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Exploring the Pedestrian Level of Interaction on Platform Conflict Areas at Metro Stations by Real-scale Laboratory Experiments

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Manuscript

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To reduce passenger interactions improvement on platform designs is needed. Present procedures use the Level of Service (LOS) based only on average values and therefore is not possible to identify which piece of space reached the highest interaction. This paper explores a new method to classify the interaction between passengers boarding and alighting through laboratory experiments under controlled conditions. The experiments were based on observation at two stations operated by London Underground Limited, which included platform edge doors and a semi-circular space defined as platform conflict area. Results were expressed according to the types of queues, formation of lanes, density by layer, and distance between passengers. The Level of Interaction (LOI) was a more precise indicator compared to the LOS. The density by layer followed a logarithmic distribution, reaching almost four times the overall density. Further research needs to be conducted to measure the passenger space on the platform.

Keywords: pedestrian; behaviour; interaction; platform; metro station

1. Introduction

There are a variety factors affecting the behaviour of passengers in metro stations (underground and over ground). According to RSSB (2008) these factors can be classified into four groups: people (e.g. boarding and alighting), information (e.g. maps), environmental (e.g. weather), and physical (e.g. number of seats inside the train).

In this paper we have focussed on factors related to people, specifically on how the number of boarders and alighters on the LUL affects what we define as the passenger interactions. We have chosen this as a focus in part because it is a pressing issue for many metro operators worldwide and in part because it is well suited to study in a laboratory setting. The reason it is a pressing issue for operators is that there is a link between the density of passengers and their behaviour and the frequency and regularity of the services, with the risk of cascading of delays or "*knock-on*" effect if trains cannot depart on time (Carey and Kwieciński, 1994; TRB, 2003; 2013).

It is the platform train interface (PTI) where most passenger interactions occur. This space is composed of a train door and the corresponding adjacent spaces on the platform and on the trains (Seriani and Fernandez, 2015a).

The PTI is the space where more interactions are produced. In the case of the UK railway network, about 3 billion interactions between passengers boarding and alighting are reached, representing 48% of the total fatality risks (RSSB, 2015). However, it is not only about safety. As an example, in the London Underground network about 4.25 million of trips are undertaken every day, in which 400,000 passengers start their journey at the peak hour between 8 am and 9 am (TfL, 2014), needing one train every 2-3 minutes. The time each passenger spends at the station is influenced by the degree of congestion and conflicts in the PTI. Therefore, the better we understand the passenger interaction, the more we can do to improve platform designs and improve passenger experience and service reliability.

According to TRB (2003; 2013) when the density on the platform reached a Level of Service (LOS) equal to F as defined by Fruin (1971), then the interaction between passengers boarding and alighting increased (e.g. physical contact is inevitable). This is the equivalent of 2.17 passengers per m^2. At this level, congestion and conflicts between passengers rise (e.g. frequently stops or sporadic flow), affecting passengers on the platform and inside the train. While informative as a general indicator and comparator between different stations, the LOS using as it does an average density is not the ideal indicator as it is difficult to identify which part of the PTI reaches a relatively higher level of interaction compared with other areas (Evans and Wener, 2007). In addition, it could be argued that there are other ways to classify interaction in high-density situations. For instance, what happens when there are more than 2.17 passengers per m^2?.

The aim of this research is to develop a new indicator for classifing the level of interaction at the PTI. The hypothesis is that the interaction between passengers boarding and alighting is influenced by the types of queues, formation of lanes, density, and distance between passengers. If the platform is divided into semi-circular layers, then the interaction would be higher near the train doors and decreases as the distance from the train door increases. In addition, interaction is reduced when the distance between passengers would be increased or when the overlap (simultaneously boarding and alighting) is reduced.

It is proposed as a general objective to determine, by means of laboratory experiments, a new method to classify the interaction between passengers boarding and alighting at metro stations. The specific objectives are: a) identify the typical patterns of movement at London Underground Limited (LU) stations; b) to simulate different scenarios of boarding and alighting at University College London's Pedestrian Accessibility Movement and Environmental Laboratory (PAMELA); c) to create a new indicator of interaction based on the types of queues, formation of lanes, density by layer, and distance between passengers; d) to propose some recommendations on how the interaction between passengers boarding and alighting can be reduced on the platform. As a case study it was used the LUL, but the results can be expanded to other metro and LRT systems.

This paper is composed of six sections, including this one. The second section reviews the different methodological approaches to measuring and interpreting passenger interactions, and directs the methodological approach presented in section three. Section 4 sets out the results from the laboratory experiments, including visualisations. In section 5 recommendations regarding the ways in which passenger interaction can be reduced are developed from the experimental evidence. Finally, the conclusion set out the key findings and review the limitations of the research.

2. Literature Review

To reduce the interaction between passengers boarding and alighting, platform edge doors (PEDs) can be installed at the PTI. PEDs work simultaneously with the train doors as barriers between the vehicle and the waiting passengers on the platform. In addition, PEDs can improve safety and energy conditions in the PTI by reducing suicides, improving air-condition, and increasing ventilation or fire detection (Clarke and Poyner, 1994; Kyriakidis et al., 2012; Qu and Chow, 2012; Loukaitou-Sideris et al., 2015).

Recently, some authors (De Ana Rodriguez et al., 2016) found that PEDs have no important effect on the boarding and alighting time (BAT). The authors identified by means of laboratory experiments (at PAMELA) and observation (at LU stations) that PEDs influenced the behaviour of passengers by waiting beside the doors rather than in front of them. As a consequence, with PEDs passengers gave way to alighters and boarding passengers were not considered an obstacle. This was caused because with PEDs passengers know where the doors were located on the platform. Although this is considered one of the first study that included PEDs in a laboratory facility, the authors did not measure the interaction between passengers boarding and alighting, and only described the BAT and qualitative behaviour of passengers queuing or clustering before the train arrived.

Another way to reduce the interaction of passengers is by the use of design standards (e.g. increase the minimum width of platforms). Some of these standards regulate station designs based on operational capacity. For instance, London Underground Limited (LUL, 2012) states that the total platform width of a station should not be less than 3.0 m (with a density of 4.0 pass/m^2 to reach capacity), but for other manuals such as NFPA-130 (2007) 1.12 m should be enough to evacuate passengers in case of a fire. In practice, compliance to these standards is tested by simulation (e.g. pedestrian models) and then compared to design thresholds (Still, 2000; Teknomo, 2006).

One of the most common indicators is the Level of Service or LOS (Fruin, 1971) defined in TRB (2003; 2013), which indicates the degree of congestion and conflicts of passengers. This indicator goes from level A (density less than 0.31 pass/m^2, free flow and no conflicts) to the level F (density more than 2.17 pass/m^2, sporadic flow, frequent stops and physical contact), where E is equal to the capacity (density between 1.08 and 2.17 pass/m^2). However, this index is used in small spaces 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 design of the PTI is changed (Evans and Wener, 2007). Carreno et al. (2002) state that the LOS indicated by Fruin (1971) is based principally on the personal space of passengers, which is not the only factor that affects walking environments. In fact, Carreno et al. (2002) developed a new indicator called Quality of Service (QOS) for pedestrians, which was applied only at the street level.

