Boarding and Alighting Matrix on Behaviour and Interaction at the Platform Train Interface

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Abstract

The platform train interface (PTI) is a space with high interactions between passengers boarding and alighting. The increasing need for faster and safer boarding/alighting led the Rail Safety Standards Board to publish the Platform Train Interface Strategy (2015). Because of the complex and multi-dimensional nature of these interactions, a simple framework is required to help designers and planners identify and benchmark the degree of interaction. This paper aims to create such a framework.

This new framework consists of four steps. Firstly, a model is created to represent the interaction problems at the PTI. This model discretises the PTI into a square grid and divides the platform into concentric layers around the doors. Secondly, the model variables are identified and classified into physical, spatial and operational. Thirdly, the degree of interaction between passengers is defined as high, medium or low based on the density and perception of risk, and each of the variables is assigned one degree of interaction. Finally, the results are presented in a matrix that groups the variables according to the area where the interaction happens (vehicle, PTI, or platform) and to the type of users that are affected by this interaction (boarders only, alighters only, or both).

As case study, this paper applies the framework to two existing stations. The results show that the new framework is able to describe well the phenomena of high interactions. In the case study, the presence of door position indications on the platform, the density, the location of passengers and the formation of lanes were the most relevant variables in the matrix.

This paper further shows how this framework can be used to suggest or evaluate suitable crowd management measures in railway infrastructure and to summarise and communicate interaction problems in a simple and effective way.

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

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1. Introduction

The platform train interface (PTI) is considered one of the most unsafe spaces for passengers boarding and alighting. In the case of the UK railway network, a complete strategy has been launched to reduce the 3 billion passenger interactions made every year, which represent 48% of the fatality risks at the PTI (RSSB, 2015). This complex space presents different risks and hazards for passengers. Accidents can occur during boarding and alighting or simply at the platform edge even when there is no boarding or alighting.

To improve safety conditions at the PTI, crowd management measures can be used. 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, 2015a, 76).

As an example of crowd management measures, some stations on the London Underground (LU) network have platform edge doors (PEDs) and a single line on the platform in front of each door, which act as door position indicators on platforms to highlight where the doors are going to be. PEDs have been installed in different metro stations worldwide (Law and Yip, 2011; Kyriakidis et al., 2012; Kroes et al., 2014). On the LU, PEDs work as sliding barriers that open simultaneously with the train doors and hence prevent passengers falling onto the track. Despite the benefits of using PEDs, only nine stations on the LU network have these elements. According to LUL (2014) the limitation to install PEDs is due to the differences in trains (e.g. different door width) and the variances in the configuration of platforms (e.g. PEDs cannot be installed in curved platforms).

The use of crowd management measures could help to minimize risks or any hazard at the PTI. But it is not only about safety. Crowd management measures can also help operators to improve the performance of the boarding and alighting process by reducing the time each train remains stopped at the station (Seriani and Fernandez, 2015a).

Despite the benefits of implementing crowd management measures, there is a lack of methods to analyse their effect on the behaviour and interaction of passengers boarding and alighting. According to Stenström et al., (2012) efficient and effective indicators have been developed to measure the performance of railway infrastructure. However, performance indicators for RAMS (reliability, availability, maintainability, and safety), capacity, punctuality, etc. are mainly focused on rail infrastructure rather than crowd management. The problem is that isolated crowd management measures do not give enough information for decision making, therefore the type of measures, what variables to study and their impact should be compiled, analysed and converted into a standardized format or framework.

The aim of this paper is to create a new framework based on matrices to analyse interaction problems at the PTI during the boarding and alighting. The specific objectives are:
a) create a model to represent the interaction problems in the boarding and alighting process;
b) identify the main variables that affect the behaviour and interaction of passengers at the PTI;
c) use a matrix to present the interaction problems;
d) study the formation of lanes and location of passengers on platforms when door position indications on platforms are used;
e) make recommendations to reduce the interaction at the PTI.

This paper has six sections, including this one. In section 2 a summary of the methods to analyse interaction is described. Next, in section 3 the new framework to study interaction problems is explained. Section 4 shows the results of the application of the new framework at existing stations. In section 5 some recommendations to reduce interaction are proposed. Finally, in section 6 the conclusions are presented.

2. Existing methods to analyse interaction

Problems of interaction between passengers are related to the concept of crowds. The definition of crowds started with the work of Still (2000) in which he defined crowd dynamics as "the study of the how and where crowds form and move above the critical density of more than one person per square metre" (Still, 2013, 93). The author also defined the concept of crowd behaviour to understand the motivation, competition, and type of passengers in a crowd.

The behaviour of crowds at the PTI can be described in two situations. Firstly, when passengers on the platform are waiting to board the train or forming queues around the doors. When queues reach a Level of Service (LOS according to Fruin, 1971) equal to F or a density of more than 5 passengers per square metre (0.2 m^2 per passenger), then passengers experiment high interaction with high potential to fall onto the track.

This high interaction also happens in a second situation known as the dynamic process of boarding and alighting, in which a density of more than 2 passengers per square metre (0.5 m^2 per passenger or LOS F in Fruin, 1971) is considered a critical density with sporadic flows and frequent stops. In this situation, passengers boarding can be an obstacle for passengers alighting. Therefore, aligthers need to form streams or lanes of flow to exit the train. This behaviour is similar to the movement of pedestrians in bottlenecks (Hoogendoorn and Daamen, 2005; Seyfried et al., 2009), in which pedestrians follow the person directly in front. Those authors found that the capacity of the bottleneck increased when a new lane of flow was formed or when the "zipper effect" (overpassing) was produced. Recent studies (Seriani et al., 2016) have found that the formation of lanes is influenced by the level of demand. These authors found that when the ratio (R) between passengers waiting to board the train and those who are alighting was equal to 4, then only one alighting lane was formed. When R = 0.25, up to two alighting lanes were formed. In the case where R = 1, the formation of lanes was intermediate between the other two cases (R = 4 and R = 0.25). However, the study only considered laboratory experiments that replicated the boarding and alighting process with a mock-up carriage, in which all passengers boarded the train (i.e. no passengers were waiting on the platform for the next train). Therefore, it would be interesting to investigate if this behaviour also occurs in operating conditions in metro stations.

