ESTIMATION OF THE PASSENGER SPACE IN THE BOARDING AND ALIGHTING AT METRO STATIONS

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1. INTRODUCTION

The platform train interface (PTI) is considered the space where the most interactions of passengers occurs. This space is defined as the area between the train doors and the corresponding adjacent platform (Seriani and Fernandez, 2015). In the UK railway network more than 3 billion of interactions are made each year, in which 21% of the safety risks (injuries and fatalities) and 48% of the fatality risk to passengers are produced (RSSB, 2015).

To improve safety conditions in the PTI, platform edge doors (PEDs) have been used in different metro systems (Clarke and Poyner, 1994; Kyriakidis et al., 2012). In the case of London Underground (LU, 2012) PEDs work as sliding barriers simultaneously with the train doors (see Figure 1). PEDs can also influence ventilation conditions and act as smoke detectors in case of a fire (Le Clech, 2005; Qu and Chow, 2012). Recently studies (De Ana Rodriguez et al., 2016; Seriani et al., 2016) showed that PEDs have no relevant impact with respect to boarding and alighting times, but they can change their behaviour by queuing at the side of the doors rather than waiting in front of them. This occurs because passenger know where the PEDs are, so they are closer to them rather than spread out over the length of the platform.

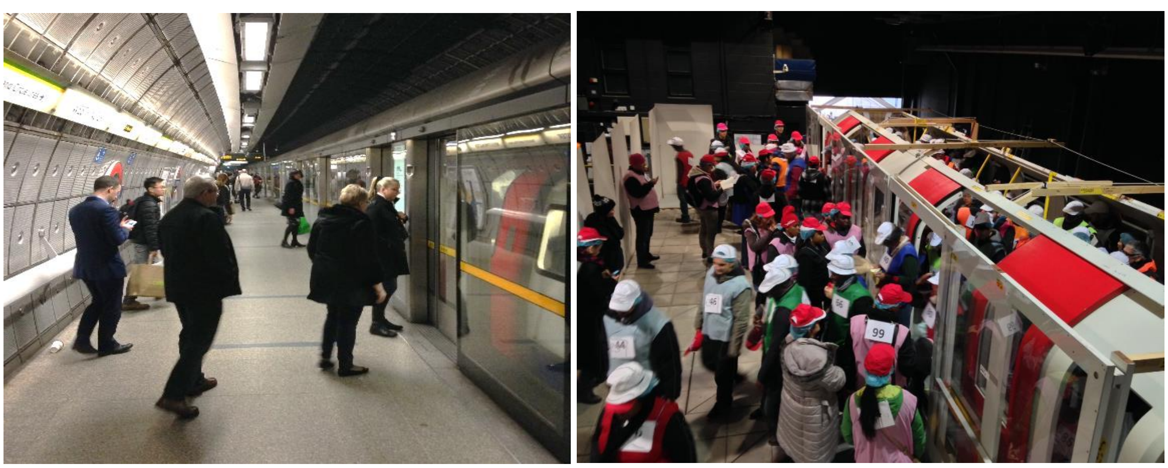

Figure 1: PEDs used in Westminster Station (left) and PAMELA (right)

The behaviour of passengers can be affected by different factors: physical (e.g. luggage), information (e.g. maps), environment (e.g. weather), and people (e.g. density on platform) (RSSB, 2008). In this work behaviour is defined as the way passengers move and interact with each other in high complex situations (e.g. boarding and alighting). To study the interaction of passengers in the boarding and alighting, the Level of Interaction (LOI) can be used (Seriani et al., 2016). The LOI increased as the distance between passengers decreased. However, the LOI only considered the space between two passengers alighting (pair A_i - A_{i+1}) or two passengers boarding (pair B_i - B_{i+1}), and not the space between each passenger alighting and boarding (pair A_i - B_i). Therefore, a more complete analysis is needed to measure the passenger space (PS), especially when boarding passengers are considered an "obstacle" for alighting.

The hypothesis of this research is that PS can be considered as an asymmetrical ellipse for passengers alighting, in which the longitudinal and lateral radii are affected by the collision avoidance of a person in front of him/her and by the interaction with other passengers alighting or waiting to board the train. In this work PS is considered as a protective safety space, i.e. PS is defined as the space available for each passenger alighting to complete two main tasks: collision avoidance and reaction to sound stimulus (e.g. "let alight before boarding").

The aim of this study was to estimate PS in the boarding and alighting at metro stations. The specific objectives were: a) to identify the types of interaction between passengers boarding and alighting; b) to mock-up a carriage and the relevant portion of the platform at University College London ´s Pedestrian Accessibility Movement Environmental Laboratory (PAMELA); c) to conduct different load (flow) scenarios of boarding and alighting at PAMELA; d) to measure PS for each scenario. The results of this study could be included in pedestrian simulation models for station improvements or in the design of the platform train interface (PTI) zone.

