Crowd management on metro station platforms

Thesis submitted to University College London for the degree of Doctor of Philosophy

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Declaration statement

I, Sebastian Seriani, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis and acknowledgements.

The following section presents a list of presentations and publications as part of this thesis. Three journal papers are already published and another two are in process of publication. In addition, various conference presentations have been delivered.

The only document in which I am not the first author is the paper of De Ana Rodriguez et al. (2016a; 2016b) presented at the TRB Annual Conference and then published in Transportation Research Record. This paper was part of a research project in collaboration with London Underground. The first author of the paper (who works at Rail & Underground Transport Planning, Transport for London, United Kingdom) was in charge of the writing and structure of the paper. The second author did the literature review, analysed the data and prepared the results. The third author leaded the research project at UCL.

Sebastian Seriani

List of Presentations and Publications

As part of this thesis the following papers were presented in conferences and published in journals (or in process of publication):

- De Ana Rodríguez, G., Seriani, S., Holloway, C. (2016a). 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, 10-14 January, Washington D.C.
- De Ana Rodríguez, G., Seriani, S., Holloway, C. (2016b). Impact of platform edge doors on passengers' boarding and alighting time and platform behavior. Transportation Research Record: Journal of the Transportation Research Board, 2540, 102-110.
- Seriani, S., Fujiyama, T., Holloway, C. (2016a). Pedestrian level of interaction on platform conflict areas by real-scale laboratory experiments. Paper presented at the 48th Annual UTSG Conference, 6-8 January, Bristol.
- Seriani, S., Fujiyama, T., Holloway, C. (2016b). Pedestrian level of interaction in the boarding and alighting at metro stations. First prize winner at the 2016 Research Poster Competition, University College London, 1-2 March, London.
- Seriani, S., Fujiyama, T., Holloway, C. (2016c). Interaction in the boarding and alighting at metro stations. Honourable Mention Award at the 2016 ABTA Doctoral Researcher Awards, University College London, 14 May, London.
- Seriani, S., Fujiyama, T., Holloway, C. (2016d). Modelling passenger distribution and interaction on platform train interfaces. Paper presented at the XIX Pan-American Conference of Traffic, Transportation Engineering and Logistics (PANAM), 28-30 September, Mexico City.
- Seriani, S., Fujiyama, T., Holloway, C. (2016e). Estimation of the passenger space in the boarding and alighting at metro stations. Paper presented at the 44th European Transport Conference, 5-7 October, Barcelona.

- Seriani, S., Fujiyama, T., de Ana Rodriguez, G. (2016f). Boarding and alighting matrix on behaviour and interaction at the platform train interface. Paper presented at the RRUKA Annual Conference 2016, 3 November, London.
- Seriani, S., de Ana Rodríguez, G., Holloway, C. (2017a). The combined effect of platform edge doors and level access on the boarding and alighting process in the London Underground. Transportation Research Record: Journal of the Transportation Research Board, 2648, 60-67.
- Seriani, S., Fujiyama, T., Holloway, C. (2017b). Exploring the pedestrian level of interaction on platform conflict areas at metro stations by real-scale laboratory experiments. Transportation Planning and Technology, 40(1), 100-118.
- Seriani, S., Fujiyama, T., de Ana Rodriguez, G. (2017c). A new framework to evaluate passenger interactions at platform train interfaces. International Journal of Railway Technology (accepted for publication 10 October 2017).
- Seriani, S., Fujiyama, T. (2017). Experimental study for estimating the passenger space at metro stations with platform edge doors. Transportation Research Record: Journal of the Transportation Research Board (accepted for publication 6 February 2018).

Abstract

To reduce problems of interaction at the platform train interface (PTI) crowd management measures (CMM) have been implemented in the London Underground (LU). As an example, platform edge doors (PEDs) are used as door positions indicators at the PTI. However, there is little research focused on the effect of these types of measures on the behaviour and interaction of passengers boarding and alighting. In addition, there is a lack of methods and frameworks to represent and evaluate their behaviour and interaction.

A simple framework is proposed to help designers and planners to identify and benchmark the degree of interaction when CMM are used such as PEDs. This framework included a new method, in which the platform conflict area (PCA) is divided into layers of 50 cm each and 40 cm square cells. The framework is supported by observation at two existing stations (with and without PEDs) and laboratory experiments under controlled conditions at UCL's Pedestrian Accessibility Movement Environmental Laboratory (PAMELA). A tracking tool was used to obtain the position of each passenger on the PCA.

The results show that PEDs on their own have no overall negative impact on the boarding and alighting time (BAT) and that in most situations they encourage passengers to wait beside the doors. Measuring the density by layers was more representative of the interaction than average values of density. The space of alighting passengers can be represented as an asymmetrical ellipse and their speed not always increased when they have more space. In addition, if R (boarding/alighting) increases then the formation of flow lines decreases at the PTI.

The new framework is able to describe well the phenomena of high interactions and can be used to evaluate suitable CMM in railway infrastructure. Possible applications of the framework, as well as further investigation, were discussed.

Acknowledgments

I am grateful to many individuals without whom this thesis would not have been possible. I would first like to thank my principal supervisor, Dr Taku Fujiyama at the Department of Civil, Environmental and Geomatic Engineering, University College London (UCL), for his support, inspiration and guidance throughout the years of my PhD research. My PhD years were mostly overlapped with his terms as the graduate tutor of the department, yet he offered an unlimited amount of advice and dedication. I am thankful for his support on having collaboration with London Underground (UK), SNCF (France), Jülich Supercomputing Centre (Germany), and the Transport Study Group at Universidad de los Andes (Chile). I would like to thank for the academic/personal advice he gave in our weekly meetings at UCL. I will not forget all the visits to Chile where we had time for an avocado sushi after the workshops/courses we did together.

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Terminology

1. Definitions

The definitions of the terms used in this thesis are as follows:

- Average boarding time per passenger (t_b): total boarding time (T_b) divided by the total number of boarding passengers (P_b) each time the train arrived.
- Average alighting time per passenger (t_a): total alighting time (T_a) divided by the total number of alighting passengers (P_a) each time the train arrived.
- Boarding and alighting time (BAT): time (in seconds) of the last person entering or exiting PTI minus the time (in seconds) of the first person entering or exiting PTI. The BAT is obtained each 5 second (5 s) segment of time.
- Distance between passengers (D): horizontal distance using the Euclidean method between the coordinates (x, y) between the centre of the heads of two passengers in the PCA.
- Density by layer (k_L): number of passengers boarding and/or alighting in each layer divided by the area of each layer in the PCA.
- Formation of lines: a line is considered to exist when passengers follow the person in front of him/her to avoid collision with other passengers moving in the opposite direction.
- Interaction time (IT): time when passengers board and alight simultaneously. This time does not consider the moments when passengers are waiting to board the train while alighting is in process.
- Number of passenger movements (pass): (total number of boarders) + (total number of alighters in segments of five seconds).
- Overall density (k_O): the total number of passengers on the platform divided by the area of the platform (rectangular space of 15 m^2 without layers in front of each door).
- Passenger overlap: number of passengers boarding and alighting simultaneously.

- Passenger behaviour: defined as the way that passengers move and interact with each other in high densities (e.g. more than 2 pass/m^2) to avoid collision with other passengers or obstacles at the PTI zone.
- PEDs: platform edge doors, installed on the edge of the platform (between the platform and the train).
- Platform conflict area (PCA): new representation of platforms. The PCA of the door i can be represented as a half circle space of radius L_i. The radius L_i of the PCA is the distance of influence of the door i. The PCA includes the PTI and the relevant section of the platform in front of each door of the train.
- Platform Train Interface (PTI) without PEDs: the space between the train doors and the yellow line on the platform,
- Platform Train Interface (PTI) with PEDs: is the space between the PEDs and the train doors.
- Platform hump: is used to raise the platform only in one section to achieve level access between the train and the platform.
- Queues: is defined as the way boarding passengers are waiting in front of or beside the doors to board the train.
- Setback: is defined as the distance between the doors and the seats (inside the train).

2. Acronyms and abbreviations

The acronyms and abbreviations used throughout the thesis are as follows:

- A_p: observed area on the platform in front of the doors [m^2]
- A: passenger alighting the train [pass]
- AS: asymmetrical space [m^2]
- B: passengers waiting to board the train [pass]
- BAT: boarding and alighting time [s]
- CMM: crowd management measures
- D_a: distance between passengers alighting [cm]
- D_b: distance between passengers boarding [cm]

- GPK: Green Park station
- HDL: Human Dynamic Laboratory (at UANDES, Chile)
- k_L: density by layer [pass/m^2]
- k_O: overall density [pass/m^2]
- IT: interaction time [s]
- L: length of the platform captured by the cameras [m]
- LU: London Underground Limited
- OS: overall space [m^2]
- P_b: number of passengers boarding [pass]
- P_a: number of passengers alighting [pass]
- P_o: overlapping passengers [pass]
- P_w: recommended platform width [m]
- PAMELA: Pedestrian Accessibility Movement Environment Laboratory (at UCL, UK)
- Peak hour AM: between 8:15 – 9:15
- Peak hour PM: between 17:15 – 18:15
- PCA: platform conflict area
- PEDs: platform edge doors
- PTI: platform train interface
- R: ratio between passenger boarding (or waiting to board) and those who are alighting [unitless]
- t_b: average boarding time per passenger [s/pass]
- t_a: average alighting time per passenger [s/pass]
- T_b: total boarding time [s]
- T_a: total alighting time [s]
- T_o: overlap time [s]
- TD: train door
- UCL: University College London (UK)
- UANDES: Universidad de los Andes (Chile)
- v_a: instantaneous speed of passengers [m/s]

- WMS: Westminster Station

Chapter 1 Introduction

1.1 Introduction

There are different ways to study the movement of passengers in metro stations. Seriani and Fernandez (2015a) define the type of infrastructure, in which metro stations could be divided into five circulation spaces for passengers: the train-platform space, the platform-stair space, the concourse, complementary – e.g., shopping – space, and the city. All of the five spaces are, individually, complex environments that need a particular in-depth level of analysis. This research will focus only on the first type of space: train-platform (henceforth platform train interface or PTI).

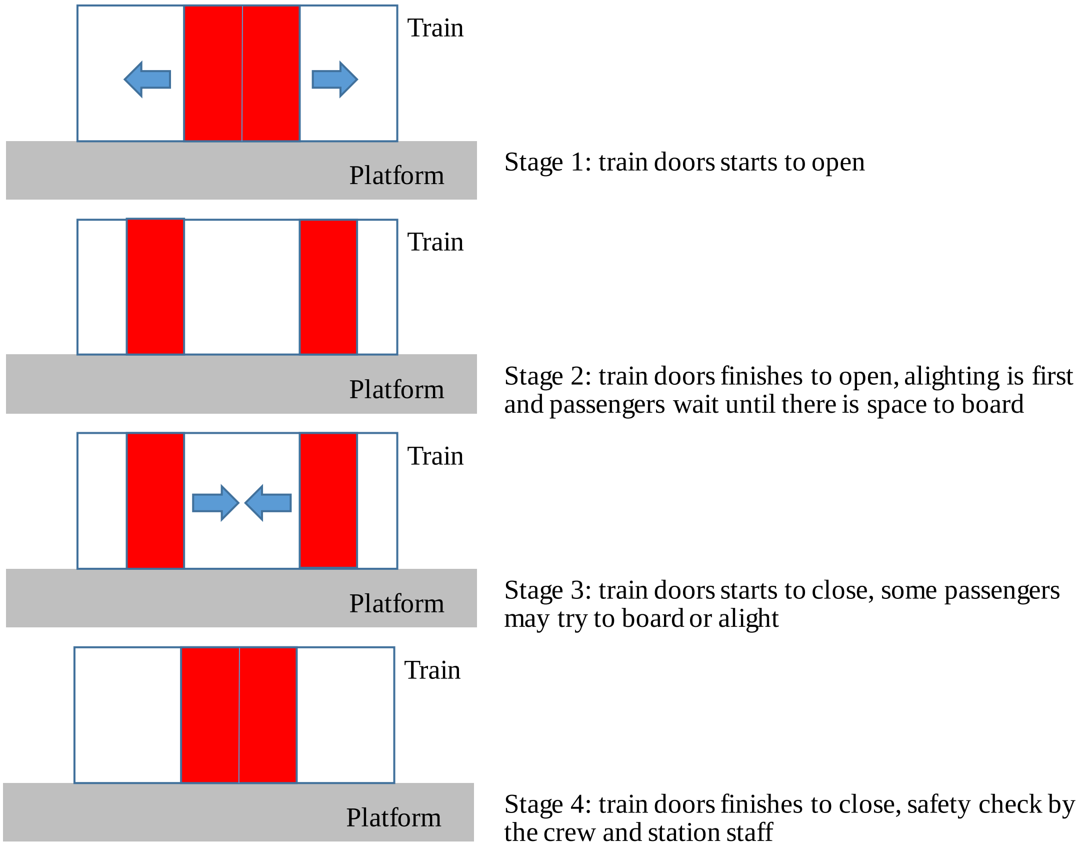
The PTI is the space where most interactions occur between passengers boarding and alighting (see Figure 1-1). The way (e.g. movement) that passengers go from the platform to the train (boarding) or from the train to the platform (alighting) is a very important issue that affects the efficiency and safety of metro stations.

Figure 1-1: Example of platform train interface zone at Green Park Station, London Underground

In the case of the UK national train network, more than 3 billion interactions take place each year, during which 48% of the fatality risks to passengers are produced at the PTI zone (RSSB, 2015). Therefore, 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. With respect to the London Underground (LU), the total network provides around 4.25 million trips per day with a high peak of demand between 8 and 9 a.m, requiring one train every 2 or 3 minutes at metro stations such as Westminster (WMS) and Green Park (GPK) on the Jubilee Line (TfL, 2014).

In relation to efficiency, when the number of passengers boarding and alighting increases, the whole train service could be affected. This is caused because the "station dwell times are the major component of headways at short frequencies" (TRB, 2003: 5-19). The dwell time is the time the train remains stopped at the station transferring passengers (TRB, 2000). In the case of low frequency services, the dwell time is considered a fixed value for transport operators. The static component of dwell time includes the door opening and closing times (stage 1 and 4 in Figure 1-2), as well as to the duration of other mechanical movements and of safety delays, whilst the dynamic component relates to passenger movements and is mainly the boarding and alighting time (BAT) (stage 2 and 3 in Figure 1-2). The BAT can be divided into three steps. Firstly, passengers alight from the train, while passengers at the platform are waiting for space to board. Secondly, passengers alight and board simultaneously, i.e. there is an overlap in time which is defined as interaction time (IT) by Harris (2006). Thirdly, alighting finishes and only those passengers at the platform board the train. This thesis considers only the dynamic component of dwell time, i.e. the BAT, which is the one affected by the passenger behaviour.

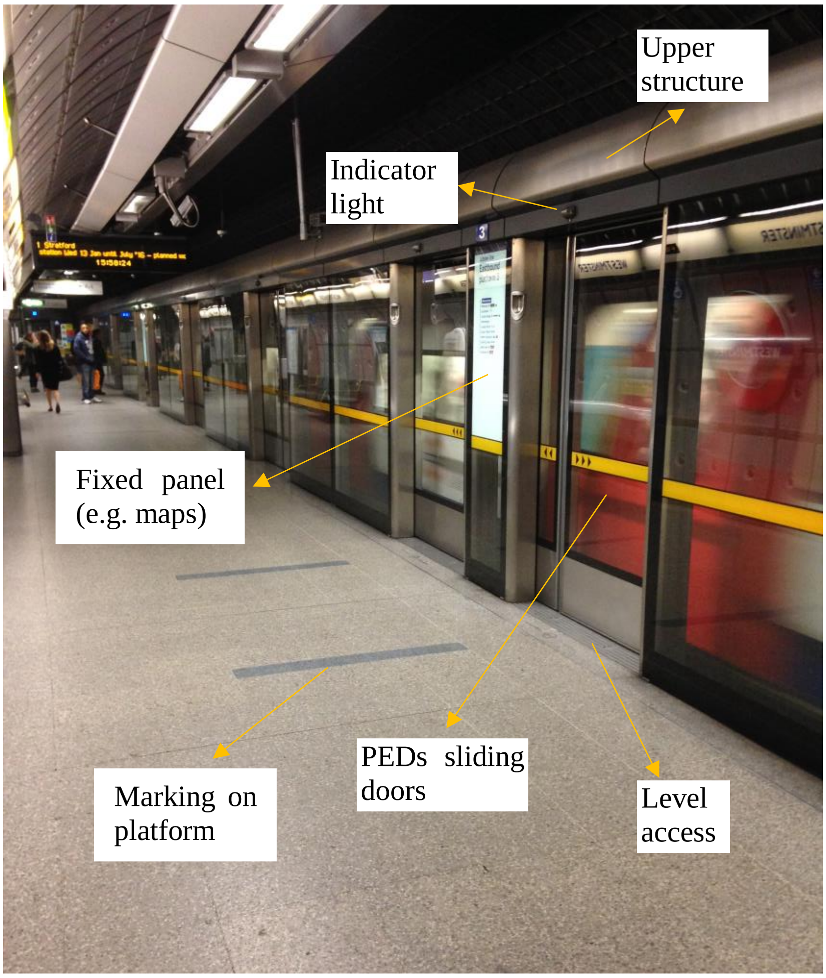
Figure 1-2: Diagram of stages in the process of boarding and alighting



To improve efficiency and reduce risks or hazards for passengers at the PTI, crowd management measures (CMM) 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, 2015b: 76). The authors state that CMM can improve safety conditions at the PTI, but also can help operators to improve the performance of the boarding and alighting process by reducing the time each train remains stopped at the station transferring passengers.

As an example of CMM, barriers have been used worldwide in different metro stations between the train and the platform. These barriers refer to full-height when they cover the total height between the floor and ceiling of the station. In the case of LU, these elements are half-height (i.e. they do not reach the ceiling) and therefore are known as platform edge doors (PEDs) (see Figure 1-3). In relation to their width, PEDs at LU are 2.0 m, i.e. 0.4 m wider than the double train doors. To identify PEDs, a grey line (1.2 m long and 10 cm wide) is marked on the platform, which act as door position indicators on platforms to highlight where the doors are going to be. Mechanically, PEDs work as sliding barriers between the train and the platform, and they open or close simultaneously with the train doors. Currently, the LU network has PEDs in nine stations on the Jubilee Line, namely in those newly built as part of the Jubilee Line Extension that opened to service in 1999. Those new stations were designed with PEDs from scratch and they all provide level access to the trains from the whole platform.

Figure 1-3: Platform edge doors at Westminster Station, London Underground



Another example of crowd management measure used in the LU is presented in Figure 1-4, in which the position of the yellow safety line on the platform has been moved back, producing some cross hatch door bays or “keep out zones” (LUL, 2015). These elements also acts as door position indicators as they intent to avoid passengers waiting in front of the doors. Therefore, passengers boarding are not an obstacle for those who are alighting.

Figure 1-4: Hatch door bays used in King's Cross St. Pancras in the LU

Despite the benefits of implementing CMM, little research has been done to understand their effect on the behaviour and interaction of passengers boarding and alighting at the PTI. As described in section 2.4, in the case of PEDs there is a common assumption that the presence of these elements increases both the static and dynamic components of dwell time, however as explored in Chapter 4 and Chapter 5 these elements do not produce an important effect on the BAT. In addition, the use of markings on the floor (e.g. PEDs as door position indicators) changed the layout of the PTI, and therefore affected the behaviour of passengers. When passengers know where the doors are located on the platform, there are some changes in the way passengers interact with each other in high densities (e.g. more than 2 passengers/m^2) to avoid collision with other passengers or obstacles at the PTI zone.

There have been many studies on pedestrians' behaviour and interaction, and since 1970s, many methods and models have been proposed. However, as discussed in section 2.3, there is a lack of methods and models to represent and evaluate the behaviour and interaction of passengers at the PTI. For example, some methods are based on indicators such as the Level of Service (LOS) defined by Fruin (1971). The LOS is a very important tool, however, existing studies suggest that this indicator is based only on average values of density, speed and flow to represent congestion problems, and therefore it is not possible to identify which part of the PTI reaches a higher interaction (see section 2.3.1 and section 2.3.2). In addition, microscopic pedestrian models are based on two main approaches: continuous space and discrete. However, each passenger is represented as a circle with constant radius that moves without virtual restrictions or as a fixed square that moves according to a grid with specific rules similar to a chessboard (see section 2.3.4). The use of LOS and these types of representations are very simplistic and could lead to underestimates of the real problems of interaction between passengers at the PTI such as collision avoidance, formation of lines, space used, or distribution. When these problems are not included, the PTI could be designed with less capacity, affecting the efficiency and safety conditions. Therefore, as explored in Chapter 4 and Chapter 5 new methods are needed to represent and evaluate the behaviour and interaction of passengers at the PTI.