According to Fruin (1971) a standing passenger can be represented as an ellipse of area 0.30 m^2 (body depth of 50 cm and shoulder breadth of 60 cm). In Little (1965) the personal space is defined as the area that an individual use to interact with other pedestrians and the environment, in which interaction between two pedestrians depends on the acquaintance between them. However, some authors (Hartnett et al., 1974; Sanders, 1976) found that the personal space is a function of the body height, body position, and gender. For example, Pushkarev and Zupan (1975) state that in the case where queues are formed, passengers need at least 0.74 m^2 to walk or wait to board the train, in which a "face-to-face" less than 0.5 m will be felt as intimate.

The effects of intimacy on interpersonal distance has been studied by other authors. For example, Hall (1966) classified the interpersonal space between two pedestrians into four groups according to their relationship: a) intimate zone (< 0.5 m) when pedestrians have a special relationship; b) personal zone (0.5 – 1.2 m) when a pedestrian knows another pedestrian; c) social consultative zone (1.2 – 4.0 m) when pedestrians do not know each other but they permitted to communicate; and d) public distance (4.0 – 10.0m) when pedestrians do not know the other pedestrians. Similarly, Sommer (1969) studied the social behaviour in stations and defined the personal space according to three levels: a) intimate (< 0.5 m); b) personal (0.5 – 1.2 m); and c) Social (>3.0 m). Considering the ellipse area of 0.30 m^2 defined by Fruin (1971) the intimate level in these classifications will be reached when the distance between heads of two pedestrians is less than 0.8 m (0.5 m plus two times half the body depth), which can be considered as a critical value for social behaviour. However, recent studies (Webb and Weber, 2003; Evans and Wener, 2007) showed that the interpersonal space depends on other factors such as crowd, vision, hearing, mobility and stress level. In addition, Gérin-Lajoie et al. (2008) state that personal space is asymmetrical in shape and in side (left and right) when overtaking an obstacle. This change of interpersonal space has been modelled considering an adjustment of the stride length of pedestrians in bottlenecks (Von Sivers and Köster, 2015).

In the case of the PTI, Shen (2008) states that social behaviour can be studied in two distinct areas with different functions: circulation and waiting zones. In the circulation area, evacuation and dissipation behaviours take place, while the boarding and alighting behaviours are carried out in the waiting zones. However, in actual metro stations with PEDs there are no clear differences between these two areas (e.g. there is a lack of demarcations or signs) and therefore the platform is considered as one whole piece for circulation of passengers (Wu and Ma, 2013). In particular, Wu and Ma (2013) proposed a new division method for these waiting zones based on different rectangular shapes. The idea of dividing the waiting area for a more in-depth analysis has been employed by other researchers as well. For example, Shen (2001) states that the shape of the waiting zone can be represented as a parabola, while Lu and Dong (2010) suggested it be a fan or spectrum. Moreover, Seriani and Fernandez (2015b) reported that the use of a rectangular “keep-out zone” in front of a door on the platform reduced the interaction of passengers when they respected this area by queuing or clustering to the side of the doors rather than waiting in front of them. However, all these authors have considered fixed values for those shapes, which do not necessarily represent the interaction of passengers, especially considering that the boarding and alighting movements change over time (e.g. before and after the train arrives).

The social behaviour in metro stations is also influenced by the formation of groups (only boarding, only alighting, and simultaneously), in which each passenger follows the passenger that is in front (Harris, 2006; De Ana Rodriguez et al., 2016). Their movement is freely in any space and is only limited by the geometry of the walking environment (Still, 2000). Some researchers (Hoogendoorn and Daamen, 2005; Seyfried et al., 2009) have studied the pedestrian flow through bottlenecks in a corridor by performing laboratory experiments, and found that the capacity was only increased if a new lane was formed or when the “zipper effect” (passengers are overlapped forming two lanes) was presented. In addition, the behaviour in bottlenecks has been simulated by Guy et al (2010), in which pedestrians formed an “arch” reaching a higher density near the doors. This is shown in different laboratory experiments of boarding and alighting (Daamen et al., 2008; Fernandez et al., 2015; Seriani and Fernandez, 2015b). Similarly, some authors (Karekla and Tyler, 2012; Fujiyama et al., 2014) have studied by the means of laboratory experiments, the effect of PTI layouts on the flow rate, accessibility and the passenger service time.

Despite the wide variety of research conducted to aid understanding and optimization of platform design both for safety and service delivery, more detailed studies are needed to inform how passengers interact on the platform, specifically when PEDS have been introduced. We extend the analysis of De Ana Rodriguez et al. (2016) to produce a new method to classify and reduce interaction, which we hope will help operators further optimize service both for when PEDs are present.

3. Method

The main variables of this study were classified into one of the three groups reported in Seriani and Fernandez (2015a): physical (e.g. width of the platform), spatial (e.g. layout of the train), and operational (e.g. frequency of the train). In this work Green Park Station (GKP) and Westminster Station (WMS) were chosen as case studies. Both stations presented the same platform layout and similar demand profiles. The biggest difference between both stations was that WMS uses platform edge doors (PEDs), while GKP does not use PEDs. Both stations were part of a complete CCTV video recording study solicited by London Underground Limited (LU) and provided the videos to the members of the Pedestrian Accessibility Movement Environmental Laboratory (PAMELA) in November 2014. In this study physical and spatial variables were fixed, while operational variables varied during the observation (see Table 1 and Table 2).

Table 1. Physical and spatial variables studied at GKP and WMS stations

Variable	**Type**	**Observation**
Total platform width (mm)	Physical	3300 (included PEDs in WMS)
Distance between yellow line and edge on platform (mm)		300 (included PEDs in WMS)
Door width (mm)		1600 (2 double doors of 800 mm)
Setback (mm)		200 between door and end seats 300 between door and centre seats
Horizontal gap (mm)		90
Vertical gap (mm)		170 (GKP); 0 (WMS)
PEDs	Spatial	No (GKP); Yes (WMS)
Number of fixed seats		12 (4 in centre and 4 at each end)
Number of tip-up seats		8 (2 on each side of centre seating)

Table 2. Operational variables studied at GKP and WMS stations

Variable	**Type**	**Observation**
Number passenger movements (pass)	Operational	Total number of boarders and alighters in segments of 5 s
Types of queues on the PCA		Passenger were clustered or queuing in front or at the side of the doors
Formation of lanes		Number of lanes formed for boarding and alighting at doors

The operational variables at GKP and WMS were recorded during the most congested hour of the day (8:15 to 9:15 am and 5:15 to 6:15 pm), reaching a flow of 30 train/h (2 minutes headway on average with a standard deviation of 1 minute). To do this, 15 days (5th – 25th of November 2014) of data were collected using the software Observer XT 11 and the videos were converted into .avi format (Holloway et al., 2015).

In relation to the scenarios, the exact train loadings were defined (i.e. number of people boarding, alighting or remaining on the train) as well as the different situations to be tested, which were based on the observation of two weeks of CCTV footage at GKP and WMS. From the total recordings, on average 15 passengers boarded and 8 alighted at GKP, whilst at WMS 12 passengers boarded and 6 alighted. For this study, it was used the loads described in Table 3. Three scenario of ratio (R) between boarding and alighting were defined (R = 4, R = 1, R = 0.25). Each of these scenarios were tested with PEDs and without PEDs. The LC_0 and LC_1 loads were only tested to prepare passengers for each day and to check initial values or boundaries of the experiment when there were no passengers inside the train or on the platform. In the case of LC_5 this scenario was used to calculate the total load of the train.