This paper is composed of six sections, including this one. In section 2 a literature review is presented. Next, the method followed by this work is explained. Section 4 shows the results of PS measurements. In section 5 a discussion is provided. Finally, in section 6 the conclusions are delivered.

2. LITERATURE REVIEW

In sociology and psychology it is used the personal space defined by Hall (1966) to represent the "virtual" space needed for each passenger to feel comfortable in different situations. This space can be classified into four groups according to the relationship between passengers: intimate zone (less than 0.5 m), personal zone (0.5 - 1.2 m), social consultative zone (1.2 - 4.0 m), and public distance zone (4.0 - 10.0 m). Similarly, Sommer (1969) used the concept of social behaviour to classify the personal space into three groups: a) intimate (< 0.5 m); b) personal (0.5 – 1.2 m); and c) social (>3.0 m). In this sense, the interaction distance between two passengers depend on the level of acquaintance of them. For example, if they are friends they will interact at a shorter distance than if they were strangers (Little, 1965). In spaces where queues are formed, Pushkarev and Zupan (1975) state that a person needs at least 0.74 m^2 to walk, in which case a "face-to-face" distance less than 0.5 m will be felt as intimate. Considering that each passenger is represented as an ellipse of 0.30 m^2 (body depth of 50 cm and shoulder breadth of 60 cm defined by Fruin, 1971), then the intimate zone between the heads of two passengers will be reached when the distance is lower than 0.8 m (0.5 m plus two times half the body depth of each passenger).

The personal space also depends on the body height, body position, and sex (Hartnett et al., 1974; Sanders, 1976; Phillips, 1979). More recent studies (Webb and Weber, 2003) showed that PS could also be a function of the vision, hearing, mobility and stress level. However, the personal space is not the same as passenger space (PS). In this work PS is related to the concept of personal control, which is divided into three forms: behavioural, cognitive and decisional (Schmidt and Keating, 1979). In relation to behavioural, crowding situations can be produced when the density on the platform interfered with the behavioural sequence or blocked the goal of passengers (e.g. boarding passengers are perceived as obstacles for alighters). Therefore, PS can be related to a situation when passengers felt that they lose control or freedom on their space (e.g. alighting passengers needing to leave a dense platform and he/she has no control over how adjacent people move). As an example, Evans and Wener (2007) measured crowding in trains using the personal invasion (distance between passengers) instead of the overall density (number of passengers per unit of space, e.g. total number of passengers on the platform). The authors stated that the overall density does not say if passengers are located or moving in a particular way, or if a particular space reached a high interaction between passengers. With respect to cognitive, personal control depends on the way each pedestrian anticipates and interprets the event or impending condition (e.g. stress). To improve cognitive control, information can be provided to passengers with anticipation of their next action (e.g. passengers inside the train have been given an announcement to avoid crowded stations so their journey is planned and the stress level is reduced). Finally, the decisional control is related to the desired situation of each pedestrian in selecting outcomes.

To return to a non-crowded situation passengers use collision avoidance techniques (e.g. overtakes or change their paths). Some authors (Gérin-Lajoie et al., 2005), reported that each person needs a space represented as an ellipse of area 0.96 m wide by 2.11 m deep, which is smaller when overtaking static versus a moving obstacle (in both cases a mannequin was used as an obstacle). In addition, Gérin-Lajoie et al. (2008) demonstrated that this space can be asymmetrical in shape and side (left and right) during the circumvention of a cylinder (or column) as an obstacle. Recent studies (Kitazawa and Fujiyama, 2010) have also used mannequins as static obstacles in laboratory experiments to define the space used by participants as a function of the vision field, in which an angle of 45 degrees was reached and a distance less than 1.5 m was perceived as difficult to avoid and react. These studies are related to the concept of sensory zone, which is “the distance a person tries to maintain between the body and other parts of the environment, so there will always be enough time to perceive, evaluate, and react to approaching hazards” (Templer, 1992, p. 61). For example, for a normal walking speed the sensor zone can be estimated as an elliptical area of 1.06 m wide by 1.52 m deep (Tembler, 1992). Similarly, Fruin (1970) calculated that the sensory zone reached a distance of 1.48 m for a normal walking speed of 1.37 m/s.

With respect to microscopic pedestrian models, the passenger space (PS) in the boarding and alighting differs in size and shape. In cellular automata models (Zhang et al, 2008; Davidich, et al, 2013; Clifford et al 2014) each passenger is represented as a square cell of 0.3 m or 0.4 m in size, while in force based models (Helbing and Molnar, 1995; 1997; Helbing et al, 2000; 2005) passengers are represented as particles (or circles). These representations simplify each passenger as a rigid body without movement of legs or arms. Therefore, PS in the overlapping or overtaking interaction between passengers is less realistic. This can be improved by looking for other ways (e.g. shapes) of representing passenger interaction (Langston et al, 2006; Baldini et al, 2014). In addition, in cellular automata models each passenger moves in a translational way, e.g., North, South, East, or West, while rotation of the body is not allowed (Harney, 2002; Pan, 2006). Therefore, overpassing and overtaking interaction between passengers is less realistic. This can be improved by combining cellular automata with some attributes from the force based models such as the angular acceleration and torque (Davidich et al, 2013; Ji et al, 2013). However, not all of these models are calibrated and validated; therefore, there is a lack of microsimulation models to represent a more realistic PS in the boarding and alighting at metro stations.