Problems affecting the efficiency and safety conditions at the PTI have previously been studied in an isolated way, and from the point of view of trains services rather than how passengers behave at the PTI. The problem is discussed in section 2.5 in which isolated CMM 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 framework as escribed at the end of Chapter 5.

1.2 Research questions and hypothesis

Three research questions are proposed for this research:

- What are the effects of crowd management measures (CMM) on the behaviour and interaction of passengers at the PTI?
- What method and model could be used to represent and evaluate the behaviour and interaction of passengers boarding and alighting?
- Which CMM are more effective at the PTI?

The hypotheses of this research are defined to correspond to the research questions above:

- If PEDs are used as door indicators, then passengers can change their behaviour as they know where the doors are, affecting the boarding and alighting time (BAT), interaction time (IT), formation of lines, space used and distribution of passengers at the PTI.
- If the PTI is discretised forming a different shape, then it can be identified which part of the PTI is more congested and problems of interaction can be evaluated according to the distance from the train doors.
- If the behaviour and interaction of passengers boarding and alighting at the PTI is better understood, a new framework could help to identify effective CMM in a more integrated way.

1.3 Objectives

The aim of this research will be centred on a new framework to represent and evaluate the effect of crowd management measures (CMM) on the behaviour and interaction between passengers boarding and alighting at metro stations.

The specific objectives are:

- Create a conceptual model to represent the interaction problems in the boarding and alighting process.
- Identify the main variables that affect the behaviour and interaction of passengers at the PTI, using a matrix to present the problems.

- Define a new method and indicator to represent and evaluate the level of interaction at the PTI.
- Mock-up a carriage to simulate the boarding and alighting in a controlled environment (e.g. laboratory) based on existing stations.
- Study the boarding and alighting time (BAT), interaction time (IT), formation of lines, space used, and distribution of passengers on platforms when door position indications on platforms are used.
- Make recommendations to reduce the interaction problems at the PTI.

1.4 Scope of this thesis

The scope of this thesis concentrates on laboratory experiments based on observation in existing stations. The behaviour and interaction of passengers is analysed at the PTI, considering the critical door (most congested) and not the whole platform. In addition, stairs, lifts, escalators, concourse, corridors or any other circulation element are not considered.

This thesis will focused on the factors related to CMM (e.g. use of PEDs) and people (e.g. boarding and alighting) in metro stations, in which behaviour is defined as the way that passengers move and interact with each other in high densities to avoid collision with other passengers or obstacles at the PTI zone. It was chosen these two factors as 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 departure on time (Carey and Kewieciński, 1994; TRB, 2013).

It will be considered only passengers boarding and alighting, and not the behaviour and interaction of those passengers on-board or with reduced mobility (e.g. wheelchair users). In addition, safety risks of CMM such as the reason why PEDs are installed or injuries caused by passengers trapped between the train doors and PEDs are out of the scope of this thesis.

The observation and experiments are based on the behaviour and interaction of passengers in the London Underground, however, this thesis could be expanded to any conventional rail or LRT system. For the laboratory experiments at PAMELA it is proposed to build a metro carriage and a corresponding platform section, and the scenarios will include the use of PEDs, level access, and different levels of demand of passengers boarding and alighting to produce variation of the density on the platform.

Therefore, the scope can be summarized as:

i. Observation and experiments on behaviour and interaction between passengers boarding and alighting at PTI.
ii. New methods and framework development of the behaviour and interaction between passengers boarding and alighting at PTI when CMM are used.

1.5 Structure of the thesis

The rest of the document is organised as described below.

Chapter 2 will describe the existing studies related to the behaviour and interaction of pedestrians in public transport environments, followed by the examination of existing methods and models. Next, existing studies on the effect of CMM are revised. Finally, the need of a framework to evaluate the measures, what variable to study and their effect are discussed.

Chapter 3 will define the methodology of this research. After a discussion on the approach selected, this chapter will define the set-up of the laboratory experiments. Then the two London Underground stations used as a case of study are described. Finally, a new method is proposed to represent and evaluate the behaviour and interaction at the PTI, in which a new space will be defined as a platform conflict area (PCA).

Chapter 4 will explore the effect of CMM such as PEDs on the behaviour and interaction of passengers boarding and alighting in a controlled environment at PAMELA. The interaction at the PCA is influenced by eight variables: the level of demand, boarding and alighting time (BAT), types of queue, formation of lines, distance between passengers, density by layer, passenger space, and instantaneous speed.

Chapter 5 will examine the effect of CMM such as PEDs on the behaviour and interaction of passengers boarding and alighting in existing stations. Two stations were selected as case of study (with and without PEDs). Only four variables were studied at the PCA: the level of demand, boarding and alighting time (BAT), types of queue, and formation of lines. Based on the LU observations, a simple framework is proposed to evaluate behaviour and interaction problems at the PTI. The framework used was divided into four stages: conceptual model, variable, assessment of risk and matrix of interaction.

Chapter 6 concludes the thesis. The main achievements will be highlighted, and possible application of the new framework will be included in this chapter. This chapter also includes a discussion on the limitations and further research.

Chapter 2 Literature Review

2.1 Introduction

The previous chapter showed the problem of interaction at the platform train interface (PTI). This chapter is divided into five parts. Firstly, it reviews the existing research on the behaviour and interaction of pedestrians in public transport environments (section 2.2). Secondly, this chapter analyses what types of methods and models best represent and evaluate the behaviour and interaction of passengers in metro stations (section 2.3). Thirdly, it discusses the existing studies on the effect of crowd management measures (CMM) at the PTI (section 2.4). Fourthly, it discusses the need of a new framework to evaluate CMM in an integrated way a the PTI (section 2.5).

2.2 Existing studies on behaviour and interaction of pedestrians

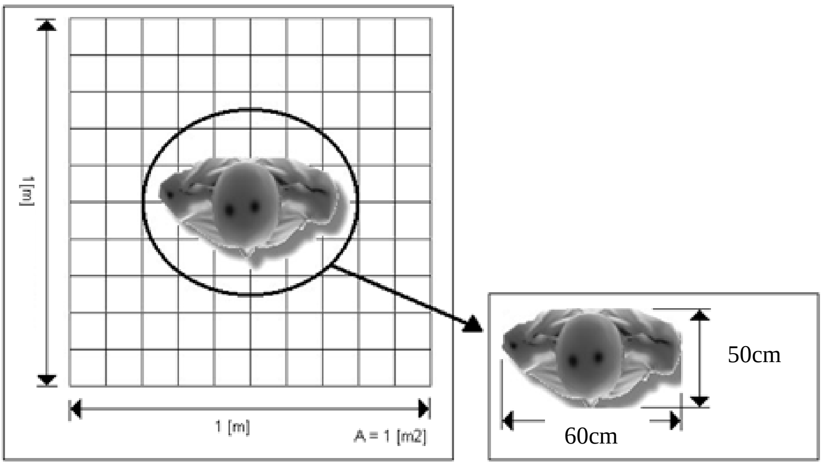
This section gives an overview of the existing studies on the behaviour and interaction of pedestrians, focused on public transport environments. According to RSSB (2008), four types of factors can affect the behaviour of pedestrians in public transport environments: presence of other people (e.g. density on the platform or personal space), physical design of the train carriage (e.g. width of the platform, number of train doors or position of the seats), information provided to pedestrians (e.g. maps, on-board displays, on-train announcements), and environment (e.g. weather). In addition, Fruin (1971) and Still (2000), state that other factors affect the walking behaviour of pedestrians such as the age, size, and culture. All these factors are described in the following sections.

2.2.1 Characteristics of pedestrians

Some manuals such as REDEVU (MINVU, 2009) and HCM (TRB, 2010), use the concept of 'pedestrian' as any person that walks within the city (rural or urban areas). However, this thesis is focused on the concept of 'passenger' (or pass), which is a person who uses the public transport system (e.g. metro stations).

To study the interaction and behaviour while boarding and alighting at metro stations, it is necessary to define the space of pedestrians. According to Fruin (1971), in any standing area (e.g. metro stations and surroundings) a pedestrian can be represented as an ellipse of area 0.30 m^2 comprising a body depth of 50 cm and a shoulder breadth of 60 cm (see Figure 2-1). However, when the pedestrian starts to walk, this area increases to 0.75 m^2 because there is extra space used for leg and arm movements (Pushkarev and Zupan, 1975).

Figure 2-1: Dimensions of an average human body (adapted from Fruin, 1971)



In presence of obstacles, Gérin-Lajoie et al. (2005) have reported that each pedestrian needs a space represented as an ellipse of area 0.96 m wide by 2.11 m deep, which is smaller when overtaking static versus a moving obstacle (in both cases a mannequin was used as an obstacle). In addition, Gérin-Lajoie et al. (2008) demonstrated that this space can be asymmetrical in shape and side (left and right) during the circumvention of a cylinder (or column) as an obstacle, in which the longitudinal axis of the ellipse is related to the speed, i.e. when the speed of pedestrians is increased, there is a longer longitudinal axis, whereas the lateral axis is related to the avoidance of contact with other pedestrians or obstacles.

These studies (Gérin-Lajoie et al., 2005; 2008) are related to the concept of sensory zone, which is “the distance a person tries to maintain between the body and other parts of the environment, so there will always be enough time to perceive, evaluate, and react to approaching hazards" (Templer, 1992, p. 61). For example, for a normal walking speed the sensor zone can be estimated as an elliptical area of 1.06 m wide by 1.52 m deep (Tembler, 1992). Similarly, Fruin (1971) calculated that the sensory zone reached a distance of 1.48 m for a normal walking speed of 1.37 m/s.

Other studies (Sinha and Nayyar, 2000) reported that older people need more space to move in high density situations, however, this increase can be moderated with social support and self-control. In this sense, Webb and Weber (2003) state that personal space is affected by vision, hearing, mobility, age, and gender (e.g. when mobility is reduced, each pedestrian needs more space). The authors developed a theoretical model to understand the cognitive process of personal space for pedestrians based on perception and interpretation of the stimulus. In addition, Sakuma et al. (2005) proposed a simulation model based on psychology theory, according to which personal space is defined by an inner critical circle within which there is immediate avoidance of any agent appearing in it, and by an external circle where caution is applied to avoid pedestrians which appear there. This model includes the effect of individual memory on determining actions to be taken.

According to Daamen and Hoogendoorn (2003) it should be considered other characteristics of pedestrians such as the age, gender and heath. In addition, the authors identified that the walking purpose, route familiarity and luggage can affect the behaviour of pedestrians. Similarly, Willis et al. (2004) state that men walk faster than women in urban areas. The authors also found that the age, mobility conditions (e.g. bags, luggage) and time of the day affect the walking behaviour of pedestrians. Recently studies (Chattaraj et al., 2009) also include the effect of differences of cultures, for example the speed of Indian pedestrians is less affected by density whereas it does affect the speed of German pedestrians. The same authors suggest that local attitudes which relate to the behaviour of pedestrians should be incorporated.

2.2.2 Presence of other people

The effect of intimacy was first studied by Hall (1966). The author classified intimate distance into four groups: a) intimate (when the distance is less than 0.5 m and pedestrians have a special relationship); b) personal zone (between 0.5 m and 1.2 m, and pedestrians know each other); c) social consultative zone (between 1.2 m and 4 m, and pedestrians do not know each other but they permitted communication); and d) public distance (between 4 m and 10 m, and pedestrians do not know each other). In the case of metro stations, Sommer (1969) studied the social behaviour of passengers and used three groups to classify personal space: a) intimate (< 0.5 m); b) personal (0.5 – 1.2 m); and c) social (>3.0 m). Therefore, if the distance between two pedestrians' heads less than 1 m (taking into account 0.5 m plus two times half the body depth of Fruin, 1971), then pedestrians will feel that their space is being invaded. However, this feeling of invasion is based on perception (e.g. comfort) rather than physical space (e.g. available space or density), which is difficult to calibrate at the PTI zone.

From another perspective, Schmidt and Keating (1979) introduced the concept of personal control which is less subjective than the personal space defined by Hall (1966) and Sommer (1969), and is categorised into three forms: behavioural, cognitive and decisional. The first form is related to crowding situations which are produced when the density interferes with the behavioural sequence or blocks the goal of pedestrians or when pedestrians feel that they lose control or freedom of their space (e.g. passengers alighting are unable to leave a dense platform), in which collision avoidance is a way to return to a non-crowded situation. With respect to cognitive aspects of travelling, Schmidt and Keating (1979) state that personal control depends on the way each pedestrian anticipates and interprets the event or impending condition (e.g. stress). Information provided beforehand can improve cognitive control (e.g. if passengers are given a map with the most crowded stations so they can plan their journey and stress is reduced). Finally, the decisional control is related to the desired situation of each pedestrian when selecting outcomes.

Passengers at the PTI also try to avoid contact with other passengers, unless such contact is inevitable (e.g. there is not enough space to board or alight) (Fruin, 1971, Still, 2000). For example, Goffman (1971) states that to avoid collision, pedestrians tend to form two lines of flows and the flows tend to be right-handed. For other authors (Wolff, 1973; Sobel and Lillith, 1975; Willis et al., 1979; Collett and Marsh, 1981; Burgess, 1983) the manner of avoiding collision depends on density and gender. Therefore, in the case of metro stations, interactions between boarding and alighting passengers can be considered as an extension of social research on how people corporate in order to avoid collisions (Wolf, 1973; Sobel and Lillith, 1975; Collet and Marsh, 1981; Helbing et al., 2005). Recent laboratory experiments (Kitazawa and Fujiyama, 2010) have used mannequins as static obstacles to study collision avoidance techniques as a function of the vision field, in which an angle of 45 degrees was reached and a distance less than 1.5 m was perceived as difficult to avoid and react. Previously, Fujiyama and Tyler (2009) reported that pedestrians also scan each other by locking their eyes and movement to estimate their avoidance distance, which is approximately 5 m to a stationary person (higher than the distance to avoid an obstacle). This behaviour happens on flat areas, but also on stairs.

In the case of corridors, concourse and open areas, when pedestrians reach a high density, they auto-organise themselves and form lines of flow (Oeding, 1963). This phenomenon is produced only by the presence of other people and not because there is signalling or markings (see Figure 2-2). Some authors (Fruin, 1971; Still, 2000) identify that this phenomenon happens when the density is higher than 2 pass/m^2. Other authors suggest that this phenomenon is caused because pedestrians compete for their space and they walk in groups (e.g. boarding or alighting) in which each pedestrian follows the pedestrian that is in front of him/her (Aveni, 1977; Coleman and James, 1961; James, 1953). In this sense, Willis et al. (2004) reported that a single pedestrian walks faster than those pedestrian with one or two companions. Recently, some authors (Moussaïd et al., 2010) reported that groups are commonly composed of 2-4 members and that there is an impact of the group on the crowd, for example, at low density members of the group tend to walk side-by-side reaching a high speed, however, when the density increases, the speed decreases and group forms “U” or “V” walking patterns, in which inverse “V” patterns are the most efficient because of their aerodynamic shape.

Figure 2-2: Pedestrians self-organisation (left) vs. chaotic situation (right) in crowds (Still, 2000)

2.2.3 Physical design

Pedestrians can move freely in any space and they are only limited by the geometry. In this regard it is important to notice how spatial elements that are perceived as an obstacle can produce a better performance of the movement of pedestrians by improving some variables. For example, some authors (Helbing and Molnar, 1997; Helbing et al, 2000; 2005) found that a column opposite the exit door of a corridor can stabilize the flow and make it more fluid by up to 50%. In addition, Frank and Dorso (2011) stated that an obstacle (e.g. pillar or flat panel) placed 1.1L from an exit door of width L in a corridor can achieve the highest evacuation speed. Moreover, Alonso-Marroquin et al. (2012) identified that an obstacle, in the same way as an hourglass, increases the flow by 16%. In this case, an hourglass is referred to the shape of the bottleneck. The authors also found that the flow reaches its maximum value when the distance to the obstacle is changed rather than its diameter.

To represent similar situations, some authors (Schadschneider et al., 2009; Seyfried et al., 2009; Seyfried et al., 2010; Duives et al., 2013) studied the pedestrian flow through bottlenecks in a corridor by performing laboratory experiments. When pedestrians are formed into lines of flow, the capacity will be increased only if a new line is formed.

This is shown in different models and experiments (Kretz et al., 2006). However, Hoogendoorn and Daamen (2005) found that the capacity of a bottleneck did not increase linearly with a gradual increase in the width of the doors, but increased in stepwise fashion. The authors defined the “zipper effect” when two lines of pedestrians overlapped, reaching a distance between pedestrians of about 45 cm, which is less than the body breadth (50 or 60 cm). This is caused because pedestrians need more space to move forward than to move laterally.

2.2.4 Information provided to pedestrians

Pedestrians use the least possible effort to move from point “A” to point “B”. This means that pedestrians not only look for the shortest route, but also the most direct route without obstacles (Still, 2000; Kagarlis, 2002; Legion Studio, 2006). Therefore, the information provided to pedestrians should help them to identify this least effort route without obstacles. Maps and other type of information elements should be installed in unused spaces such as corners or ceilings.

2.2.5 Environment experience of pedestrians

According to Daamen and Hoogendoorn (2003) pedestrian walking behaviour is affected by exogeneous factors such as the ambient and weather conditions. In addition, Willis et al. (2004) reported that pedestrians are affected by the location (e.g. presence of vehicles, amount of space reserved for pedestrians). However, according to Carreno et al. (2002) the behaviour of pedestrians is affected not only by the weather or location, but also by their experience. The authors developed a new indicator called Quality of Service (QOS) to evaluate the experience of pedestrians in walkways environments, composed of 6 main factors: comfort, safety, security, attractiveness, convenience, and accessibility.

Similarly, Kaparias et al. (2012) studied the experience of pedestrians in urban spaces. The authors reported that existing studies have highlighted the relevant factors that specifically affect walking experience, such as the level of service of Sarkar (1993), which is based on safety, security, comfort and convenience, continuity, system coherence, and attractiveness; or the study of Pikora et al. (2002) in which the quality of walking depends on functional, safety, aesthetic and destination factors. The authors (Kaparias et al., 2012) evaluated the environment and factors that specifically affect the experience of pedestrians based on questionnaire and regression models, following the PERS software (Allen, 2005).

In the case of Kaparias et al. (2012), the authors found that the main sources of dissatisfaction were unclean streets, level of traffic pollution, lack of space, restricted walking speed, poor condition of pavements, and negative perceptions of safety. In addition, positive dependences were found between comfort and ease of movement; positioning of crossing and ease of movement; perceived waiting time and capacity of crossing; age and ease of movement and perceived crossing capacities; and frequency of visit to an area and perceived crossing positioning.

2.3 Existing methods and models to represent and evaluate behaviour and interaction of pedestrians

In this section the literature review on methods and models to represent and evaluate the behaviour and interactions of pedestrians is discussed. Firstly, Fundamental Diagrams are presented based on three variables: speed, flow and density. Secondly, the LOS is described as a tool to identify the degree of congestion in walkways, waiting areas and stairs. Thirdly, methods are discussed to evaluate crowding at the PTI. Fourthly, the representation of pedestrians in microscopic models is discussed based on continuous space and discrete approaches.

2.3.1 Fundamental Diagrams

The behaviour and interaction of pedestrians have been studied for the last 50 years. The first studies (Henderson, 1971; 1974; Fruin, 1971) were done by observation such as videos or photographs in which pedestrians were represented as fluids or particles. This type of representation is called macroscopic, in which pedestrians are analysed in a global view by three main variables: speed, density and flow. Therefore, this representation is simple to use for standards and it culminates in a graphical representation of the results such as videos, tables and maps.

Fruin (1971) defines 1.43 m/s (5.15 km/h) as the free-flow speed of a pedestrian when there is a unidirectional flow and 1.36 m/s (4.9 km/h) when there is a bidirectional flow. In addition, the author states that the average speed of pedestrians (v_e) is directly related to the free-flow speed (v_l) and the density (ρ), which is defined as the ratio between pedestrians and the total area. For instance, the well-known linear model for vehicles devised by Greenshields (1934) can be used for pedestrians to analyse the relationship between speed and density with the following formula:

$$v_e(\rho) = v_l - \frac{v_l}{\rho_c} \cdot \rho \tag{2.1}$$

In which ρ_c is the density when it is reaches capacity.

