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Modelling the distribution of passengers waiting to board the train at metro stations

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Abstract

This study explores a new method to model the distribution of passengers waiting to board the train when platform edge doors (PEDs) are used. The method consisted of using a carriage and platform designed to simulate typical boarding and alighting behaviour at University College London's Pedestrian Accessibility Movement Environment Laboratory (PAMELA). A conceptual model is proposed in which the Platform Train Interface (PTI) was divided into squared cells and semi-circular layers that originated at the doors. A tracking tool was used to identify the position of each passenger waiting to board at PAMELA. To model the distribution of passengers at PAMELA a multinomial function is proposed, and then applied to Westminster station (with PEDs) and Green Park station (without PEDs) in the London Underground. The conceptual model presented no significant differences between the expected and observed data. With PEDs passengers are located at the side of the doors rather than in front of them. In addition, the density by layers helps to identify which part of the PTI is more congested, which is more representative of passengers' interactions than average values of density. Further research needs to verify the assumed multinomial distribution model for different types of stations and passengers.

Keywords: passenger, platform edge doors, tracking, distribution, experiment, metro station.

Manuscript

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1. Introduction

The platform train interface (henceforth PTI) is the most complex space in which the boarding and alighting takes place (Seriani and Fernandez, 2015a). The way (e.g. movement) that passengers go from the platform to the train (boarding) or from the train to the platform (alighting) is a very important issue that affects the safety and efficiency of metro stations. With respect to safety, in the case of the UK, more than 3 billion interactions each year take place in the national network, in which 21% of the safety risks (injuries and fatalities) and 48% of the fatality risks to passengers are produced at the PTI zone (RSSB, 2015). With respect to the London Underground, the total network provides around 4.69 million trips per day with a high peak of demand between 8 and 9 a.m, requiring one train every 2 or 3 minutes at metro stations such as Westminster (38,241 trips/day) and Green Park (58,814 trips/day) on the Jubilee Line (TfL, 2018).

In relation to efficiency, when the number of passengers boarding and alighting increases, the whole train service could be affected. This is caused because the “station dwell times are the major component of headways at short frequencies” (TRB, 2003: 5-19). The dwell time is the time the train remains stopped at the station transferring passengers (TRB, 2000). In the case of low frequency services, the dwell time is considered a fixed value for transport operators. The static component of the dwell time includes the door opening and closing times, as well as to the duration of other mechanical movements and of safety delays, whilst the dynamic component relates to passenger movements and is mainly the boarding and alighting time.

To improve safety and efficiency conditions at the PTI, crowd management measures have been used in a variety of metro stations worldwide. Crowd management at stations is defined as “the rational administration of the movement of people to generate adequate behaviour in public spaces to improve the use of pedestrian infrastructure (Seriani and Fernandez, 2015b: 76). As an example of these measures, platform edge doors (PEDs) have been implemented in nine stations on the London Underground. These elements are half-height (i.e. they do not reach the ceiling) and work as sliding barriers between the train and the platform, and they open or close simultaneously with the train doors. In relation to their width, PEDs at London Underground are 2.0 m, i.e. 0.4 m wider than the double train doors. To identify PEDs, a grey line (1.2 m long and 10 cm wide) is marked on the platform, which act as door position indicators on platforms to highlight where the doors are going to be. As a consequence, PEDs

improve safety conditions and reduce interaction problems between passengers at the PTI (Kroes et al., 2014; De Ana Rodriguez et al., 2016).

Despite the benefits of implementing crowd management measures, there is a lack of models to study the effect of PEDs on the distribution of passengers waiting to board on the platform. The use of markings on the floor (e.g. PEDs as door positions indicators) change the layout of the PTI, and therefore can affect the behaviour of passengers as they know where the doors are located on the platform. In addition, there is a lack of methods to represent and evaluate the distribution of passengers at the PTI. Typically, data is collected manually and therefore it is not possible to obtain a complete and detailed movement of passengers.

Therefore, the aim of this paper is to propose a new method to model the distribution of passengers waiting to board the train when PEDs are used. The approach used is based on observation at London Underground stations and simulation of different scenarios of boarding and alighting at University College London's Pedestrian Accessibility and Movement Environment Laboratory (PAMELA), in which a conceptual model is proposed to discretise the PTI area and a tracking tool was implemented to identify the location of passengers on the platform. Although the London Underground was used as a case study, the results can be expanded to other public transport systems.

This paper is composed of six sections, including this one. In section 2 a summary of studies to measure the distribution of passengers is presented. Next, in section 3 the method followed for this work is explained. Section 4 shows the results of the distribution of passengers. Section 5 presents the discussion. Finally, in section 6 the conclusions are delivered.

2. Literature Review

According to Daamen et al. (2008) the most common approaches used to study the effect of crowd management measures are based on empirical measurements and models, i.e. real-world observation (e.g. the number of passengers boarding and alighting, dwell time, and physical layout) and surveys (e.g. perceptions of passengers) which are then used to calibrate linear and non-linear models. These approaches have been used for more than 30 years. The European experience started with Pretty and Russel (1988) who proposed a dwell time model for buses as a function of the time used to open and close the doors, plus the maximum period between the time it takes to board and the time it takes to alight, taking into consideration the total number of boarding and alighting passengers. A similar linear dwell time model is proposed in the American literature based on the well-known Highway Capacity Manual which can be applied to metro stations (TRB, 2000; TRB, 2013).

In the case of light trains, Lin and Wilson (1992) studied one and two-cars vehicles in which the dwell time model was a function of the number of boarding, alighting and on-board passengers. In addition, Aashtiani and Irvani (2002) suggested a dwell time model as a function of the number of doors, vehicle load factor and fare collection method. Similarly, Harris (2006), based on the London Underground identified that the dwell time model depends on the time needed for opening and closing of doors, number of doors per car, door width factor, number of passengers boarding, number of passengers alighting, peak door factor, number of through passengers, and number of seats per carriage.

Empirical studies presented by Wiggendaad (2001) states that the process of boarding and alighting takes up to more than 60% of the dwell time and found that wider doors decreased the boarding and alighting time by 10%. However, the relationship between capacity at doors and door width seems not to be linear. Harris et al. (2014) reported that the capacity is also influenced by the space available on the platform. This is also supported by Heinz (2003), who stated that an increase of the width from 0.8 m to 0.9 m did not increase the capacity of doors, due to passengers not using the whole width of the door. Similarly, surveys were done by Currie et al. (2013) in which the boarding and alighting time is influenced by the number of passengers on-board (congestion inside the vehicle). Recently, Christoforou et al. (2016) studied the boarding and alighting time using data collected from an on-board automatic passenger counting system in urban light train systems. The authors state that the boarding and alighting passengers' volumes and on-board passengers affect the boarding and alighting time as well as the layout of the vehicle (e.g. low floor), time of the day and stop location.