Table 3. Loads used in the experiment at PAMELA

Load condition code	**Boarding passengers per door**	**Alighting passengers per door**	**On-board passengers per door**	**Ratio (boarding/ alighting)**	**Number of runs per 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	-	10

These scenarios were simulated at PAMELA using a mock-up of an underground tube carriage and a portion of the platform with similar characteristics of GKP (without PEDs) and WMS (with PEDs). The mock-up was 10.00-m long and 2.65-m wide, with 20 seats (12 fixed seats and 8 tip-up seats), and two double doors of 1.6-m wide. This produced a total floor area of 17.46 m^2, which allowed a capacity of 90 passengers (for a density of 4 pass/m^2) or 142 passengers (for a density of 7 pass/m^2) inside the train. The horizontal gap between the train and the platform was equal to 90 mm, while the vertical gap was 170 mm (without PEDs) and 0 mm (with PEDs). The platform was 10.00-m long and 3.30-m wide. In addition, the Platform Train Interface (PTI) was defined as the space between the train doors and PEDs (similar to WMS), whilst in the case without PEDs (similar to GKP) it was the space between the train doors and the yellow safety line on the platform.

As there was limited space at PAMELA to simulate the behaviour of each passenger before the train arrived, the analysis was focused on the period between the train doors opening and closing (i.e. after the train arrived). For this simulation, we recruited 110 participants to form 11 groups of 10 passengers each. In addition, boarding passengers used red hats and alighting passengers used white hats, and each set of 10 passengers wore different coloured bibs in which each passenger had a unique number on their bib. Therefore, each passenger was identified by their bib colour, hat colour and number. This produced an input density on the platform of 3.3 pass/m^2 (when all passengers were standing on the platform) and 5.15 pass/m^2 inside the car (when all passenger were inside the train). At the experiments, passengers were instructed to walk “naturally” as if they were boarding and alighting a train in the LU. To make sure that this behaviour was represented over time, randomly groups were chosen to board, alight or remain inside the carriage. In addition, a complete sound system was provided in order to make participants feel the experiment to be real. The sound included the train arriving, braking, door opening alarm, door closing alarm, and departure.

Considering the hypothesis of this research the interaction was measured in a new space defined as platform conflict area (PCA), which is represented as a semi-circular space with radius L. The radius L of the PCA denotes the distance of influence of the train door (see Figure 1 and Figure 2). To measure the interaction, the PCA was divided into six layers of 50 cm each, which represents the body depth of each passenger defined by Fruin (1971).

Figure 1. PCA divided into layers at PAMELA (with PEDs)

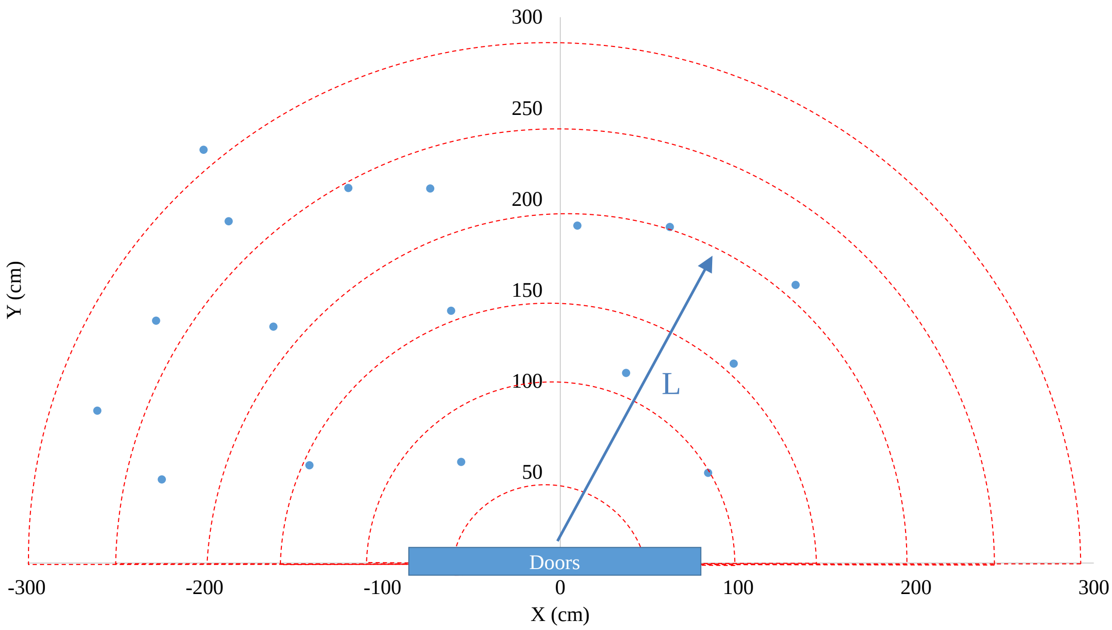

Figure 2. Representation of the PCA in layers of 50 cm each to measure the position of passengers boarding and alighting (circles)

In this work, the Level of Interaction (LOI) was defined as a qualitative method to classify the degree of interaction (low, medium, high) between passengers boarding and alighting at metro stations. This indicator was created to analyse the complete PCA. To create the LOI four operational variables were measured in the laboratory experiments: a) types of queues; b) formation of lanes; c) density by layer; and d) distance between passengers.

Queues were classified into four types: waiting in front of doors, clustered to the side of the doors, queuing in front of the doors, and queuing at the side of the doors. Passengers formed lanes when they avoid collision with passengers walking in opposite direction. In this sense, passengers followed the person in front of him/her.

The density by layer was obtained by counting the number of passenger boarding and alighting divided by the area of each layer in the PCA. The distance between passengers was calculated by the Euclidian method between the coordinates (x, y) of the heads of two passengers in the PCA. To obtain the position (x, y) of each passenger a tracking software was used. The use of automatic (or semi-automatic) tracking helped to save time and it was much easier to identify how passengers were moving, especially in spaces with high interaction (e.g. boarding and alighting). In this study Petrack was used, which is the latest software used to extract each passenger trajectory from video recordings (Boltes and Seyfried, 2013). The cameras were located at a height of 4 m from the floor at PAMELA.

4. Results

4.1 Passengers demographics

The subjects used in PAMELA were volunteers, 46% men and 54% women, 78% of them were regular users of the London Underground and mostly were under 45 years old (15% were under 24 years, 26% 25-34, 19% 35-44, 27% 45-59, 7% 60-64, and 7% more than 65 years old). The total passenger load tested in the scenario LC_0 and LC_1 was 8221 kg (including seated passengers). The average height of passengers was 170 cm with a deviation standard of 8 cm.

4.2 Types of queues and formation of lanes

As a result of the observation at GKP and WMS, the typical pattern of behaviour between boarding and alighting was identified (see Figure 3). When the train doors commenced opening passengers started to form queues. In the case of WMS the use of PEDs helped passengers to know where the doors were located on the platform. Thus, the interaction was reduced and passengers were queuing at the side of the doors rather than in front. When a high-density situation was reached at WMS passengers formed an “arch” similar to the effect observed in bottlenecks by Guy et al. (2010). In the case without PEDs (GKP), passengers entered earlier the PTI than with PEDs, reaching a higher interaction between passengers.