Since then, different studies have been done to analyse the walking speed of pedestrians and its relationship to density. All these studies have been compared to the well-known relation between walking speed and density proposed by Weidmann (1993), which has the following components:

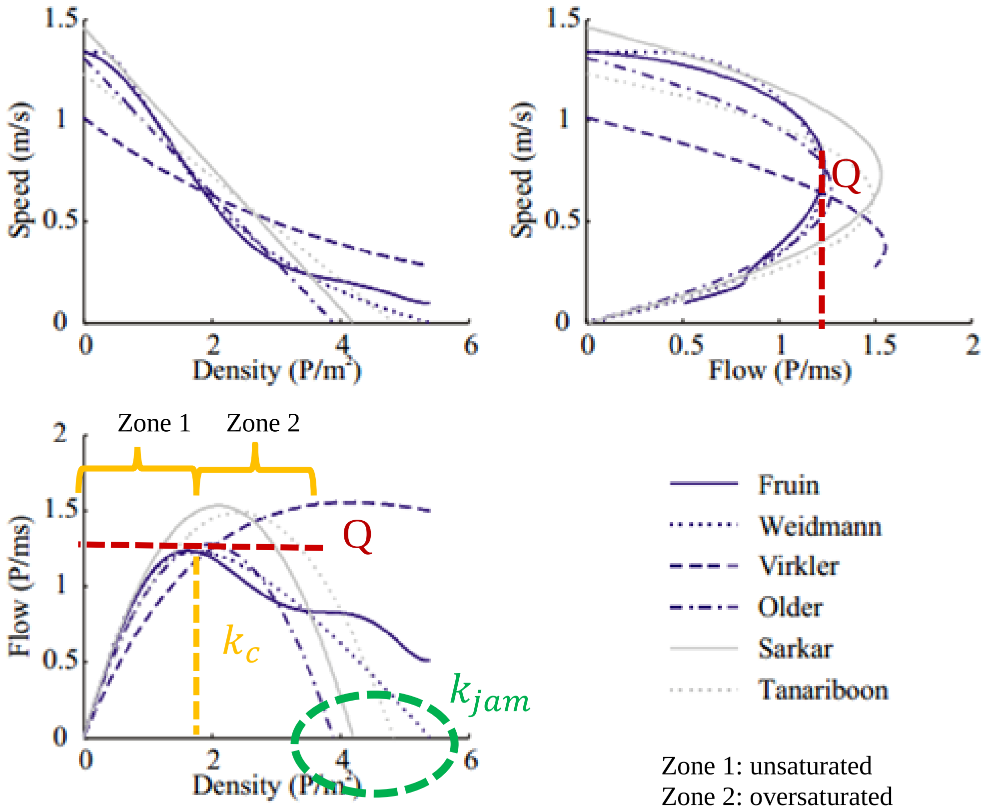
$$v_e(\rho) = v_l \left[1 - e^{-1.913\left(\frac{1}{\rho} - \frac{1}{\rho_{jam}}\right)} \right] \tag{2.2}$$

where ρ_{jam} denotes the jam-density of 5.4 pass/m^2. The free-flow speed (v_l) for pedestrians is defined as 1.34 m/s. However, this free-flow speed can vary among types of pedestrians. For example, shoppers have a free-flow speed of 1.04 m/s, commuters 1.45 m/s, and tourists 0.99 m/s (Weidmann, 1993).

Another study of bidirectional corridors at Hong Kong MTR stations presented a walking speed at free flow of 1.37 m/s and 0.61 m/s in capacity (Cheung and Lam, 1997). The authors compared these values to bidirectional corridors at London Underground (LU) stations, in which the walking speed at capacity was 0.6 m/s.

Equations (2.1) and (2.2) are not the only types of relationships. Recently, Jelić et al. (2012) calculated the instantaneous Fundamental Diagrams, in which the instantaneous density is defined as the inverse of the spatial headway - h (number of pass/m) and the instantaneous velocity is a function of h. The authors found that pedestrian avoid other pedestrians and they adapt their speed to the following pedestrian. As a summary Daamen et al. (2005) reported the Fundamental Diagrams based on three main variables: speed, density and flow (see Figure 2-3). The Fundamental Diagrams are important tools to evaluate if a space is congested.

Figure 2-3: Fundamental Diagrams adapted from Daamen et al (2005)



In relation to density and speed, it can be seen from Figure 2-3 that if the density increases then the speed will decrease almost linearly. However, this type of linearity is not produced for flow (q). This variable (q) is defined as the ratio between the number of pedestrians and time per meter of section. For instance, if we look at Fruin's curves, it can be seen that if the density increases, the flow will also increase to its capacity (Q), which is reached at approximately 1.3 pass/m-s. At this point the density is almost 2.0 pass/m^2 (ρ_c). This value of ρ_c generates two new zones: zone 1 (unsaturated) and zone 2 (oversaturated). These new zones are related to the concept of saturation flow, which is defined as the following:

$$X = q/Q \tag{2.3}$$

2.3.2 Fruin's Level of Service (LOS)

Another example of macroscopic method is the use of the Level of Service or LOS of Fruin (1971), which indicates the degree of congestion and conflict in an area (flat areas, queues or stairs) using general parameters such as speed, density or flow. Fruin (1971) studied the behaviour of passengers in existing stations, in which the objective of the LOS was to obtain the capacity of a path. Figure 2-4 shows that if the space is reduced, then the flow will also increase up to the capacity and then passengers' movement will be reduced. The author considered two different types of pedestrians: commuter and shoppers.

As a result of the observations, Fruin (1971) classified the results in different levels. Table 2-1 and Figure 2-4 show a representation of the LOS in walkways, which goes from Level A (free flow with no conflicts) to the Level F (critical density, sporadic flow, frequent stops and physical contact), where Level E is equal to capacity. Similarly, Table 2-2 and Table 2-3 present the LOS in waiting areas and stairs, respectively. In other words, with the LOS any macroscopic representation will only need the number of pedestrians to determine what space (e.g. width of platform) is needed (Teknomo, 2002).

Figure 2-4: Relationship between space (square feet/pedestrian) and flow (person/min-foot width) (Fruin, 1971)

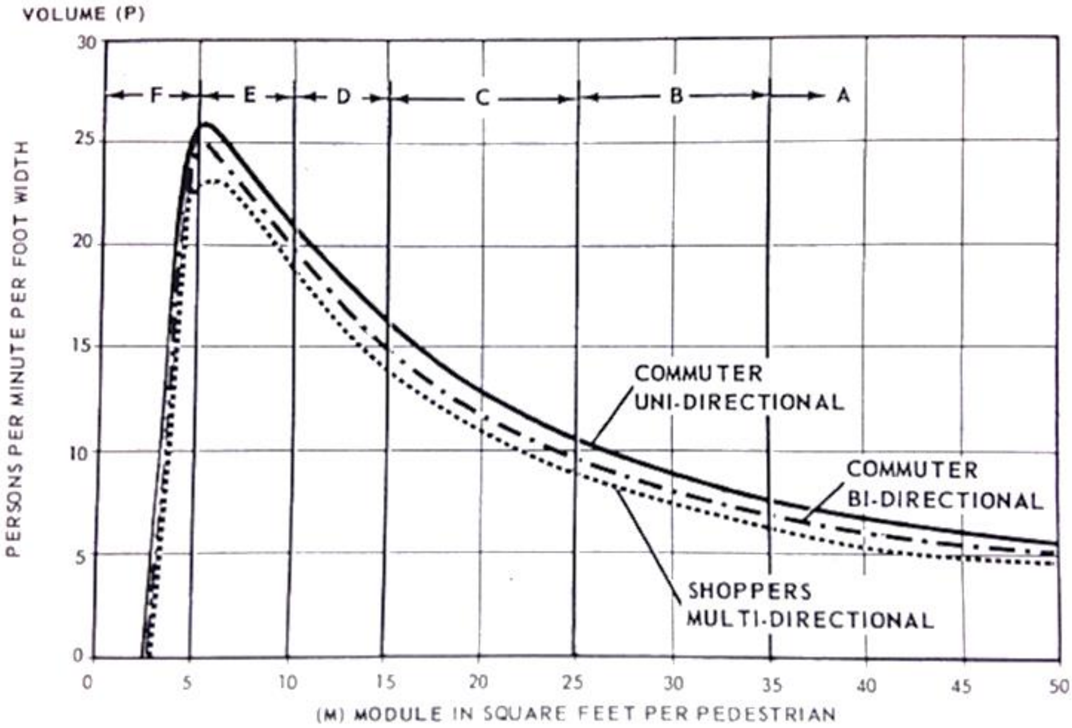


Table 2-1: Values of LOS in walkways (Fruin, 1971)

LOS	Density [pass/m^2]	Space [m^2/ pass]	Distance between pass [m]	Flow [pass/m -min]	Speed [m/s]	Occupation [%]
A	≤0.31	≥3.24	≥1.80	≤23	≥1.3	0-30
B	0.43-0.31	2.32-3.24	1.52-1.80	23-33	1.27-1.3	30-40
C	0.72-0.43	1.39-2.32	1.18-1.52	33-49	1.22-1.27	40-60
D	1.08-0.72	0.93-1.39	0.96-1.18	49-66	1.14-1.22	60-80
E	2.17-1.08	0.46-0.93	0.68-0.96	66-82	0.76-1.14	80-100
F	≥2.17	≤0.46	≤0.68	Vary	≤0.76	Vary

Figure 2-5: Representation of LOS density (pass/m²) in walkways (Fruin, 1971)

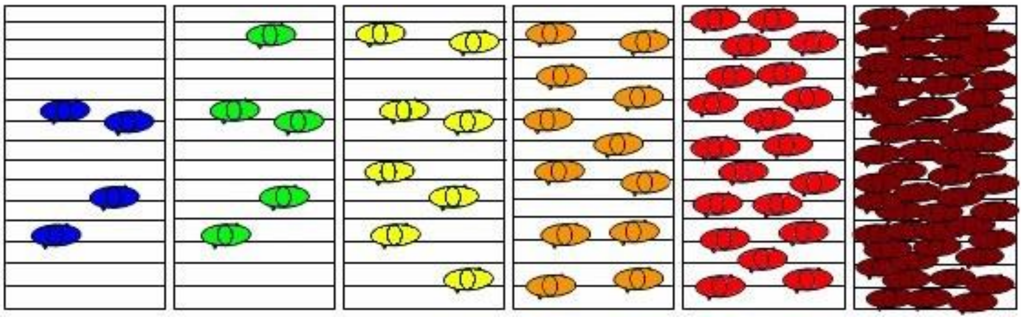


Table 2-2: Values of LOS in waiting areas (Fruin, 1971)

LOS	Density [pass/m²]	Space [m²/ pass]
A	≤0.82	≥1.21
B	0.82-1.07	1.21-0.93
C	1.07-1.53	0.93-0.65
D	1.53-3.57	0.65-0.28
E	3.57-5.26	0.28-0.19
F	≥5.26	≤0.19

Table 2-3: Values of LOS in stairs (Fruin, 1971)

LOS	Density [pass/m²]	Space [m²/ pass]
A	≤0.54	≥1.85
B	0.54-0.72	1.85-1.39
C	0.72-1.07	1.39-0.93
D	1.07-1.53	0.93-0.65
E	1.53-2.07	0.65-0.37
F	≥2.07	≤0.37

The LOS is an important tool to identify problems of congestion in walkways, waiting areas and stairs. However, the problem with LOS is that is based on a global view or macroscopic, in which the flow of pedestrians is understood as “fluid dynamics”, i.e. pedestrians are analysed only by physical variables already explained before (speed, density and flow). Moreover, some authors (Still, 2000; Kagarlis, 2002) state that pedestrians are not like fluids and they must be analysed by taking into consideration each individual’s characteristics and preferences, because individual pedestrians can do overtaking (they can pass each other), be stuck in a bottleneck or move in different directions.

With respect to density in metro stations, it seems that using general values of densities (number of passengers in a physical space such as a platform) is not the ideal way to measure the interaction between passengers. According to Evans and Wener (2007), the overall density used in the LOS does not predict which space presents more interaction between passengers. The authors studied density, stress and commuting in trains where passengers have to be seated next to others, and found that the level of stress increased as the density went up.

2.3.3 Crowding

In the case of railway and metro systems, a crowded situation at the PTI can occur when passengers are walking with a density of more than 2 passengers per square metre, or more than 5 pass/m^2 in a waiting area (e.g. queuing) (LUL, 2012). However, according to Cox et al. (2006) there is a difference between density (physical characteristics of the environment) and crowding (psychological phenomenon) because a high-density situation is not always perceived as crowded with a high level of stress. The authors proposed a model with a high level of density and perception of crowding and stress level, and also identified the relationship between crowding and risk safety. Similarly, Evans and Wener (2007) studied high density and stress while commuting in trains where passengers have to sit next to others. The authors found that when the density increased, passengers perceived a high stress level.

For Still (2013; 2014), crowding is also related to the perception of risk and safety. The author states that the use of typical manuals and standards is not an ideal method to measure the risk and safety of passengers as they are “cut and paste” solutions from other realities. Therefore, the space of passengers is related to situations in terms of physical measurements, i.e. as a function of density and capacity on the platform and train, but also as a psychological dimension which is more about the perception of crowding (RSSB, 2005).

To capture crowding in railway and metro systems Lam et al. (1999) proposed a binary logit model to represent discomfort of passengers. The authors used interviews as a physical measurement based on the LOS of Fruin (1971) and degree of crowding on the platform and inside the train. Similarly, to study the effect on the level of stress and feeling of exhaustion, Mahudin et al. (2012) proposed a model to measure crowds based on 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).

Other authors (Trozzi et al., 2013) have studied the effect of crowding at public transport stops, which can change the route, destination and mode choice of passengers. The authors propose a choice model that considers the effect of queues on the waiting time and choice of route at high density public transport stops. This is an interesting study that could also be applied to metro stations, in which the process of boarding is not a FIFO (first-in first-out) queue and the density on the platform affects the decision of boarding passengers when selecting their carriage. Recently, Kim et al. (2015) identified that people avoid delays caused by crowding and the stress caused by crowding such as lack of availability of seats, and avoid other passengers, or worry about sexual harassment. To measure delays, the authors used the dwell time (e.g. delay inside train and transferring), to measure stress they used the passenger load, and to collect the path choice of passengers they used ‘smart card’ data. However, according to Preston et al. (2017), in short commuter journeys crowding is based on stress and physical discomfort, while in long distance services the space to relax and use the journey productively are much more important for passengers. The author found that information provision of crowding levels and seating availability inside the train would encourage passengers to change their behaviour and select a less crowded train, although morning commuters are less likely to wait for the next train as they need to arrive at work on time.

2.3.4 Microscopic representation of pedestrians

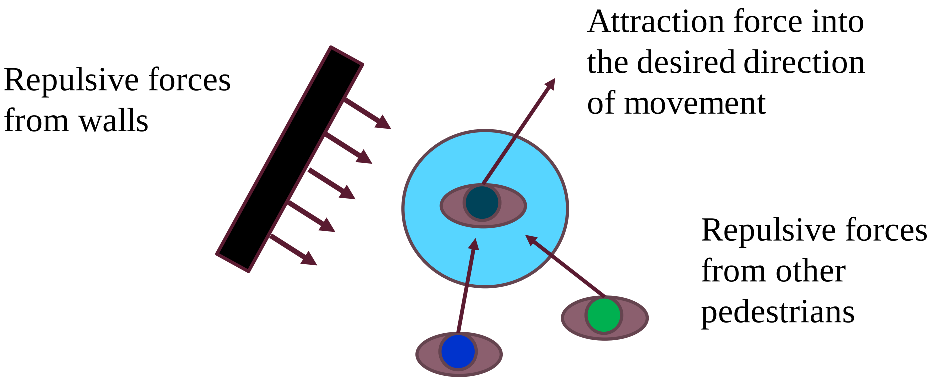
There is another type of representation called microscopic, in which the interaction of pedestrians can be analysed in any space in two ways: global (general behaviour of masses) and individual (behaviour of individuals, interactions with each other and with the environment). In addition, the microscopic representation allows researchers to distinguish attributes, characteristics and interaction of pedestrians (preferences, routes, overtaking, etc.) that determine the behaviour of the crowd (Helbing and Molnar, 1997). Moreover, Teknomo (2002) states that these methods lead to the development of a new paradigm, in which the quality of the movement of pedestrians is the main objective rather than only the use of a level of service like LOS.

In the literature there are different types of pedestrian representations in microscopic models. In particular, based on the research of Harney (2002) and Duives et al. (2013) two main approaches can be identified: continuous space and discrete.

In the case of continuous space each pedestrian is represented as a circle with fixed radius in which their movement is based on mathematical relationships such as differential equations or social forces (Helbing and Molnar, 1995; 1997; Helbing et al., 2000; 2005). Each pedestrian has properties including the present position, speed and acceleration. Furthermore, pedestrians' movement is described in terms of attraction and repulsive forces in relation to three components (see Figure 2-6): a) acceleration behaviour to move in a particular direction at a specific speed; b) effect of corridor walls on the pedestrian; c) interaction effect with other pedestrians.

However, according to Chraibi et al. (2010) each pedestrian represented as a circle with constant radius may not guarantee realistic behaviour in high densities. As a result the authors state that the space required by each pedestrian depended on his/her speed, forming an ellipse shape. Some later adaptations were made by Xi et al. (2011), which integrated the field of vision into the tactical level of human decision-making. Also, Dai et al. (2013) represented each pedestrian as an agent with autonomous movement managing different psychological forces (gradient force, repulsive force, resistance force, and random force).

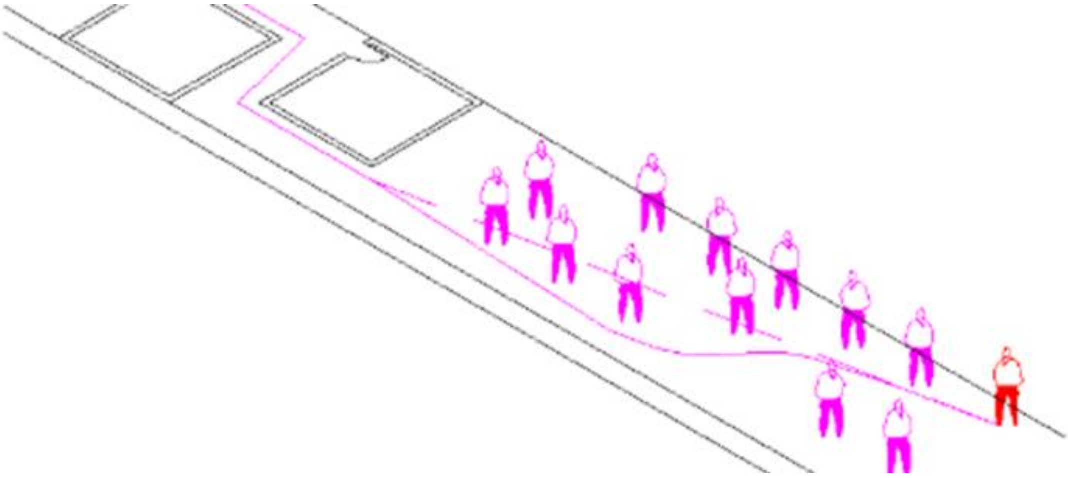
Figure 2-6: Representation of forces affecting each pedestrian in continuous space (Helbing et al., 2005)



Force-based representations are especially used in metro stations, since they can deliver great detail on the movement of masses in high densities. However, according to Casburn et al. (2007), these representations present three types of problems. First, passengers within the clusters at high densities exhibit unusually nervous behaviour. Secondly, experience shows that in this representation there is no single set of parameters for all cases. Therefore, the parameters must be carefully calibrated to fit each scenario (e.g. calibration of forces of attraction and repulsion). Finally, it is unclear how could be represented the movement of pedestrians with restricted capabilities such as a person in a wheelchair.

Another representation of continuous space is based on the least effort route (see Figure 2-7). In this case each pedestrian is represented as an "intelligent entity", i.e. autonomous individuals who possess their own pattern of behaviour and thus interact with each other and with the environment, and it is possible to differentiate their behaviour, preferences, personal characteristics, etc (Still, 2000; Legion Studio, 2006). In addition, each pedestrian is represented as a circle with constant radius, there are no forces, cells or grids and the moving of entities is shown in a continuous or vector way. Thus, the space environment is free from artificial constraints (as opposed to a chessboard pattern) and the simulation is more realistic.

Figure 2-7: Representation of the least effort route in continuous space (Still, 2000)



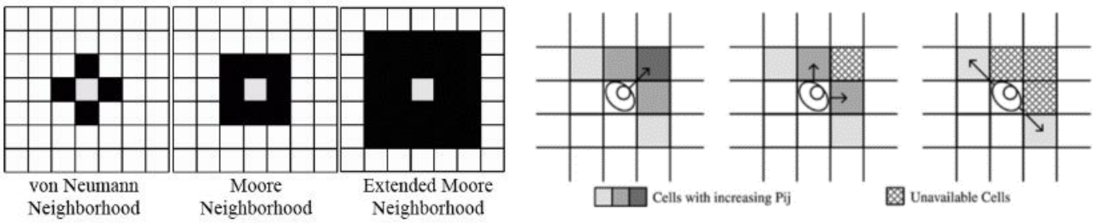
Representations based on the least effort route are used for all types of spaces (closed, semi-closed and open), especially medium-sized or large spaces such as a shopping centre or a stadium (sports and concerts), where each pedestrian makes direct trips, rambles, and faces multiple queues. However, according to Casburn et al. (2007), these representations have been used successfully when densities are low to moderate and if there is a heterogeneous crowd (different behaviour, preferences and characteristics). When the density is high, this type of model presents some problems, such as when there is a deadlock near the doors.