In the case of PEDs, a level access is needed between the platform and train. These elements work as sliding barriers to prevent passengers falling onto the tracks, reducing the number of suicides acts and accidents, due to the doors being closed until the train arrives and before it leaves (Kyriakidis et al., 2012). The use of PEDs is limited to the number of train doors, number of coaches and design of the platform (Coxon et al. 2010), and therefore these elements can affect the boarding and alighting time. However, it is not clear how the authors reached this conclusion and if there is any evidence to support it.

Other authors (Qu and Chow, 2012) have studied the use of PEDs in evacuation emergencies, taking as a case study Hong Kong subway stations. They found that PEDs improved ventilation and smoke detection in metro tunnels, however, the evacuation time at platforms may increase when using these elements, due to the inconsistency of train stopping at the same position on the platform or by the fragility of their materials. In addition, PEDs can be very sensitive and cause delays when the closing of the doors is interrupted, especially in situations when passengers are trapped between the PEDs and the train doors (Allen, 1995). When PEDs are installed at the PTI with little demarcation (e.g. few markings on the

platform), no clear distinction could be identified to measure the interaction between passengers in front of the doors compared to the rest of the platform (Wu and Ma, 2013). Passengers in the waiting areas behave differently from those who are in the circulation zone. For Wu and Ma (2013) there are two main types of behaviour of passengers who are waiting: queuing or clustering to the side or in front of the train doors. In particular, the authors found that there is an empty space between train doors on the platform which is not occupied by passengers. Other authors such as Krstanoski (2014) considered the whole platform as a waiting area to study the distribution of passengers waiting to board the train. The author proposed a detailed model of crowd density on the platform by a Maximum Likelihood Estimation, in which boarding and alighting processes are represented with a multinomial distribution and depend on various factors such as the position of the exit gate in the destination station, density inside the car, how crowded the platform is, if there are markings of the doors' position on the platform, and random variables (e.g. meeting with a friend). According to Shen (2001; 2008), passengers are not distributed uniformly and waiting areas can be considered as rectangular spaces or as a parabola, while Lu and Dong (2010) suggest that this space can be considered as fan or spectrum. However, all these authors used fixed values to define those shapes, and therefore it could be difficult to know which part of the platform reached a high interaction, especially considering that the number of passengers boarding and alighting changed before and after the train arrived.

The waiting and circulation areas at the PTI can be modelled and compared to design thresholds (LUL, 2012). One of the most common indicators to represent the degree of congestion and conflict in metro stations is the Level of Service or LOS (Fruin, 1971). In the case of platforms, in which passengers are waiting or queuing, the LOS goes from Level A (≤ 0.82 pass/m²) to the Level F (≥ 5.26 pass/m²), where Level E (3.57 - 5.26 pass/m²) is equal to capacity. However, this index is based on the overall density, which is defined as the number of passengers per physical space (e.g. total number of pedestrians on the whole platform). Therefore, identification cannot be made of which part of the space is more congested or where the highest interaction of passengers at metro stations would be if the layout of the train is changed (Evans and Wener, 2007). In addition, there is not a clear classification for high-density situations in walkways (i.e. what happens when there are more than 2.17 pass/m²?). In addition, microscopic pedestrian models are based on two main approaches: discrete and continuous space. Cellular automata models (Zhang et al., 2008; Davidich, et al., 2013; Tang et al., 2017) are an example of discrete approach, in which the space is divided into cells and where the set of cells form a grid, and therefore pedestrians' movement is discrete. In the case of continuous space each pedestrian could be represented as a circle with a fixed radius in which their movement is based on mathematical relationships such as differential equations or social forces (Helbing et al., 2005). The use of LOS and these types of representations are very simplistic and could lead to underestimates of the real

problems of interaction between passengers at the PTI. When these problems are not included, the PTI could be designed with less capacity, affecting the efficiency and safety conditions. Therefore, to study interactions at the PTI the complex nature of people's movements should be included. For example, some researchers (Lam et al., 1999; Kim et al., 2015) have studied crowd densities, in which the path choice of passengers is a function of the stress, availability of seats, sexual harassment, and discomfort due to congestion on platforms.

The main problem of empirical measurements and models is that it is not possible to control all the variables (weather, design, demand, information for passengers, etc.). In addition, the design is limited to existing vehicles and stations, and therefore it is not possible to investigate a complete range of situations. Therefore, not all models have been calibrated and validated for all situations relating to boarding and alighting, especially when PEDs are used. To solve this problem, an experimental approach is proposed to extend our previous studies at PAMELA (De Ana Rodriguez et al, 2016; Seriani et al, 2017). In those studies at PAMELA, it was reported that PEDs have no relevant impact on the boarding and alighting time. Other studies (Fernandez et al., 2010; Fujiyama et al., 2012; Karekla, and Tyler, 2012; Tyler et al., 2015; Holloway et al., 2016; Seriani et al., 2018) have been performed at PAMELA to analyse the passenger behaviour and how they interact with the station or train furniture, door spacing, door width, accessibility, etc. However, these experiments did not include the distribution of passengers when PEDs are used at the PTI.

3. Method

3.1 Laboratory experiments set-up

A series of experiments were conducted at PAMELA in December 2014, following other experiments from 2012 where design factors affecting the behaviour of passengers were explored. These experiments were part of a first study to analyse the effect of crowd management measures on the behaviour of passengers boarding and alighting. In the experiments, two cases were compared: a) PEDs with level access to simulate stations such as Westminster; b) NoPEDs with a 170 mm vertical gap to simulate stations such as Green Park.

A mock-up carriage was configured and assembled at PAMELA with a set of parameters to represent the new generation of London Underground trains. This replicated the same physical and spatial variables as in London Underground stations when PEDs are used, i.e. 2 double 1600 mm wide doors, 20 seats, a horizontal gap between train and platform of 90 mm, and a vertical gap of 0 mm (in the absence of PEDs the vertical gap changed to 170 mm). The configuration of the mock-up produced a total floor area inside the carriage of 17.46 m²,

which allows a capacity of 90 passengers (for a density of 4.0 pass/m², used in static modelling for capacity at metro stations in LUL, 2012). The platform at PAMELA was 10.00 m long and 3.0 m wide. The PTI was defined in consultation with Transport for London. In the absence of PEDs, the PTI is the space between the yellow line on the platform edge and the train doors, whilst when PEDs are present it is the space between them and the train doors.

Three loading (flow) conditions were simulated in this mock-up to represent high-density situations (see Table 1). The load condition 0 and load condition 1 were only tested to warm up passengers for each day and to check initial values or boundaries of the experiment when there were no passengers in the train or on the platform. The load condition 5 was used to calculate the total load of the train. As there was limited space at PAMELA to simulate the behaviour of each passenger, the analysis focused on the period between the train doors opening and closing (i.e. after the train arrived). The value of R = 4, R = 1, and R = 0.25 was chosen in consultation with London Underground based on previous laboratory experiments at PAMELA and current demand levels at existing stations such as Westminster and Green Park stations.