The PTI will reach a critical density when the total number of passengers on the platform exceeds the capacity of the platform. The Level of Service (LOS) of Fruin (1971) could be used to identify the degree of congestion on the platform. The LOS goes from Level A (free flow) to Level F (critical density), in which LOS = E is defined as "at capacity". However, for Evans and Wener (2007) average values of density seem not to be the ideal way to represent interactions in train environments. These authors argued that an overall density does not say if passengers are stationary or moving in a particular way. To solve this, Seriani et al. (2016) proposed to divide the platform into semi-circular layers of 50 cm each and count the number of passengers boarding and alighting in each layer before and after the train stopped at the station. These authors found that the density by layers is more representative of the interaction than the overall density.

In terms of modelling, crowds could be represented using Newton's Law. Yin et al. (2014) used the kinetic, potential and internal energy of passengers to describe the local and global crowd energy at metro stations. Other authors (Mahudin et al., 2012) proposed a model to measure crowding in railway passengers and identify the effect on the level of stress and feeling of exhaustion. The authors included psychological aspects of crowds (dense, disorderly, confining, chaotic, disturbing, cluttered, unpleasant), evaluation of the environment where the crowd is situated (stuffy, smelly, noisy, hot), and how crowds react in specific situations (squashed, tense, uncomfortable, distracted, frustrated, restricted, hindered, stressful, irritable).

The inclusion of psychological aspects is also analysed by Cox et al. (2006). These authors stated that there is a difference between density and crowding. A high-density situation is related to the physical environment and not necessary considered as crowded with a high level of stress. RSSB (2005) defines crowding as a physical measurement, i.e. as a function of density and capacity on the platform and train, but also with a psychological dimension which is more about the perception of risk and safety. Recently, Kim et al. (2015) identified that passengers at metro stations tend to avoid delays, the stress of crowding, other passengers, or any risk related to sexual harassment.

For Still (2014) crowds are also related to risk and safety perception. The author stated that conventional risk assessment documents are not the ideal alternative to study crowds. Many of these documents overestimate risks or use “cut and paste” solutions from other manuals. Therefore, the format used in this type of reports usually does not help to achieve a good comprehension of the risk problems. Moreover, Still (2009, 2014) reported that most environments present high level of risk when there are problems in design, information, and management. In addition, he suggested that high-density environments will be reached in three categories: ingress, circulation, and egress. The author combined this into a matrix framework named DIM-ICE model, which is used to compare a normal and an evacuation situation. The DIM-ICE model could be combined with the RAMP analysis to model crowds (Still, 2013). With RAMP it would be possible to identify the routes, areas, movement and profiles of the crowd. All these tools could be complemented with diagrams and pictures, using colours, maps, and codes.

Despite the important research related to crowds, the development of new tools such as DIM-ICE or RAMP is mainly based and focused on sport events. Therefore, new research is needed to elaborate a framework to study interaction problems in the boarding and alighting at the PTI. In particular, this work will focus on the behaviour and interaction of passengers in the London Underground, however, it could be expanded to any conventional rail or LRT system.

3. New framework BAMBI

A new framework to study the behaviour and interaction of passengers boarding and alighting is proposed. This framework is named BAMBI (Boarding and Alighting Matrix on Behaviour and Interaction), and consists of 4 stages described below.

3.1 Model

Firstly, a model is created to represent the interaction problems on the PTI area (see Figure 1). Rectangles are used to represent the main infrastructure and arrows to show the direction of passenger flows. The main infrastructure is classified into three elements of circulation: vehicle, PTI and platform. When PEDs are installed the PTI is defined as the space between the train doors and the PEDs, whilst in the case without PEDs, the PTI is the space between the train doors and the yellow safety line on the platform. The model discretises the PTI into 40 cm square cells, as is typically used in cellular automata (Zhang et al., 2008; Davidich, et al., 2013; Clifford et al., 2014). Each cell represents one block on the floor of the platform. A total of 105 cells (15 x 7 cells) are considered to represent each door. Each cell is occupied by one passenger each time the train stops at the station. The use of cells to represent the platform area helps to obtain the density as the number of cells occupied. In addition, the location of each passenger (e.g. if they are standing beside the doors or in front of them) can be obtained.

The model also helps to understand the movement of passengers boarding and alighting. The behaviour and interaction in the boarding and alighting process should be analysed at the critical door of each platform. At the critical door, the platform is divided into concentric layers of 50 cm each using the method proposed by Seriani et al. (2016). According to these authors, passengers' interaction can be classified in three categories: interaction between passengers boarding (only boarding), between passengers boarding and alighting (when there are simultaneous movements), and between passengers alighting (only alighting). The use of layers helps to identify which part of the platform is more congested and how close to the doors passengers are. As an example in Figure 1, passengers boarding are closer to the doors, and therefore considered an obstacle for those who are alighting, producing a collision of flows at the PTI.