On the other hand, the most common discrete representation is the cellular automata or CA. This representation divide the space into cells, where the set of cells form a grid and therefore pedestrians' movement is discrete, i.e. each pedestrian uses a cell.

In relation to the platform train interface (PTI) some authors (Zhang et al., 2008; Davidich, et al., 2013; Clifford et al., 2014) state that CA can be effectively used rather than other types of representations. Firstly, represent crowds and friction effects. This representation captures the behaviour of passengers at a micro-level and it is easier to code based on negotiation and simple behavioural rules such as "first alighting and then boarding". Therefore, CA consume less computing time in comparison with other models. Secondly, unlike other representations, the boarding and alighting process is not a "First in First out" process, so CA are more realistic than other models, especially when the movements are direct and on a small scale. Therefore, CA is commonly used as they can measure and represent different things.

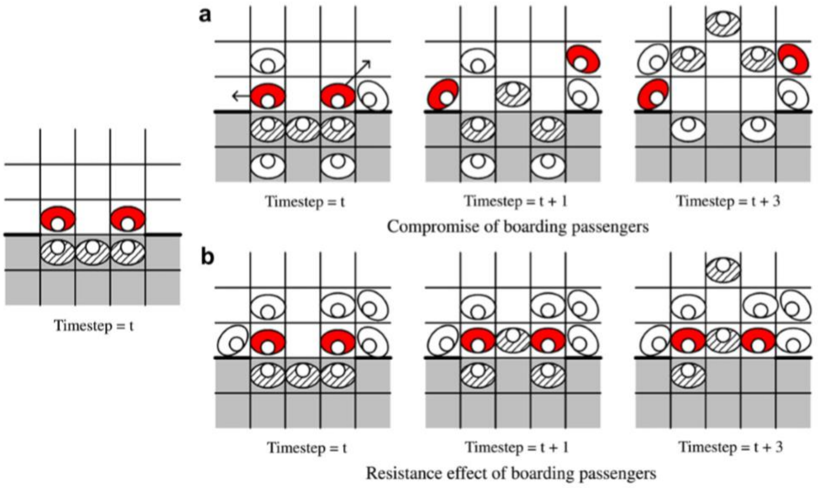
For example, in Zhang et al. (2008) each passenger is represented as a square cell 0.3 m size. The environment of representation includes two layers of information. There is a static layer pointing towards the nearest exit, expressed by a potential field associated to a probability for each cell (P_{ij}). Therefore, each passenger will move toward to the unoccupied cell where the potential field is smaller and the probability P_{ij} is higher (see Figure 2-8 right). The other layer is dynamic, which contains the general direction of the crowd movement which tries to avoid another passenger in the neighbourhood (see Figure 2-8 left). In both layers passengers use information from their cell to know where to make the next move.

Figure 2-8: Representation of passengers in metro station using CA models (Zhang et al., 2008)



In CA passengers can move according to rules of negotiation and competition (Zhang et al. (2008). There are two ways to describe the boarding and alighting passenger behaviour. Firstly, passengers can be compromised, which happens when there is a larger number of alighters so that boarding passengers step back and let alighting passengers go first. The second type of behaviour is called resistance and is produced when there is a lower number of alighters so that boarding passengers maintain their position and there is only a narrow passage for alighting passengers. (See Figure 2-9).

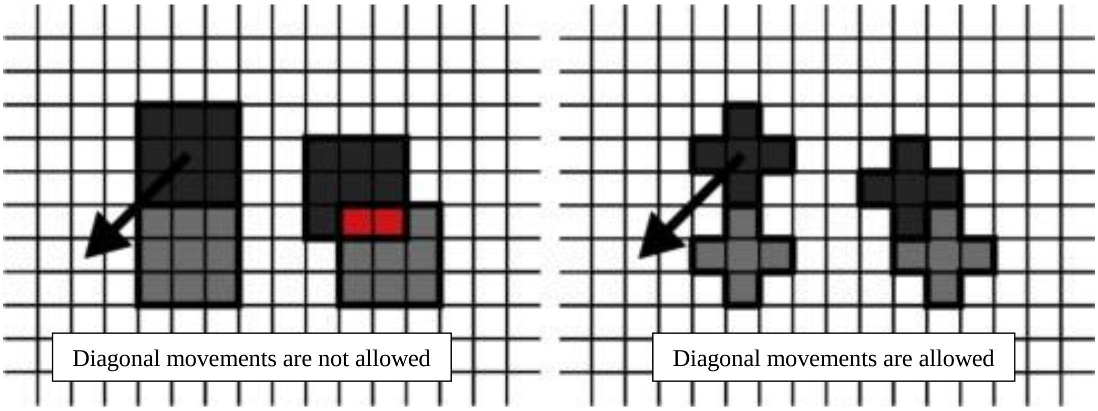
Figure 2-9: Possibilities of movement in the boarding and alighting (Zhang et al., 2008)



However, other authors (Harney, 2002; Pan, 2006) state that the movement of pedestrians in CA seems to be unrealistic in the graphical output and people appear to hopping on or across the cell as the movement proceeds. One of the problems is that how the grid is set (e.g. depending on the direction of the grid) different results can be obtained. Another problem is related to the representation, because the size of the pedestrian is the size of each cell, which causes a false picture of the densities experienced. In relation to movement, pedestrians are limited within their grid system, because they can only move in certain directions like on a chessboard. Therefore, the biggest challenge of CA is to better represent pedestrians' movement.

In this regard, some authors have been improving CA to give a better representation of the behaviour and interaction of pedestrians. For example, Ma et al. (2010) represented pedestrians interacting only with their closest neighbours rather with all the neighbours, forming lines of flow to avoid collision with pedestrians in opposite direction. Recently, Baldini et al. (2014) represented the negative interaction between pedestrians, in which a finer-grained cell was tested and each pedestrian could do diagonal movement by occupying more than one cell (see Figure 2-10).

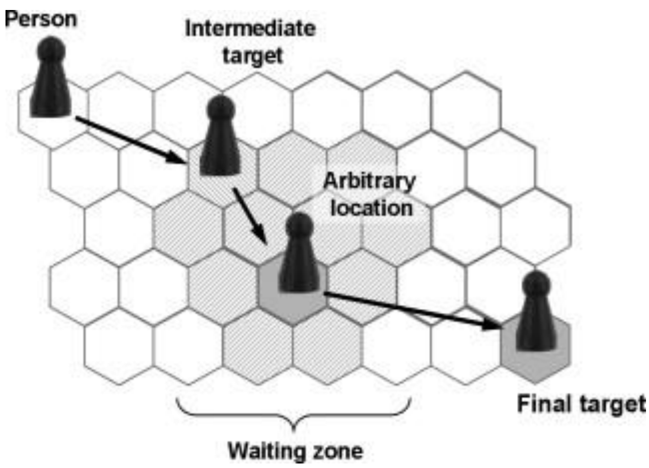
Figure 2-10: Different shapes for a face-to-face situation (Baldini et al., 2014)



In relation to metro stations, Ji et al. (2013) represented each passenger in a square 0.4 m size, which can be aggressive (2 cells per time step) or conservative (1 cell per time step). The passenger can move, stop, and turn, influenced by other passengers or obstacles from behind and front. To measure the interaction between pedestrians and obstacles, repulsive forces and friction forces are used. In this case, if the distance between passengers or between passengers and obstacles increases, then the repulsive force decreases, while if the speed of passengers accelerates then the repulsive force will also rise. The authors also included a familiarity parameter, which means that if passengers are friendly and considerate then the repulsive force will be small.

Similarly, Davidich, et al. (2013) represented the behaviour of passengers standing or waiting for the train (where do passengers wait, how do passengers wait, what is their motivation, and how do passengers interact with those who are waiting on the platform). In this representation, each passenger has individual properties (free flow velocity, final target, intermediate targets, etc.) and their way of moving is simulated according to forces of repulsion (between passengers and obstacles) and forces of attraction (between passengers and targets) that are expressed by the potential field (passengers move toward the unoccupied cell where the potential field is smaller). The representation considers waiting zones as polygonal areas, which can be considered as intermediate targets (see Figure 2-11).

Figure 2-11: Waiting zones modelled as an intermediate target (Davidich et al., 2013)



2.4 Existing studies on the effect of crowd management measures

In this section the literature review on studies on the effect of crowd management measures (CMM) is discussed. Firstly, the effect on the boarding and alighting time (BAT) and interaction time (IT) is revised. Secondly, the effect on circulation and waiting areas at the PTI is analysed.

2.4.1 Effect on the BAT and IT

The literature on boarding and alighting time (BAT) and interaction time (IT) is profuse and typically it could be divided into models, field observation and laboratory experiments. As defined in section 1.1 the BAT is considered as the dynamic component of the dwell time, and the IT is the time when passengers board and alight simultaneously (Harris, 2006).

In the case of models, the European experience started with Pretty and Russel (1988) who proposed a dwell time (t_d) linear model as a function of the time used to open and close the doors, plus the maximum period between the time it takes to board (b_j) and the time it takes to alight (a_i), taking into consideration the total number of boarding

(m) and alighting (n) passengers (see Equation 2.4). Based on this linearity, York (1993), proposed an expression to obtain t_d for vehicles of one and two doors.

$$t_d = C + max\{\sum_{i=1}^{m} a_i ; \sum_{j=1}^{n} b_j\} \qquad (2.4)$$

Similarly, the American literature such as the well-known Highway Capacity Manual (TRB, 2000; TRB, 2003) states that the t_d is influenced by the time needed to open and close the doors (t_{oc}), the number of passengers boarding (p_b) and alighting (p_a), and the average time each passenger takes to board (t_b) and alight (t_a) (see Equation 2.5). In the case of non-linear models, Lin and Wilson (1992) studied t_d in light trains of one and two-cars vehicles as a function of the number of boarding, alighting and on-board passengers. In addition, Aashtiani and Irvani (2002) found that t_d is affected by the number of doors, vehicle load factor and fare collection method. More recent studies (Tirachini, 2013) used multiple regression models to calibrate the t_d as a function of the fare system, steps at the doors, type of passengers and crowding situation.

$$t_d = t_{oc} + t_b \cdot p_b + t_a \cdot p_a \qquad (2.5)$$

However, neither Equation 2.5 nor the multiple regression model of Tirachini (2013) present how an explicit variable can be obtained to measure the interaction time (IT). This time does not take into consideration the periods when passengers are waiting to board the train while alighting is in process or when alighting is complete and passengers are only boarding.

On the other hand, in Latin-American countries such as Chile some authors (Fernandez et al, 2008) have developed a non-linear model to obtain t_d. The model states that t_d is a function of the number of passengers alighting (P_{Aj}) and boarding (P_{Bj}) through the door j, β^i_k are parameters, β^i_0 are dead times, β^i_1 are boarding times per passenger, β^i_2 are alighting times per passenger, and β'_2 is the parameter of the exponential function), δ_k are dummy ($\delta_1 = 1$ if the platform is congested, $\delta_2 = 1$ if more than four passengers board the vehicle, and $\delta_3 = 1$ if the aisle of the vehicle is full, otherwise $\delta_k = 0$, $\forall k$).

Equation 2.6 shows the expression of t_d, in which parameters t_{oc}, t_a, t_b from the Highway Capacity Manual model are indicated. The authors found that the average boarding time at the metro system was 40% higher than the average alighting time. However, similarly to linear models, no explicit parameter is included to obtain the IT.

$$t_d = \underbrace{\left(\beta_0 + \beta_o^{'}\delta_1\right)}_{t_{oc}} + \max_{j=door}\left\{\underbrace{\left(\beta_1 + \beta_1^{'}\delta_1 + \beta_1^{''}\delta_2\right)}_{t_b} P_{B\,j} + \underbrace{\left(\beta_2\ e^{-\beta_2^{'}P_{A\,j}} + \beta_2^{''}\delta_3\right)}_{t_a} P_{A\,j}\right\} \quad (2.6)$$

According to Harris (2006), t_d can be obtained based on the London Underground non-linear model reported by Weston (1989) and Harris (1994). Equation 2.7 shows that t_d depends on the time needed for opening and closing of doors (15 s), number of doors per car (D), door width factor (DWF), number of passengers boarding (B), number of passengers alighting (A), peak door factor (F), number of through passengers (T), and number of seats per carriage (S).

$$t_d = 15 + \left[1.4 \cdot \left(1 + \frac{F}{35}\right) \cdot \left(\frac{T-S}{D}\right)\right] \cdot \left[\left(F \cdot \frac{B}{D}\right)^{0.7} + \left(F \cdot \frac{A}{D}\right)^{0.7} + 0.027 \cdot \left(F \cdot \frac{B}{D}\right) \cdot \left(F \cdot \frac{A}{D}\right)\right] \cdot DWF \quad (2.7)$$

In contrast to linear models, the IT measured by Harris (2006) is influenced by the multiplication of B, A and a coefficient factor ($\beta = 0.027$) (see Equation 2.8). Harris (2006) found that the coefficient of 0.027 was not representative of high densities, and therefore suggested the value of $\beta = 0.011$ used by (Rosser, 2000). However, Harris (2006) did not identify if this coefficient could reach a maximum value or be dynamic, especially when the layout of the platform train interface (PTI) changes.

$$IT = \beta \cdot B \cdot A \quad (2.8)$$

In relation to circulation areas at the PTI, each passenger's movement is influenced by the presence of other passengers. According to Harris (2006), if there are few passengers, then high overlap is produced because passengers have enough space to board and alight simultaneously. When there is a crowded situation, then low overlap occurs because passengers will wait until alighting is complete or until there is a ‘gap’ or space available to board the train. The author reported that passengers consider the train doors as bottlenecks, in which each passenger follows the person in front of him/her.

With respect to field studies Wiggenraad (2001) states that the process of boarding and alighting takes up more than 60% of the dwell time. The author studied 5 door widths in the Dutch train system (0.8 m, 0.9 m, 1.1 m, 1.3 m, and 1.9 m), and found that wider doors decreased BAT by 10%. However, the relationship between capacity at doors and door width seems not to be linear. Harris et al. (2014) reported that the capacity is also influenced by the space available on the platform. This is also supported by Heinz (2003), who stated that an increase of the width from 0.8 m to 0.9 m did not increase the capacity of doors, due to passengers not using the whole width of the door.

In relation to the difference in height between the train and the platform, Heinz (2003) studied 18 entrance designs with three heights (level access, 2 steps, and 3 steps) in the Swedish train system, and found that the BAT increased when the number of steps increased. No problems were observed when the horizontal distance between the train and the platform was lower than 5 cm, however, problems for passengers were noted when this distance reached a value higher than 15 cm. In particular, passengers with luggage experienced problems with 2 or 3 steps.

Surveys were done by Currie et al. (2013) in which the BAT is influenced by the number of passengers on-board (congestion inside the vehicle). Recently, Christoforou et al. (2016) studied the BAT using data collected from an on-board automatic passenger counting system in urban light train systems. The authors state that the boarding and alighting passengers’ volumes and on-board passengers affect the BAT as well as the layout of the vehicle (e.g. low floor), time of the day and stop location.

In the case of platform edge doors (PEDs), a level access is needed between the platform and train. These elements work as sliding barriers to prevent passengers falling onto the tracks, reducing the number of suicides acts and accidents, due to the doors being closed until the train arrives and before it leaves (Clarke and Poyner, 1994; Kyriakidis et al., 2012). The use of PEDs is limited to the number of train doors, number of coaches and design of the platform (Coxon et al. 2010), and therefore these elements can affect the BAT. However, it is not clear how the authors reached this conclusion and if there is any evidence to support it.

Other authors (Qu and Chow, 2012) have studied the use of PEDs in evacuation emergencies, taking as a case study Hong Kong subway stations. They found that PEDs improved ventilation and smoke detection in metro tunnels, however, the evacuation time at platforms may increase when using these elements, due to the inconsistency of train stopping at the same position on the platform or by the fragility of their materials. In addition, PEDs can be very sensitive and cause delays when the closing of the doors is interrupted, especially in situations when passengers are trapped between the PEDs and the train doors (Allen, 1995). On LU these problems have been addressed with more robust materials and by limiting the use of PEDs to stations where the differences in door spacing between new and old trains are adequate (LUL, 2014).

The problem with field studies is that the design is limited to existing vehicles and stations, and therefore it is not possible to investigate a complete range of situations. To solve the limitations of field studies and dwell time models, various laboratory experiments have been performed to simulate the boarding and alighting process. These experiments have been very useful in that only one variable is examined while the rest of the variables remain without modification. An example of this type of infrastructure is the UCL's Pedestrian Accessibility Movement Environmental Laboratory (PAMELA) which has been one of the first facilities in Europe to study the movement of passengers in a controlled environment.

One of the first experiments at PAMELA (Fernandez et al., 2010) showed that the dwell time depends not only on the number of passengers boarding and alighting, but also on the platform height, door width, fare collection method, internal layout of the vehicle, and occupancy of the vehicle. The authors tested two different widths of doors (0.8 m and 1.6 m) and found that a 1.6 m door width reduced the alighting time by

40%, while the boarding time dropped by 45% when the fare collection was outside the vehicle. In addition, the authors stated that for the same door width (1.6 m) a small vertical gap (150 mm) reduced the alighting time by 9%.

This study was then followed by another experiment at the Human Dynamic Laboratory (HDL) in Universidad de los Andes (Chile). Fernandez et al. (2015) simulated unidirectional flows (first all passengers board and then all passengers alight), three vertical gaps (0 mm, 150 mm, and 300 mm) and 7 door widths (0.6 m, 0.8 m, 1.1 m, 1.3 m, 1.65 m, 1.85 m, and 2.0 m), and found that 1.65 m is the optimum width, enabling a maximum capacity of 2.06 pass/s-m at the doors. In addition, the authors suggested that an optimum height could be in the range of 0 to 150 mm, enabling a door capacity of 1.0 pass/s-m in the case of a door width of 1.65 m. From a similar experiment at PAMELA Fujiyama et al. (2012) reported that a 50 mm vertical gap achieved a maximum flow at the doors of 1.42 pass/s (for a 1.8 m door width and a setback of 800 mm). In this case the authors simulated bidirectional flows (boarding and alighting simultaneously), three vertical gaps (50 mm, 165 mm, and 250 mm), three door widths (1.3 m, 1.5 m, and 1.8 m), and three different setbacks (0 mm, 400 mm, and 800 mm). In this experiment the setback is defined as the distance between the doors and the seats.

At PAMELA the use of steps has shown an increase in the boarding and alighting time (BAT). According to Holloway et al. (2016) boarding passengers spent more time (4.13 s on average) than those who are alighting (3.68 s on average). The authors found that 40% of the total passengers found it difficult to complete the process of boarding and alighting. In this research the authors tested three steps: 20 mm (zero step), 350 mm (2 steps), and 510 mm (3 steps). Other laboratory experiments at Deft University (Daamen et al., 2008) simulated four steps (level access, 1 step, 2 steps and 3 steps) and three horizontal gaps (50 mm, 150 mm, and 300 mm), and found the capacity of the doors decreased from 0.91 pass/s to 0.81 pass/s when the step was changed from 50 mm (level access) to 400 mm (2 steps). In this experiment the horizontal gap was 50 mm and the door width 80 cm. However, the authors also reported an increase in capacity (from 0.85 pass/s to 0.88 pass/s) when the vertical gap was changed from 50 mm (level access) to 200 mm (1 step). In addition, the authors reported that the flow was higher when passengers were only alighting than when they are boarding. In the case of passengers with luggage, the door capacity decreased by 25%.

Recently, Thoreau et al. (2016) studied the BAT through laboratory experiments. The authors found that a horizontal gap of 200 mm could increase the flow and an optimum door width is obtained between 1.7 and 1.8 m, however the central pole, setback and PEDs produced no major effects. In the same line of research, Rexfelt et al (2014) used a mock-up of a public transport vehicle to prove that a vehicle with 4 doors will have a dwell time 17% lower than a vehicle with 3 doors. Moreover, Karekla and Tyler (2012) developed a model to predict dwell time in metro stations based on laboratory experiments. The authors reported that a small vertical gap can reduce the dwell time in 8%. Similarly, Rudloff et al. (2011) used experiments to calibrate a model that simulates the boarding and alighting process. The authors performed experiment scenarios with different door widths to study the BAT and density around the train doors.