Table 1 – Loads used in the experiment at PAMELA

Load Condition code	Board per door	Alight per door	On-board per door	Ratio (R) (board/alight)	Runs per scenario
0	55	0	0	-	2
1	0	55	0	-	2
2	40	10	5	4	20
3	10	40	5	0.25	20
4	20	20	15	1	20
5	55 +crush	0	0	-	2



Figure 1 – Experiment simulations at PAMELA: red hats (boarding passengers) and white hats (alighting passengers)

As it is shown in Figure 1, to make sure passengers walked “naturally” as if they were boarding and alighting in the London Underground, random groups were chosen to board, alight or remain inside the carriage. Boarding passengers wore red hats and alighting passengers wore white hats, each passenger wore different coloured bibs and each passenger had a unique number on their bib. Therefore, each passenger was identified by their bib colour, hat colour and number. In addition, a complete sound system was provided in order to make the environment seem more familiar to the participants. The sound simulated the train movements, i.e. included the train arriving, braking, door opening alarm, door closing alarm and departure.

The objective of these experiments was to simulate the boarding and alighting when one variable changed (e.g. use of PEDs) while the rest keep fixed, i.e. the laboratory experiments could help to study the behaviour and interaction of passengers in a controlled environment, in which the effect of external factors that influence the movement of passengers such as social interactions, activities and safety constraints are separated. Therefore, PAMELA represent an ideal opportunity for researchers to test “what if” scenarios. However, this do not mean that the behaviour of passengers during the experiments is the same as the behaviour of passengers at existing stations (Childs et al, 2005).

3.2 Conceptual model and data processing at PAMELA

The experiments were recorded and then analysed with an automatic video analytics software. The software Observer X11 (The Observer, 2014) was used with a bespoke coding template. Two types of codes were used (to establish the time and to register an event) and 6 types of events were processed (train arrival, first passenger enters PTI, door opening, boarding or alighting, last passenger exits PTI, door closing), in which the period of analysis was between the times of the doors being opened and closed.

The distribution of passengers waiting to board the train was obtained by the position (x, y) of each person in periods of 5 seconds using Petrack software (version 0.8) as a tracking tool (Boltes and Seyfried, 2013), in which videos from cameras located at a height of 4.0 m from the floor in PAMELA were analysed (see Figure 2). Petrack is the latest software to count passengers in controlled environments. The use of Petrack included a PTI divided into 40 cm square cells, which is typically used in cellular automata models (Zhang et al., 2008; Davidich, et al., 2013; Tang et al., 2017). The use of cells helps to identify which space is most used at the PTI. In addition, the PTI was represented as a semi-circular space divided by layers of 0.50 m each (starting from the location of the doors), equivalent to the body depth of passengers defined in Fruin (1971). The use of layers at the PTI enables the identification of how far passengers waiting to board are located from the doors.

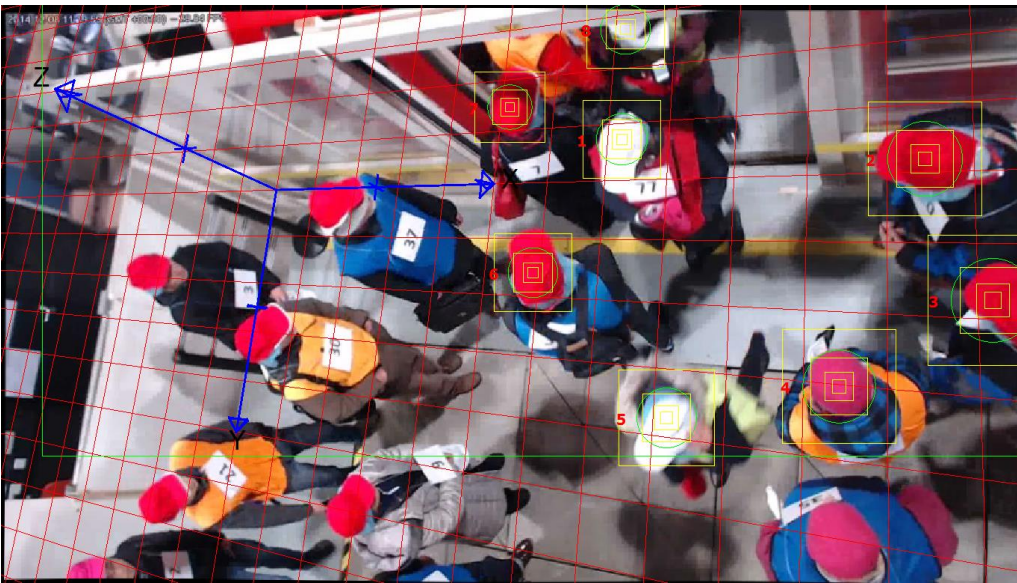


Figure 2 – Example of Petrack used to track the position of passengers at the simulated experiments in PAMELA

Only one double door was analysed (see Figure 2) which was located at the end of the platform. The second double door was located at the beginning of the platform, and therefore closer to the exit gate on the platform. In our previous studies (de Ana Rodriguez et al., 2016; Seriani et al., 2017) we found that there was no relevant difference between the two double doors.

The position of each passenger was also used to obtain the density at the PTI. Two types of density were compared:

- The density by layer (pass/m²) or k_L was obtained by the number of passengers in each layer at the PTI divided by the area of each layer.
- The overall density (pass/m²) or k_O was calculated as the total number of passengers on the platform divided by the area of the platform (i.e. the overall area represented as a rectangular space of 15 m² without layers in front of each door).

The density was classified in different levels according to the LOS in waiting areas (Fruin, 1971), which goes from Level A (≤ 0.82 pass/m²) to the Level F (≥ 5.26 pass/m²), where Level E (3.57 - 5.26 pass/m²) is equal to capacity. In addition, due to the small sample size ($n = 20$) non-parametric tests were performed. A Kruskal–Wallis one-way was done to compare the maximum density by layer between groups of $R =$ boarding/alighting ($R = 4, R = 1, R = 0.25$). A Mann-Whitney U test was also done to compare if there were significant differences in the maximum density by layer over the different values of R , comparing the case with and without PEDs. The null hypothesis was defined as the samples having the same median.

With respect to the distribution of passengers at the PTI, it was considered that the boarding/alighting was stable over time for each door on the platform. This assumption was expanded to the interaction at the PTI when the ratio between the number of passengers boarding and alighting (R) did not change over time in front of each door at PAMELA. As a consequence, the distribution of passengers in each layer on the PTI remains stable over time, and therefore can be modelled using a multinomial distribution proposed by Krstanoski (2014).