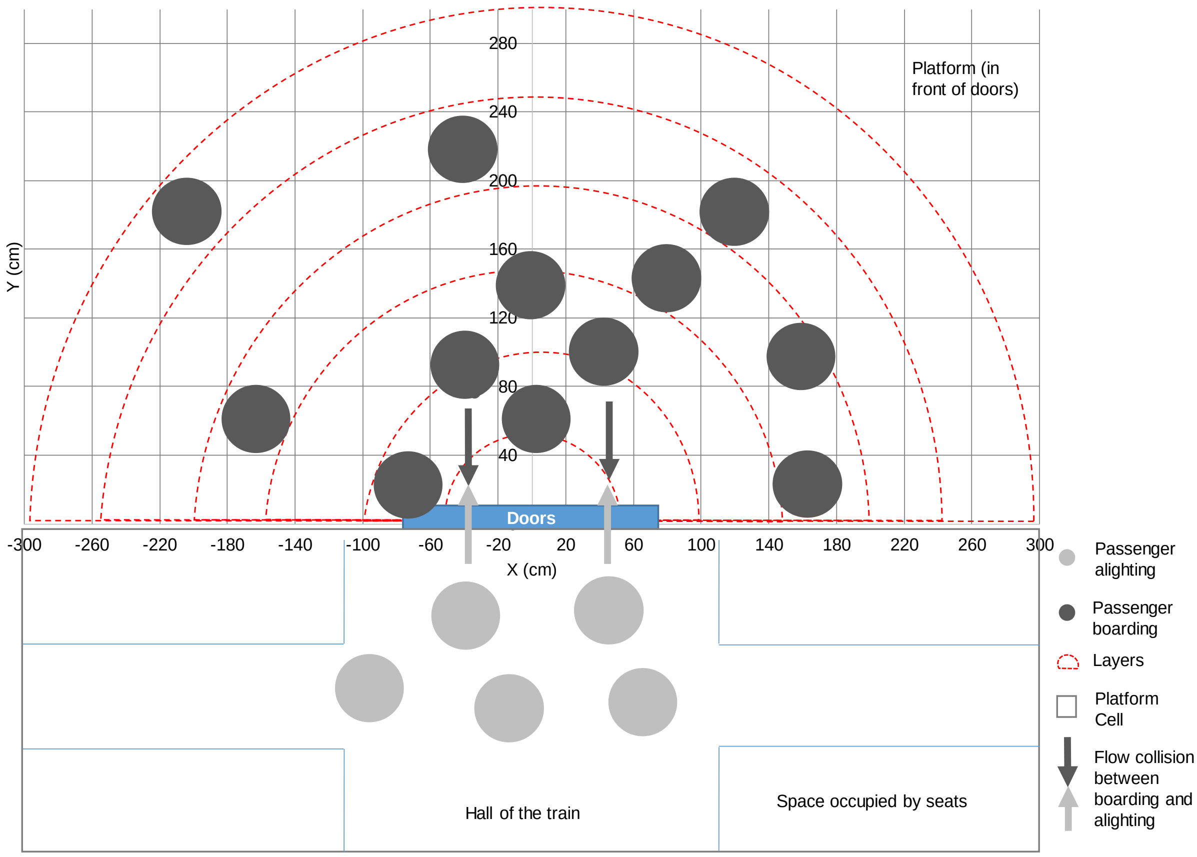


Figure 1. Model divided in concentric layers of 50 cm each to measure behaviour and interaction on platforms formed of 40 cm square cells

3.2 Variables

Secondly, the variables that affect behaviour and interaction of passengers at the PTI are identified and classified according to Seriani and Fernandez (2015b). Three groups of variables are considered: physical, spatial and operational. Table 1 shows the variables that should be included in BAMBI, which are supported by laboratory experiments and field studies.

Physical variables are defined as those which are related specifically with dimensions (length, height, width, etc.). Spatial variables are considered as those circulation elements that could be used to change the behaviour of passengers (e.g. furniture). In the case of operational variables, the classification in Table 1 is focused on how the interaction can be measured. For example, according to Seriani et al. (2016) the level of interaction is influenced by four operational variables: formation of lanes, types of queues, density by layer, and distance between passengers.

Table 1. Variables that affect the behaviour and interaction of passengers boarding and alighting on the PTI area

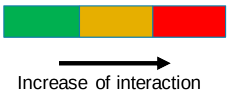
Category	Variable (comments) [unit]	References		#
		Laboratory experiments	Field studies	
Physical	Door width [m]	Fernandez et al. (2010); Fujiyama et al. (2012); Fernandez et al. (2015)	Harris (2006); Harris and Anderson (2007); Wiggenraad (2001)	V1
	Vertical and horizontal gap [mm]	Daamen et al. (2008); Fernandez et al. (2010; Fujiyama et al. (2012); Karekla and Tyler (2012)	Heinz (2003); Atkins (2004	V2
	Vertical steps [no. or dimensions]	Holloway et al. (2015)	Heinz (2003); Atkins (2004)	V3
	Platform width [m]	Seriani and Fernandez (2015b)	Harris (2006); Harris and Anderson (2007);	V4
Spatial	Platform humps (length, width, and height) [m]	Tyler et al. (2015)	Karekla et al. (2011)	V5
	Seats and setback [no., m]	Fujiyama et al. (2012)	Harris (2006); Harris and Anderson (2007)	V6
	Platform edge doors (half or full height) [no.]	De Ana Rodriguez et al. (2016)	Wu and Ma (2013); Loukaitou-Sideris et al. (2015)	V7
	Poles, barriers and waiting areas, markings on the floor (position, width, and length) [no. or m]	Seriani and Fernandez (2015a)	Wu and Ma (2013); Loukaitou-Sideris et al. (2015); WMAT (2015)	V8
Operational	Type of passengers (demographics, luggage, restricted mobility, prams) [no.]	Holloway et al. (2015)	Wiggenraad (2001); Atkins (2004); Heinz (2003); Harris (2006); Harris and Anderson (2007);	V9
	Density (boarding, alighting, on-board passengers) [no., or pass/m^2]	Rowe and Tyler (2012); Seriani et al. (2016)		V10
	Passenger space (distance between passengers, area occupied) [m or m^2]	Seriani et al. (2016)		V11
	Location on the platform, formation of lanes and types of queues [no.]	De Ana Rodriguez et al. (2016); Seriani et al. (2016)		V12
	Flow (at the doors) [pass/min-m]	Daamen et al. (2008); Fujiyama et al. (2012); Fernandez et al. (2015)		V13
	Boarding and alighting times (BAT) [s]	Fernandez et al. (2010); Holloway et al. (2015); De Ana Rodriguez et al. (2016)		V14

3.3 Risk assessment

Thirdly, the degree of interaction between passengers is defined as high, medium or low based on the density and perception of risk. This is based on the concept of critical density defined by Still (2000; 2009; 2013; 2014). Therefore, a high interaction (red colour) will result when there is a situation of risk of accidents with more than 2 passengers per square metre (or more than 4 pass/m^2 for static movement of passengers). A medium interaction (amber colour) is considered when the risk of accidents is reduced (but still is important to be taken into account) or when there is a density between 1 pass/m^2 and 2 pass/m^2. The low interaction (green colour) occurs when there is a low risk of accidents with no possible problems or a density lower than 1 pass/m^2. Table 2 shows the degree of interaction as a combination between perception of risk and density between passengers boarding and alighting on the PTI area. Both density and perception of risk are weighted the same for each of the combinations. The highest interaction has a score of 6, whilst the lowest interaction has a score of 1. Each of the variables from Table 1 is assigned one degree of interaction.

