632 the interactions of AVs with specific demographic groups e.g. older road users. However, the  
633 pattern of results suggests that, for AVs to provide a service better than humans, they may benefit  
634 from algorithms that differentiate between specific road user groups, targeting interaction and  
635 communication strategies accordingly.

636 Previous research has shown an increased likelihood of risky crossing behaviours for groups rather  
637 than individuals (Zhou et al., 2009). However, in the current study, the only significant difference in  
638 interaction behaviours between individuals and groups was observed in La Rochelle, when  
639 compared to groups, individuals were actually significantly more likely than expected to cross ahead  
640 of the AV. It is not clear why this difference might have emerged, but it is possible that in the shared  
641 space environment, the impact of a group was actually to avoid the AV route altogether, rather than  
642 to cross ahead of it.

643 One area of concern which has been identified in the media (see Connor, 2016; Mitchell, 2015) is  
644 that road users may take advantage of easily identifiable AVs by engaging in dangerous behaviours  
645 on the assumption that the AV will always stop. A qualitative exploration of these cases suggests  
646 that these types of incidents are quite rare, with only 5 cases emerging across approximately 24  
647 hours of video. However, this implies that there is a “testing” incident once every 4.8 hours of video  
648 recording and 100 or so interactions, suggesting that while the novelty of these vehicles is still high;  
649 this issue may arise somewhat regularly.

650 There were also a total of 14 critical incidents identified in this data-set, which amounts to roughly  
651 one “near-miss” incident for every three hours of autonomous driving. This is a major issue for AV  
652 designers, because, as the speed of these vehicles increases the likelihood of a collision occurring

653 will also increase. Therefore, the pedestrian and cyclist detection systems on these AVs need to be  
654 extremely accurate, particularly on approaches to turns, and in busy, shared, urban spaces. Many of  
655 the road users captured in this study will have only interacted with the AVs once or twice. Thus, it  
656 remains to be seen how interaction patterns change when the novelty of these types of vehicle  
657 wears off. Future research should use the TTC criteria identified for near-misses in this study to  
658 investigate whether this rate of near-misses is typical when larger data-sets become available.

### 659 **4.3 Implications for the design of automated road user detection**

660 This study provides a first understanding of the interaction detection capabilities required for future  
661 automated incident detection systems. The qualitative video analysis technique used allowed the  
662 identification of a wide variety of interaction scenarios and influential factors, which can be used by  
663 the developers of intention recognition algorithms to better understand which elements in the  
664 environment may accurately predict road users' likely behaviour. The results indicate that AVs must  
665 have the capability to identify the surrounding road infrastructure in order to successfully negotiate  
666 with other road users. Further development of this technology will allow AVs to move more  
667 efficiently and safely through the traffic system, particularly in busy, urban spaces, where AVs will  
668 need to be able to quickly differentiate between pedestrians and cyclists whose trajectories are  
669 likely to intersect with the AV.

### 670 **4.4 Conclusions**

671 The results of this analysis show that the interaction requirements of road users are unlikely to  
672 change dramatically with the introduction of AVs. Similar to the findings of recent studies conducted  
673 by Rothenbücher et al. (2016) and Clamann et al. (2017), our analysis showed that in the absence of  
674 erratic behaviour by the vehicle, road users generally adhered to existing interaction patterns.  
675 However, in situations where the AV did not behave as expected, pedestrians showed some  
676 uncertainty regarding how to behave, and there appeared to be a higher risk of near-miss events  
677 occurring. Therefore, in close-proximity situations AVs should be required to communicate their  
678 intentions accurately to other road users, to avoid frustration, and increase safety (Fuest et al., 2017;  
679 Habibovic et al., 2018; Schieben et al., 2018).

680 The AVs in both La Rochelle and Trikala operated in a mixed traffic environment, with high  
681 pedestrian density, leading to a higher probability of interactions. Previous research has shown that  
682 pedestrians do not always feel comfortable or safe when moving through a shared space with either  
683 conventional vehicles (Moody & Melia, 2014) or AVs (Merat et al., 2018), and the results of this  
684 study provide support for the idea that, where possible, VRUs will leave as much space as possible  
685 between their trajectories and that of the AV. However, in situations where the infrastructure did  
686 not allow for the separation of traffic, risky behaviours were more likely to emerge, with cyclists, in  
687 particular, travelling closely alongside the AVs on narrow paths of the road rather than waiting for  
688 the AV to pass.

689 The results highlight the importance of implementing the correct infrastructure to support the safe  
690 introduction of AVs, while also ensuring that the behaviour of the AV matches other road users'  
691 expectations as closely as possible, in order to avoid traffic conflicts. Finally, this paper provides  
692 some insights into the factors required for the development of accurate detection systems for AVs,  
693 by highlighting the differences in behaviour which arise in different environments, and among  
694 different road user groups.

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