To this objective, let us denote the maximum number of passengers waiting to board (b) in layer j with b_j . The sum of b_j for all layers will be equal to B , which is the total maximum number of passengers waiting to board on the PTI. The conditional probability that there are b_1 in layer 1 (X_1), ..., b_n in layer n (X_n), with probabilities p_1, \dots, p_j is given by the following, in which $E(X_j)$ is the mean and $\text{Var}(X_j)$ is the variance.

$$P(X_1 = b_1, \dots, X_n = b_n) = \frac{B!}{b_1! \dots b_n!} \cdot p_1^{b_1} \dots p_n^{b_n} \quad (1)$$

$$\sum_j^n b_j = B \quad \text{and} \quad \sum_j^n p_j = 1 \quad (2)$$

$$E(X_j) = B \cdot p_j \quad \text{and} \quad \text{Var}(X_j) = B \cdot p_j \cdot (1 - p_j) \quad \text{for } j = 1, \dots, n \quad (3)$$

Similar to the method proposed by Krstanoski (2014), in which the authors used the

Maximum Likelihood Estimation (Cox, 1984) to obtain the probability of passengers waiting to board at a specific door on the platform, in this study the Maximum Likelihood Estimation of probabilities p_j from Equation (1) was used to obtain the probability of the maximum number of passengers waiting to board in each layer at the PTI at PAMELA. As a result the multinomial probabilities (\hat{p}_j) are defined in Equation (4). The numerator in Equation (4) represents the sum of the maximum number of passengers waiting to board in layer $j = 1, \dots, n$. This sum is then calculated for each of the runs from $i = 1, \dots, s$. The denominator in Equation (4) represents the sum of the maximum number of passengers waiting to board in each layer considering all the runs.

$$\hat{p}_j = \frac{\sum_{i=1}^s b_{j,i}}{\sum_{i=1}^s \sum_{j=1}^n b_{j,i}} \quad \text{for } j = 1, \dots, n \quad \text{and } i = 1, \dots, s \quad (4)$$

In which s is the sample size, i.e. number of runs per scenario.

The probabilities (\hat{p}_j) obtained from the PAMELA experiments can be used in Equation (3) to predict the mean and standard deviation (square root of the variance) of the maximum number of passengers waiting to board in each layer at London Underground stations, and then compared to the data observed at the stations. To this objective, a chi-square test (significant level of $\alpha = 0.05$) was performed to compare the expected and observed values using the distribution model of passengers.

3.3 Observation on London Underground stations

Currently, the London Underground network has PEDs in nine stations on the Jubilee Line, namely in those newly built as part of the Jubilee Line Extension that opened to service in 1999. Those new stations were designed with PEDs from scratch and they all provide level access to the trains from the whole platform. The Jubilee line southbound platforms at Westminster and Green Park stations were chosen as case of study to compare the expected and observed values using the distribution model of passengers. These stations are one of the most important interchanges in the London Underground network. Observations were made on video footage recorded under actual operating conditions as part of a complete CCTV video recording study solicited by London Underground in collaboration with members of PAMELA.

Variables at Westminster and Green Park stations were recorded during the most congested hour of the day (8:15 to 9:15 am), reaching a flow of 30 train/h. A total of 285 trains were observed during one week of recording (Monday to Friday). Videos were from 5 November to 11 November 2014.

Two variables were observed at Westminster and Green Park stations: total number of passengers boarding and alighting per train, and the distribution of passengers waiting to board at the PTI using the conceptual model explained in section 3.2. Similar to the experiments, the analysis was conducted using Observer XT 11 software (The Observer, 2014), and prior to analysis the videos were converted into .avi format.

4. Results

4.1 Passenger demographics at PAMELA

From the total of passengers at the experiments (110 passengers), 46% (50 passengers) were men and 54% (60 passengers) were women. Most of them (78%) were regular users of the London Underground. With respect to their age, most of them (60%) were under 45 years old. The total passenger load tested in the load condition 0 and load condition 1 (defined in Table 1) was 8221 kg (including seated passengers). The average height of passengers was 170 cm with a deviation standard of 8 cm.

4.2 Density of passengers at PAMELA

The average maximum density by layer (k_L) was obtained before the doors opened, i.e. segment of time 0th s (see Figure 3). This average was obtained from the 20 runs at PAMELA for each layer considering each value of R (boarding/alighting ratio). The variable is obtained by the ratio between the maximum number of passengers in each layer and the area of each layer. Before the PEDs opened, passengers at PAMELA were more concentrated in the middle of the platform. When $R = 4$ a high value was presented on average compared to $R = 0.25$ and $R = 1$, due to the higher number of passengers boarding, reaching a maximum of 1.44 pass/m² (LOS = E using Fruin, 1971) in the fourth layer (150 – 200 cm). A similar situation was obtained in the case without PEDs, in which passengers were concentrated in the middle of the platform. The first layer (0 – 50 cm) was not used due to passengers respecting the yellow line for safety reasons.

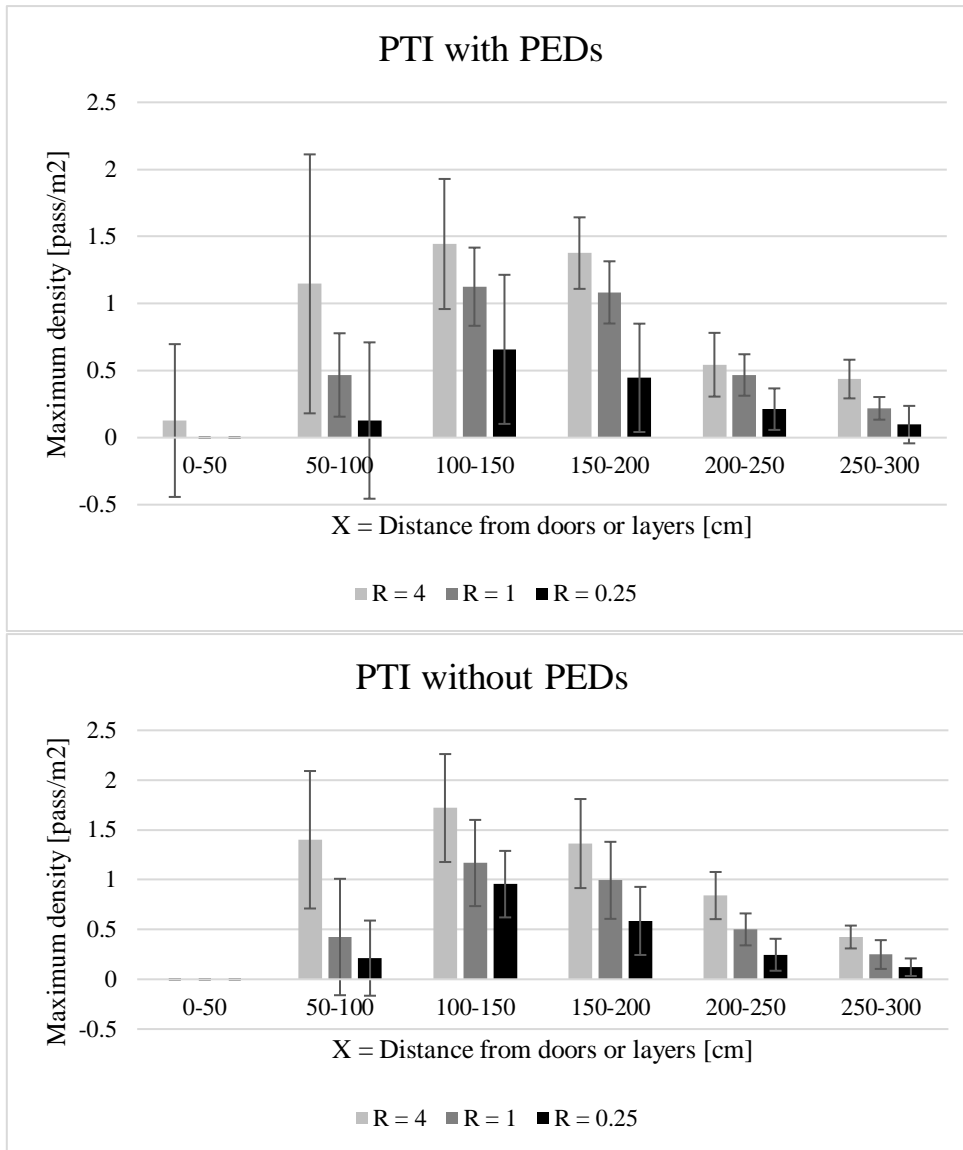


Figure 3 – Average maximum density by layer (k_L) and standard deviation at the simulated experiments just before doors opened