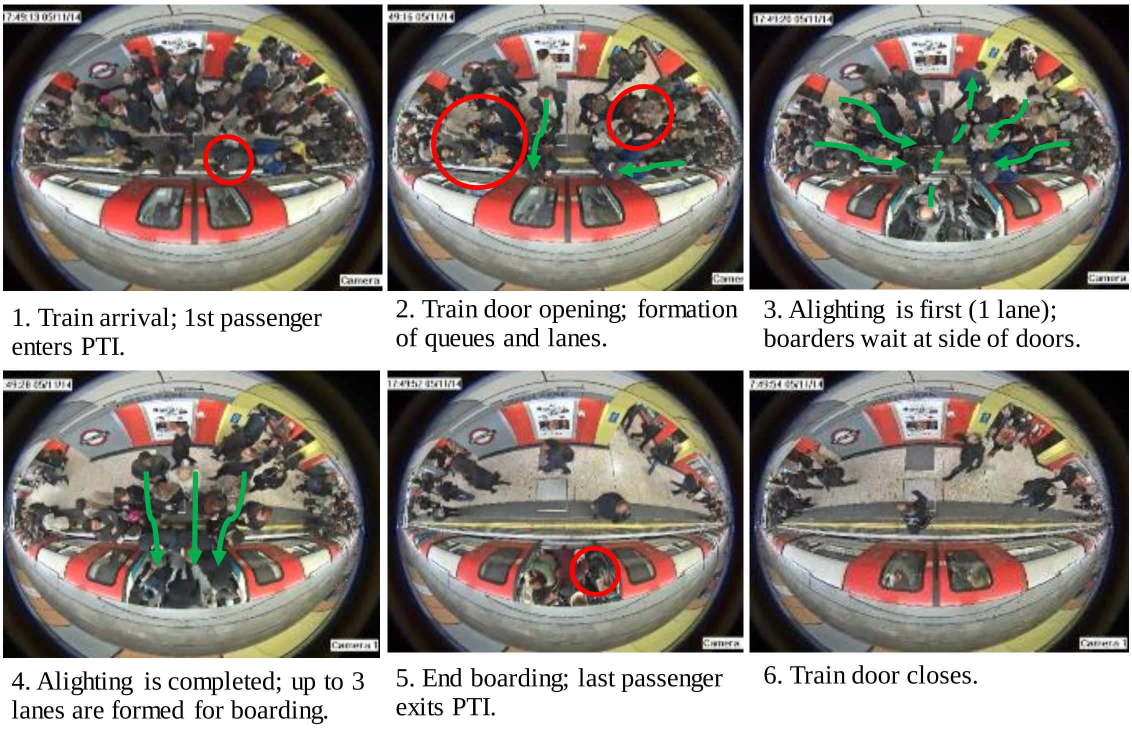

Figure 3. Typical pattern of behaviour between boarding and alighting at GKP

These behaviours related to the PTI and types of queues were also identified at the PAMELA experiments. When the ratio between passengers boarding to those who are alighting (R) was equal to 4, then passengers were mostly waiting in front of the doors, while when R was equal to 0.25, passengers were clustered or queueing at the side of the doors before boarding. In the case where R = 1 the behaviour of passengers was in between the two cases R = 4 and R = 0.25. The types of queues were influenced not only by the number of passengers boarding but also by the on-board passengers. A further explanation about this relationship can be founded in De Ana Rodriguez et al. (2016).

Lanes are the spaces created that enable passengers to move on or off the train. Figure 3 illustrates how one lane formed between queueing passengers to enable passengers to alight before boarding in 3 lanes. The interaction is related to the amount of time where passengers are simultaneously alighting and boarding. For example, when the ratio between boarding and alighting (R) was equal to 0.25, passengers waited until the alighting process was almost finished to board the train, reaching less interaction between passengers boarding and alighting. When R = 1, passengers wait until segment 10th-15th seconds to start boarding the train, reaching a medium interaction. In the case of R = 4, passengers started to board earlier (from the segment 5th-10th seconds) as there were four times more boarding passengers than alighting. This situation (R = 4) produced more opportunities to board the train before the end of alighting, reaching more interaction between passengers boarding and alighting.

The formation of lanes were also seen in the PAMELA experiments. For each case of R, alighting lanes were produced due to collision avoidance with passenger boarding. This situation produced the phenomena of formation of lanes at the doors, which were different to a supermarket’s queue in which people are served in FIFO (“First in First out”). Figure 4 shows that when R = 4, passengers reached a high interaction and alighting formed a narrow single lane, whilst two lanes for alighting were formed and a lower interaction resulted when R = 0.25. In both cases, two lanes for boarding were formed at the side of the doors and an average bidirectional flow of 1.0 passengers per second was reached at the doors. In the case when R = 1, between one and two lanes were formed for alighting reaching an average bidirectional flow of 0.80 pass/s at the doors.

Figure 4. Formation of lanes when R = 4 (left) and R = 0.25 (right) at PAMELA

The results of the LU observations and laboratory experiments shows that the formation of lanes in the PTI depends not only on the width of the bottleneck or train doors (Hoogendoorn and Daamen, 2005; Daamen et al., 2008; Seyfried et al., 2009) but also on the ratio between passengers boarding to those who are alighting (R). As a conclusion, the Level of Interaction (LOI) was defined as an indicator to classify the interaction (low, medium, and high) between passengers boarding and alighting based on the types of queues and formation of lanes (see Table 4).

Table 4. Proposed classification of LOI with respect to types of queues and formation of lanes

LOI	**R (boarding/ alighting)**	**Type of queues for boarding passengers**	**Formation of lanes for alighting passengers**
High	4	Passengers wait in front of doors	1 lane
Medium	1	Clustered at the side and in front of doors	Between 1 and 2 lanes
Low	0.25	Clustered or queuing at the side of doors	2 lanes

4.3 Density by layer

Figure 5 shows the average maximum density by layer on the PCA just before the doors started to open (segment of time 0^{th} seconds). When R = 4 a high density was presented on average compared to R = 0.25 and R = 1, due to the higher number of passenger boarding, reaching a maximum of 1.4 pass/m^2 in the fourth layer (150 – 200 cm). The first layer (0 – 50 cm) was unused because boarding passengers respected the yellow line for safety reasons. These results supported the behaviour of passengers with respect to the types of queues and formation of lanes (see section 4.2), in which a high Level of Interaction (LOI) was reached when R = 4 and a low LOI was reached when R = 0.25.

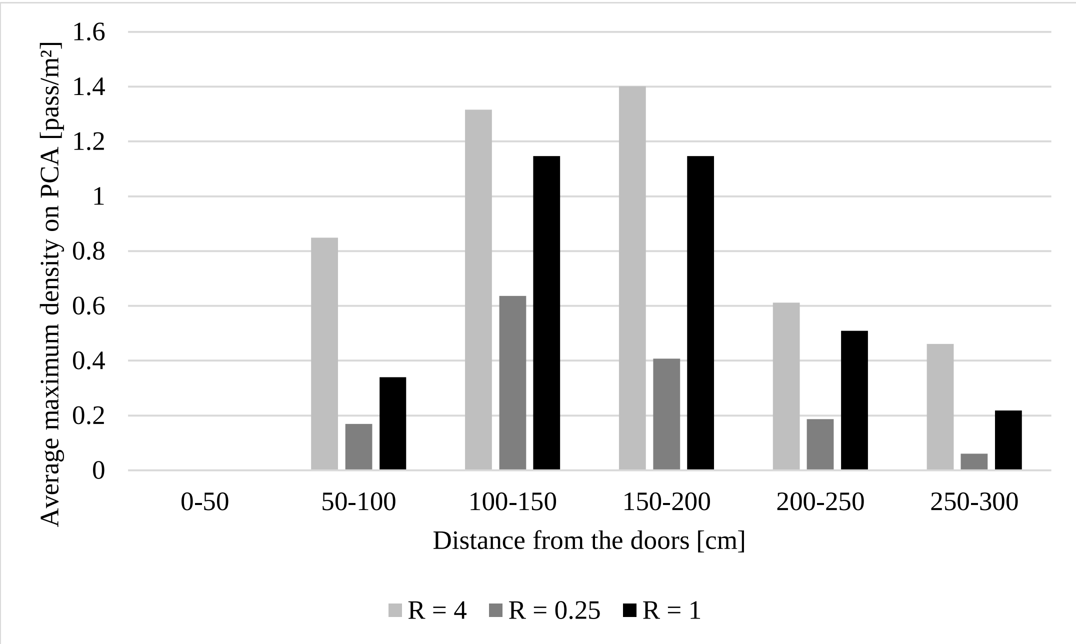

Figure 5. Average maximum density by layer on the PCA just before PEDs started to open at PAMELA

