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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.

1. Introduction

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

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

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

1.1. Factors that influence traffic interactions

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

1.1.1 Road infrastructure characteristics

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

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

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

1.1.2 Road user characteristics

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

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

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

1.1.3 Vehicle characteristics

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

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

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

1.2. Aims and objectives

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

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

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

2. Method

2.1 Video collection

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

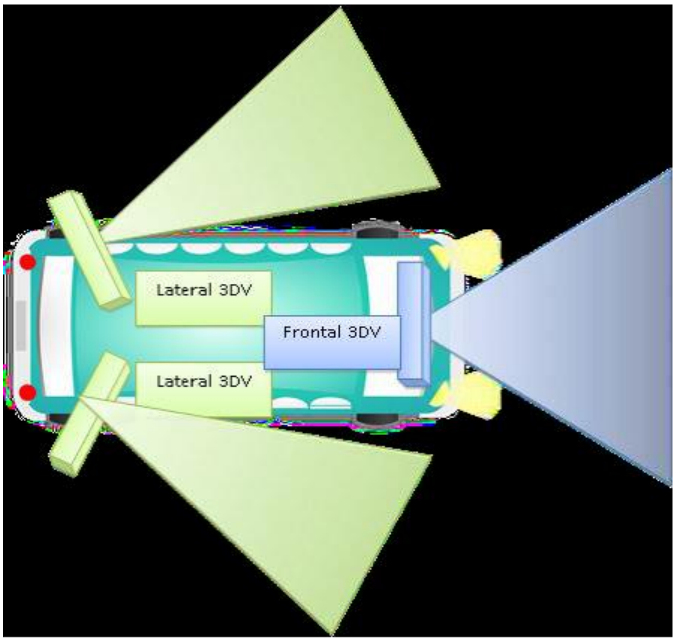

Figure 2: Aerial view of the positioning and area covered by the three 3DV cameras

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

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

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

2.2 Description of locations

The characteristics of the road infrastructure differed across the two CityMobil2 demonstration sites. In Trikala, the "normal route" used by the AV (see Table 1) consisted of a demarcated, dedicated lane, segregated from the rest of the vehicular, cyclist, and pedestrian traffic. Much of this area had previously been allocated as 800 parking spaces, and there were times when the AV had to move around a parked vehicle. The trial involved the installation of a control centre, road segregation equipment, road signage, and new traffic lights (Raptis, 2016). There were two areas where the AV travelled in a shared space; one where it moved through an off-road area with pedestrians and cyclists, and another area where it entered the same stream as vehicular traffic on the approach to a set of traffic lights. In a number of areas, the traffic alongside the AV was moving on a one-way street, and there was not much space between the AV and other vehicles. The AV was given priority at all intersections, and did not have to obey traffic lights. The majority of the route (see Figure 6) was located in a busy town centre, in an area surrounded by shops and offices.

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

2.3 Video coding and analysis

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

2.3.1 Manual video coding procedure

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

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

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

Contextual Factors	Categories
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)

The remaining videos were then divided between two trained coders, who were given a detailed description and examples of each of the interaction categories. These coders watched each video in its entirety, pausing the video when any interaction scenario was identified, noting the type of interaction scenario, and categorising the contextual factors (road, user, and vehicle factors) which contributed to the scenario. In some cases, this required the creation of additional interaction categories to describe newly identified situations. These new categories were shared between the coders, and all coding was independently checked by a third coder to ensure inter-rater reliability and coding consistency. As more videos were watched and a deeper understanding of typical interactions emerged, some of the initial coding categories were amalgamated, and some new overarching categories were created. This led to a total of five overarching interaction types, with 15 subcategories (see Table 2). Where disagreements or uncertainty in coding arose, the interactions were discussed by all three coders until a consensus was reached.

Table 2: Description of interaction scenarios and sub-categories

Interaction type	Sub-categories
1. Traffic participant crosses in front of the AV	(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).
2. Traffic participant passes alongside of the AV	(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).
3. Traffic participant changes trajectory of movement	(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.
4. Traffic participant stops to let AV pass (or cross)	(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.
5. Traffic participant "tests" the AV	(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.