To compare k_L for each situation of R , a Kruskal–Wallis one-way (or one-way ANOVA on ranks) was performed. The null hypothesis (H_0) was defined as the medians of the samples are equal. A significance level of 5% ($\alpha = 0.05$) was used to compare groups ($R = 4$, $R = 1$, $R = 0.25$) for each layer. It is assumed that the outcome is not normally distributed due to the small sample size ($n = 20$ for each scenario of R). The results of the Kruskal–Wallis one-way test always presented a p -value lower than 0.05 for each layer, i.e. there are significant differences in terms of maximum density by layer for all cases of R when PEDs are used. In the case without PEDs, similar results are obtained, i.e. there are significant differences for all cases of R when comparing the maximum density by layer.

Another statistical analysis was done to compare k_L with and without PEDs for each situation of R. In this case a Mann-Whitney U test was performed with $\alpha = 0.05$ ($n = 20$ for each scenario of R). The null hypothesis (H_0) was defined as the medians of the samples are equal. The only cases that presented significant differences were layer 5 ($R = 4$) and layer 3 ($R = 0.25$), in which the case with PEDs reached a lower k_L compared to the absence of PEDs. Therefore, it is not possible to conclude that the presence of PEDs produced a variation on k_L .

In addition, the average maximum overall density (k_O) was obtained and compared to k_L (see Table 2). The variable k_L was more representative to measure the interaction problems at the PTI than k_O which is used in the Level of Service – LOS in waiting areas (Fruin, 1971), reaching up to 38% greater density when $R = 1$ (a difference of $+0.35$ pass/m²) in the case with PEDs. In absence of PEDs, k_L reached up to 75% more density than k_O when $R = 0.25$ (a difference of $+0.41$ pass/m²). The main difference is caused because the k_L represents the density when the platform is divided in layers, while the k_O considers the whole platform as a waiting area in front of each door (area of 15 m²). Therefore, the k_L helps to identify which part of the PTI is more congested.

Table 2 – Difference between the average maximum overall density (k_O) and density by layer (k_L) at the PTI in PAMELA

R (board/ alight)	With PEDs			Without PEDs		
	Max. k_O (pass/m ²)	Max. k_L (pass/m ²)	Diff.* (pass/m ²)	Max. k_O (pass/m ²)	Max. k_L (pass/m ²)	Diff.* (pass/m ²)
4.0	1.35 (LOS C)	1.44 (LOS C)	+0.09	1.57 (LOS D)	1.72 (LOS D)	+0.15
1.0	0.90 (LOS B)	1.25 (LOS C)	+0.35	0.92 (LOS B)	1.16 (LOS C)	+0.24
0.25	0.39 (LOS A)	0.65 (LOS A)	+0.26	0.54 (LOS A)	0.95 (LOS B)	+0.41

*Diff. = Max. k_L – Max. k_O

Another way to analyse the results in Figure 3 is to calculate the average time each cell was used at the PTI (or frequency) for the 20 runs in each case of R. The variable is obtained by counting the number of cells used each time a train arrived at the station. Then it is calculated an average for all the runs. For the calculation it is assumed that each cell is occupied by one passenger who is waiting to board the train. The green colour in Figure 4 and Figure 5 represents less occupied cells, while the red corresponds to frequently used cells. In the three scenarios of R, Figure 4 shows there were more occupied cells beside the doors (and more unoccupied cells in front of them) compared to the case in Figure 5 as passengers waiting to board knows were the PEDs are located on the platform. With respect to the first row, cells in Figure 4 and Figure 5 were less used because passengers waiting to board respected the

yellow line for safety reasons. In addition, the left part of the platform presented more occupied cells than the right part because passengers entered from the left to the right on the platform, due to the set-up of the experiments as there was only one exit gate at the platform.