Figure 6 shows the maximum density by layer on the PCA after the doors started to open. For all values of R (ratio between boarding and alighting) the average maximum density on the PCA followed a logarithmic distribution with a coefficient of correlation between 0.97 and 0.99. This mean that the density reached a higher value in the first layer (up to 6.88 pass/m^2 when R = 4) and decreased as the distance from the door increased. Considering that the personal space is the inverse of the density, then layers on PCA with a high density of passengers presented a lower distance between passengers, and therefore a high interaction. This situation validated the hypothesis of this research, in which interaction was considered higher near the doors and decreased as the distance from the door increased.

As a result of the laboratory experiments (PAMELA) the LOI was defined as an indicator to classify the interaction of boarding and alighting (after the doors started to open) as a function of the density by layer. The LOI was classified into three levels (see Figure 6). A "high" LOI was defined when the density reached over 4.0 passengers per square metre, which is the density used by LUL (2012) to obtain capacity in static modelling. In the case of a "low" LOI the density reached a value lower than 2.17 pass/m^2, which is the value defined by TRB (2013; 2003) for crowded situations.

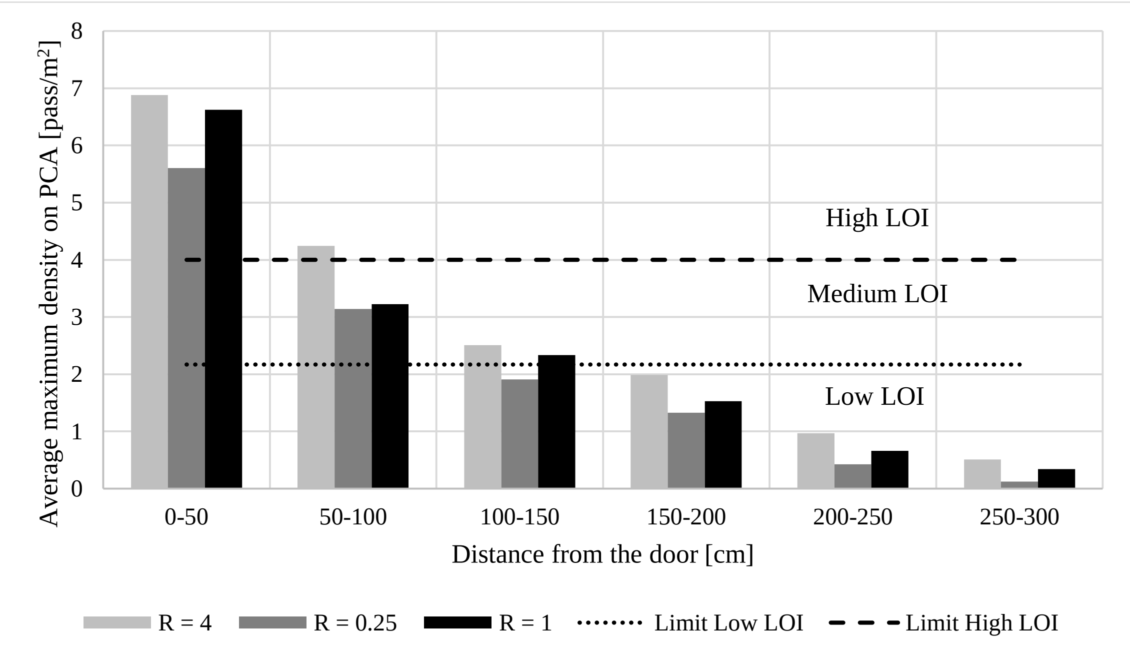

Figure 6. Average maximum density by layer on the PCA after PEDs started to open at PAMELA

The LOI was compared to the LOS of Fruin (1971), in which the overall density was obtained by counting the average maximum number of passengers on the PCA.

However, in this case the PCA was considered as a rectangular area of 15 m^2 (3.0 m-wide and 5.0 m-long) instead of a semi-circular space. Table 5 shows that this rectangular area reached a maximum overall density of 1.98 pass/m^2 in the case without PEDs and R = 4, which is equivalent to a "low" LOI, obtaining up to 3.5 times less density than the method of PCA divided into layers (see Figure 6). Therefore, the LOI was more representative of the interaction between passengers boarding and alighting than the LOS with respect to density.

Table 5. Maximum overall density (pass/m^2) on rectangular PCA at PAMELA

Scenario	**Before the doors started to open**		**After the doors started to open**	
	PEDs	No-PEDs	PEDs	No-PEDs
R = 4	1.34	1.65	1.82	1.98
R = 1	0.35	0.54	1.30	1.38
R = 0.25	0.91	0.98	0.99	1.06

To identify if the use of PEDs influenced the density of passengers by layer, a Mann-Whitney U test was used with a significance level of 5% ($\alpha = 0.05$) to compare each group (PEDs and No-PEDs) for each layer and value of R. The null hypothesis (H_0) was defined as the two medians being equal or when there was no difference in the sum of the two groups. The results of the Mann-Whitney U test showed that all cases presented a U-value higher than the U-Critical = 23 (group size of $n_1 = n_2 = 10$) obtained from the statistical analysis (see Table 6). This mean that the null hypothesis is accepted, i.e. the use of PEDs had no significant difference in relation to the density by layer compared to the case without PEDs.

Table 6. Average maximum density (pass/m^2) after doors started to open with PEDs and without PEDs at PAMELA

Scenario	R = 4			R = 1			R = 0.25		
Layer (cm)	PEDs	No-PEDs	U-value	PEDs	No-PEDs	U-value	PEDs	No-PEDs	U-value
0-50	6.88	6.62	45.50	6.62	6.11	39.00	5.61	5.86	46.50
50-100	4.25	4.33	49.00	3.23	3.31	47.00	3.14	3.40	42.00
100-150	2.51	2.68	35.00	2.34	2.17	39.50	1.91	1.95	46.50
150-200	1.99	1.99	49.00	1.53	1.50	46.50	1.32	1.25	42.00
200-250	0.97	1.14	27.50	0.66	0.76	35.50	0.42	0.49	37.00
250-300	0.51	0.49	48.50	0.34	0.38	39.00	0.12	0.19	29.00

4.4 Distance between passengers

Figure 7 shows that when the ratio between boarding and alighting (R) was equal to 0.25, there was more space for passengers to alight, and therefore the average distance between passengers alighting was slightly larger compared to the case when R = 1 or R = 4. This behaviour occurred in the case with PEDs and without PEDs.