Despite the important research done to study PS in different spaces, there has been little research to estimate PS in the boarding and alighting process when PEDs are present. We expanded the study of De Ana Rodriguez et al. (2016) and Seriani et al. (2016) to estimate PS for alighting passengers under different load (flow) conditions.

3. METHOD

The method used in this work consisted of a mock-up of a carriage at University College London's Pedestrian Accessibility Movement Environmental Laboratory (PAMELA). PAMELA represents an ideal opportunity for researchers to study "what if" scenarios, in which all variables can be controlled such as the number of passengers boarding, alighting and remaining inside the train.

The mock-up at PAMELA represented the future London Underground rolling stock, i.e. two double doors of 1.6 m-wide, 20 seats, 0.2-0.3 m standback, and a vertical gap of 0 mm with platform edge doors (PEDs). The platform was 3.3 m-wide and 10 m-long. This mock-up replicated the same conditions of Westminster Station at London Underground (LU). When PEDs were used the platform train interface (PTI) was defined as the space between the train doors and the PEDs (see Figure 2). As there was limited space at PAMELA the analysis was focused only between the train doors when opened and closed. The cameras were located in the ceiling (h = 4 m height), which allowed to record only a space on the platform of 2.4-m wide by 5.0-m long in front of each train door (this produced an observed area on the platform A_p = 12 m^2).

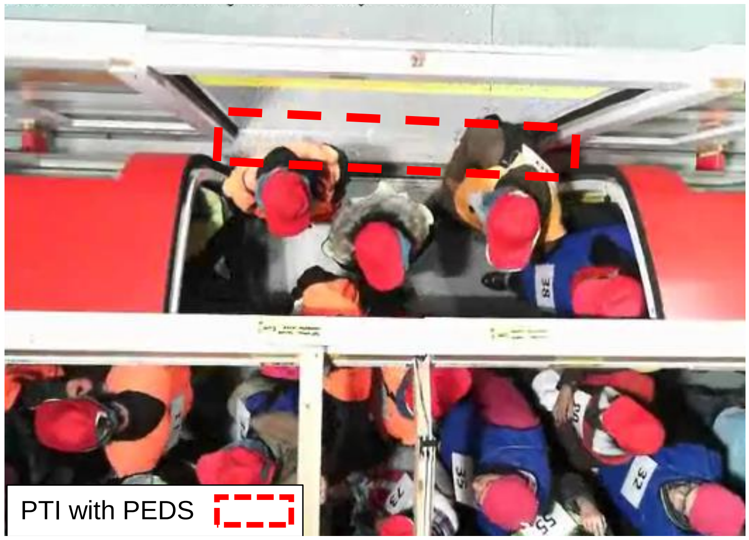

Figure 2: PTI when PEDs were used at PAMELA

The scenarios of simulation were defined based on a previous study of the boarding and alighting done by De Ana Rodriguez et al. (2016). In this case, three situations were simulated according to different ratios between passengers boarding and alighting (R). Ten runs were recorded for each value of R (see Table 1). The scenario LC_0 and LC_1 were used to prepare passengers and to check initial values. The last scenario (LC_5) permitted to calculate the maximum capacity of the train, which reached a density of 5.15 passengers per square meter (when all passengers were inside the train).

Table 1: Loads Used in the Experiment

Load Condition code	N_b (Board per door)	N_a (Alight per door)	N_{o-b} (On-board passenger per door)	Ratio (boarding/ alighting)	Number of runs / scenario
LC_0	55	0	0	-	2
LC_1	0	55	0	-	2
LC_2	40	10	5	4	10
LC_3	10	40	5	0.25	10
LC_4	20	20	15	1	10
LC_5	110 +crush	0	0	-	2

In each scenario passengers were grouped by their bib colour, bib number and hat colour (red for boarding and white for alighting). In total 11 groups were needed for the experiment, reaching a total of 110 passengers. To simulate the boarding and alighting, passengers were instructed to walk as they would if in the LU. To make sure that this condition was perceived by each passenger; the groups were mixed in each run (e.g. group 1 boarded at run 1 but then in run 2 they alighted) and instructions were provided using the sound system. In this case three types of announcements were given to passengers: a) mind the gap between the train and the platform; b) let alight before boarding; c) doors closing.