Table 2. Degree of interaction between passengers boarding and alighting on the PTI area

Perception of risk	Density		
	Low	Medium	High
Low	1	2	4
Medium	2	3	5
High	4	5	6
Key:			



3.4 Matrix

Fourthly, a framework matrix is created. The results of assigning each variable (from Table 1) one degree of interaction (from Table 2) are presented in a matrix that groups the variables according to the area where the interaction happens (vehicle, PTI, or platform) and to the type of users that are affected by this interaction (boarders only, alighters only, or both). Since there are three types of interactions and three different areas, the matrix has 3 rows and 3 columns.

This way of displaying the results helps to communicate the interaction problems to the relevant decision makers more effectively. For example, if interaction problems arise in the vehicle, then the manufacturer company that designed the vehicle should be contacted. On the contrary, if high interactions happen on the platform, then it the station managers should be informed. In the case of a problem at the PTI, then it is the platform guard who needs to be contacted.

Similarly for the other matrix dimension (types of users), the framework helps to look for the correct action in terms of information. For example, if high interactions are affecting alighters, then announcements could be made inside the vehicle. However, if problems are related to boarding passengers, then the announcements should be made by the station manager or platform guard at the relevant platform or station.

The framework could be used as a diagnosis tool to identify potential problems that could be addressed with the application of crowd management measures. After this initial diagnosis, problems that affect behaviour and interaction can be studied in more detail. Each variable from Table 1 can be measured by observation at stations or laboratory experiments. In section 4 this framework is applied to two London Underground stations.

4. Case study on the LU

BAMBI was applied to a case study on the London Underground (LU). To this aim, two stations were selected: Westminster (WMS) and Green Park (GPK). Both stations are important interchanges on the Jubilee line. The main difference between them is that WMS has platform edge doors (PEDs) and a single grey line 1.2 m long by 10 cm wide in front of each door, which act as door position indications on platforms, whilst GPK does not.

Table 3 shows the application of the framework matrix using BAMBI at GPK. To identify the variables from Table 1, site visits were done during peak hours (8:15-9:15 AM and 5:15-6:15 PM). The main variables that have an impact on the behaviour and interaction of passengers (only boarding, boarding and alighting, and only alighting) were highlighted by means of observation. Possible problems were identified at the vehicle, PTI, and platform.

Table 3. Framework matrix applied to GPK

BAMBI method	Only boarding	Boarding and alighting	Only alighting
Vehicle	Although trains have 20 seats (V6) per carriage and a setback 200-300 mm, in some cases it is not sufficient to allocate passengers boarding (V10) in the hall or entrance of the train, reaching a medium density and a low perception of risk.	Passengers on-board (V10) affect the flow (V13) and BAT (V14). In some cases passengers cannot board or alight the train. Pressure on passengers being stuck at the doors. This situation produces medium density and medium perception of risk.	Although the vertical pole (V8) in the train hall is displaced from the centre, it produces on-board passengers (V10) agglomeration, being in some cases an obstacle for those who are alighting, reaching a medium density and a low perception of risk.
	Degree: 2	Degree: 3	Degree: 2
PTI	Although vertical and horizontal gaps (V2) are small, few boarders presented reduced mobility (V9), reaching low density and medium perception of risk for passengers boarding.	Although double doors are 1.6 m wide (V1), the high density (V10) produced only one lane of flow (V12) for alighting and two lanes of flow for boarding. Pressure and “confined flow”, reaching a high density and a medium perception of risk.	Although vertical and horizontal gaps (V2) are small, few alighters presented reduced mobility (V9). This situation presents low density and medium perception of risk for passengers alighting.
	Degree: 2	Degree: 5	Degree: 2
Plat-form	Without PEDs (V7) passengers do not know where the doors are, so they are located (V12) in front of the doors rather than beside them. In addition, passengers can fall onto the tracks, reaching a high density and high perception of risk.	The lack of markings on the floor (V8) does not identify which part of the platform should be used as waiting or circulation area. “Crossing flows” and collisions are produced with high density and medium perception of risk for passengers boarding and alighting.	The high density (V10) on the platform produces that boarding passengers are considered an obstacle for alighting. Pressure and “confined flow”, reaching high density and medium perception of risk.
	Degree: 6	Degree: 5	Degree: 5

Another way to represent interaction problems at GPK is shown in Figure 2. According to the type of users, boarding and alighting represent the most critical situation of interaction reaching a total degree of 13 points. With respect to the type of infrastructure, the platform reached the highest degree of interaction problems with 16 points.

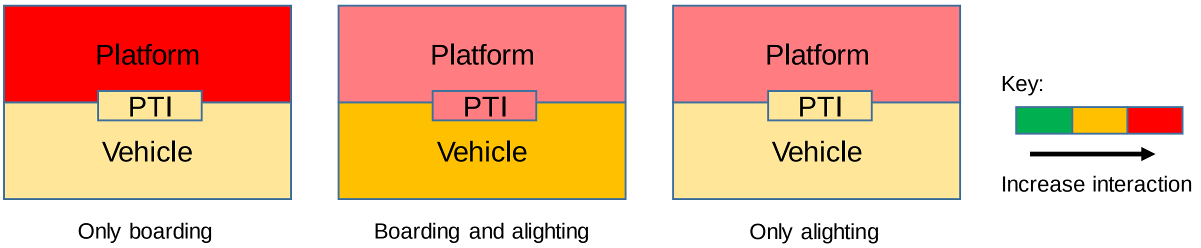


Figure 2. Interaction maps by category of user and type of infrastructure at GKP

The same framework was applied to WMS. This station presents the same problems of high interactions as GPK. The only difference is that the use of PEDs at WMS reduced the density and perception of risk, as PEDs work as sliding barriers that prevent passengers from falling onto the tracks. In addition, PEDs serve as door position indications on the platform, and therefore the behaviour of passengers changed to waiting beside the doors rather than in front of them.