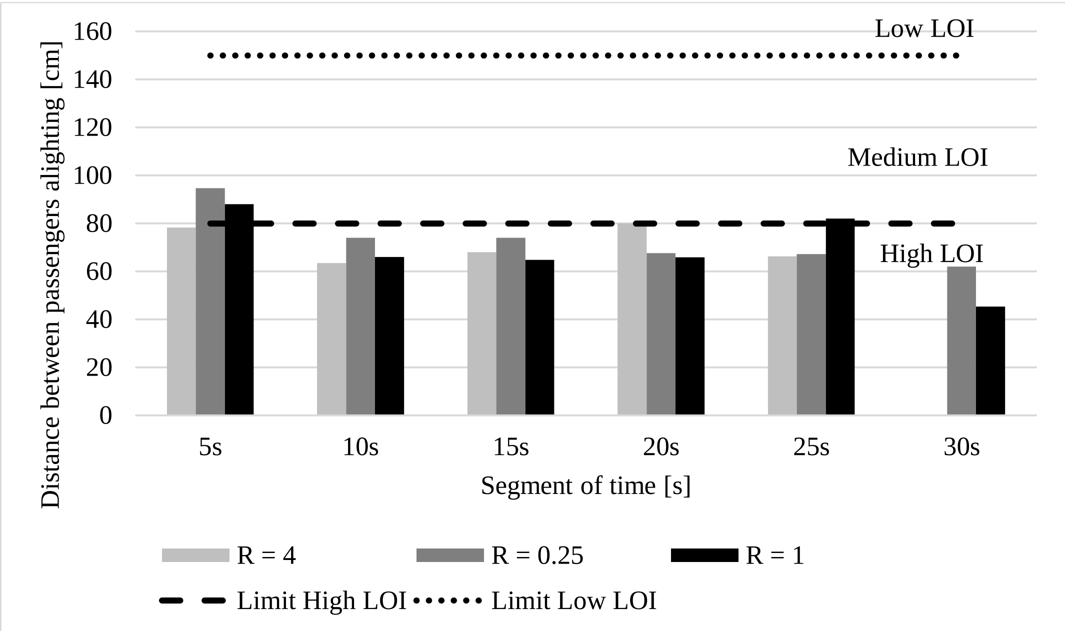

Figure 7. Average distance between passengers alighting with PEDs at PAMELA

Similarly, Figure 8 shows the average distance between heads of passengers boarding in segments of 5 seconds with PEDs at PAMELA. In the case of R = 0.25 just before the doors started to open (segment time 0th seconds) the distance between heads reached almost the double compared to R = 4 or R = 1 due to the available space on the platform (R = 0.25 had four times less boarding passengers than with R = 4). These results supported the behaviour of passengers with respect to the types of queues and formation of lanes (see section 4.2).

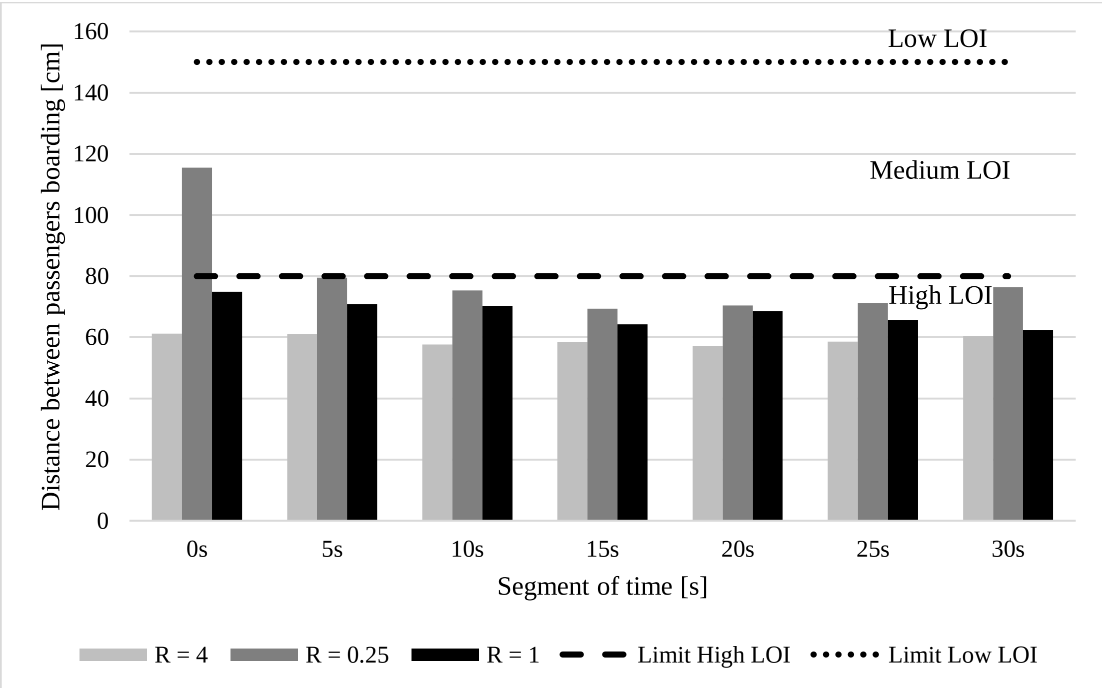

Figure 8. Average distance between passengers boarding with PEDs at PAMELA

As a result of these experiments the Level of Interaction (LOI) was created to classify the interaction between passengers as a function of the distance between them. A “high” LOI was defined when the distance between passengers was lower than 80 cm, which is the distance that passengers felt intimate as reported in the literature review of this paper (0.5 m plus two times half the body depth). A “medium” LOI was defined when the distance was between 80 cm and 150 cm, equivalent to the personal zone of Hall (1966) and Sommer (1969). Finally, a “low” LOI was represented with a distance higher than 150 cm (i.e. a social consultative zone in Hall, 1966). Therefore, according to the new indicator both situations (PEDS and No-PEDs) presented a “high” LOI after the doors started to open, reaching an average distance between heads of passengers lower than 80 cm in all the scenarios of R.

Similar to the density by layer (see section 4.3) a Mann-Whitney U Test for a pairwise comparison between scenarios of R was done. As it is shown in Table 7 the U-value was always higher than the U-Critical = 23 (group size of n1 = n2 = 10). Therefore, the null hypothesis (H_0) is accepted, i.e. the use of PEDs had no statistical difference in relation to the distance between heads of passengers compared to the case without PEDs.

Table 7. Average distance (cm) between heads of passengers with PEDs and without PEDs at PAMELA

Scenario	**Between passengers alighting**			**Between passengers boarding**		
	PEDs	No-PEDs	U-value	PEDs	No-PEDs	U-value
R = 4	68.41	74.82	33	59.32	60.27	35
R = 1	67.94	70.76	45	68.08	76.67	41
R = 0.25	69.85	75.48	35	81.21	71.66	31

5. Recommendations to reduce interaction

The method used in this research helped to identify the main problems of interaction on the PCA. These problems were associated to the Level of Interaction (LOI) as a function of types of queues, formation of lanes, density by layer and distance between passengers. In particular, the PCA divided by layers allowed to identify which part of the platform was more congested. To reduce the LOI and avoid densities higher than 2.17 passengers per m^2 (or LOS F in Fruin, 1971) in the boarding and alighting process, pedestrian traffic management (PTM) measures can be implemented such as demarcations or signs on the platform. PTM is defined as the "rational administration of movement of people to generate adequate behaviour in public spaces to improve the use of pedestrian infrastructure" (Seriani and Fernandez, 2015b, 76).