Using the software PETRACK (Boltes and Seyfried, 2013) the position (x, y) of each alighting passenger A_i was recorded each time he/she exited the PTI zone. Therefore, the time step (Δt = i – (i-1)) was defined as the difference in seconds between two following alighters (A_i and A_{i-1}) who exited the PTI zone. In this work the interaction between the first passenger alighting and the first passenger boarding was not considered, therefore i = 2,..,N_a (N_a = total number of passengers alighted per door). In addition, PETRACK was used to track the number of passengers around A_i. Each alighter A_i had at least 4 passengers around him/her (front, back, left and right). For example, Figure 3 shows the position A_i (1) and seven other passengers around him/her. Position 5 and 8 were alighting passengers located in front and at the back of A_i, respectively, while the positions 2, 3, 4, 6 and 7 represented boarding passengers around A_i.

Figure 3: Example of PETRACK used to track the position of A_i (i = 3) when R = 1

Following the example in Figure 3 the position of passengers around each A_i was plotted to represent the passenger space (PS) of each alighter A_i, which represented an asymmetrical ellipse. The area of each asymmetrical ellipse was calculated using an approximation of triangles between the position of A_i and the surrounding passengers boarding (B_i or B_{i+1}) or alighting (A_{i+1} or A_{i-1}). According to Heron's Formula the area of each triangle i can be obtained using Equation 1. The sum of all triangles will be the area of the asymmetrical PS for A_i (see Equation 2 and Figure 4). The distance between A_i and A_{i+1} is defined as longitudinal front radius. The longitudinal back radius is the distance between A_i and A_{i-1}. The distance between A_i and B_i (or B_{i+1}) is defined as the lateral right or left radii.

$$Area\ triangle = \sqrt{(t \cdot (t-a) \cdot (t-b) \cdot (t-c))}\text{ , where } t = (a+b+c)/2 \quad (1)$$

$$Assymetrical\ PS = \sum_{i=2}^{N_a} (Area\ triangle)_i \quad (2)$$

Where a, b, and c are the length of the sides of each triangle i, obtained using the Euclidian method between A_i and the surrounding passengers tracked with PETRACK. The number of triangles is equal to the number of passengers around each A_i.

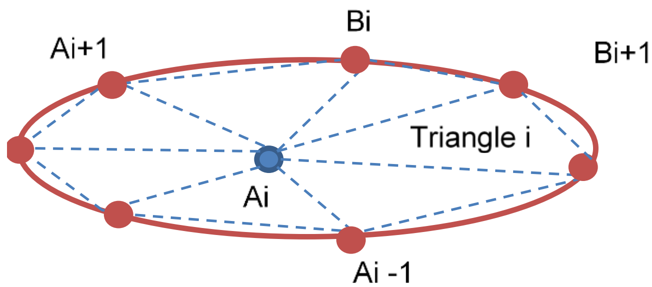

Figure 4: Approximation of triangles to obtain the area PS for each A_i

The results of PS obtained using the approximation of an asymmetrical ellipse were used to calculate the platform width. In the case of LU (2012) to calculate the recommended platform width (P_w) a value of overall PS = 0.93 m^2 per passenger or LOS D from Fruin (1971) is needed for designing these spaces. The overall PS is obtained considering the total area of the platform in front of the doors (A_p) divided by the total number of passengers boarding (N_{bi}) and alighting (N_{ai}) for each time step i (see Equation 3).

$$Overall\ PS = A_p/(N_{bi} + N_{ai}) \text{ for } i = 2, \ldots, N_a \quad (3)$$

The original formula used by LU (2012) was modified for the experimental case (see Equation 4), in which L = 5 m (length of the platform captured by the cameras) and E = 1 m (edge effect caused by the yellow line and seats on the platform).

$$P_w = [(N_{bi} + N_{ai}) \cdot PS)/(L)] + E \quad (4)$$

The Level of Service or LOS of Fruin (1971) was used to indicate the degree of congestion and conflicts of passengers on the platform. This indicator goes from level A (passenger space of 3.3 m^2/pass or more, free flow and no conflicts) to the level F (passenger space less than 0.5 m^2/pass, sporadic flow, frequent stops and physical contact), where E is equal to the capacity (passenger space between 0.5 m^2/pass and 0.9 m^2/pass).

In addition, the instantaneous speed of each passenger alighting A_i was obtained following Equation 5. The expression $\Delta t = i - (i\text{-}1)$ is the time step defined as the difference in seconds between each passenger A_i exited (x_i,y_i) and entered (x_{i-1}, y_{i-1}) the PTI zone.

$$v_{Ai} = \frac{\sqrt{(y_i - y_{i-1})^2 + (x_i - x_{i-1})^2}}{\Delta t} \quad (5)$$

4. RESULTS

4.1 Demographics of participants

In the experiments at PAMELA 110 volunteers were recruited to represent boarding and alighting passengers. Most of them (78%) were regular users of the LU and 60% were under 45 years of age. Forty-six percent of them were men and 54% women. Passengers reached an average height of 170 cm with a standard deviation of 8.5 cm. In addition, the passenger's average weight was 71 kg with a standard deviation of 19.2 kg.