The analysis using this framework in Table 3 is focused on the critical door (most congested). In both stations one set of double doors (1.6 m wide in total) was studied. The layout of the train corresponded to the 1996 rolling stock. These trains have a setback (distance between the doors and the seats inside the train) between 200 mm and 300 mm, one vertical pole in the hall or entrance, and 20 seats per carriage, approximately. In the case without PEDs (GPK) the vertical gap reached 170 mm, whilst at WMS (with PEDs) there is no vertical gap between the train and the platform. In both cases the horizontal gap is 90 mm and the platform width is 3.0 m.

From the analysis in Table 3 it can be concluded that four variables are related to problems of high interactions (as a combination of density and perception of risk) at both stations:
1) PEDs (V7);
2) markings on the floor (V8);
3) density (V10);
4) location on the platform and formation of lanes (V12).

To understand these problems and identify possible solutions to reduce the interaction between passengers boarding and alighting, a more detailed study is needed at both stations.

To study the interaction and behaviour on the platform and PTI areas, observations on both stations were done using CCTV footage from one week of recording (weekdays from 5th November to 11th November 2014). Because of the location of the cameras, it was not possible to observe the behaviour of passengers inside the train. Therefore, this paper will focus on the platform and PTI area, however this does not mean that other spaces do not need a detailed analysis. Further research should be done to include these other analyses.

Data was analysed using the software Observer XT11 and the videos were converted into .avi format with the software Nucleus. The period of analysis was between the doors open and close times. The behaviour and interaction of passengers were obtained for peak hours (8:15-9:15 AM and 5:15-6:15 PM). During this period an average frequency of 30 trains per hour operates, so that in total about 600 boarding and alighting events were analysed.

To measure the density (V10) the number of passengers waiting to board (B) the train was counted using the model proposed in Figure 1 (see Section 3). Each time a train stopped at the station, a cell was assigned to B using the model. The number of passengers alighting (A) was counted every 5 seconds. It was not possible to obtain the number of passengers on-board due to the location of the cameras hanging from the platform celling.

Similarly, the location of passengers on the platform and formation of lanes for alighting (V12) was measured using the model proposed in Figure 1 (see section 3). In the case of WMS (with door position indications on the platform) the number of passengers waiting to board the train (B) was measured just before the train doors opened. However, at GPK (without markings) B was measured between 2 and 3 seconds before the train stopped at the platform to correct for possible last moment passenger movements to adjust their position once they could guess the final location of the train doors. The centre of the doors is considered as the starting point (0, 0) for the variable V12.

In the case of the number of passengers alighting (A), a lane of flow was defined as one or more passengers walking one behind another. With the 1.6 m wide double doors at WMS and GPK, between one and two lanes could be formed for alighting. Therefore, the formation of lanes was coded into four categories: zero (no alighters), one lane, two lanes, and between one and two lanes.

The formation of lanes for alighting was compared to the ratio R = B/A. In this paper it is expected to identify the relationship between the formation of lanes and the value of R. In the following sections the results of the observation at WMS and GPK are presented.

4.1 Formation of lanes

Figure 3 shows the frequency of events at both stations with respect to five categories of the ratio R (passengers waiting to board/passengers alighting) at both stations. From the total of events studied (600 approximately), 26% of them presented a value of R around 1.0, which means that there was a similar number of passengers boarding and alighting at the critical door. Few cases presented a R = 0.25 (or less), which means that in most cases there were more passengers boarding than alighting. This is also noticed in the case of R = 4 (or more), which occurred in 20% of the observations.

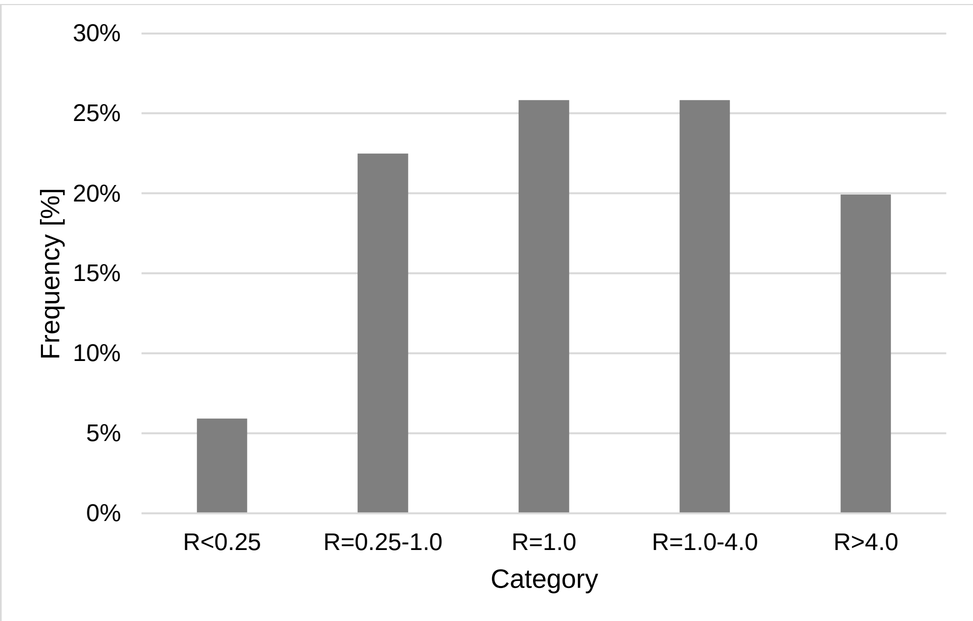


Figure 3. Frequency of events by category of R (B/A) at GKP and WMS

Figure 4 shows the relationship between the number of lanes formed for alighting and the ratio R (B/A) at both stations. For low R (R<0.25) up to two lanes for alighting are formed, reaching 60% of the cases in that category, whilst the other 40% of the cases presented between one and two lanes for alighting. The two lanes are formed due to the available space on the platform. When this space is reduced, then the number of lanes is reduced, too. When there are between one and two lanes, it means that during the process of alighting passengers formed one and sometimes two streams of flow to get off the train. In this category (R<0.25) practically no cases presented only one lane for alighting.