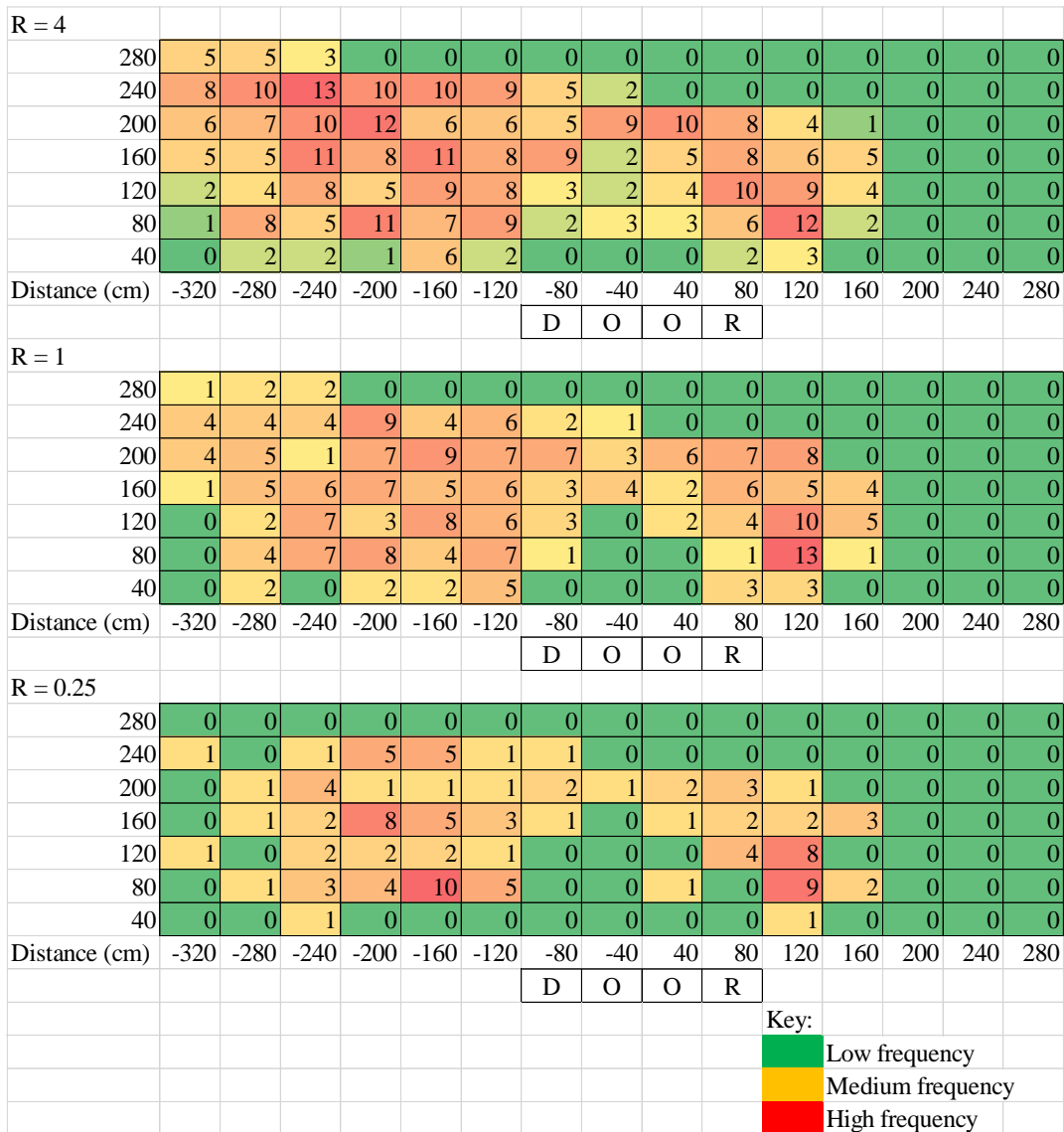


Figure 4 – Average time each cell was used at the PTI (frequency) just before doors started to open at PAMELA with PEDs

Table 3 – Multinomial probabilities (\hat{p}_j) obtained from the maximum number of passengers waiting to board the train with and without PEDs at PAMELA

PTI with PEDs?	R (board/alight)	Layers (cm)					
		0-50	50-100	100-150	150-200	200-250	250-300
Yes	4.0	0.0029	0.0794	0.2000	0.3176	0.1882	0.2117
	1.0	0.0000	0.0458	0.2208	0.3541	0.2291	0.1500
	0.25	0.0000	0.0272	0.2818	0.3181	0.2272	0.1454
No	4.0	0.0000	0.0846	0.2076	0.2743	0.2538	0.1794
	1.0	0.0000	0.0411	0.2263	0.3209	0.2427	0.1687
	0.25	0.0000	0.0344	0.3103	0.3172	0.2000	0.1379

The probabilities in Table 3 are obtained for the simulated experiments, and therefore can be used to predict the maximum number of passengers waiting to board in each layer at London Underground stations. In the case of Westminster and Green Park stations, three types of interactions were identified between opening and closing of the doors: only alighting (when boarding passengers were waiting on the platform), overlap (when boarding and alighting occurred simultaneously), and only boarding (when alighting was complete). The use of PEDs in Westminster station helped passengers to know where the doors were located on the platform. Thus, when a high-density situation was reached (e.g. more than 2 pass/m²) passengers formed an “arch”. As an example, Figure 6 shows the “arch” shape created using Observer XT 11 software (The Observer, 2014) by tracking the head of each passenger waiting to board the train and forming lines to connect each of these heads.



Figure 6 – Example of “arch” behaviour of passengers waiting to board at Westminster station

From the videos at Westminster (145 trains observed) and Green Park (140 trains observed) stations, the average total number of passengers boarding and alighting per train are obtained and presented in Figure 7. In Westminster station (with PEDs), from the 5 days of videos on average the total number of passengers boarding (B) was equal to 9 and the total number of passengers alighting (A) was equal to 12. In the case of Green Park station (without PEDs), B was equal to 9 and A was equal to 15.

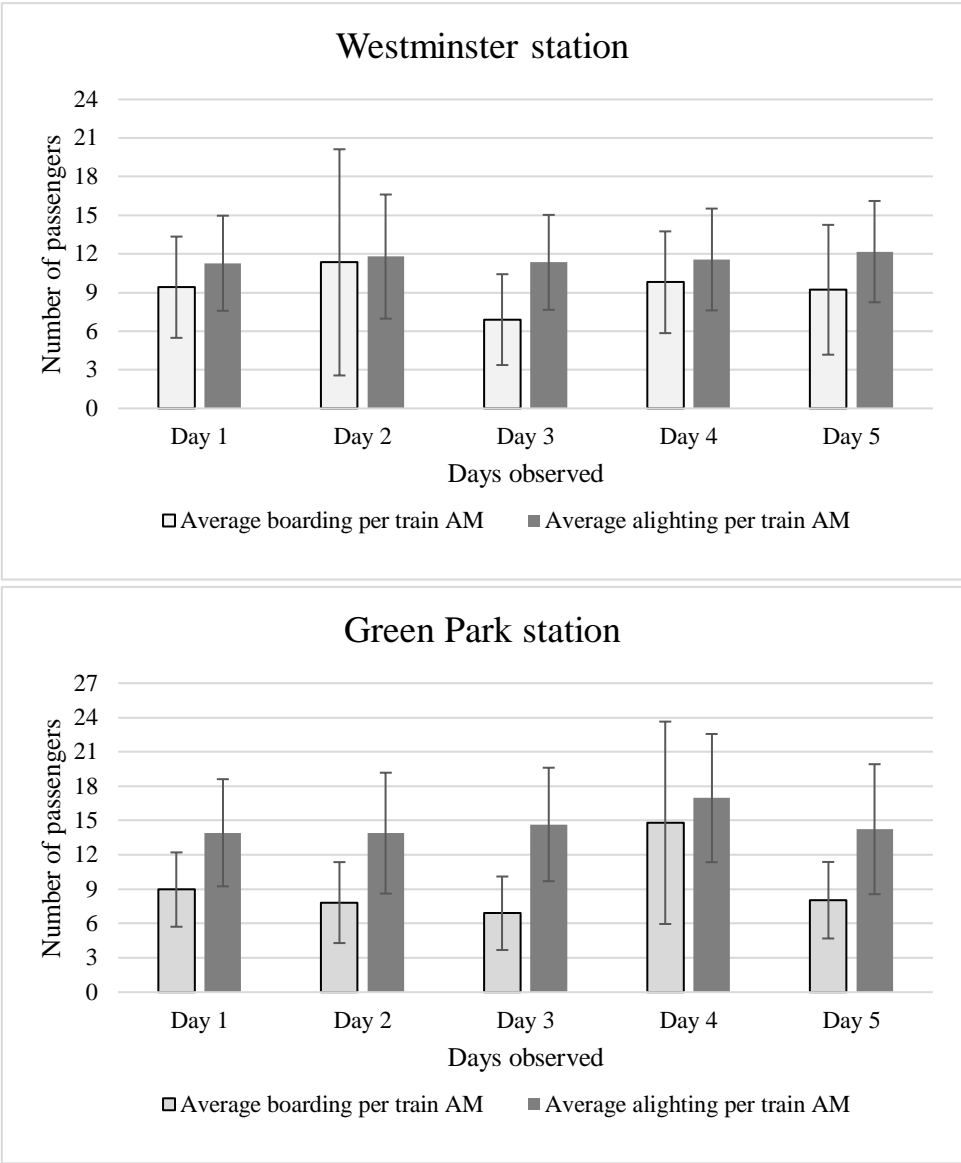
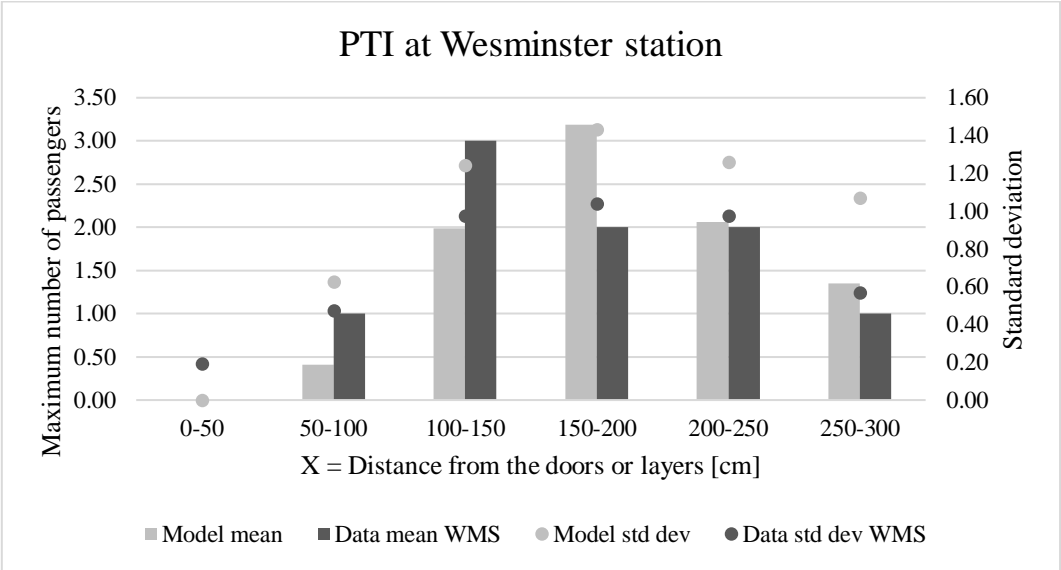