4.2 Dimensions of asymmetrical ellipse

Table 2 shows the average longitudinal dimension of the asymmetrical ellipse for each passenger alighting A_i in the different scenarios of ratio between boarding and alighting (R) at PAMELA. All cases (total tracked of 450 alighters) of R presented smaller longitudinal back radii than the longitudinal front radii, reaching up to a 22.4% difference when R = 0.25. The standard deviation of the longitudinal front radii was about 26 cm for all cases of R, whilst the longitudinal back radii reached a standard deviation in the range of 14 cm and 19 cm.

Table 2: Average longitudinal radii of asymmetrical ellipse for each A_i

R	Number alighters Ai tracked	Longitudinal front radius (cm)		Longitudinal back radius (cm)		Diff. Long.*	p-value
		Average	Standard Deviation	Average	Standard Deviation		
4	68	63.23	25.95	61.29	14.61	-3.1%	<0.05
0.25	232	79.45	26.57	61.65	18.64	-22.4%	<0.05
1	150	76.74	26.15	59.80	16.39	-22.1%	<0.05

*Diff. Long. = Average longitudinal back radius – Average longitudinal front radius

In addition, an ANOVA test single factor was used with a significance level of 5% ($\alpha = 0.05$) to compare each variable (longitudinal front radii and longitudinal back radii) for each value of R. The null hypothesis (H_0) was defined as the samples having the same mean. The results of the ANOVA in Table 2 showed that the p-value was lower than 0.05. This means that the null hypothesis is rejected, i.e. there is significant difference between the longitudinal front radii and the longitudinal back radii in each case of R.

Another ANOVA test single factor (significance level of 5%) was done to compare if there was significant differences in the longitudinal front radius over the different values of R. The null hypothesis was defined as the samples having the same mean. In the case of the longitudinal front radius the compared cases of R = 4 - R = 0.25 and R = 4 - R = 1 presented a p-value lower than 0.05. The only case that presented no significant difference was the comparison R = 0.25 - R = 1 (p-value = 0.302). In the case of the longitudinal back radius a similar test was performed, in which all the compared cases of R presented no significant differences (p-value > 0.05).

With respect to lateral radii, Table 3 shows that passengers alighting maintained more distance from the left side than from the right side, reaching up to 15% in difference when R = 0.25. This was produced in all scenarios of R (total tracked of 1464 passengers around each A_i). The standard deviation of the lateral left radii was around 25 cm; whilst the lateral right radii in R = 1 reached almost 10 cm lower standard deviation compared to R = 0.25 and R = 4.

Table 3: Average lateral radii of asymmetrical ellipse for each A_i

R	Number passenger tracked around Ai	Lateral right radius (cm)		Lateral left radius (cm)		Diff. Lat. *	p-value
		Average	Standard Deviation	Average	Standard Deviation		
4	227	79.47	36.66	85.67	24.21	+7.8%	<0.05
0.25	714	82.32	36.27	94.64	26.01	+15.0%	<0.05
1	523	77.19	25.36	84.54	23.75	+9.5%	<0.05

* Diff. Lat. = Average lateral left radius – Average lateral right radius

In addition, the ANOVA test (one factor and significance level of 5%) showed in Table 3 that the p-value was lower than α = 0.05, which means that there is significant differences between the lateral left radii and the lateral right radii for all cases of R.

Similarly, an ANOVA test (one factor and significance level of 5%) was performed to compare the lateral right and left radii with each of the values of R. The results show that the only case that presented significant differences was the comparison between R = 0.25 and R = 1, in which p-value was lower than α = 0.05. In the rest of the compared cases of R there was no significant differences.

The longitudinal and lateral radii can be plotted for each scenario of R (see Figure 5). The coordinate (0,0) represents the alighting passenger A_i, who is surrounded by boarding passengers (B_i). In the case of R = 1, B_i goes from B_1 up to B_7. The coordinate (13.5, 69.7) represents the alighting passengers A_{i+1}, whilst the alighting passenger A_{i-1} is located in (1.4, -49.1).