As the value of R increases, the number of lanes is reduced. In Figure 4, within the category R = 1, 64% of the cases show only one lane for alighting, whilst the rest of the observations in that category present between one and two lanes. In this category (R = 1) virtually no events showed two lanes for alighting.

For high values of R (4 or more), Figure 4 shows that only one lane for alighting was formed in all cases. In this category, the high pressure of passengers trying to board reduces the space for passengers to get off the train, therefore only a single narrow lane is formed for alighting.

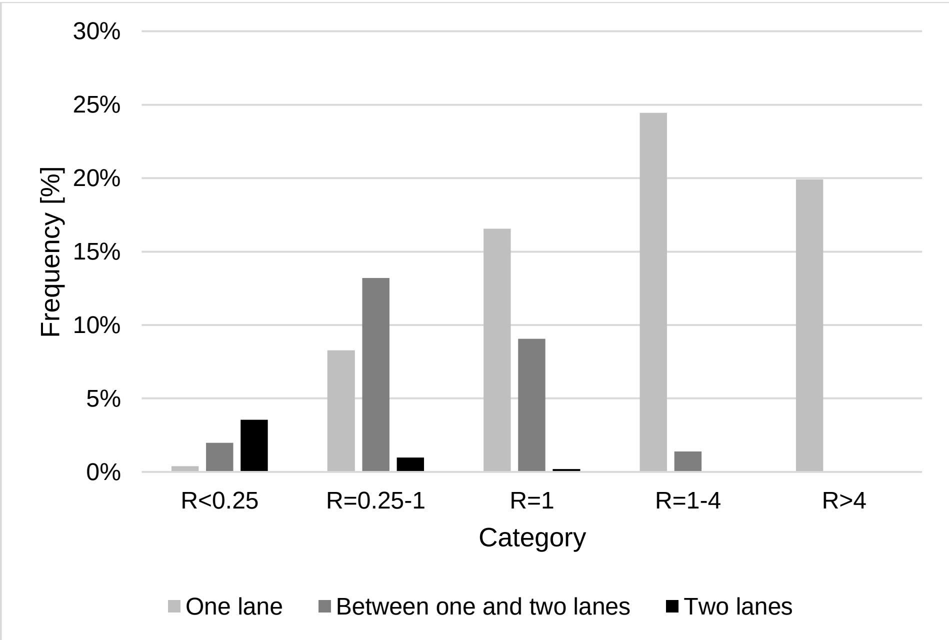


Figure 4. Relationship between number of lanes and R (B/A) at GKP and WMS

4.2 Location of passengers waiting to board the train

Figure 5 shows the average location (in terms of layers) of passengers on the platform waiting to board the train (B) at GPK for the AM and PM peak hours. On average, B = 11 passengers are distributed in six layers. The first layer (0-50 cm) is not used, due to the yellow safety line, which is respected by passengers. The last layer (>300 cm) is not used either because this space is occupied by passengers walking along the platform to and from the entrances. The third, fourth and fifth layers are the most congested spaces, reaching 2 passengers on average. This means that the most used space is between 1/3 and 2/3 of the platform width. The same distribution of passengers is obtained at WMS, with a similar profile.

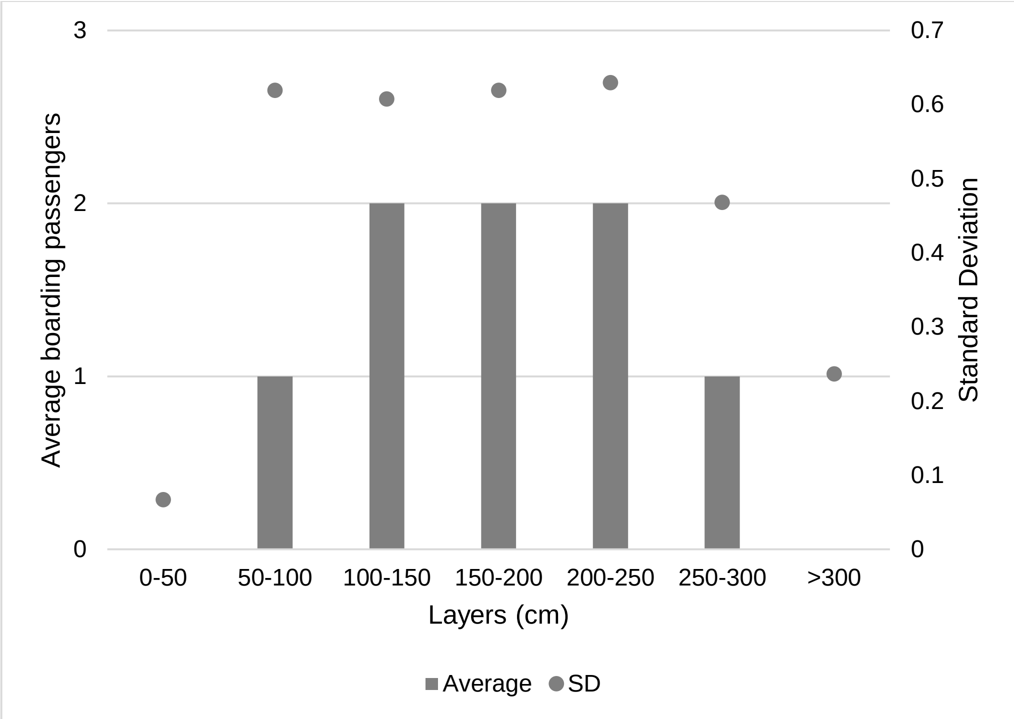


Figure 5. Average location of passengers on the platform waiting to board the train at GPK in the AM and PM peak hours

As a complementary visualisation tool of the distribution of passengers on the platform by layers, Figure 6 shows the interaction maps at both stations. These maps represent the average number of times each 40-cm cell is used by one passenger waiting to board the train. Therefore, the maps represent the density of passengers and potential risks based on the framework such as agglomeration, high pressure, “crossing of flows”, collision and “confined flow” (see Table 3 in section 4). The green colour represents a low interaction area, whilst the red colour denotes high interactions. Medium interactions are symbolised in an amber colour.