Figure 7 – Average total number of passengers boarding and alighting per train and standard deviation at Westminster and Green Park stations

From the results in Figure 7 it was obtained the ratio (R) between passengers boarding and alighting. From the total of trains observed at Westminster station (145 trains) R was equal to 0.9 (standard deviation of 0.55), which means that on average the number of passengers

boarding is similar to the average number of passengers alighting. In the case of Green Park station (140 trains) the value of R was equal to 0.7 (standard deviation of 0.42), which is similar to the case of Westminster station.

The probabilities (\hat{p}_j) obtained from the PAMELA experiments can be used in Equation (3) to predict the mean and standard deviation (square root of the variance) of the maximum number of passengers waiting to board in each layer at Westminster station. From the observation at Westminster station the average total maximum boarding passengers (B) is equal to 9 and R is equal to 0.9 (obtained from Figure 7). This value of R can be approximated to $R = 1$, and therefore, the \hat{p}_j values can be obtained from Table 3. The results of the mean and standard deviation are presented in Figure 8, in which the difference of passengers waiting to board in each layer (b) reached 1 passenger compared to the observed data at Westminster station. Similarly, in the case of Green Park station B is equal to 9 and the value of R is equal to 0.7 (obtained from Figure 7) and can be approximated to $R = 1$. Therefore, the \hat{p}_j values can be obtained from Table 3. Using Equation (8), the maximum number of passengers waiting to board in each layer (b) can be predicted at Green Park station. The results are presented in Figure 8, in which the difference between the expected and observed data reached 1 passenger.



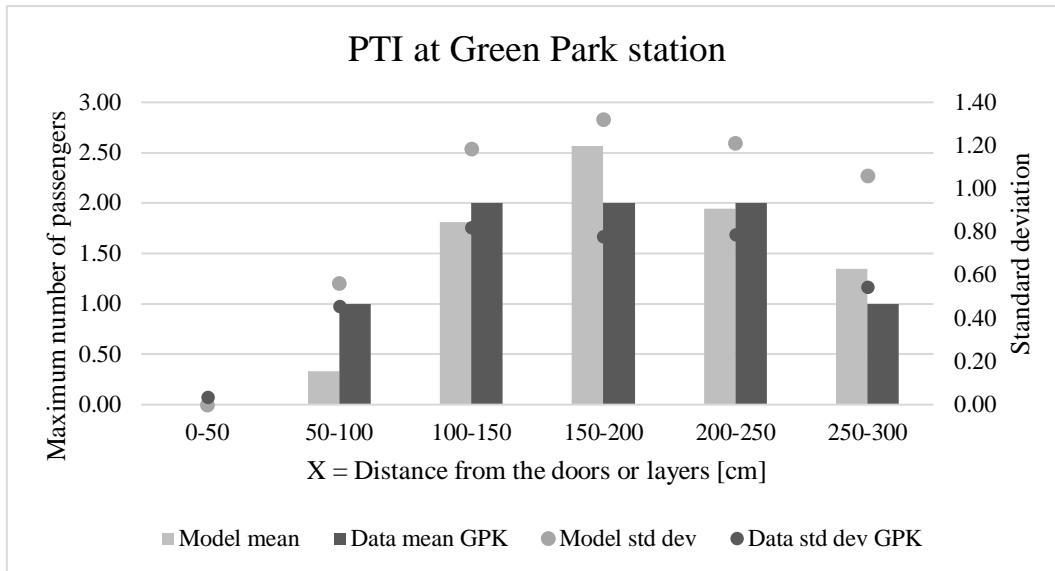


Figure 8 – Predicted and observed maximum number of passengers waiting to board at Westminster and Green Park stations using the conceptual model when $R = 1$

A chi-square test was performed with a significant level of $\alpha = 0.05$ to compare the expected and the observed total maximum number of passengers waiting to board in each layer at Westminster and Green Park stations. The null hypothesis (H_0) was defined as when there is no difference between the expected and observed values. The result of the chi-square test showed a p-value higher than 0.05 in both stations, which means that the hypothesis is accepted and there are no significant differences between the expected and observed data.

5. Discussion

When PEDs are used, passengers knew where the train was going to stop on the platform, and therefore they were located beside the doors rather than in front. As it was shown in Figure 4 and Figure 5 square cells in front of PEDs were less used compared to the case without PEDs. In consequence, the interaction between passengers was reduced in presence of PEDs. These results were observed at PAMELA experiments, which are in concordance to our previous studies (De Ana Rodriguez et al., 2016; Seriani et al., 2017). Therefore, the PTI divided by square cells helped to identify where are passengers located on the platform, and which part is more congested.