Due to the small number of cases falling into some of the subcategories, only the five overarching interaction categories were included in the analyses. In addition, some of the road infrastructure characteristics were coded in too few scenarios to enable interpretation and therefore only the main factors outlined in Table 1 were included in the analysis (e.g. one interaction took place at a taxi stand).

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

2.3.1.1 Data analysis

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

2.3.2 Automated video coding

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

3. Results

3.1 Manual analysis: Overall pattern of interaction scenarios

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

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

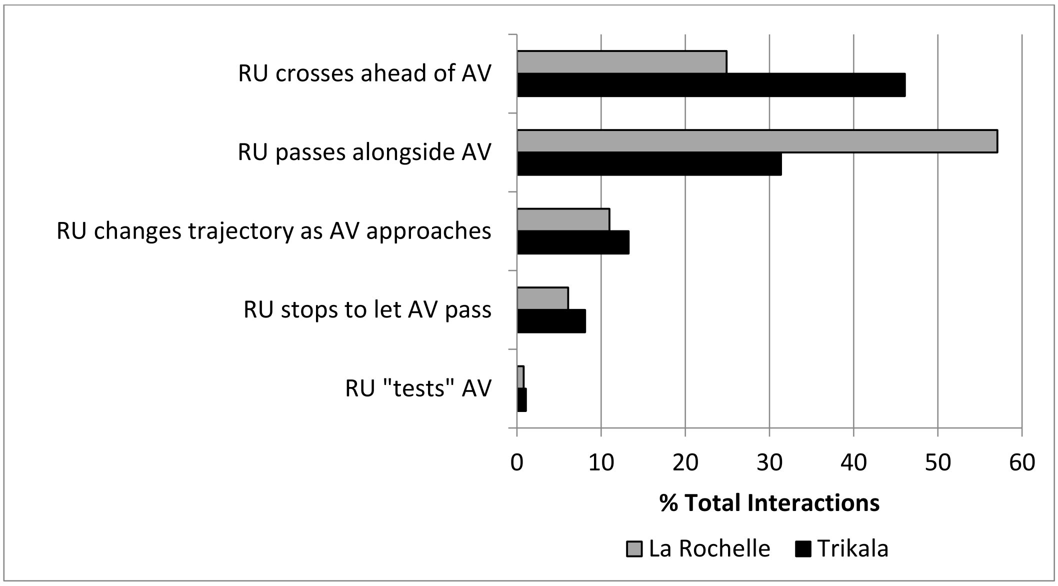

Figure 4: Percentage of interactions falling into each of the categories in Trikala and La Rochelle

Figure 5 shows the age range of the individuals involved in interactions with the AV, for both La Rochelle and Trikala. The evaluation of age was based on subjective judgement (e.g. Harrell, 1991; Harvard & Willis, 2012). Although there may be flaws in this method regarding differentiating between people who are close in age, it enables a descriptive overview of differences arising between younger and older age groups. Across both locations, the majority of interactions involved young adults (aged 18-35 years) and middle-aged adults (aged 35-55 years). Overall, more males were identified as having interactions with the AVs in both Trikala (69.7% Male, 26.9% Female) and La Rochelle (62.4% Male, 34.7% Female). However, it was not possible to identify gender and age in every interaction.