The LU observations and experiments results in section 4 suggest that two lines on the platform can be marked to show the direction of passengers alighting, and two circles for passengers boarding can be painted as waiting areas (see PTM 1 in Figure 9). With these PTM measures the interaction would be reduced by avoiding passengers to wait in front of the doors, being not an obstacle for alighting passengers. The minimum width of each line w_a should be 0.6 m, which represents the shoulder breadth of each passenger as reported in Fruin (1971). Therefore, the maximum length of the line on the platform L_a should be no more than 2.4 m (starting from the doors) to allow a circulation space of at least 0.6 m-wide from the edge of the platform to the wall. In the case of the waiting area the radius r_b can be obtained depending on the number of passengers waiting to board for a density of 2.17 pass/m^2 defined as the limit of low LOI in this paper. For example, in the case of GKP and WMS the video recordings showed an average number of passengers boarding equal to 15 and 12, respectively. Therefore, if they distributed evenly in each of the two waiting area, then r_b will be equal to 1.10 m (GKP) and 0.95 m (WMS).

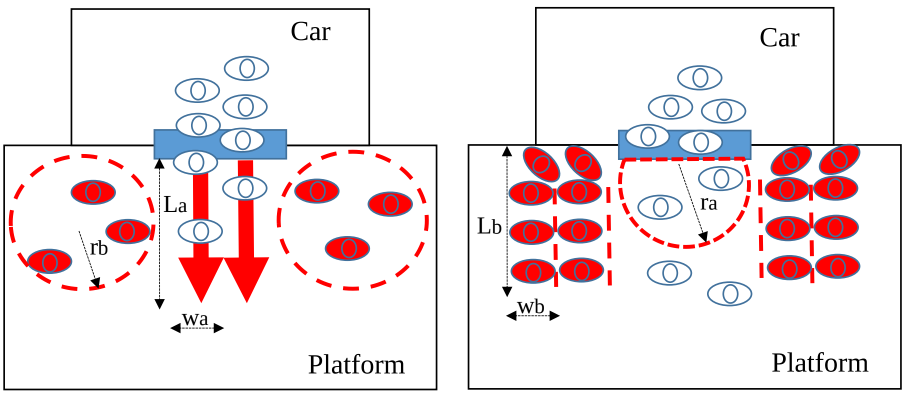

Figure 9. Recommendation of PTM 1 (left) and PTM 2 (right) on the platform to reduce interaction

Another PTM measure can be suggested from the results in section 4, in which a semi-circular space of radius r_a = 150 cm can be marked on the platform as a “keep out zone” and 2 lanes for queuing at each side of the doors can be signed as a way to maintain clearance and avoid boarding passengers to enter this zone until alighting is finished (see PTM 2 in Figure 9). The value of r_a can be obtained considering the first three layers on the PCA in which the average maximum density reached more than 2.17 pass/m^2 (see Figure 6 in section 4.3). The length (L_b) and width (w_b) of the queue lanes for boarding in PTM 2 are equal to the length (L_a) and width (w_a) of the lines for alighting in PTM 1. These recommendations can be combined with other PTM measures (as reported in Fujiyama et al., 2008; Wu and Ma, 2012) and tested as future research by the use of sensors and instruments at PAMELA. Metro systems such as Singapore, New York, Washington and Tokyo have introduced PTM measures (Loukaitou-Sideris et al., 2015; The Straits Times, October 3, 2015; WMAT, 2015), however the current knowledge of the extent to which each PTM measure is effective is limited. Further research would be necessary to quantitatively examine their effects and the conditions they are suited for.

6. Conclusions

This study presented a new method to classify the Level of Interaction (LOI) of passengers who were boarding and alighting a train and which included a new space defined as platform conflict area (PCA). The PCA consisted of a semi-circular shape of radius L and a density measured by layers as interaction were higher near the doors and decreased as the distance from the door increased. To validate this hypothesis, 15 days of observation were recorded at two London Underground stations and 4 days of simulation experiments were done at the University College London’s Pedestrian

Accessibility Movement Environmental Laboratory (PAMELA) to control exactly the number of passengers boarding and alighting. It was thought, this method would help traffic engineers and policy makers to classify the interaction and use the LOI as a more precise indicator for the design of spaces in metro systems. This new indicator is based on four variables: a) types of queues; b) number of lanes; c) density by layer; d) distance between passengers. The LOI is classified into low, medium, and high.

The observation results for GKP and WMS showed an important relationship between R (ratio of passengers boarding to those who are alighting) and the interaction of passengers. This was also presented in the PAMELA experiments. When R was equal to 4, passengers started to board the train earlier (i.e. before all the passengers had fully alighted) than when R was equal to 1 or 0.25, reaching a higher interaction. When R = 0.25 passengers wait until alighting was almost finished to board the train, reaching a lower interaction. In addition, when R increased the number of lanes for alighting was reduced, reaching a narrow single lane when R = 4. Therefore, the formation of lanes was influenced by the value of R.

The use of PEDs changed the behaviour of passengers. In WMS, passengers knew where the train was going to stop on the platform and therefore a reduction in the interaction was reached due to passengers mostly queuing at the side of the doors rather than in the front just before boarding. This benefit was obtained especially when R was equal to 1. The use of PEDs also helped to reduce the interaction of passengers at PAMELA.

At PAMELA, the density by layer was obtained on the PCA, which followed a logarithmic distribution in all the scenarios (R = 4, R = 1, R = 0.25) with a coefficient of correlation between 0.97 and 0.99. The LOI reached a “high” level for the first layer (density > 4.0 pass/m^2) and a “low” level in the last three layers (density < 2.17 pass/m^2). These results supported the hypothesis done in this work, in which the interaction between passengers was higher near the doors and decreased as the distance from the door increased. Another important result is that the density by layer was more representative of the interaction than the overall density, which reached only a maximum value of 1.98 pass/m^2 (3.5 times less than the density by layer). The last variable studied at PAMELA was the distance between the heads of passengers, in which for all cases of R the LOI reached a “high” level (distance between passengers lower than 80 cm). In addition, based on a Mann-Whitney U test there was no significant differences between PEDs and No-PEDs in relation to density by layer and distance between passengers. To reduce the interaction of passengers on the platform, pedestrian traffic management (PTM) measures are proposed based on waiting areas or queue lanes.

Some limitations of this study are related to the use of the tracking tool. Unfortunately, because of the varying frame rate and large steps in-between the videos it was not possible to extract any trajectories automatically. This situation was not possible to solve 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 other pedestrian traffic management measures as well as new sensors and technologies to track passengers.

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References

Boltes, M., and A. Seyfried. 2013. "Collecting Pedestrian Trajectories." *Neurocomputing* 100: 127-133.

Carey, M., and A. Kwieciński. 1994. Stochastic approximation to the effects of headways on knock-on delays of trains. *Transportation Research Part B: Methodological*, 28 (4): 251-267.

Carreno, M., A. Willis, and S. Stradling, 2002. "Quality of Service for Pedestrians: Closing the Gaps in Knowledge." Proceedings of the International Conference on Traffic and Transportation Studies (ICTTS) 2002, 326-333, Guilin.

Clarke, R. V., and B. Poyner. 1994. "Preventing Suicide on the London Underground." *Social science & medicine* 38 (3): 443-446.