With respect to the distribution of passengers waiting to board at PAMELA, the density by layer or k_L (in which the PTI is divided by layers) was more representative of the problems of interaction between passengers waiting to board (before doors opened) compared to the overall density or k_O (platform as a rectangular space). When $R = 4$, there was not a big difference between the maximum value of k_L and k_O , due to the high number of passengers

waiting to board the train (≥ 20 passengers). However, in the case of $R = 0.25$ and $R = 1$ the value of k_L was higher than the maximum k_O . As the PTI is divided by layers, the k_L helps to identify where passengers are located from the train doors, and therefore where a high interaction occurs. Therefore, it is recommended to use k_L to better design the PTI rather than the k_O which is used to design the whole platform. In addition, k_L can be used to identify when crowd management measures are needed at the PTI. For example, operators can define which layer should be empty to better circulate passengers on the platform and evacuate them to the exit gates (direction to stairs). When layers are crowded, other measures can also be implemented at the PTI such as closing the platform and holding incoming passengers at a previous stage (e.g. gateways or outside the station). The Kruskal–Wallis one-way test supported these results as there were significant differences (p-value < 0.05) in all the cases. When comparing the case with and without PEDs, the only cases that presented significant differences (using Mann-Whitney U test) were layer 5 ($R = 4$) and layer 3 ($R = 0.25$). Therefore, it is not possible to conclude that PEDs changed the way passengers are distributed in semi-circular layers. In both cases (with and without PEDs) passengers are concentrated in the middle of the platform (i.e. layer 100-150 cm).

From the simulated experiments at PAMELA, a multinomial probability distribution was used to calculate the maximum number of passengers waiting to board (b_j) for each layer j at existing stations. This conceptual model presented a difference of only 1 passenger between the predicted and observed data at Westminster and Green Park stations. In addition, no significant differences were obtained. The results of this model can be used to calculate/estimate the necessary platform width in front of each door. The model seems to be more representative than the typical models such as the LOS of Fruin (1971) which consider uniform distribution of passengers on the platform. Because of the sample size (only 20 runs each scenario) it was not possible to do a rigorous statistical analysis (Thompson, 1987) to obtain the parameters of the multinomial distribution, however this does not mean that this distribution model is not accurate, and it can still predict the variable b_j . However, to reduce the differences between the model and the data more experiments should be done at PAMELA focused on the calibration of \hat{p}_j (multinomial probabilities) for different type and numbers of passengers, even if the ratio between passengers boarding and alighting remains constant over time. Further research is needed to consider a larger sample size and calibrate the model in different types of stations. In addition, new experiments should also consider the effect of queues and other types of lines formed on the density by layer of passengers boarding at the PTI. These new experiments should also consider the behaviour of passengers located on the platform between doors, which was out of the scope of this study.

With respect to the observation at existing stations, three types of interactions (only boarding, boarding and alighting simultaneously, and only alighting) were studied at Westminster

(where PEDs were used) and Green Park (absence of PEDs) stations. In addition, a phenomenon of arching was formed in high density situations at Westminster station, which is similar to the effect observed in bottlenecks by Guy et al. (2010). In relation to circulation areas at the PTI, the interaction at Westminster station and Green Park station was influenced by the presence of other passengers and their distribution. If there are few passengers, then high overlap is produced because passengers have enough space to board and alight simultaneously. When there is a crowded situation, then low overlap occurs because passengers will wait until alighting is complete or until there is a 'gap' or space available to board the train. These observations are similar to Harris (2006), in which the author reported that passengers consider the train doors as bottlenecks, and passengers follow the person in front of him/her.

Some limitations of this study are related to the use of the tracking tool. Because of the quality and type of file, it was not possible to use a tracking tool to count automatically the number of passengers waiting to board at Westminster and Green Park stations. In the case of PAMELA, it was possible to use Petrack, however because of the varying frame rate and large steps in between the videos it was not possible to extract any trajectories automatically but only the position (x, y) for each passenger. It was not possible to solve this situation because the videos were highly compressed. In future, these errors can be rectified before the beginning of the study. In addition, further research needs to be conducted to test new sensors and technologies to track passengers.

Another limitation was related to the set-up experiments. We did not use any markings on the platform, as the objective of this study was to identify the distribution of passengers when PEDs are used at the PTI. The approach used in this study (based on experiments) considered only changing one variable, while the rest of them remain the same. Then it is possible to compare the changes with the base scenario, i.e. PEDs vs NoPEDs. Further research should be done to study other type of crowd management measures such as markings on the floor. In addition, the income, ethnic and other cultural characteristics of passengers should be incorporated at the experiments to represent London Underground passengers, and therefore calibrate PAMELA.

6. Conclusions

This study presents a new method to model the distribution of passengers waiting to board the train when platform edge doors (PEDs) are used. This was completed using a tracking tool to identify the location of passengers on the platform and a conceptual model based on a discretised PTI and a multinomial probability distribution to obtain the maximum number of passengers at each layer. To test this method simulated experiments were done at the

University College London’s Pedestrian Accessibility Movement Environmental Laboratory (PAMELA) and observations were recorded at Westminster and Green Park station using the CCTV system.

The use of laboratory experiments helped to test different situations (e.g. with and without PEDs) in a controlled environment. This would be difficult to do in a real situation due to the different variables affecting the layout and vehicles of existing public transport systems. In addition, few laboratories in the world such as PAMELA have been built, and the fact that we could work there has enabled us to be in a privileged position and to be able to perform new research.

Currently at PAMELA new experiments are simulating the use of a waiting area or a “stay clear” to avoid alighting being blocked by passengers waiting in front of the doors. In addition, more experiments are being carried out to study the effect of PEDs on the behaviour of passengers with other characteristics (e.g. reduced mobility).

Abbreviations and acronyms

In this study the following abbreviations and acronyms were used.

Variable	
Platform edge doors (PEDs)	Installed on the edge of the platform (between the platform and the train).
Platform Train Interface (PTI) without PEDs	The space between the train doors and the yellow line on the platform.
Platform Train Interface (PTI) with PEDs	Is the space between the PEDs and the train doors.
PAMELA	Pedestrian Accessibility Movement Environment Laboratory (at UCL, UK)
Density by layer (k_L)	Number of passengers boarding and/or alighting in each layer divided by the area of each layer in the PTI.
Overall density (k_o)	The total number of passengers on the platform divided by the area of the platform (rectangular space of 15 m ² without layers in front of each door).
LOS	Level of Service or Fruin’s LOS, which indicates the degree of congestion and conflict in an area (flat areas, queues or stairs) using general parameters such as speed, density or flow.
R	Ratio between passengers boarding and those who are alighting at the PTI.
b_j	Maximum number of passengers waiting to board (b) in layer j.

B	Total maximum number of passengers waiting to board on the PTL.
$E(X_j)$	Expected value or mean of passengers waiting to board at the layer X_j
$Var(X_j)$	Variance of passengers waiting to board at the layer X_j
\hat{p}_j	Multinomial probabilities obtained using the Maximum Likelihood Estimation.

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