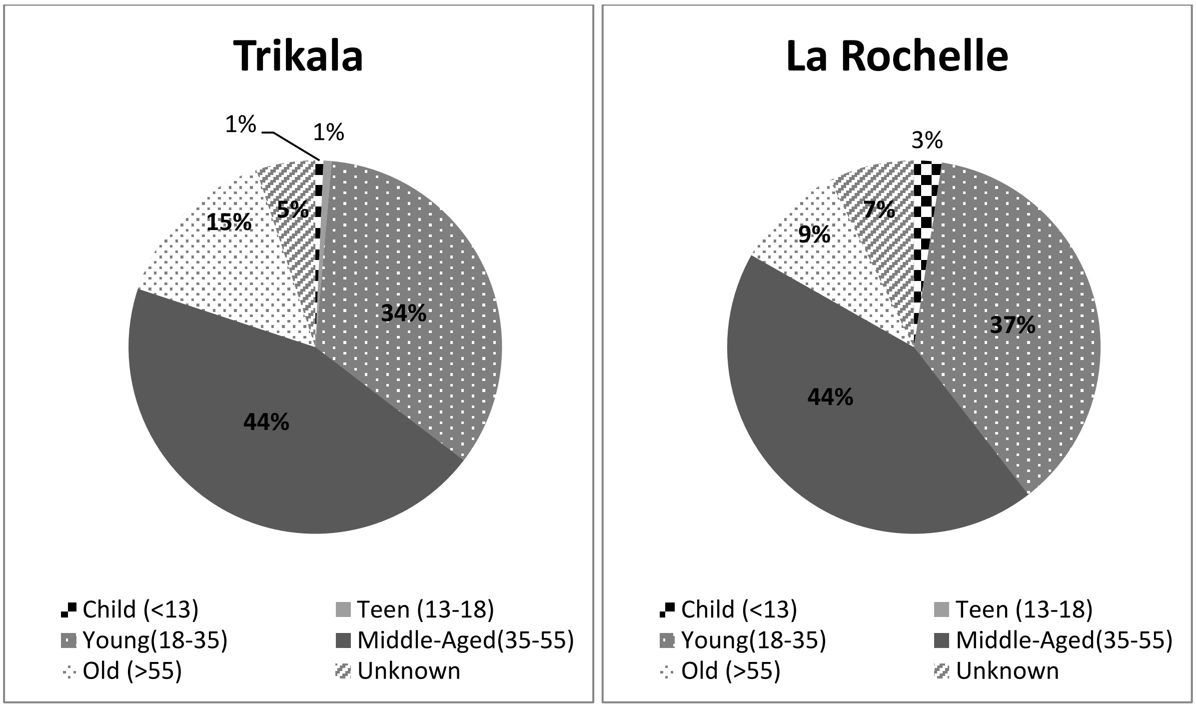

Figure 5: Proportion of people from each age group involved in interactions in Trikala (left) and La Rochelle (right)

3.2 Manual Analysis: Impact of contextual variables on interaction scenarios

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

3.2.1 Impact of Road Infrastructure

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

Table 3: Results of chi-square analyses examining associations between road infrastructure present and observed road users' behaviours in Trikala (Tr) and La Rochelle (LR). (Numbers marked in bold represent 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
Normal Route	**Tr**	39	47.9	**-2.3**	38	34.9	0.8	24	13.8	**3.9**	3	9.1	**-2.8**
	LR	21	19	0.7	40	41.5	-0.4	8	8.6	-0.3	5	5.2	-0.1
Intersection	**Tr**	46	34	**3.3**	20	24.8	-1.4	2	9.8	**-3.2**	8	6.4	0.8
	LR	12	8.9	1.3	14	19.4	**-2.0**	2	4	-1.2	7	2.4	**3.3**
Zebra Crossing	**Tr**	22	15.7	**2.3**	2	11.4	**-3.7**	2	4.5	-1.4	9	3	**4.0**
	LR	0	0	0	0	0	0.0	0	0	0.0	0	0	0.0
At or near AV stop	**Tr**	3	4	-0.7	5	2.9	1.5	1	1.2	-0.2	0	0.8	-0.9
	LR	5	2	**2.5**	3	4.4	-1.0	0	0.9	-1.0	0	0.6	-0.8
Narrow path	**Tr**	1	9.4	**-3.9**	16	6.9	**4.4**	3	2.7	0.2	1	1.8	-0.6
	LR	13	20.8	**-2.5**	56	45.3	**3.0**	11	9.4	0.7	2	5.7	**-2.0**
Roundabout	**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
Wide Road: 2-lanes	**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	**-2.9**	4	1.2	**2.9**	1	0.7	0.4

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

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

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

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

3.2.2 Impact of type of Road User

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

Table 4: Results of tests of association between type of road user and observed road user behaviours in Trikala (Tr) and La Rochelle (LR). (Numbers marked in bold represent 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
Pedestrian	**Tr**	94	75.3	**4.7**	27	51.6	**-6.6**	23	21.9	0.4	17	13.4	1.7
	LR	49	46.2	1.0	100	107	**-2.1**	23	20.8	1.1	13	11.5	0.9
Cyclist	**Tr**	21	38.1	**-4.5**	48	26.1	**6.2**	10	11.1	-0.4	4	6.8	-1.3
	LR	10	12.1	-0.8	37	28	**2.9**	1	5.4	**-2.3**	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	**-2.0**	3	0.3	**4.9**	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