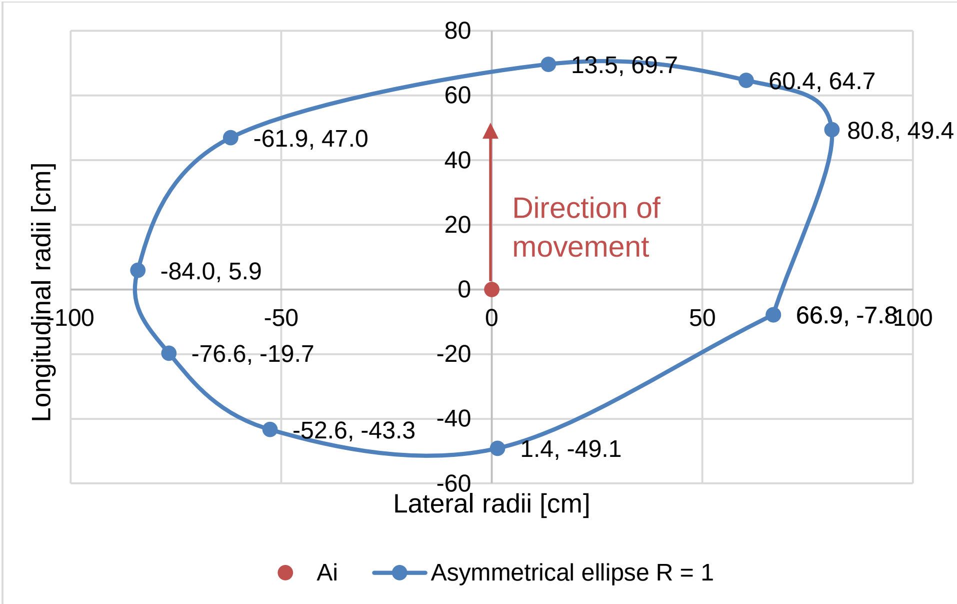

Figure 5: Average asymmetrical ellipse for 150 tracked Ai when R = 1

4.3 Area and speed of alighting passengers

Figure 6 shows the average passenger space (PS) for each passenger alighting (A_i) using Equation (2). In total 450 alighters were tracked and the three scenarios of R were simulated at PAMELA. The x-axis shows the number of passengers alighting when they came out from the doors (i = 2,..,N_a). The variable PS followed a "U" curve approximated by polynomial equations of order 3, reaching an R-square value of 0.85 (R = 1), 0.87 (R = 4), and 0.79 (R = 0.25).

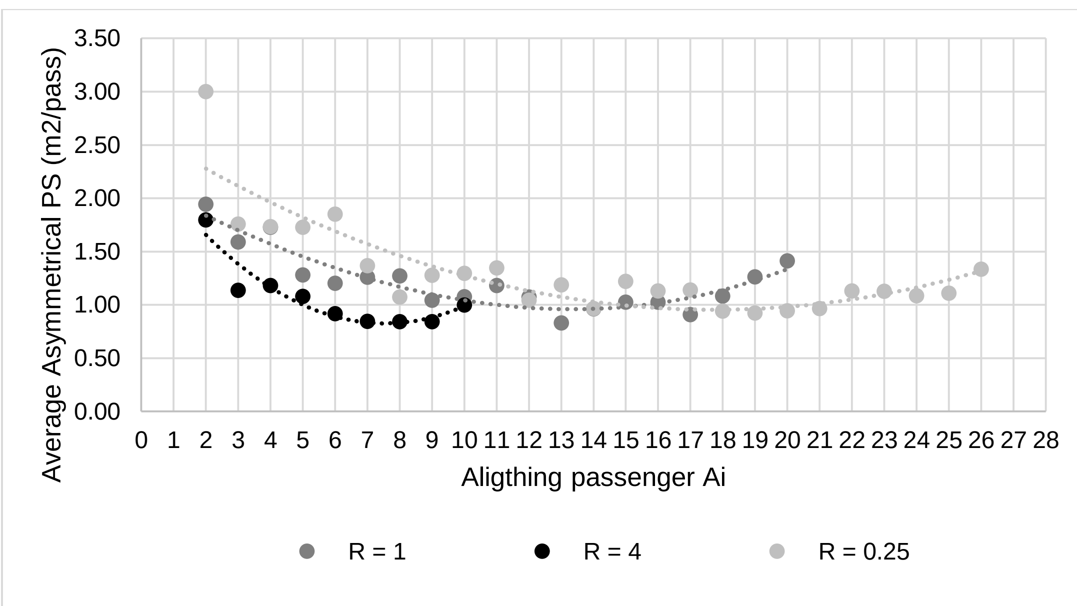

Figure 6: Average PS of each passenger A_i according to each R

With respect to minimum values of PS, when R = 1 it is reached 0.83 m^2/pass or LOS E (passenger A_{13} from a total of 20 alighters). When R = 4 and R = 0.25 the minimum value were slightly higher, reaching 0.84 m^2/pass (passenger A_7 from a total of 10 alighters) and 0.92 m^2/pass (passenger A_{19} from a total of 26 alighters), respectively. In all the cases of R the minimum values of PS presented a LOS = E. In terms of alighting time (t_a) Figure 6 shows that the minimum values of PS are reached on average at 11.79 s when R = 1 (equivalent to the 73% of the total average t_a = 16.15 s). When R = 4, the minimum PS is obtained at 6.38 s which is 77% of the total average t_a = 8.26 s, whilst in the case of R = 0.25 it is reached at 17.05 s (equal to 67% of the total average t_a = 25.37 s.

In the case of maximum values of PS Figure 6 shows that passengers alighting reached a LOS C in the case R = 1 (1.94 m^2/pass) and R = 4 (1.80 m^2/pass). However, in the case of R = 4 a LOS B was obtained with 3.0 m^2/pass on average, which is 70.45% higher with respect to the following passenger alighting. These values are presented in the early stages of the alighting process (second passenger alighting).