In Figure 6 the differences between both stations are clear. In the case of WMS the use of PEDs acting as doors position indications on the platform change the behaviour of passengers to waiting beside the doors rather than in front of them. Cells G5 and G9 are the most used cells at WMS. However, the cells in front of the doors (e.g. F6, F7) are less used at WMS compared to GPK, where no door position indications on platforms are used. Thus, these door indicators help passengers alighting to get off the train with fewer interaction problems.

In the case of GPK, Figure 6 shows that passengers are more evenly distributed on the platform, but less clustered as they do not know where the train is going to stop. Cells in front of the door at GPK (e.g. F6, F7) are used up to 2.7 times more compared to the same cells at WMS, causing high interaction problems. Passengers waiting to board the train at GPK do respect the yellow safety line on the platform, therefore the first row of cells (row G) is less used on average. This produces a reduction of 40 cm or 13% less platform compared to WMS, in which all the platform width is used.

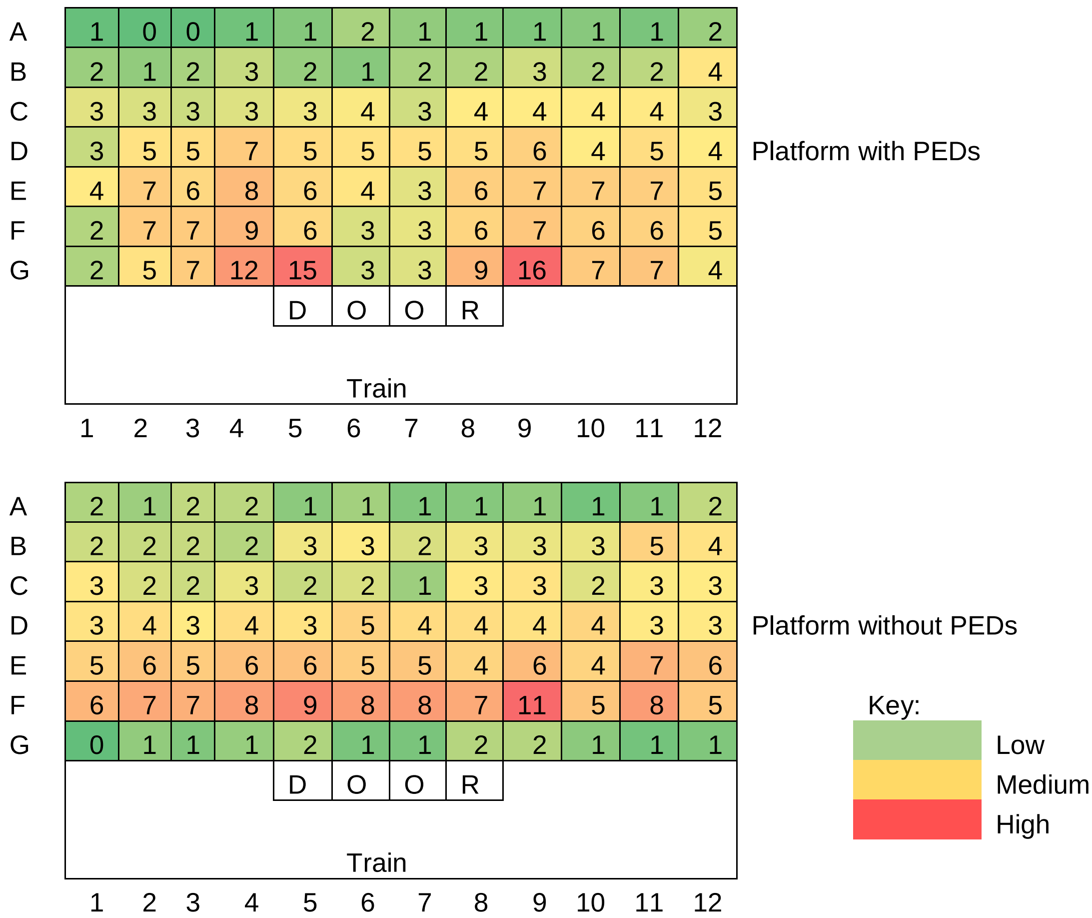


Figure 6. Average interaction maps on the platform at WMS and GPK

5. Recommendations to reduce interaction

In this section recommendations to reduce interaction are provided based on the framework applied to WMS and GPK. Problems of interaction between passengers boarding and alighting at GPK can be reduced by incorporating some door indications positions on the platform. In practice, different metro systems in Singapore, Washington and Tokyo have already tested some crowd management measures on platforms (Loukaitou-Sideris et al., 2015; Lim, 2015; WMAT, 2015). In the case of London Underground, the position of the yellow safety line on the platform has been moved back in some stations as a trial, producing some cross hatch door bays or “keep out zones” (LUL, 2015). However, limited analysis has been done to identify which measures are more effective. Further research is needed to identify which type of crowd management measure should be used considering each condition and effect on platforms.

In the case of GPK, the train stops at the same position on the platform each time it arrives at the station. This is because the train occupies the whole length of the. Figure 7 shows a possible application of crowd management measures at GPK. A “keep out zone” could be used to avoid passengers being an obstacle for those who are alighting. Similar to Seriani and Fernandez (2015a) the rectangle of this zone should cover the door width, include diagonal lines and the name on the platform. However, in the case of GPK the depth of the rectangle should be 1.2 m. This depth is obtained according to the interaction maps from Figure 6 (section 4.2), which represents the first three rows of cells after the yellow safety line that reached medium or high interactions. Passengers waiting to board the train should be located around this “keep out zone”. Compared to some existing field studies, this zone is almost double in size to the one used by LUL (2015) at King's Cross St. Pancras, in which the "keep out zone" had a depth of 0.7 m only.