Daamen, W., Y. Lee, and P. Wiggenraad. 2008. "Boarding and Alighting Experiments: An Overview of the Set Up and Performance and Some Preliminary Results on the Gap Effects." *Transportation Research Record* 2042: 71-81.

De Ana Rodriguez, G., S. Seriani, and C. Holloway. 2016. "The Impact of Platform Edge Doors on Passengers Boarding and Alighting Time and Platform Behaviour".

Paper presented at the Transportation Research Board 95th Annual Meeting, Washington D.C., January 10-14.

Evans, G. W., and R. E. Wener. 2007. “Crowding and Personal Space Invasion on the Train: Please Don’t Make me Sit in the Middle.” *Journal of Environmental Psychology* 27 (1): 90-94.

Fernandez, R., A. Valencia, and S. Seriani. 2015. “On Passenger Saturation Flow in Public Transport Doors.” *Transportation Research Part A* 78: 102-112.

Fruin, J.J. 1971. “Designing for Pedestrians: A Level-of-service Concept.” *Highway Research Record* 377: 1-15.

Fujiyama, T., J. Nowers, and N. Tyler. 2008. *Investigation Into Train Dwell Time*. Submitted to the Department for Transport, UK (unpublished).

Fujiyama, T., R. Thoreau, and N. Tyler. 2012. “The Effects of the Design Factors of the Train-Platform Interface on Pedestrian Flow Rates.” *Pedestrian and Evacuation Dynamics*, Springer International Publishing, 2014, 1163-1173.

Gérin-Lajoie, M., C. L. Richards, J. Fung, and B. J. McFadyen. 2008. “Characteristics of Personal Space During Obstacle Circumvention in Physical and Virtual Environments.” *Gait & posture* 27 (2): 239-247.

Guy, S. J., J. Chhugani, S. Curtis, P. Dubey, M. Lin, and D. Manocha. 2010. “Pledestrians: a Least-effort Approach to Crowd Simulation.” In *Proceedings of the 2010 ACM SIGGRAPH/Eurographics symposium on computer animation* 119-128. Eurographics Association.

Hall, E. 1966. *The Hidden Dimension*. Doubleday, Garden City 14:103-124.

Harris, N. G. 2006. “Train Boarding and Alighting Rates at High Passenger Loads.” *Journal of advanced transportation* 40 (3): 249-263.

Hartnett, J.J., K. G. Bailey, and C.S. Hartley. 1974. “Body Height, Position, and Sex as Determinants of Personal Space.” *Journal of Psychology* 87: 129–136.

Holloway, C., S. Seriani, D. Boampong, and N. Tyler. 2015. *The Effect of PEDs on Passenger Movement Time: Initial Analysis of PAMELA Experiments*. Submitted to the Transport for Transport, UK (unpublished).

Hoogendoorn, S. P., and W. Daamen. 2005. “Pedestrian Behavior at Bottlenecks.” *Transportation Science* 39 (2): 147-159.

Karekla, X., and N. Tyler. 2012. “Reduced Dwell Times Resulting from Train–platform Improvements: the Costs and Benefits of Improving Passenger Accessibility to Metro Trains.” *Transportation Planning and Technology* 35 (5): 525-543.

Kyriakidis, M., R. Hirsch, and A. Majumdar. 2012. “Metro Railway Safety: An Analysis of Accident Precursors.” *Safety science* 50 (7): 1535-1548.

Lim, A. 2015. “On your marks, get set, queue.” *The Straits Times*, October 5. Accessed 6 July 2016 in http://bit.ly/29esYIs.

Little, K. B. 1965. “Personal Space.” *Journal of Experimental Social Psychology* 1 (3): 237-247.

Loukaitou-Sideris, A., B. D. Taylor, and C. T. Voulgaris. 2015. *Passenger Flows in Underground Railway Stations and Platforms MTI Report 12-43*, Mineta Transportation Institute Publications, San Jose, California.

Lu, J., and F. Dong. 2010. “Statistical Analysis of the Passenger Distribution Before Getting on Subway Train.” *Urban Mass Transit* 13 (7): 53-56 (in Chinese).

LUL. 2012. *Station Planning Standards and Guidelines*. London Underground Limited, London.

NFPA-130. 2007. “Stations.” In *Standard for Fixed Guideway Transit and Passenger Rail Systems*. National Fire Protection Association, Massachusetts.

Pushkarev, B., and J. Zupan. 1975. *Urban Space for Pedestrians*. The MIT Press, Cambridge, Massachusetts.

Qu, L., and W. K. Chow. 2012. "Platform Screen Doors on Emergency Evacuation in Underground Railway Stations." *Tunnelling and Underground Space Technology* 30: 1-9.

RSSB 2008. *Management of On-train Crowding Final Report*. Rail Safety and Standards Board. London.

RSSB 2015. *Platform Train Interface Strategy*. Rail Safety and Standards Board. London.

Sanders, J.L. 1976. "Relationship of Personal Space to Body Image Boundary Definiteness." *Journal of Research in Personality* 10: 478–481.

Seriani, S., and R. Fernandez. 2015a. "Planning Guidelines for Metro-bus Interchanges by Means of a Pedestrian Microsimulation Model in Chile." *Transportation Planning and Technology* 38 (5): 569-583.

Seriani, S., and R. Fernandez. 2015b. "Pedestrian Traffic Management of Boarding and Alighting in Metro Stations." *Transportation Research Part C* 53: 76-92.

Seyfried, A., T. Rupprecht, O. Passon, B. Steffen, W. Klingsch, and M. Boltes. 2009. "New Insights Into Pedestrian Flow Through Bottlenecks." *Transportation Science* 43: 395-406.

Shen, J. 2001. “The Research for Dynamic Distribution of Passenger and the Width of Platform.” *Urban Rapid Transit* 4 (1): 21-25 (in Chinese).

Shen, J. 2008. “Simplified Calculation for the Width of on and off Regions of Station Platform.” *Urban Rapid Transit* 21 (5): 9-12 (in Chinese).

Sommer, R. 1969. *Personal Space: The Behavioral Bases of Design*. Prentice Hall, NJ.

Still, K. 2000. “Crowd Dynamics.” PhD thesis, University of Warwick, UK.

Teknomo, K. 2006. “Application of Microscopic Pedestrian Simulation Model.” *Transportation Research Part F* 9 (1): 15-27.

TfL 2014. *London Underground Performance Reports. Entry and Exit Figures by Station*. Transport for London, London. Accessed 6 July 2016 in http://bit.ly/29oF6FE

TRB 2003. *Report 100: Transit Capacity and Quality of Service Manual*, 2nd Edition, National Research Council, Transportation Research Board. Washington, DC.

TRB 2013. *Report 165: Transit Capacity and Quality of Service Manual*, 3rd Edition, National Research Council, Transportation Research Board, Washington D.C.

Von Sivers, I., and G. Köster. 2015. “Dynamic Stride Length Adaptation According to Utility and Personal Space.” *Transportation Research Part B* 74: 104-117.

Webb, J.D., and M.J. Weber. 2003. "Influence of Sensor Abilities on the Interpersonal Distance of the Elderly." *Environment and Behavior* 35 (5): 695–711.

WMAT. 2015. *Passenger Flow and Train Dwell Time*, Washington Metropolitan Area Transit Authority. Accessed 6 July 2016 in http://bit.ly/29jCMDl.

Wu, J., and S. Ma. 2013. "Division Method for Waiting Areas on Island Platforms at Metro Stations." *Journal of transportation engineering* 139 (4): 339-349.