To achieve accessibility the sum of the vertical and horizontal gaps should not exceed 300 mm, and an optimum value for design would be 200 mm (Atkins, 2004). According to the Rail Vehicle Accessibility Regulation (Stationery Office, 1998), when the vertical gap is higher than 50 mm and the horizontal gap exceeds 75 mm, a boarding device is needed for passengers with reduced mobility or functionality. Alternatively, to increase accessibility platform humps can be installed to raise one specific part of the platform. At PAMELA Tyler et al. (2015) mocked-up a platform hump to simulate different slopes (3%, 5.2%, 6.9%) and cross-fall gradients (1.5%, 2.0%, 2.5%). The authors found difficulties for passengers to board and alight from/onto the slope, while the cross-fall gradient had little impact. Their recommendation is that trains should not stop next to the ramp.

In relation to other factors that affect the BAT, Seriani and Fernandez (2015b) simulated the application of crowd management measures (CMM) at the HDL. The authors found that a vertical handrail in the middle of the doors divided the flow to each side of the handrail, reducing the BAT by between 13% and 34%. In addition, a ‘keep out zone’ on the platform (which passengers boarding needed to respect while passengers were alighting) could reduce the BAT by 50%. The best solution to manage passenger flow was the implementation of one-way doors, i.e. one door for alighting and another door for boarding, by means of which the BAT was reduced by between 31% and 82%.

In despite of the relevant research related to the design and layout of stations and vehicles, new laboratory experiments are needed to explore the effect of CMM on the BAT and IT.

2.4.2 Effect on circulation and waiting areas at the PTI

To study the behaviour and interaction at the PTI, Shen (2008) proposed two main areas: circulation and waiting zones. Both areas have their own characteristics and functionality for passengers. When PEDs are installed at the PTI, little demarcation (e.g. markings on the floor) is used on the platform to separate these two areas, and therefore no clear distinction could be identified to measure the interaction between passengers in front of the doors compared to the rest of the platform (Wu and Ma, 2013).

Passengers in the waiting areas behave differently from those who are in the circulation zone. For Wu and Ma (2013) there are two main types of behaviour of passengers who are waiting: queuing or clustering to the side or in front of the train doors. In their study, the authors did not find any difference between the case with PEDs and without PEDs, as passengers were always clustered in front of the doors rather than queuing at the side of the doors, due to the high density situation. In particular, the authors found that there is an empty space between train doors on the platform which is not occupied by passengers. This space is considered as a rectangular area. In addition, the authors found that passengers waiting to board had a greater space between them compared with the moment after the train arrived. This was because passengers in waiting areas were lined up, forming a rectangular shape in front of train doors.

Some authors such as Krstanoski (2014) considered the whole platform as a waiting area to study the distribution of passengers waiting to board the train. The author states that the distribution of passengers on the platform depends on various factors: the position of the platform exit at their destination station, the search for the least crowded carriage, how crowded the platform is (e.g. if there is no space to move along the platform passenger will wait near the entrance of the platform), whether there are markings of the position of doors on the platform (e.g. PEDs), and some passengers are located because of random variables (e.g. meeting with a friend). To represent this distribution, Krstanoski (2014) proposed a Multinomial distribution, in which each passenger boarding has the same probability to board door 1, door 2, …, door d for each run (each time the train arrives to the platform).

Other authors have considered that the platform should be divided into different waiting areas in front of each door for an in-depth analysis of the interaction and behaviour of passengers. For example, Shen (2001; 2008), states that passengers are not distributed uniformly and waiting areas can be considered as rectangular spaces or as a parabola, while Lu and Dong (2010) suggest that this space can be considered as fan or spectrum. Similarly, Seriani and Fernandez (2015b) proposed that a rectangular area should be used in front of the train doors as a “keep out zone” to prevent passengers boarding from being an obstacle for those who are alighting. In this case, the authors state that the interaction between passengers was reduced when boarding passengers were located outside this rectangular area, using the space between the train doors. However, all these authors used fixed values to define those shapes, and therefore it could be difficult to know which part of the waiting area reached a high interaction, especially considering that the number of passengers boarding and alighting changed before and after the train arrived.

2.5 Need of a new framework

In this section the need of a new framework is discussed to identify the type of measures, what variable to study and the methods to represent and evaluate the behaviour and interactions of passengers at the PTI.

Recently, different frameworks have been developed to evaluate the safety and efficiency of pedestrians in public transport environments.

For example, Miranda-Moreno et al. (2011) reported a new framework to study the safety of pedestrians at street level. The safety of pedestrians is affected by a combination of the built environment (land use, demographics, transit supply and road network), the risk exposure (pedestrian activity, traffic volume, and motor-vehicle operating speed), and the geometric design (road width, numbers of lines, presence of marked pedestrian crossings, etc.) at a microscopic level. The authors used regression techniques to identify the relationship between those variables.

Similarly, in the case of sport events or street level, Still (2013; 2014) proposed a framework to evaluate normal and evacuation scenarios named the DIM-ICE model, in which problems of crowds are influenced by the Design, Information and Management, and can be produced at the Ingress, Circulation and Egress of the event. This model can be complemented with a strategy named RAMP, in which Still (2013; 2014) identifies the Routes, Areas, Movements and Profiles of the crowd. The DIM-ICE model is based on the safety of the crowd, in which a density higher than 2 passengers per square metre will be considered as a "high risk" for accidents in walking areas. In the case of static density (e.g. waiting areas) a density over 4 pass/m^2 is considered "high risk" for accidents.

With respect to metro and railway stations, Sameni et al. (2016) state that limited research has been done on evaluating and ranking the efficiency and performance of railway stations from a passenger's perspective. In fact, most studies are focused on minimising delays at stations from a train's perspective. For example, train operations can be improved at stations focused on train routing through stations (Zwaneveld et al., 1996; 2001), robust timetabling and train scheduling (Jia et al., 2009) and combinations of routing and scheduling (Carey and Carville, 2003). In addition, Stenström et al. (2012) state that efficient and effective indicators have been developed to measure the performance of railway infrastructure based on RAMS (reliability, availability, maintainability and safety), capacity, and punctuality focused on the train's perspective.

This is slightly changing with new frameworks applied to evacuation scenarios in metro stations. In the case of China the standard for design of metro (CDM, 2003) is to evacuate the platform in less than 6 minutes, which is 33% higher than the USA standard (less than 4 minutes, according to NFPA130, 2003). Considering these standards, the framework of Shi et al. (2012) was created as a function of the type of station (e.g. two side platform or island station), layout (e.g. number of stairs), safety elements (e.g. platform edge doors), alarming system (e.g. smoke detection ventilation), type of fire (train on fire stopped at station, fire in public spaces such as concourse and fire in railway tunnel) and type of passengers (in train, waiting in platform or concourse, staff in platform or concourse). As a result of the framework the evacuation time was calculated and a strategy was adopted (e.g. opening of platform edge doors, all escalators up-going from platform to concourse or all automatic gate passage should be opened). Similarly, D'Acierno et al. (2013) proposed an operational framework to reduce the discomfort of passengers in the case of failure at metro stations. The authors used an optimisation model to identify the relationship between the network performance (rail infrastructures, rolling stock, signalling system, planned timetable), the demand level and the failure context. The output of the model is the reduction of the train speed and the generalised cost for passengers. The authors found that if the headway increases then the number of passengers boarding will increase too, affecting the congestion at the station.

Although Shi et al. (2012) and D'Acierno et al. (2013) studied metro stations from the point of view of the quality of the service (and therefore including the passenger discomfort) rather than the service punctuality, the strategies that were used measured the consequences of evacuation scenarios or when a breakdown occurred, but not for normal situations with high densities. Recent studies (Sameni et al., 2016) presented a new methodology based on data envelopment analysis (DEA) to evaluate the efficiency of railway stations from the passengers' perspective (operation, platforms and tracks). The methodology included a macro capacity utilisation model to analyse the efficiency of stations, and a service effectiveness model to identify if stations attract potential demand. The train stops, catchment area population and jobs are defined as inputs, while total passenger entries and exits to/from the stations and passenger interchanges at the station. In addition, Li et al. (2017) identified that existing frameworks allow to identify and quantify hazards at metro stations, however they could not address the relationship between these hazards. To solve this the authors developed a metro operational hazard network (MOHN) based on accidents database, government reports, expert interviews and modelling.

In summary:

i. Two pedestrians will perceive that their space has been invaded when the distance between the centre of their heads is less than 1 m. The perception of invasion is also related to the concept of crowding as a combination of density or capacity and the psychological aspect of pedestrians (e.g. stress). However, little research has been done to study crowding at the PTI zone.
ii. Macrosimulation representations are based on Fundamental Diagrams and indicators such as LOS, in which pedestrians are represented as fluid dynamics. However, fluid dynamics behaviour assumes unreal pedestrians so the interaction between pedestrians and their environment cannot be measured. In microscopic representations each pedestrian is a circle with constant radius (continuous space) or as a fixed square (discrete), which may not be realistic of some behaviour and interaction such as collision avoidance, formation of lines, space used, or distribution of passengers at the PTI.

iii. Relevant research has been carried out, showing that the BAT is influenced mainly by the door width and the vertical and horizontal gaps. In addition, the use of PEDs may increase the BAT in emergency situations and when there is inconsistency of train stopping at the same position of train doors. When PEDs are used existing waiting areas are fixed values which do not necessarily represent which part of the PTI is more congested.

iv. Despite the benefits of existing frameworks, most of them have been applied to the street level, sport events or evacuation scenarios, rather than the PTI. In addition, most of the existing frameworks are focused on crowds (e.g. evacuation of whole platform), but not on individuals (e.g. spaces with more interaction at the congested door). Moreover, crowd management measures (CMM) have been applied in an isolated way isolated, and therefore do not give enough information for decision making. Therefore, a new framework is needed to identify the type of measures, what variables and their effect at the PTI.

Chapter 3 Methodology

3.1 Introduction

In this chapter the methodology is defined. Firstly, the approach is selected (section 3.2). Secondly, the set-up of the laboratory experiments for this research is explained (section 3.3). Thirdly, two London Underground metro stations are described as case of study (section 3.4). Fourthly, a new method is defined to represent and evaluate the behaviour and interaction at the PTI (section 3.5).

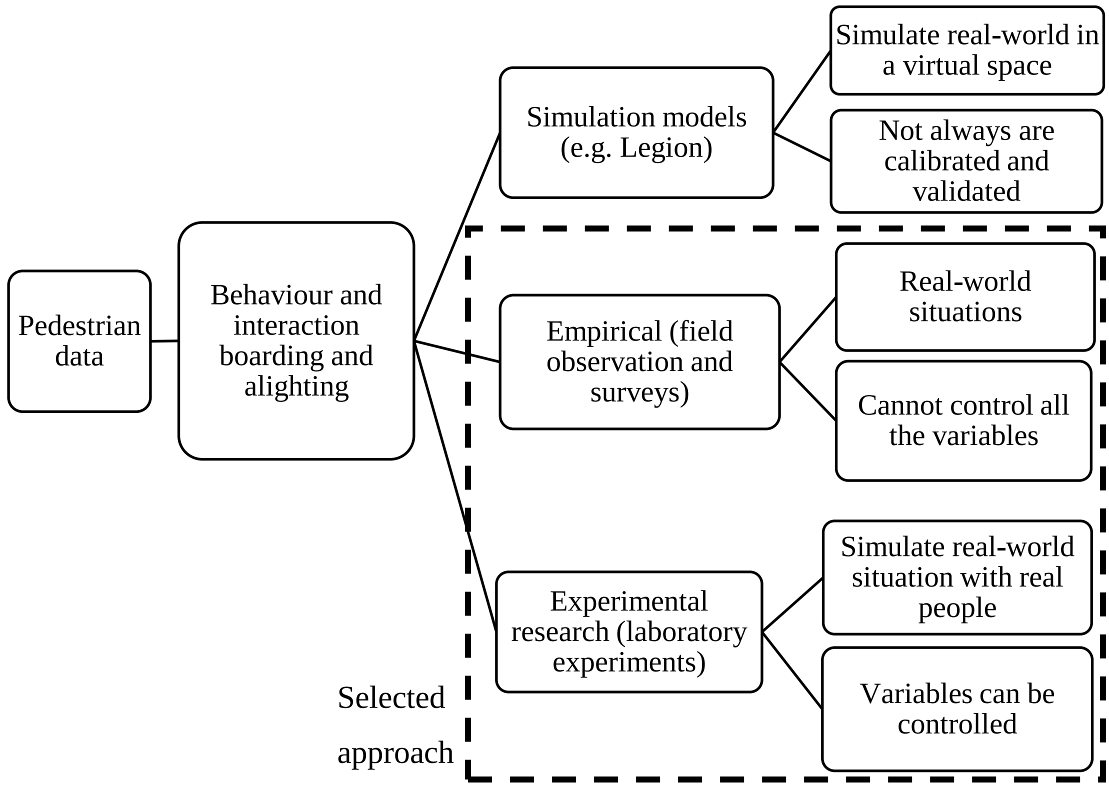
3.2 Approach used in this research

As shown in Figure 3-1, to obtain passenger data and study the behaviour and interaction of passengers boarding and alighting at a microscopic level, three types of approaches can be used (Daamen et al., 2008):

i. In the case of pedestrian models, real-world situations can be simulated, but not all of them have been calibrated and validated for all situations relating to boarding and alighting.
ii. Empirical measurements are based on real-world observation (e.g. the number of passengers boarding and alighting, dwell time, and physical layout) and surveys (e.g. perceptions of passengers). However, the main problem is that it is not possible to control all the variables (weather, design, demand, information for passengers, etc.).
iii. In laboratory experiments all variables can be simulated as in the real-world. The experiments are controlled in a special environment.

The laboratory experiments and field observations are the selected approach for this thesis (see Figure 3-1). According to Childs et al. (2005), laboratory facilities such as University College London's Pedestrian Accessibility Movement Environmental Laboratory (PAMELA) are an ideal opportunity for researchers to test 'what if' scenarios. At PAMELA all the external factors that could affect the performance of passengers are controlled, such as social interactions, activity and safety constraints. A mock-up of a carriage can be created to represent the PTI zone in a scale 1:1.

Figure 3-1: Selected approach for this thesis (adapted from Daamen et al., 2008)



As described in section 3.4, two London Underground (LU) stations were studied to identify if the use of PEDs as door positions indicators affect the behaviour and interaction of passengers at the PTI. However, at the existing stations variables such as the level of demand varied in each observation. Therefore, laboratory experiments were needed to control all the variables and replicated the layout and environment conditions in existing stations.

In the laboratory experiments (see section 3.3) only one variable was changed while the rest remain the same, and volunteers were recruited to simulate the boarding and alighting process. This does not mean that the behaviour of participants in the experiment was identical to the behaviour of passengers in existing stations. Therefore, this experiment helps researchers to identify the 'best scenario', which would be tested later in existing stations.

3.3 Set-up of laboratory experiments

A series of experiments were conducted at PAMELA in December 2014, following other experiments from 2012 where design factors affecting the dwell time were explored. These experiments were part of a first study to compare the cases of PEDs with level access and NoPEDs with a 170 mm vertical gap.

A mock-up carriage designed and built for the 2012 experiments was re-assembled and configured with a set of parameters representative of a next generation LU train: 2 double 1.60 m wide doors, 12 fixed seats (4 in the centre and 4 at each end), 8 tip-up seats (2 on each side of the fixed central seating), a setback of 200 mm between the door and the end seats, and a setback of 300 mm between the door and the centre seats. The horizontal gap between the train and the platform was 90 mm and the vertical gap was 170 mm in the absence of PEDs and zero when there were PEDs (because level access is usually a precondition for PEDs). These parameters were chosen to represent typical LU operating conditions (see Figure 3-2).

The cameras at PAMELA were located in the ceiling (4 m height), which enabled the recording of a space on the platform of only 3 m wide by 5 m long in front of each train door (which produced an observed area on the platform $A_p = 15\ m^2$).

Similar to the LU observations, the PTI was defined in consultation with Transport for London (TfL). In the absence of PEDs, the PTI is the space between the yellow line on the platform edge and the train doors, whilst when PEDs are present it is the space between them and the train doors (see Figure 3-3).

Figure 3-2: Drawing, dimensions (mm), and areas calculations (m^2) for mock-up at PAMELA

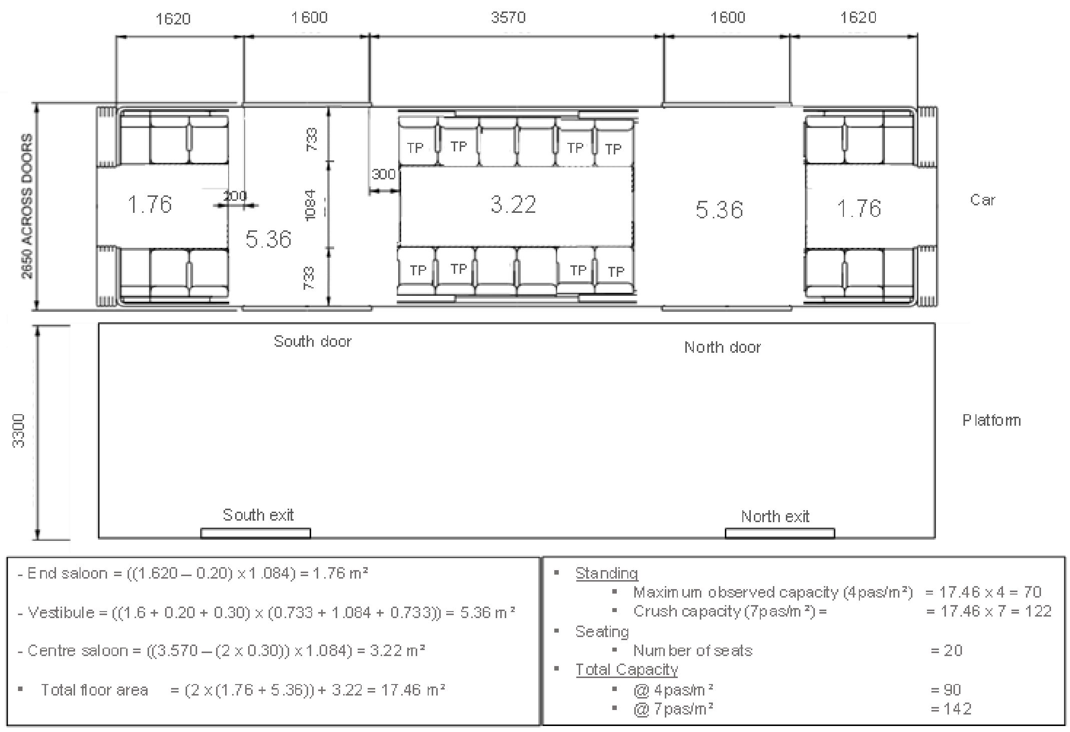
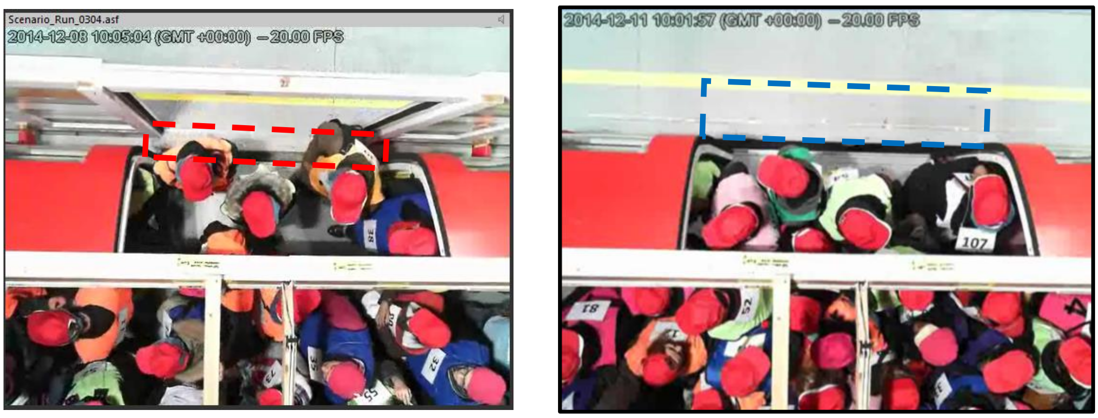


Figure 3-3: Platform train interface (PTI) with (left) and without (right) PEDs at PAMELA

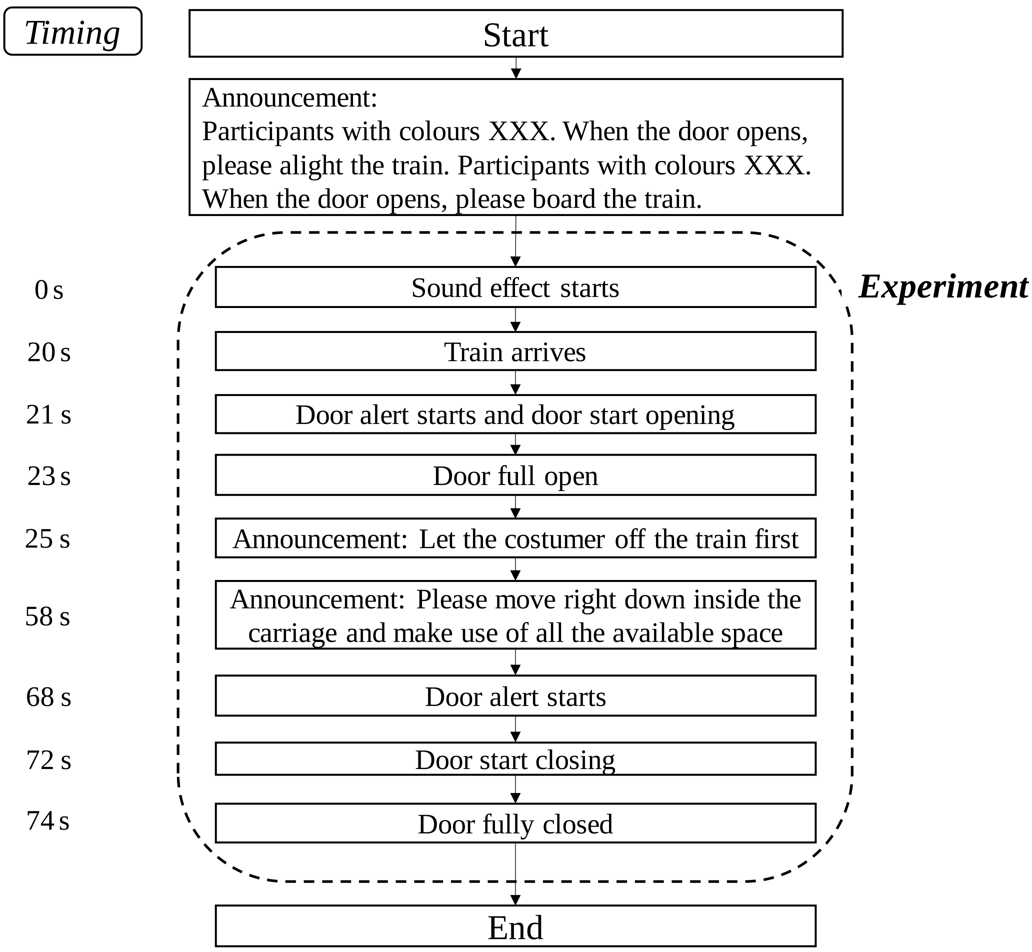


PTI with PEDs PTI without PEDs

The 110 participants recruited at PAMELA represented the boarding (red hats) and alighting (white hats) at the PTI. Each participant had a number and they formed 11 groups with different colour bibs. Participants were asked to complete a form to register for the experiments, which included the following details: name, email, gender, age, height, weight and if he/she is a regular commuter or has any mobility impairments.