Table 4 shows that in average the asymmetrical PS for alighters (obtained using Equation 2) presented a LOS D for all cases of R, however the overall PS (obtained using Equation 3) reached up to LOS F for R = 4. In other words, the overall PS reached up to 0.60 m^2/pass difference compared to the asymmetrical PS when R = 4. In the case of R = 1 this difference is slightly lower reaching 0.56 m^2/pass, whilst in R = 0.25 it is reduced to 0.30 m^2/pass.

Table 4: Average passenger space (PS) and instantaneous speed for each A_i

R	**Average asymmetrical using Eq. (2)**		**Average overall using Eq. (3)**		**Diff. PS***
	PS (m^2/pass)	**LOS**	**PS (m^2/pass)**	**LOS**	
4	1.07	D	0.47	F	-0.60
0.25	1.31	D	1.01	D	-0.30
1	1.22	D	0.66	E	-0.56

*Diff. PS = Average overall PS - Average asymmetrical PS

In addition, Figure 7 shows the average instantaneous speed V_{Ai} of each passenger alighting for each case of R at PAMELA. The average V_{Ai} is obtained for all runs using Equation 5. In the case of R = 4 the first alighters reached a higher value than the rest of the passengers alighting, however this did not occur in the case of R = 0.25 and R = 4. In all cases a linear approximation can be obtained with an R-square value of 0.41 (R = 1), 0.91 (R = 4), and 0.81 (R = 0.25).

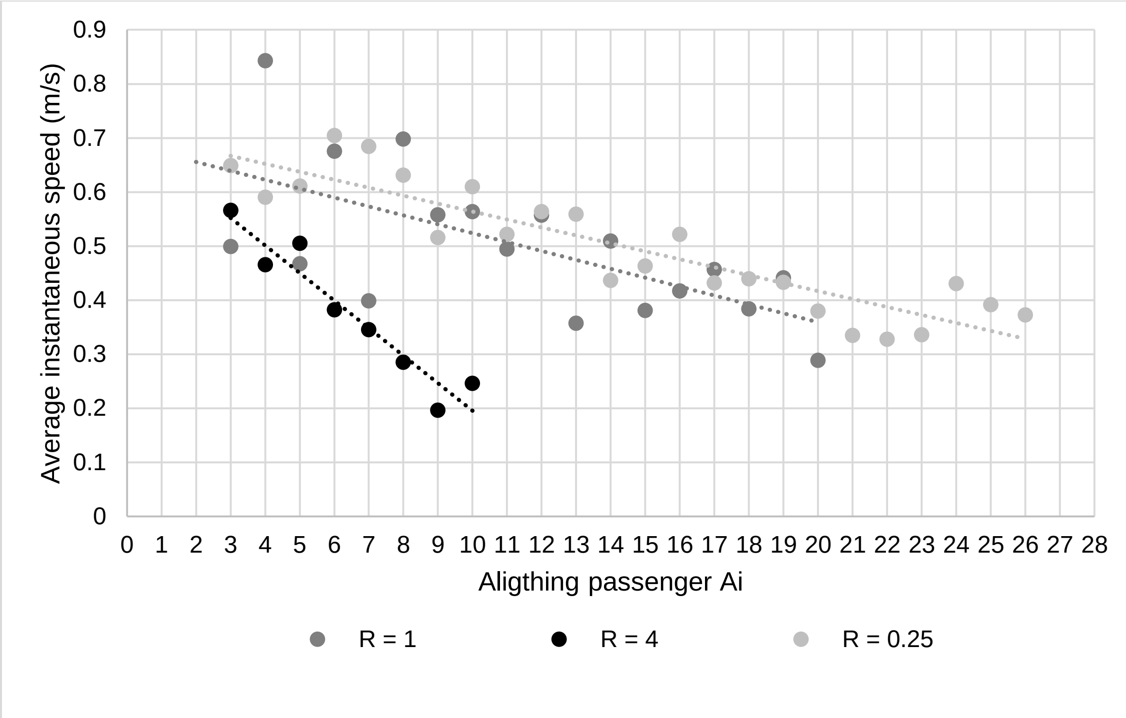

Figure 7: Average instantaneous speed of each passenger A_i according to each case of R

5. DISCUSSION

As reported in De Ana Rodriguez et al. (2016) and Seriani et al. (2016) the interaction between passengers can be classified into three groups: only alighting (when passengers boarding were waiting on the platform), overlap (when boarding and alighting occurred simultaneously), and only boarding (when alighting was complete). This work is a combination between the first and the second type, in which each passenger alighting interacted with other passengers around him/her who were also alighting or waiting on the platform to board the train.