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

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

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

3.2.3 Impact of pedestrian demographics and group size

In order to understand whether pedestrian interactions with AVs are influenced by their gender or age-group, tests of association were conducted between each of the road user behaviour categories and observed categorisation of their age and gender, as well as whether they were travelling in a group (group status). Table 5 provides a breakdown of the results of the Fishers exact and chi-square tests of association, examining the relationships between age, gender and group status, and each of the road user interaction categories. It was not always possible for the coders to identify the pedestrians' gender or estimate their age. Therefore, the analyses for gender are based on 262 observations of a possible 271 in Trikala, and 238 of a possible 245 in La Rochelle; while the analyses for age are based on 257 observations in Trikala, and 227 in La Rochelle.

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

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

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

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

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

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

Table 6: Results of tests of association between age-group of road users and observed road user behaviours in Trikala (Tr) and La Rochelle (LR). (Numbers marked in bold represent 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
Child (<13)	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	**2.1**	0	0.6	-0.8	0	0.4	-0.6
Teen (13-18)	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
Young Adult (18 - 34)	Tr	38	42.6	-1.2	37	28.6	**2.3**	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
Middle-aged (35 - 55)	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
Older (>55)	Tr	23	18.5	1.5	7	12.5	**-2.0**	5	5.1	-0.1	5	3.4	1
	LR	9	5.9	1.6	8	13.4	**-2.4**	1	2.1	-0.9	5	1.4	**3.3**