Participants at the experiment 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, random groups were chosen to board, alight or remain inside the carriage. In addition, a complete sound system was provided in order to make the experiment feel real for the participants. The sound included the train arriving, braking, door opening alarm, door closing alarm, and departure. The complete procedure of each run at PAMELA is described in Figure 3-4.

Figure 3-4: Typical procedure of each run at PAMELA experiments



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

Statistical significance tests were done at PAMELA experiments. One-way between-groups analysis of variance (ANOVA) was performed when possible (i.e. when the samples satisfied the normality and homoscedasticity hypotheses, checked through the Kolmogorov-Smirnoff and Levene tests, respectively) or alternative tests (Kruskal–Wallis one-way) when an ANOVA was not applicable. In addition, a t-Test assuming unequal variances was performed when comparing two-sample (e.g. PEDs and NoPEDs for each scenario of R) or alternative tests (Mann-Whitney U test) when a t-Test was not applicable.

3.4 London Underground observations

Observations were made on video footage recorded under actual operating conditions at two LU platforms. The Jubilee line southbound platforms at Green Park (GPK) and Westminster (WMS) stations were chosen as case of study because of their similarities in terms of demand and platform layout, other than the main PTI difference that was being tested, i.e. the presence of PEDs at WMS versus a PTI without PEDs at GPK.

Since one of the specific objectives of this thesis is to analyse the impact of door positions indicators such as PEDs, it was necessary to get footage from doors at GPK and WMS, in which cameras were installed 4 m height at the platform ceiling. On LU all platforms with PEDs (such as WMS), have level access along their whole length; but this is not the case in GPK. However, GPK has some doors which stop at a platform hump where there is no vertical gap between the train and the platform (see Figure 3-5 and Figure 3-6). Therefore, three doors at GPK were used for this study. Two of them with a vertical gap of 170 mm (one near the exit/entrance of the platform and the other in the middle of the platform) and one with a platform hump (level access). In the case of WMS two doors were studied. The first door was near the exit/entrance of the platform, while the second door was in the middle of the platform.

The platform hump in Figure 3-5 and Figure 3-6 extends over the whole platform width and has a total length of 27 m, therefore covering the second and third cars and a total of four doors (two doubles and two singles). It provides accessibility and ease the boarding and alighting of passengers with mobility impairments or encumbrances such as heavy luggage or buggies. The design includes gentle access slopes on either side and specific signage.

Figure 3-5: Representation of half the length of the platform hump at Green Park station

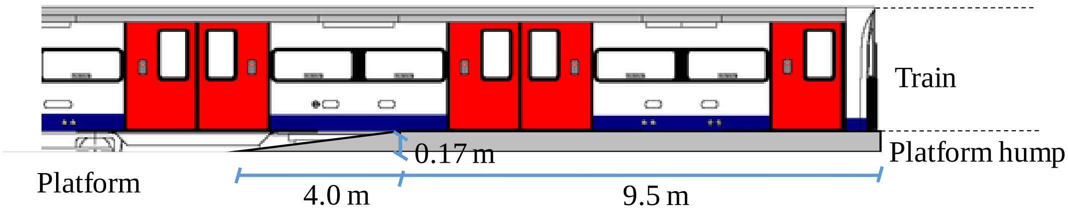


Figure 3-6: Platform hump at Green Park station

The footage analysed for one of the hump doors at GPK was recorded between 23 November 2015 and 7 December 2015 and comprises only the weekday morning and evening peak hours (08:15-09:15 and 17:15-18:15), when trains on that line reach an average frequency of 30 trains/h (approximately 2 minutes headways).

These videos were compared to the footage from two doors at WMS and two doors at GPK. Those videos are from November 2014, i.e. during the same time of the year but one year earlier, but it is considered that the differences that could arise because of the year difference are negligible compared to the differences due to the different PTI arrangements (presence of PEDs) and to the demand, which was measured for all boarding and alighting processes in the same way.

In summary, this thesis compared two studies:

i. Two double doors at WMS where there is level access on the whole platform, with two double doors at GPK with a vertical gap of 170 mm.
ii. Two double doors at WMS where there is level access on the whole platform, with one double door at GPK located at the platform hump.
iii. At both stations the double doors are 1.60 m wide and the horizontal gap at the PTI is 90 mm.

Similar to the laboratory experiments, the data was analysed using the software Observer XT11 and the videos were converted into .avi format with the software Nucleus. To process the images with Observer XT11 two types of codes were used (The Observer, 2014): to stablish the time (e.g. “boarding 0-5 s” which mean segment 0 to 5 seconds), and to register an event (e.g. “B0-5s 1” which mean that one passenger boarded in the segment between 0 and 5 s). In total 6 types of events were processed: train arrival, first passenger enters PTI, door opening, boarding or alighting, last passenger exits PTI, door closing. The period of analysis was between the times of the doors being opened and closed.

The PTI was defined slightly differently with and without PEDs. This was done in consultation with Transport for London (TfL) to reflect the difference in deciding when a participant has committed to entering or leaving the train. In the absence of PEDs, the PTI is the space between the yellow line on the platform edge and the train doors, whilst when PEDs are present it is the space between them and the train doors (see Figure 3-7).

Figure 3-7: Platform train interface (PTI) with (left) and without (right) PEDs at LU stations.

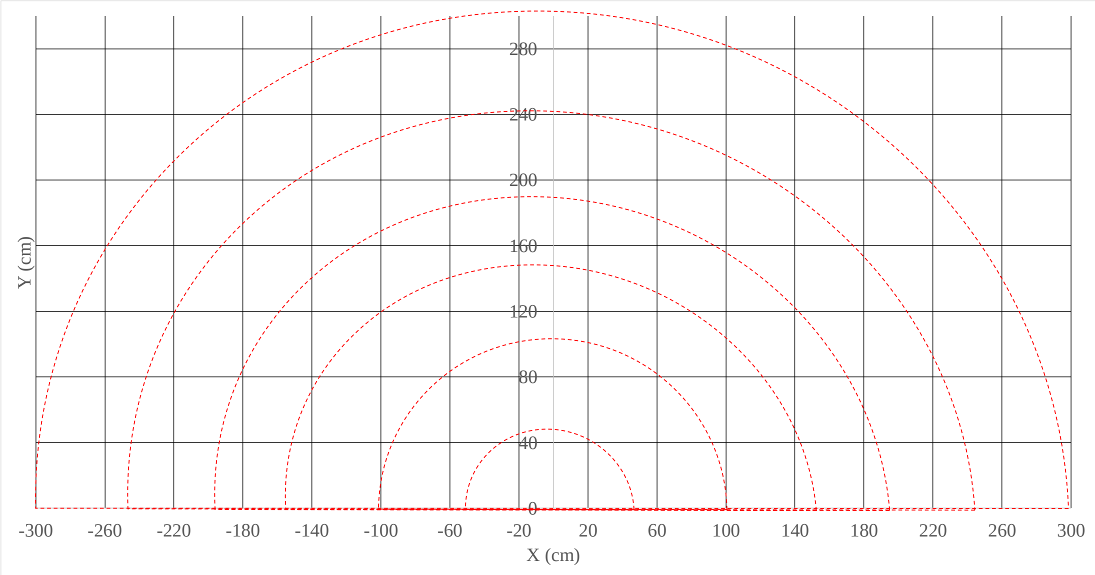
In this case only descriptive statistics are provided, without formal statistical significance tests. This is because the data did not satisfy the assumptions of parametric tests (e.g. ANOVA) or even non-parametric tests (e.g. Mann-Whitney). In particular, the distribution of the BAT did not follow a normal distribution; not even after data transformations (e.g. logarithmic). This led to trying non-parametric tests, for which a main requirement is that the distributions on each group are similar. This was checked comparing the skewness and kurtosis of each group, and in most cases the differences were too big to confidently assume that the tests could be applied correctly, therefore the analysis was limited to a descriptive one.

3.5 New method to represent and evaluate behaviour and interaction at PTI

A new method was proposed to represent and evaluate the behaviour and interaction of passengers based on LU observations and PAMELA experiments. This method included 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 3-8 and Figure 3-9). To measure the behaviour and 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 3-8: PCA divided into layers at PAMELA (with PEDs)

Figure 3-9: Representation of the PCA divided in 40 cm square cells and six layers of 50 cm each to measure the position of passengers boarding and alighting (circles)



The PCA was also divided into 40 cm square cells, which is typically used to represent pedestrians in cellular automata models as described in section 2.3.4 (Zhang et al., 2008; Davidich, et al., 2013; Clifford et al., 2014). The use of cells helped to identify which space is most used on the PCA, and other behaviour of passengers (e.g. if passengers are located in front or beside the doors).

To obtain the position (x, y) of each passenger in the PCA at PAMELA, 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). However, in the LU observations it was not possible to track automatically (or semi-automatically) the trajectories and count the number of passengers boarding and alighting at the stations. Even though recently studies (Simonnet et al., 2012; Yin et al., 2014) have identified important progress in the detection of pedestrians in images and videos, it is still a very difficult task specially in complex and crowded environments such as the PTI in existing stations due to small pedestrian sizes and frequent occlusions.

The software Petrack was possible to use at PAMELA experiments as passengers had markings on their heads (hat colours), and therefore manually recognition was an easier task. As a first stage of the tracking process, a new project was created, in which cameras were calibrated for the given conditions of the experiments. As an output the software gives the coordinates (x, y) of each passenger in a .txt file.

In this study it is proposed that the behaviour and interaction between passengers boarding and alighting at the PCA is affected by eight variables: the level of demand, boarding and alighting time (BAT), types of queue, formation of lines, distance between passengers, density by layer, passenger space, and instantaneous speed. For example, interaction problems will be obtained when the distance between passengers is reduced or when the density by layers is increased. With respect to the level of demand (i.e. values of R), when R = 4, there are four times more passengers boarding than alighting, and therefore a high interaction is expected for those passengers waiting to board the train compared to the case R = 0.25 in which there are 4 times more passengers alighting than boarding. These variables are defined in the following sections.

In the case of LU observations, only four variables were studied related to the behaviour and interaction of passengers boarding and alighting: level of demand, BAT, types of queue, and formation of lines. It was not possible to measure the other four variables (distance between passengers, density by layer, passenger space, and instantaneous speed) due to the lack of a tracking tool to obtain the exact position of each passenger at the PCA. In addition, the demand was not controlled in the LU observations, and therefore as it is explained in section 3.4 only descriptive statistics were provided, without formal statistical significance tests.

3.5.1 Level of demand and BAT

In the case of LU observations, to measure the boarding and alighting time (BAT), the number of passengers boarding (P_b) and alighting (P_a) was manually counted in segments of 5 seconds from the time the doors opened until they closed or after 120 s, whichever the greater. Ideally, a resolution of more than 5 s should have been used, since every second matters in the boarding and alighting time. However, a compromise had to be reached with the time, effort and resources put into the manual review of the footage and the data collection process.

The BAT, P_b and P_a were corrected to eliminate the effect of “late runners”, i.e. passengers boarding the train after the main group has already boarded. This helps to remove the impact of longer dwells which are caused by the train being held at the platform rather than with passenger movements, which are the focus of this analysis. The criterion used for this correction considers “late runners” those passengers who board or alight after two or more segments (10 s) in which there are no other movements. After this correction the average interaction time (IT) was calculated (in

5 s segments), which is defined as the total time (sum of 5 s segments) when passengers board and alight simultaneously.

Aside from the presence of PEDs, demand is considered to have a significant impact on the BAT. Since it was not possible to control the level of demand under actual operation, demand was measured and the observations aggregated with respect to two factors:

i. Total number of boarders and alighters;
ii. Train demand on arrival.

Because of the location of the cameras (4 m height at the platform ceiling), it was not possible to count the number of passengers on-board and observe their behaviour. Therefore, this study is focused on the platform and PTI areas, however, this does not mean that other spaces do not need a detailed analysis. The train demand on arrival was obtained from an alternative source, namely NetMIS, TfL's network management information system, which provides a level of demand (low-medium-high) for each arriving train.

Ideally, the analysis of the impact of demand on the BAT should have been done using rates of time per passenger, i.e. normalising the BAT by the demand. However, this was not possible because of the limitation imposed by the use of 5 s bins to count boarders and alighters. Dividing a multiple of 5 s by an integer number resulted in discontinuous and unstable values which did not follow a smooth distribution and varied largely in face value with minor variations in the number of passengers. This was deemed not to be representative and the method was considered unsuitable and of little use for the analysis. However, because it is well known that a relationship exists between demand and BAT, it was decided to study it by comparing the BAT in aggregated categories of demand. To this end, three demand categories were defined (0-15, 15-25, and 25+ passengers), and for each group the BAT with and without PEDs was calculated and compared.

In the case of PAMELA experiments, different loading conditions were tested, because demand is considered the main driver of passenger behaviour. These loading conditions as given in Table 3-1 were informed by a preliminary video analysis from LU's Green Park (GPK) and Westminster (WMS) stations and by the 2012 experiments. They cover a typical range of demand levels of passengers on the train, on the platform, and boarding and alighting with different values of ratio (R) between passengers boarding and alighting.

Table 3-1: Load condition descriptions at PAMELA

Load Condition code	Board per door	Alight per door	On-board per door	Similar to station loading	R = boarding/ alighting	Number of runs per scenario
LC_0	55	0	0	No	-	2
LC_1	0	55	0	No	-	2
LC_2	40	10	5	No	4	20
LC_3	10	40	5	No	0.25	20
LC_4	20	20	15	WMS-AM	1	20
LC_5	20	5	30	GPK-PM	4	20
LC_6	5	20	30	No	0.25	20
LC_7	10	10	35	GPK-AM	1	20
LC_8	55 +crush	0	0	No	-	10

The experiments were repeated with and without PEDs for each loading condition in Table 3-1 to test whether the introduction of PEDs (with level access) had an impact on passenger behaviour and BAT compared to the PTI with vertical gap and no PEDs. The first two conditions (LC_0 and LC_1) in Table 3-1 were used to make participants feel familiarized with the experiments, while the last condition (LC_8) was performed to calculate the capacity of the carriage.

For the purpose of this analysis, the BAT at PAMELA experiments was defined as the time that elapsed between the first passenger crossing the PTI after the doors open and the last passenger crossing the PTI before doors closing. The BAT was later batched into intervals of 5 seconds so that they were comparable with the analysis of the LU observations.

3.5.2 Types of queue and formation of lines

In the case of LU observations (GPK and WMS), the behaviour of passengers was studied in two areas at the PTI: circulation and waiting areas. In the case of circulation areas two different types of lines of flow were observed. The first type was recorded near the wall of the platform when passengers walk along the platform and avoid collision with other passengers (e.g. coming in opposite direction or standing on the platform to board the train). The second type was identified in passengers alighting, in which a line of flow was defined as two or more passengers walking one behind another. With the 1.60 m wide double doors at WMS and GPK, between one and two lines could be formed for alighting. Therefore, the formation of lines was coded into four categories: zero (no alighters), one line, two lines, and between one and two lines. The formation of lines for alighting was compared to the ratio R = B/A. In this study it is expected to identify the relationship between the formation of lines and the value of R.

With respect to waiting areas two types of behaviour were recorded at GPK and WMS when trains stopped at the platform:

i. Passengers waiting beside the doors;
ii. Passengers waiting in front of the doors.

It is important to note that these behaviours are not exclusive, i.e. in the same boarding and alighting process there may be passengers waiting both in front of and beside the doors (e.g. in crowded situations when there are passengers everywhere around the doors). 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. To obtain the position of each passenger waiting to board the train, it was measured the average time each cell was used at the PCA. This was done to identify which part of the PCA is used, and therefore to observe the types of queue. At both stations the cells on the PCA matched the size of the blocks on the platform floor, which could be easily distinguish from the CCTV footage.

In addition, the number of passengers who entered the PTI zone and wait for the next train (i.e. did not board the current train) was observed at GPK and WMS. This was counted manually just after the doors closed and the train started to leave the platform.

At PAMELA experiments, only 3 loads were chosen from laboratory experiments to study the types of queue and formation of lines. From Table 3-1 (section 3.5.1) three scenarios were selected: LC 2, LC 3, and LC 4. From these three scenarios the ratio (R) between boarding and alighting were defined (R = 4, R = 1, R = 0.25). Each of these scenarios was tested with PEDs and without PEDs for 10 runs.

Queues in the PCA at PAMELA were classified into four types, namely: queuing in front of the doors; clustering in front of the doors; queuing beside the doors; and clustering beside the doors.

Clustering at PAMELA experiments refers to a disordered congregation of people on the platform, whereas queuing implies a discernible order where the first and next boarder can be identified. The difference between clustering and queuing was possible to distinguee at PAMELA. However, at the LU observations as the level of demand was not controlled it was difficult to make this distinction, and therefore only two types of behaviour were recorded: waiting beside or in front of the doors.

The average time each cell was used at the PCA was also registered at PAMELA experiments just before the doors opened. This was done to identify which part of the PCA is used, and therefore to observe the types of queue.