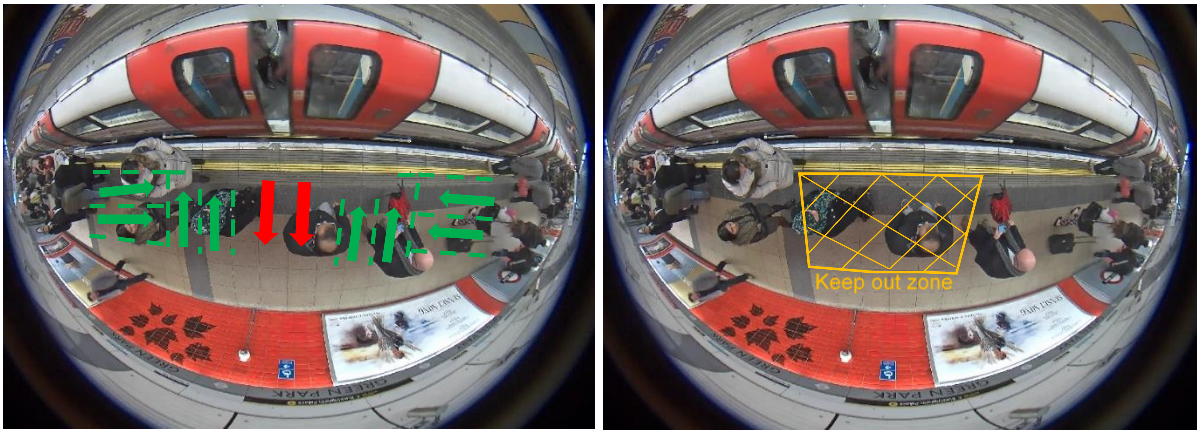


Figure 7. "Keep out zone" (right) and queue lanes (left) to reduce interaction at GPK

Another crowd management measure proposed in Figure 7 is the use of queue lanes. For example, Seriani et al., (2016) proposed queue lanes of 2.6 m length by 0.6 m width for boarding and alighting based on laboratory experiments.

In the case of GPK, queue lanes for alighting could be 1.2 m long by 0.4 m wide. Similar to the "keep out zone", these dimensions are obtained considering the interaction maps from Figure 6 (section 4.2), in which each passenger is represented by one square cell of 0.4 m size and the first three rows of cells after the yellow safety line reached medium or high interactions. According to the observations at GPK, up to 2 lanes for alighting are formed, therefore only two queue lanes are needed to be marked on the floor for these passengers. In addition, according to Figure 6 (section 4.2), a minimum of four queue lanes at both sides of the doors are needed for boarding. Two of them could be perpendicular to the doors, whilst the other two could be parallel to them. This layout helps to accommodate more passengers waiting to board the train and allows passengers to circulate between the queue lanes and the wall on the platform. Both types of queues are similar in size to queue lanes for alighting (i.e. 1.2 m long by 0.4 m wide).

6. Conclusions

In this paper, a new method to analyse the behaviour and interaction of passengers at platform train interfaces (PTI) has been proposed. This method could help to identify potential problems at an early stage. The problems are described in each cell of the framework matrix to help professionals in the decision making (e.g. choosing the best crowd management measure).

The new framework is named BAMBI (Boarding and Alighting Matrix on Behaviour and Interaction), and consist of four stages. The first stage is the conceptual model to represent the movement of passengers boarding and alighting. In the second stage, variables are identified. In the third stage, the degree of interaction (density and perception of risks) between passengers is defined as high, medium and low. Finally, a matrix is proposed to present the results according to the area (vehicle, PTI, and platform) and the type of user (boarders only, alighters only, or both) in a specific station.

BAMBI was applied to two stations in the London Underground. The new framework successfully described the phenomena of high interactions between passengers boarding and alighting. The model was used to identify interaction maps at both stations. The use of maps helps to identify which part of the PTI area is more congested or potentially presents higher risks. Variables such as door position indications on platforms (e.g. the use of platform edge doors, markings on the floor), density, formation of lanes and location of passengers on the platform appeared to be the most important variables that produced high interaction problems at both stations.

A complete observation of peak hours during one week was performed to understand those problems by means of CCTV footage. From the observations at both stations, it can be concluded that passengers are mostly located between 1/3 and 2/3 of the total width of the platform. In addition, the use of door position indications on the platform can reduce the interaction between passengers. In particular, door indicators changed the behaviour of passengers to waiting beside the doors rather than in front of them. For example, when there were no door indicators, the space in front of the doors was used up to 2.7 more times than in the case with door indicators, which causes high interaction between passengers.

With respect to the formation of lanes, as the ratio R between passengers waiting to board the train and those who are alighting increases, the number of lanes for alighting decreases. When R = 0.25 (or less), 60% of the observations presented two lanes for alighting. These two lanes were formed due to the available space on the platform. On the other hand, when R = 4 (or more) passengers on the platform produce a high interaction to board and therefore only one narrow lane for alighting can be formed. In the case R = 1, 35% of the observations had between one and two lanes for alighting.

To reduce the interaction between passengers, crowd management measures are proposed. Solutions such as a “keep out zone” would help to avoid passengers standing in front of the doors and reduce interaction for those who are alighting. Another solution presented in this paper was the implementation of queue lanes for boarding and alighting. Up to two queue lanes are needed for alighting, while queues for boarding could be divided into perpendicular and parallel to the doors, needing a minimum of four each side of the door.

This paper studied the behaviour and interaction of passengers on the London Underground, however the framework and results could be expanded to any conventional rail or LRT system. Other limitations of the study were related to the location of cameras, in which on-board passengers could not be captured. Further research is needed to include these passengers and capture interactions inside the train. In addition, new laboratory experiments and field studies are needed to identify which type of crowd management measures are more effective, considering each condition and their effect on platforms.

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