3.2.4 Road user "tests" AV

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

3.3 Automated analysis: Speed profiles and pedestrian locations

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

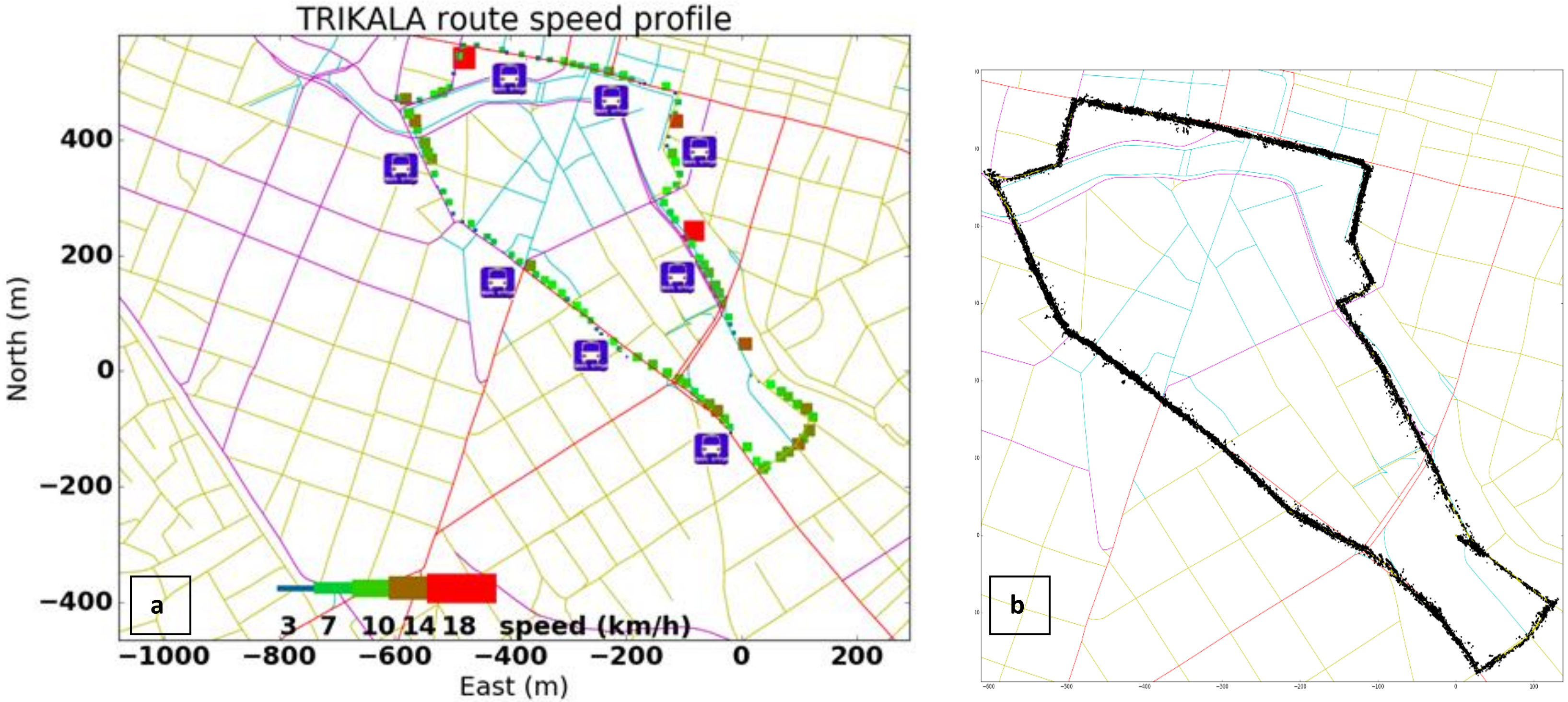

Figure 6: Average speed profile (a) and pedestrian densities (b) across the route in Trikala