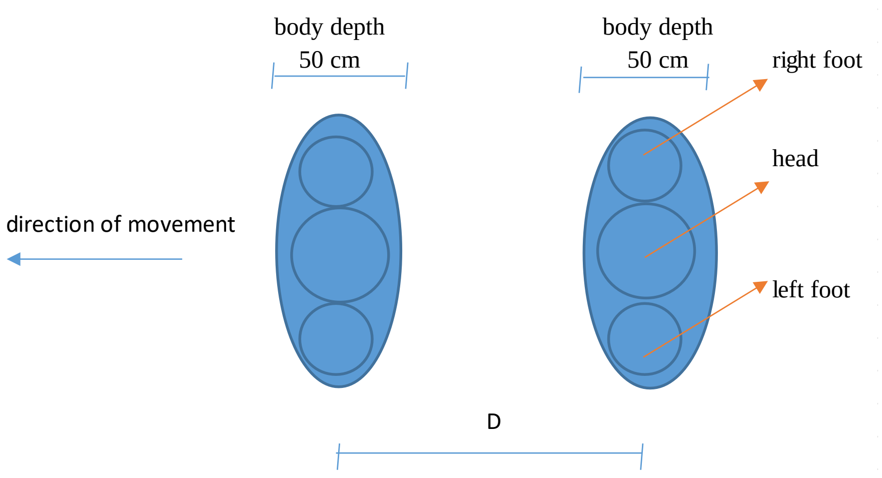
With respect to formation of lines, similar to the LU observations, passengers alighting at PAMELA experiments formed lines of flow when they were avoiding collision with passengers waiting to board the train (or walking in the opposite direction). In other words, passengers alighting followed the person in front of him/her. Four types of lines were recorded, namely: zero (no alighters), one line, two lines, and between one and two lines.

3.5.3 Distance between passengers

The distance (D) between passengers was calculated by the Euclidian method between the coordinates (x, y) of the centre of the heads of two passengers in the PCA at PAMELA experiments. The position (x, y) of each passenger was obtained with the tracking software Petrack (Boltes and Seyfried, 2013) each time the passenger exited the PTI zone defined in section 3.3.

The variable D was compared with and without PEDs for each scenario of R (4, 1, 0.25) in a sample size of s = 10 (total number of runs per scenario of R) at PAMELA. Two types of distances were studied: between two passengers alighting each time passengers exited the PTI (D_a, between passenger alighting A_i and passenger alighting A_{i+1}), and between two passengers boarding (D_b, between passenger boarding B_i and passenger boarding B_{i+1}). Figure 3-10 shows an example of the representation of D which is obtained between the centre of two passengers alighting. The body depth is considered as 50 cm defined in Fruin (1971).

Figure 3-10: Representation of the distance (D) between two passengers alighting in the PCA



Similar to the type of queues and formation of lines, only 3 loads were chosen from laboratory experiments to study the distance between passengers. From Table 3-1 (section 3.5.1) three scenarios were selected: LC 2, LC 3, and LC 4. From these three scenarios the ratio (R) between boarding and alighting were defined (R = 4, R = 1, R = 0.25). Each of these scenarios was tested with PEDs and without PEDs for 10 runs.

3.5.4 Density by layer

Two types of density were compared at PAMELA experiments. The density by layer k_L (pass/m^2) was obtained by the number of passengers in each layer on the PCA divided by the area of each layer, while the overall density k_O (pass/m^2) was calculated as the total number of passengers on the platform divided by the area of the platform (rectangular space of 3.0 m-wide and 5.0 m-long, i.e. 15 m^2 without layers in front of each door). The use of layers in the PCA enables the identification of how far passengers boarding or alighting are located from the doors.

The density by layer K_L and overall density K_O were obtained before and after the doors opened for the case with and without PEDs for each scenario of R (4, 1, 0.25) in a sample size of s = 10 (total number of runs per scenario of R) at PAMELA. The position (x, y) of each passenger was obtained using the tracking software Petrack (Boltes and Seyfried, 2013).

Similar to the other variables measured at PAMELA, only 3 loads were chosen from Table 3-1 (section 3.5.1) to study the density by layer (LC 2, LC 3, and LC 4) with PEDs and without PEDs for 10 runs.

3.5.5 Passenger space and instantaneous speed

The last variables measured in the PCA at PAMELA were the passenger space and the instantaneous speed for those passengers who were alighting with and without PEDs for each scenario of R (4, 1, 0.25) in a sample size of s = 10 (total number of runs per scenario of R) at PAMELA.

Using the software Petrack (Boltes and Seyfried, 2013), the position (x, y) of each alighting passenger A_i was recorded each time he/she exited the PTI zone defined in section 3.3. Therefore, the time step ($\Delta t = i - (i-1)$) was defined as the difference in seconds between two consecutive alighters (A_i and A_{i-1}) who exited the PTI zone. As the time step was measured only between passengers alighting, the interaction between the first passenger alighting and the first passenger boarding was not considered, therefore $i = 2,..,N_a$ (N_a = total number of passengers who alighted per door).

In addition, Petrack was used to track the number of passengers around A_i. Each alighter A_i had at least 4 passengers around him/her (front, back, left and right). The following criteria was used to select those passengers X_i who were around A_i:

- Passenger A_i should have a clear view of passenger X_i, i.e. if the angle between A_i and X_i is smaller than five degrees then X_i is not tracked; and
- Passenger A_i should be closer to passenger X_i, i.e. if the distance between A_i and another passenger X_{i+1} is double the distance between A_i and X_i then X_{i+1} is not tracked.

For example, Figure 3-11 shows the position A_i (passenger in position 1) and seven other passengers around him/her. Passengers in position 5 and 8 were alighting passengers located in front and at the back of A_i, respectively, while passengers in positions 2, 3, 4, 6 and 7 represented boarding passengers around A_i.

Figure 3-11: Example of Petrack used to track the position of A_i (i = 3) when R = 1

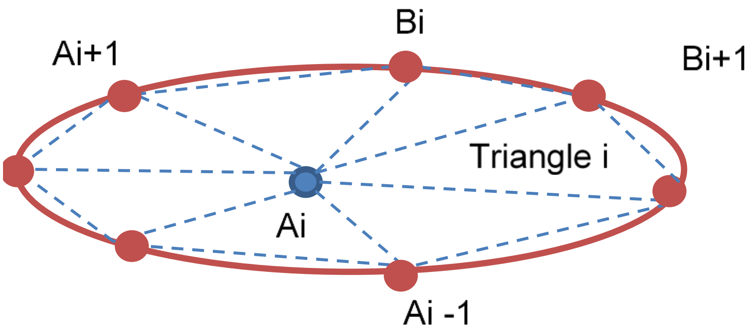
The position of passengers around each A_i was plotted to represent the space used of each alighter A_i, which represented an asymmetrical ellipse. The area of each asymmetrical ellipse was calculated using an approximation of triangles between the position of A_i and the surrounding passengers X_i who were boarding (B_i or B_{i+1}) or alighting (A_{i+1} or A_{i-1}). According to Heron's Formula the area of each triangle i can be obtained using Equation 3.1. The sum of all triangles will be the area of the Asymmetrical Space (AS) for A_i (see Equation 3.2 and Figure 3-12). The distance between A_i and A_{i+1} is defined as longitudinal front radius. The longitudinal back radius is the distance between A_i and A_{i-1}. The distance between A_i and B_i (or B_{i+1}) is defined as the lateral right or left radii.

$$A_{triangle} = \sqrt{(t \cdot (t-a) \cdot (t-b) \cdot (t-c)}\text{ , where } t = (a+b+c)/2 \qquad (3.1)$$

$$AS = \sum_{i=2}^{N_a} (A_{triangle})_i \tag{3.2}$$

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

Figure 3-12: Approximation of triangles to obtain the area PS for each Ai



The results of AS obtained using the approximation of triangles can be used in further research to calculate the platform width. In the case of LU (2012), to calculate the recommended platform width (P_w), a value of Overall Space (OS) = 0.93 m^2 per passenger or LOS D from Fruin (1971) is used for designing these spaces. The OS is obtained by considering the total rectangular area of the platform in front of the doors (A_p = 15 m^2) divided by the total number of passengers boarding (N_{bi}) and alighting (N_{ai}) for each time step i (see Equation 3.3).

$$OS = A_p/(N_{bi} + N_{ai}) \quad \text{for} \quad i = 2, \ldots, N_a \tag{3.3}$$

In addition, the instantaneous speed (v_{ai}) of each passenger alighting A_i was obtained following Equation 3.4. The expression Δt = i – (i-1) is the time step defined as the difference in seconds between each passenger A_i exiting (x_i, y_i) and entering (x_{i-1}, y_{i-1}) the PTI zone.

$$v_{Ai} = \frac{\sqrt{(y_i - y_{i-1})^2 + (x_i - x_{i-1})^2}}{\Delta t} \tag{3.4}$$

Similar to the other variables measured at PAMELA, only 3 loads were chosen from laboratory experiments to study the passenger space and instantaneous speed (from Table 3-1 in section 3.5.1 LC 2, LC 3, and LC 4 with PEDs and without PEDs for 10 runs).

Chapter 4 Results from PAMELA experiments

4.1 Introduction

The objective of this chapter is to study the effect of crowd management measures (CMM) on the behaviour and interaction of passengers boarding and alighting in a controlled environment at PAMELA. In addition, this chapter propose a new method to represent and evaluate the behaviour and interaction of passengers at the PTI area. Firstly, the characteristic of the volunteers that participated in the experiments at PAMELA are described (section 4.2). Secondly, the impact of platform edge doors (PEDs) on the BAT (section 4.3), type of queue and formation of lines of flow (section 4.4), distance between passengers (section 4.5), density by layer (section 4.6), passenger space and instantaneous speed (section 4.7) is studied. Thirdly, these results are discussed in section 4.8.

4.2 Passenger characteristics

The subjects used in PAMELA were volunteers, who were asked the following questions:

- What is your name?
- What is your email?
- What is your gender?
- What age group do you fall into?
- Do you have any special dietary requirements? (for lunch enquiries)
- Regular Commuter? (Yes/No)
- Do you have any mobility impairment?
- What is your weight in kg and height in cm?

From the total of passengers at the experiments (110 passengers), 46% (50 passengers) were men and 54% (60 passengers) were women. Most of them (78%) were regular users of the London Underground (LU). With respect to their age, most of them (60%) were under 45 years old (see Table 4-1). The total passenger load tested in the scenario

LC_0 and LC_1 (defined in Table 3-1 section 3.5.1) was 8221 kg (including seated passengers). The average height of passengers was 170 cm with a deviation standard of 8 cm.

Table 4-1: Age group of volunteers at PAMELA experiments

Age group	Percentage
<24 years old	15%
25-34 years old	26%
35-44 years old	19%
45-59 years old	27%
60-64 years old	7%
>65 years old	7%

The recruitment process was successful, and therefore volunteers represented similar conditions of boarding and alighting in exiting stations. Firstly, volunteers at PAMELA represented a good range of ages. According to Seriani and Fernandez (2015a; 2015b) this condition is difficult to achieve when there are limited resources, and therefore volunteers are typically young and healthy students, who do not really represent the characteristics of passengers in existing stations. Secondly, most of the volunteers at PAMELA were regular commuters of the LU, and therefore they were familiar with the process of boarding and alighting.

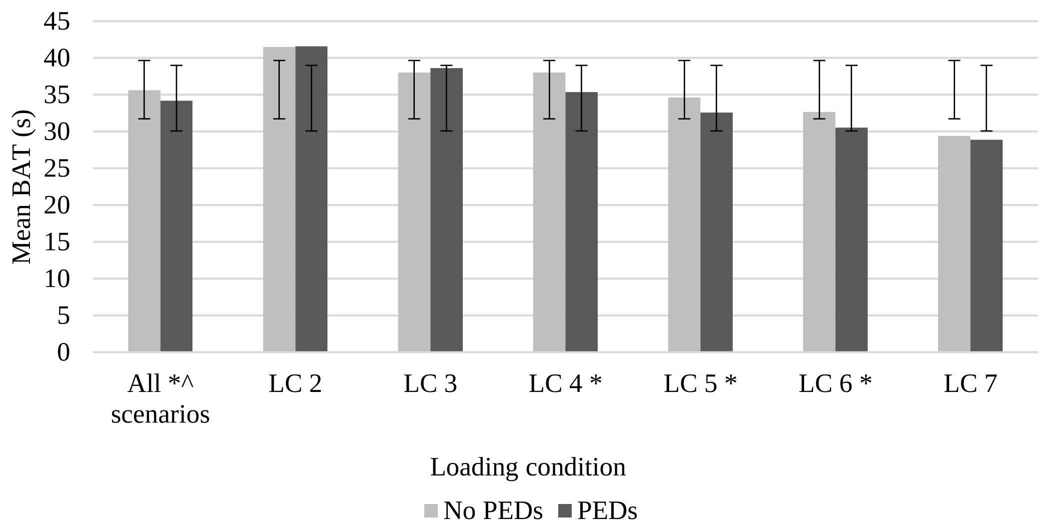
4.3 Impact on BAT with PEDs and 170 mm gap

The experiments showed that, when all loading scenarios are considered together, PEDs reduce the BAT on average by 1.4 seconds, but increase the standard deviation by 0.8 seconds. When the different loading conditions were considered separately, only those with medium on-train loads (LC 4, LC 5, and LC 6) showed a significantly lower BAT with PEDs, by approximately 2 seconds, with no significant difference in the variability (measured as difference in the variance through the Levene test) (Figure 4-1). It should be noted that LC 4 and LC 5 are representative of the demand found at WMS in the morning peak and GPK in the evening peak times.

When the total number of passengers remaining on board the train was low (LC 2 and LC 3), there was no significant effect of PEDs on the BAT. There was also no effect on BAT under LC 7, which had a high on-board load with relatively few boarders and alighters. These results are further explained by the behaviour of passengers on the platform (see section 4.4).

In Figure 4-1 the numbers in brackets represent, respectively, number of boarders/alighters/passengers on board; the error bars indicate the standard deviation; * shows that there are statistically significant differences (confidence level 95%) on the BAT with and without PEDs according to the ANOVA test (for each individual loading condition) or Welch's t test (for "all scenarios"); ^ indicates that there are statistically significant differences (confidence level 95%) on the variance of the BAT with and without PEDs according to the Levene test.

Figure 4-1: Impact of PEDs on BAT at PAMELA



To further explore the differences in the boarding and alighting process with and without PEDs, the average boarding and alighting profiles were analysed. In order to get results that were directly comparable, relative profiles have been used, which isolate the shape of the curve from the demand. Thus, the relative profiles for each observation were obtained by dividing the number of boardings (alightings) in each 5 second interval by the total number of boardings (alightings) in that boarding (alighting) process. The profiles presented are formed by taking the average of all observations for each interval. Therefore, they represent the average proportion of boardings (alightings) in any given interval.

Since there were noticeable differences in the profiles for each loading condition, it was unfair to aggregate them into an average profile and therefore specific profiles for each loading condition are presented. It can be seen from Figure 4-2 to Figure 4-7 that for each loading scenario the boarding and alighting profiles with and without PEDs are similar in shape, thus suggesting that the fundamental boarding and alighting dynamics are not greatly affected by the presence of PEDs. It can be noticed, however, that the ratio (R) of boarders to alighters has an effect on the time when the boardings or alightings peak and on the boarding and alighting rates. For instance, when the ratio of boarders to alighters is 4 (LC 2, LC 5), the alighting process occurs quickly and early, whereas when the ratio is 0.25 (LC 3, LC 6), the boardings start much later and occur very quickly in relative terms. Finally, when the ratio is 1 (LC 4, LC 7), the behaviour is intermediate between the other two cases (R = 4 and R = 0.25).

Figure 4-2: Average relative boarding and alighting profiles in the PAMELA experiments LC 2: 40 boarders, 10 alighters, 5 on-board.

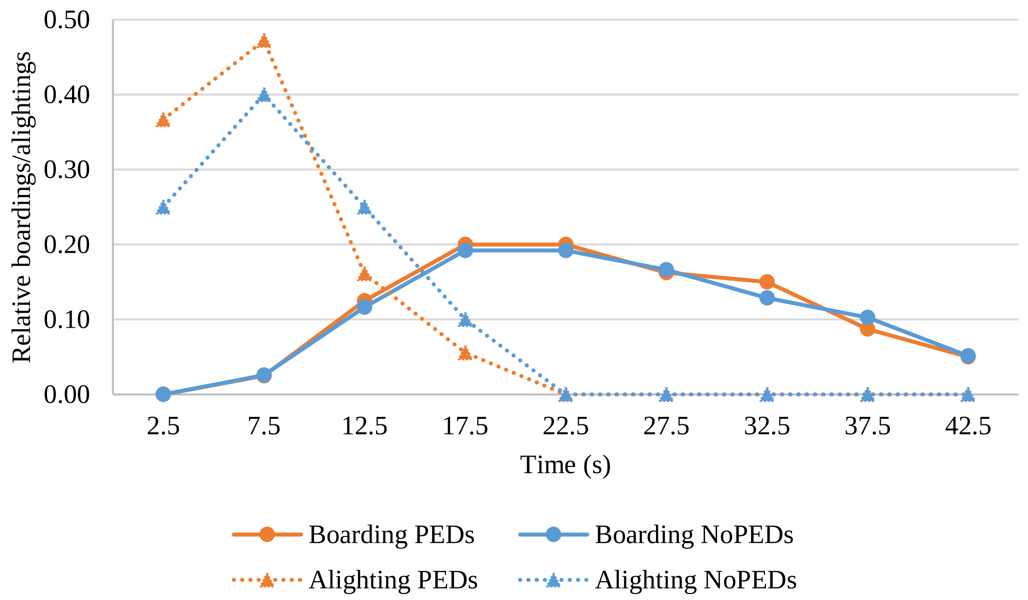


Figure 4-3: Average relative boarding and alighting profiles in the PAMELA experiments LC 3: 10 boarders, 40 alighters, 5 on-board.

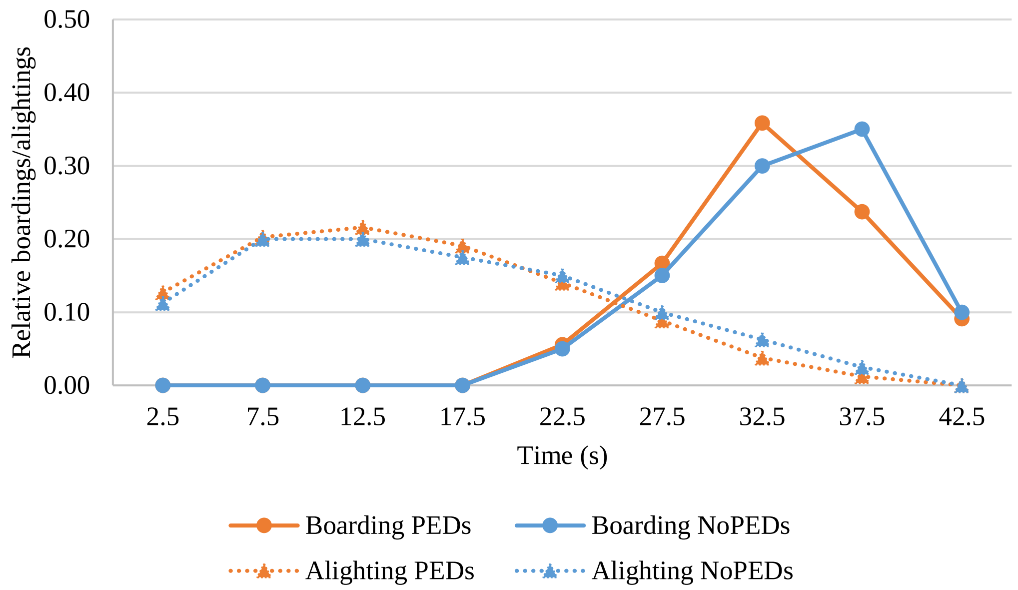


Figure 4-4: Average relative boarding and alighting profiles in the PAMELA experiments LC 4: 20 boarders, 20 alighters, 15 on-board.

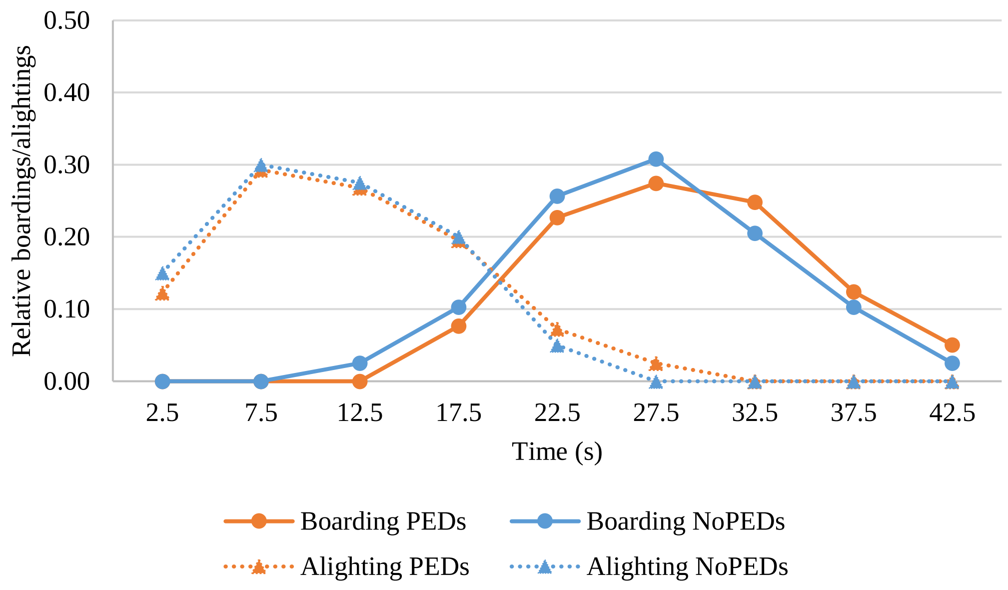


Figure 4-5: Average relative boarding and alighting profiles in the PAMELA experiments LC 5: 20 boarders, 5 alighters, 30 on-board.