Significant differences in the dimensions of the asymmetrical ellipse were reached for each scenario at PAMELA. The average values for all the three cases of R (4, 1, and 0.25) showed that the lateral left radius was bigger than the lateral right radius. In particular, there is significant differences when comparing R = 0.25 and R = 1. The difference between them can be caused because passengers preferred to maintain a certain distance to avoid collision, which is in concordance with the hypothesis of this research. This distance can be considered as intimate when a value lower than 80 cm is reached between the heads of two passengers (Hall, 1966; Sommer, 1969; Pushkarev and Zupan 1975). Going further form our previous study (Seriani et al., 2016), the results of this work showed that on average, the lateral distance between passengers alighting and boarding (pair A_i - B_i) was around 80 cm, which means that passengers felt a high Level of Interaction (LOI). However, this distance could be influenced by the behaviour of passengers boarding and the location of the exit gate on the platform, which could be considered as further research. In addition, new experiments are needed to determine if this distance is reached as a function of the smaller personal space in his/her domain side as it is reported in Gérin-Lajoie et al. (2008).

Similarly, it seems that passengers alighting preferred to maintain a greater distance in front of him/her than behind them due to collision avoidance techniques. In average the longitudinal front and back radii reached a value lower than 80 cm, perceiving a high LOI as reported in (Seriani et al., 2016). The results also showed that the value of R had an impact on the longitudinal front radius. In particular, R = 4 had significant difference in the longitudinal front radius compared to R = 0.25 and R = 1. On the contrary, in all the cases of R passengers maintained a similar distance from behind.

In relation to the instantaneous speed, it was expected that "U" curves would be obtained with a correlation to the passenger space (PS), but it was only possible to reach linear approximations. In general, the speed of the first passengers alighting was higher than the rest of the passengers. This can be caused because the first passengers alighted had more PS on the platform than the rest of the passengers. In addition, towards the end of alighting, alighters could have more space between themselves as the supply of alighters from the seating sections of the carriage decreases. This could be related to the field of vision of each passenger, which was not covered in this work. However, further experiments can be carried out at PAMELA and the results can be compared to existing laboratory studies (Kitazawa and Fujiyama, 2010), in which participants used an eye camera to identify their space.

In relation to the area of the asymmetrical ellipse, the results showed that the first passengers alighting perceived a higher space than the rest of the alighters. This can be caused because the number of passenger alighting increased over time, producing congestion in the platform train interface (PTI) zone. The maximum congestion is produced when the area of the asymmetrical ellipse reached a minimum value, which reached 0.83 m^2/pass when R = 1. Congestion problems are reduced when alighting is almost finishing, due to a slight increase in the passenger space of each alighter. On average asymmetrical PS reached a lower value than obtained by Gérin-Lajoie et al. (2005) and Templer (1992) in walkways.

The Level of Service of Fruin (1971) was used to determine the degree of congestion and conflict in the process of alighting. The difference between the overall PS and the asymmetrical PS is due to the fact that the first variable considered the total number of passengers on the platform, whilst the second variable is more specific and only considered the space perceived by each passenger alighting A_i with respect to the passengers around him/her at the PTI zone. Therefore, the asymmetrical PS showed more detail of interactions between passengers alighting and boarding than the overall PS.

To avoid situations in which a LOS higher than D is reached, the platform width needs to be re-calculated using Equation 4 as an average of all runs. The optimum platform width should be obtained using a PS = 0.93 m^2/pass which is recommended by LU (2012). Table 5 shows that the recommended width reached a maximum value of 6.2 m when R = 4, which is almost 2.5 times the observed width at PAMELA. When R = 1 the recommended width reached almost two times the observed width, whilst in the case of R = 0.25 it is about 1.6 times.

Table 5: Platform width for each scenario of R

R	Observed width at PAMELA (m)	Recommended width (m)	Diff. width*
4	2.4	6.2	160%
0.25	2.4	3.9	64%
1	2.4	4.9	103%

*Diff. width (%) = [(Recommended width*100)/Observed width]-100

6. CONCLUSIONS

This study showed a new method to estimate the passenger space (PS) by means of real-scale laboratory experiments. Three different load (flow) conditions were conducted at University College London's Pedestrian Accessibility Movement Environmental Laboratory (PAMELA). Thirty runs (10 runs per load condition) simulated the boarding and alighting of passengers when platform edge doors (PEDs) are used between the train doors and the platform. The simulation considered a mock-up to represent the new rolling stock of the London Underground network. In total 450 passengers alighting were tracked using the software PETRACK. In addition, 1464 passengers were tracked around each passenger alighting. The results of this study can help in designing the platform train interface (PTI). In particular, the recommended width of platforms at transport infrastructures should be in the range of 4.0 m and 6.2 m depending on the flow conditions. In addition, the estimation of the asymmetrical ellipse can be included in existing and new pedestrian models, in which the first passengers alighting reached up to 70% more PS than the rest of the alighters. Further research needs to be done to validate PS with more experiments at PAMELA, in which virtual (e.g. auditory stimulus) and physical (e.g. waiting areas or queue lanes) recommendations will be used to avoid passengers feeling intimate with others.

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