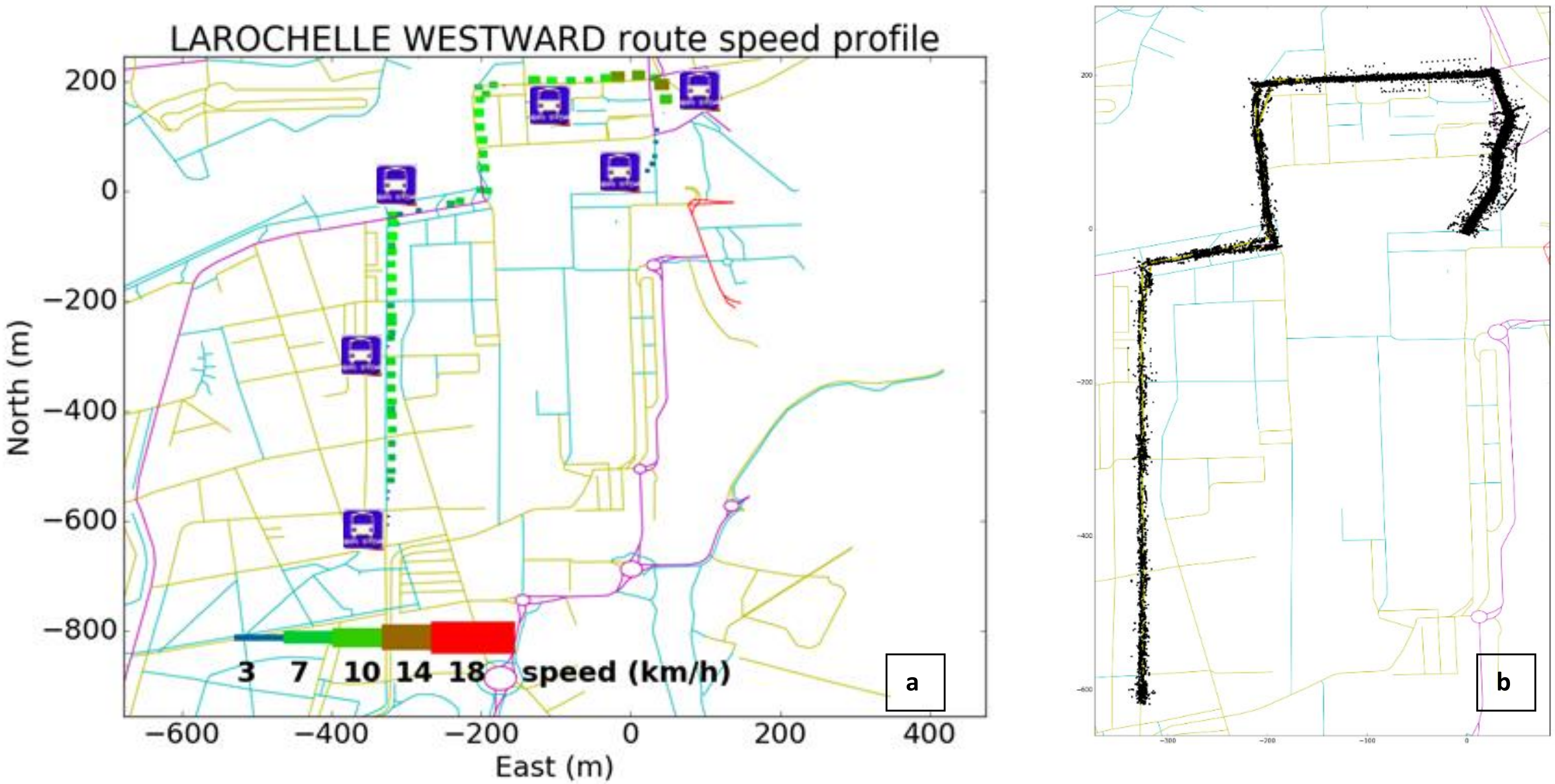

Figure 7: Average speed profile (a) and pedestrian densities (b) across the AV route in La Rochelle

3.4 Video analysis: Critical events

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

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.

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

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

4. Discussion

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

4.1 Road infrastructure factors: Findings & implications

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

One of the most common techniques used by VRUs to establish whether a vehicle will yield, is it's travelling speed (Bertulis & Dulaski, 2014; Clamann et al., 2017). Therefore, pedestrians and cyclists interacting with the slow-moving AVs during the CityMobil2 trials may have expected the vehicle to adhere to conventional traffic behaviour, and give way. This disparity between the behaviour of the AV and the implicit expectations of the pedestrian/cyclist may have increased the riskiness of these situations. Indeed, previous research with AVs has highlighted the importance of ensuring that the signals given both explicitly (e.g. through external human-machine interfaces) and implicitly (e.g. through speed or braking behaviour) are consistent (Lagström and Lundgren, 2015). In La Rochelle, this was likely to have been less of an issue due to the shared nature of the space, where other road users could adjust their route from a distance away, to avoid having to cross directly ahead of the AV.

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

4.2 Road user factors: Findings and implications

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

In terms of giving way to the AVs, the pattern of road user behaviours was slightly different for the two locations. In La Rochelle, car drivers were more likely than other road users to change their trajectory for the AV, a behaviour that was not apparent in Trikala. On the other hand, pedestrians in Trikala crossed ahead of the AV more often than expected, whereas this was not the case in La Rochelle. Once again, these differences in road user behaviours may be a reflection of the difference in the infrastructure provided in Trikala and La Rochelle. For the majority of the route in La Rochelle, the AVs operated in a shared space, where pedestrians could adjust their route from a distance away to avoid having to closely interact with the AVs. However, some parts of the route were quite narrow, where there was not enough space for two vehicles to travel, and this led to a change in trajectory by car drivers, to move out of the AV's path. In Trikala, the pedestrian crossing options were more limited, and there were a number of intersections and zebra crossing areas, which may have led to the increased likelihood of pedestrians crossing a short distance ahead of the AV. These results once again highlight the importance of taking context into account when investigating AV interaction behaviours, as requirements for vehicle communications are likely to vary depending on the environmental design in a given location.

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

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

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

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

There were also a total of 14 critical incidents identified in this data-set, which amounts to roughly one “near-miss” incident for every three hours of autonomous driving. This is a major issue for AV designers, because, as the speed of these vehicles increases the likelihood of a collision occurring will also increase. Therefore, the pedestrian and cyclist detection systems on these AVs need to be extremely accurate, particularly on approaches to turns, and in busy, shared, urban spaces.Many of the road users captured in this study will have only interacted with the AVs once or twice. Thus, it remains to be seen how interaction patterns change when the novelty of these types of vehicle wears off. Future research should use the TTC criteria identified for near-misses in this study to investigate whether this rate of near-misses is typical when larger data-sets become available.

4.3 Implications for the design of automated road user detection

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

4.4 Conclusions

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

The AVs in both La Rochelle and Trikala operated in a mixed traffic environment, with high pedestrian density, leading to a higher probability of interactions. Previous research has shown that pedestrians do not always feel comfortable or safe when moving through a shared space with either conventional vehicles (Moody & Melia, 2014) or AVs (Merat et al., 2018), and the results of this study provide support for the idea that, where possible, VRUs will 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.

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. Finally, this paper provides some insights into the factors required for the development of accurate detection systems for AVs, by highlighting the differences in behaviour which arise in different environments, and among different road user groups.

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