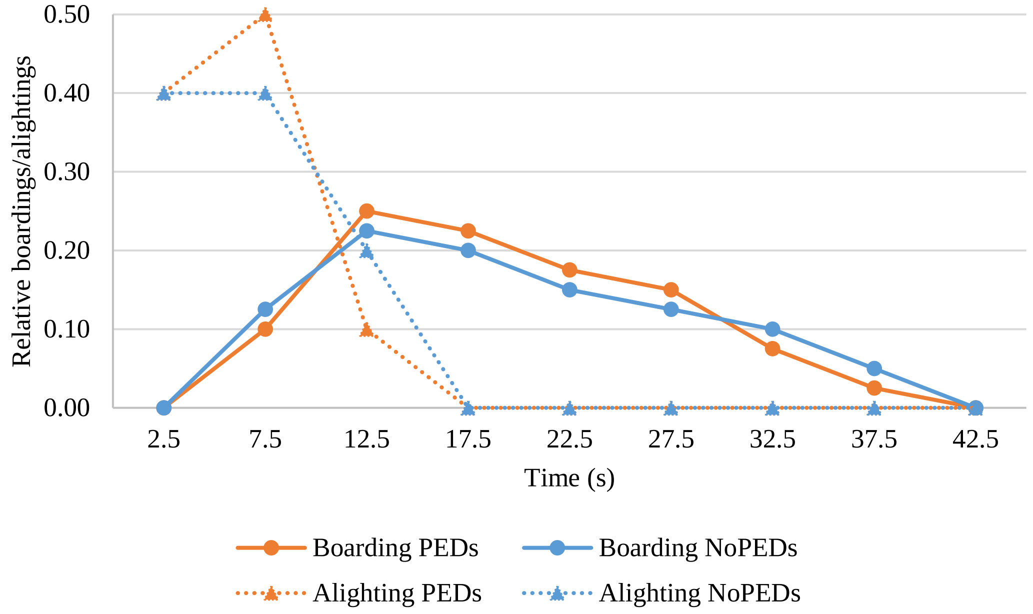


Figure 4-6: Average relative boarding and alighting profiles in the PAMELA experiments LC 6: 5 boarders, 20 alighters, 30 on-board.

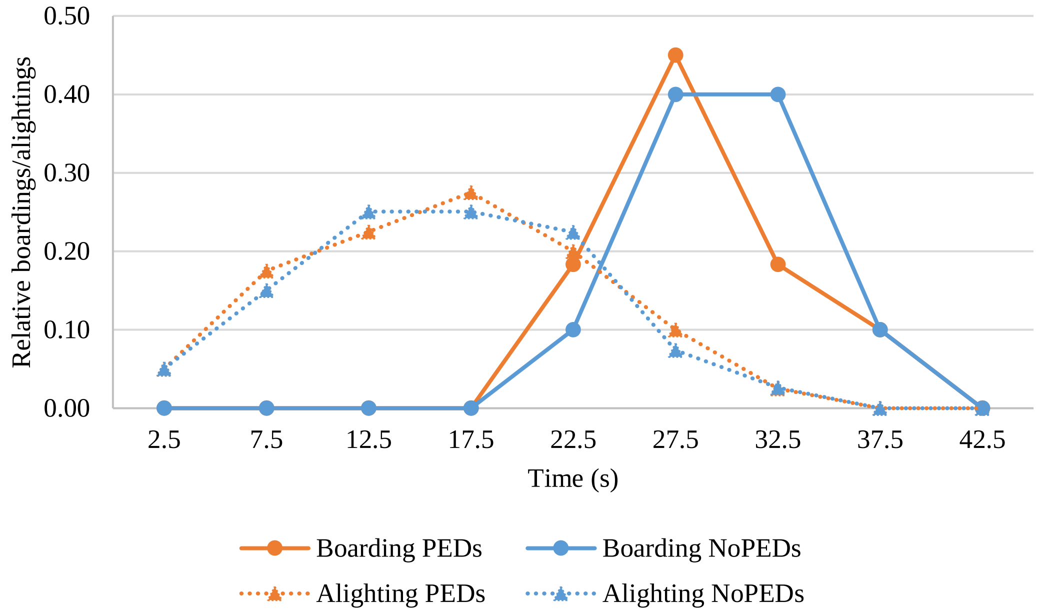
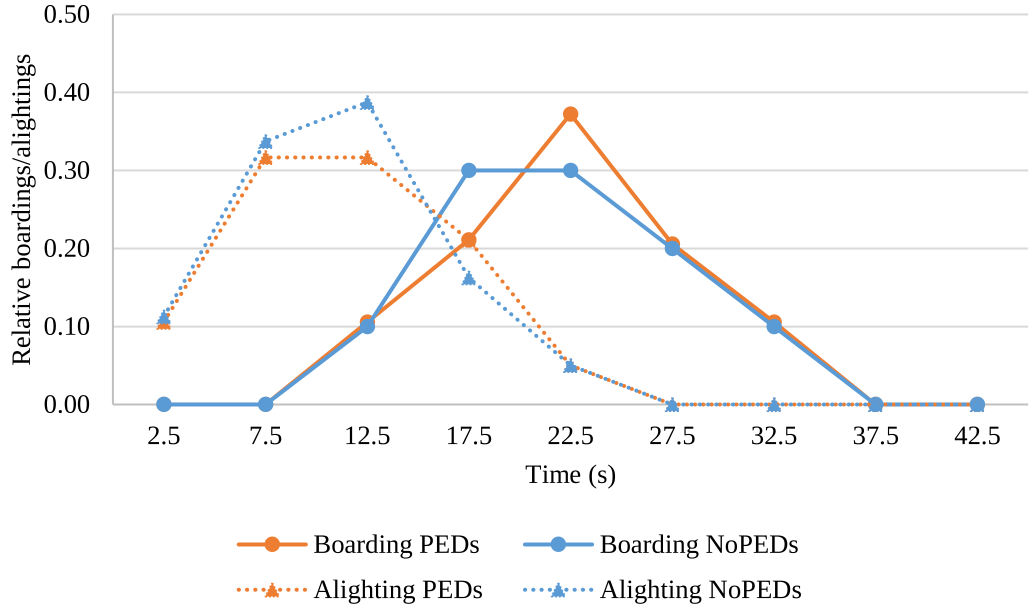


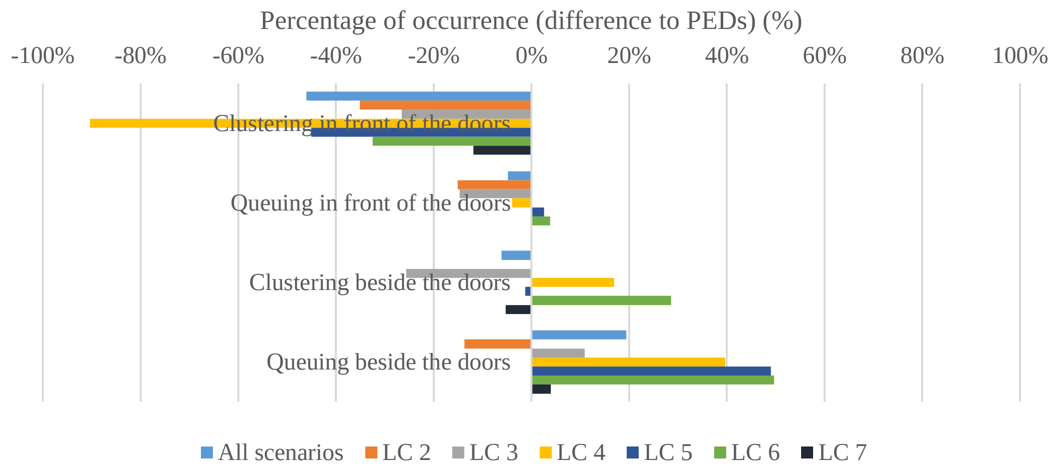
Figure 4-7: Average relative boarding and alighting profiles in the PAMELA experiments LC 7: 10 boarders, 10 alighters, 35 on-board.



4.4 Impact on types of queue and formation of lines

The results of the passenger behaviour analysis are shown in Figure 4-8, in which the difference is the subtraction of the percentage occurrence with PEDs from the percentage occurrence without PEDs. Therefore, a positive percentage indicates that the behaviour is more likely with PEDs. The results show that with PEDs there were fewer participants clustering and queuing in front of the doors. Queuing and clustering beside the doors instead of in front of them was evident in the PEDs scenarios when the BAT was significantly lower (LC 4, LC 5, and LC 6), i.e. with PEDs there were more participants beside the doors, which reduces friction between boarders and alighters and improves the alighting process. This supports the results in Figure 4-4, Figure 4-5, Figure 4-6 where LC 4, LC 5 and LC 6 presented a reduced BAT with PEDs, respectively, while the others, which showed no impact of PEDs on the BAT, presented in some cases an undesirable reduction in the percentage of people clustering and queuing beside the doors, resulting in an increase in the numbers in front of the doors, which increases friction.

Figure 4-8: Difference to with PEDs scenario in frequency of passenger behaviours over total number of observations in the PAMELA experiments



Another way to represent the types of queue at PAMELA is showed in Figure 4-9 and Figure 4-10, in which the PCA is divided into 40-cm square cells. At both figures it was recorded the average time each cell was used, i.e. occupation maps were obtained between the case with and without PEDS.

Figure 4-9 shows that the case with PEDs presented more green cells than red cells in front of the doors. This mean that the use of PEDs changed the behaviour of passengers by causing them to wait beside the doors rather than in front of the doors. The green colour represents less occupied cells, while the red corresponds to frequently used cells.

On the contrary, Figure 4-10 shows that the case without PEDS presented more yellow or red cells than green cells in front of the doors. This mean that more passengers are located in front than beside the doors in absence of PEDs.

Figure 4-9: Average time each cell was used in the PCA just before doors started to open with PEDs at PAMELA

R = 4														
280	1	2	0	0	0	0	0	0	0	0	0	0	0	0
240	5	9	7	3	6	5	0	0	0	0	0	0	0	0
200	5	5	4	3	3	3	4	5	5	1	1	0	0	0
160	3	6	5	6	4	4	0	3	4	3	5	0	0	0
120	3	5	2	4	3	0	1	2	4	2	4	0	0	0
80	4	1	6	3	3	2	1	1	4	6	2	0	0	0
40	1	0	1	4	0	0	0	0	0	1	0	0	0	0
Distance (cm)	-280	-240	-200	-160	-120	-80	-40	40	80	120	160	200	240	280
						D	O	O	R					

R = 1														
280	0	1	0	0	0	0	0	0	0	0	0	0	0	0
240	2	3	2	2	4	0	1	0	0	0	0	0	0	0
200	0	1	4	4	3	3	2	2	6	3	0	0	0	0
160	3	3	6	3	4	2	3	1	2	2	4	0	0	0
120	1	2	2	3	3	1	0	2	2	2	5	0	0	0
80	2	3	3	2	4	0	0	0	0	5	1	0	0	0
40	1	0	2	0	3	0	0	0	3	2	0	0	0	0
Distance (cm)	-280	-240	-200	-160	-120	-80	-40	40	80	120	160	200	240	280
						D	O	O	R					

R = 0.25														
280	0	0	0	0	0	0	0	0	0	0	0	0	0	0
240	0	1	2	1	0	1	0	0	0	0	0	0	0	0
200	1	1	1	1	1	1	0	2	1	0	0	0	0	0
160	1	0	5	0	2	1	0	0	1	0	3	0	0	0
120	0	1	2	1	0	0	0	0	2	6	0	0	0	0
80	0	1	1	5	2	0	0	1	0	1	2	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Distance (cm)	-280	-240	-200	-160	-120	-80	-40	40	80	120	160	200	240	280
						D	O	O	R					

Figure 4-10: Average time each cell was used on the PCA just before doors started to open without PEDs at PAMELA

R = 4														
280	2	2	3	0	0	0	0	0	0	0	0	0	0	0
240	5	6	3	3	6	3	1	4	0	0	0	0	0	0
200	3	3	8	6	5	6	3	2	5	7	2	0	0	0
160	3	4	6	7	6	2	3	7	4	5	5	0	0	0
120	1	2	5	3	4	6	2	3	4	5	5	0	0	0
80	5	3	8	4	2	4	2	1	5	4	6	0	0	0
40	0	0	0	1	1	0	0	0	1	1	0	0	0	0
Distance (cm)	-280	-240	-200	-160	-120	-80	-40	40	80	120	160	200	240	280
						D	O	O	R					
R = 1														
280	1	0	3	0	0	0	0	0	0	0	0	0	0	0
240	1	4	2	4	3	1	3	0	0	0	0	0	0	0
200	0	4	2	3	2	4	1	3	2	6	1	0	0	0
160	1	3	3	3	2	4	0	0	5	4	4	0	0	0
120	4	3	4	3	4	1	2	1	0	4	3	0	0	0
80	1	2	2	5	5	1	0	0	3	6	5	0	0	0
40	0	0	0	0	1	0	0	0	2	0	0	0	0	0
Distance (cm)	-280	-240	-200	-160	-120	-80	-40	40	80	120	160	200	240	280
						D	O	O	R					
R = 0.25														
280	0	0	0	0	0	0	0	0	0	0	0	0	0	0
240	0	1	4	0	2	0	0	0	0	0	0	0	0	0
200	1	1	2	0	0	0	1	0	2	3	0	0	0	0
160	2	2	1	3	5	1	1	5	2	2	1	0	0	0
120	0	1	2	1	1	1	1	0	2	1	1	0	0	0
80	0	1	5	4	5	0	0	0	1	7	2	0	0	0
40	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Distance (cm)	-280	-240	-200	-160	-120	-80	-40	40	80	120	160	200	240	280
						D	O	O	R					

In relation to the formation of lines of flow for passengers alighting at PAMELA experiments, this behaviour was produced due to collision avoidance with passengers boarding at the PTI. Similar to the LU observations (section 5.4), this situation was different to a supermarket's queue where people are served in FIFO ("First in First out"). Figure 4-11 shows that when R = 4, passengers reached a high interaction and alighting formed a narrow single line, whilst two lines for alighting were formed and a lower interaction resulted when R = 0.25. In both cases, two lines for boarding were formed at the side of the doors and an average bidirectional flow of 1.0 passengers per second (pass/s) was reached at the doors. In the case when R = 1, between one and two lines were formed for alighting, reaching an average bidirectional flow of 0.80 pass/s at the doors.

Figure 4-11: Formation of lines when R = 4 (left) and R = 0.25 (right) at PAMELA

4.5 Distance between passengers

4.5.1 Alighting

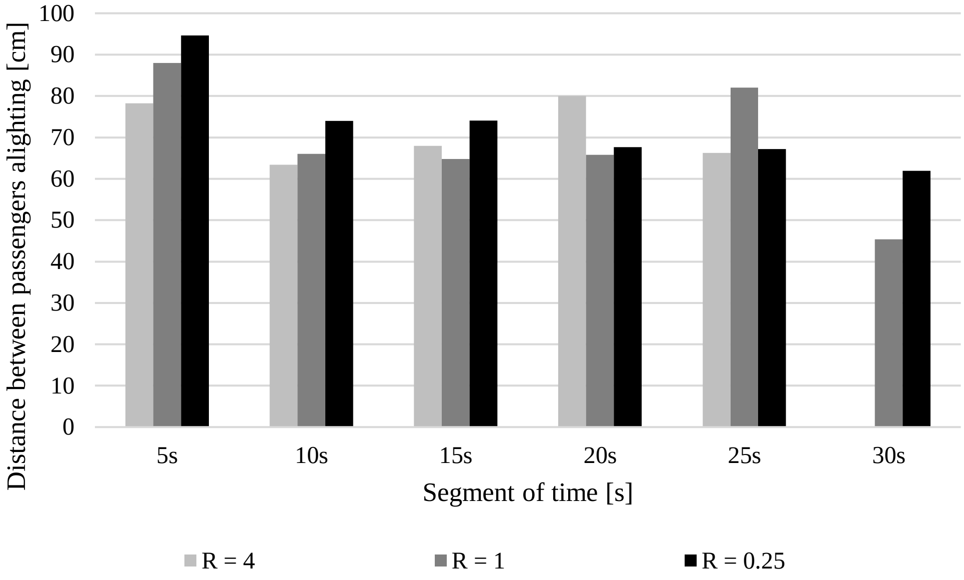
Table 4-2 shows the number of observations to compare the distance between passengers alighting. In the case with PEDS, a total of 598 observations were compared, while in the case without PEDs, a total of 502 observations were analysed.

Table 4-2: Number of observations to compare the distance between passengers alighting with PEDs and without PEDs at PAMELA for each scenario of R

Scenario	Observations between passengers alighting	
	PEDs	NoPEDs
R = 4	94	90
R = 1	127	128
R = 0.25	377	284
Total	598	502

Figure 4-12 shows the average distance between heads of passengers alighting ($\overline{D_a}$) in segments of 5 seconds with PEDs at PAMELA. 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.

Figure 4-12: Average distance between passengers alighting with PEDs at PAMELA

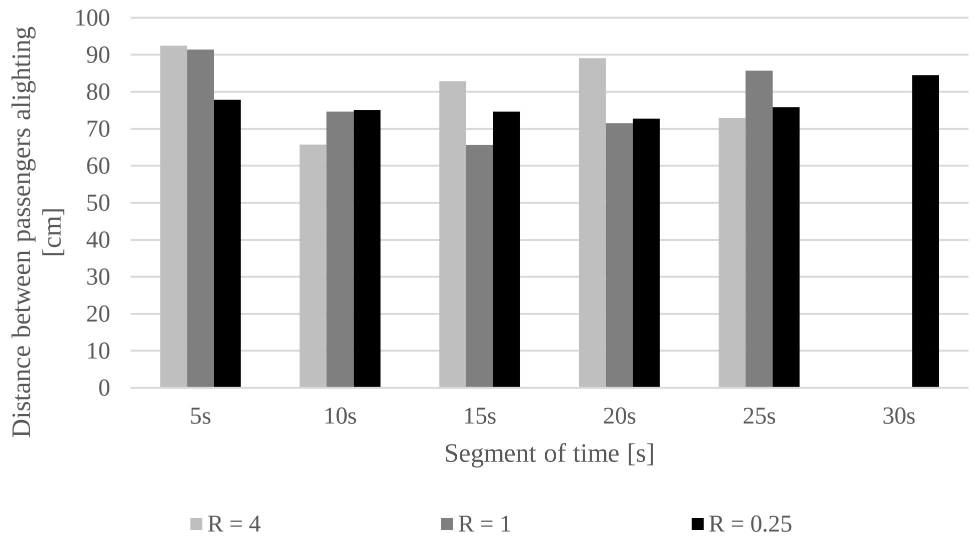


An ANOVA test single factor was used with a significance level of 5% (α = 0.05 or 95% of confidence level) to see whether, for $\overline{D_a}$, there is a significant difference between different R (i.e. compare groups R = 4 vs R = 1 vs R = 0.25). The null hypothesis (H_0) was defined as the samples having the same mean ($\overline{D}_{a\_R=4} = \overline{D}_{a\_R=1} = \overline{D}_{a\_R=0.25}$). The results of the ANOVA showed that the p-value was higher than 0.05. This means that the null hypothesis cannot be rejected, i.e. there is no significant difference for the distance of passengers alighting between each case of R when PEDs are used.

The same test was performed for the case without PEDs. The results of the ANOVA showed that in absence of PEDs there is no significant differences between the distance of passengers alighting comparing each case of R. Figure 4-13 shows $\overline{D_a}$ in segments of 5 seconds without PEDs at PAMELA.

As there are no significant differences between different R, there is no clear which case of R could present a higher or lower interaction.

Figure 4-13: Average distance between passengers alighting without PEDs at PAMELA



A t-Test (two-sample assuming unequal variances) was done with α = 0.05 for a pairwise comparison with and without PEDS for each scenario of R. The null hypothesis (H_0) was defined as the samples having the same mean for each case of R (e.g. $\overline{D}_{a\_R=4\_PEDs} = \overline{D}_{a\_R=4\_NoPEDs}$). A total of 598 observations with PEDs were compared to a total of 502 observations without PEDs (see Table 4-2). As shown in Table 4-3, the p-value was higher than 0.05 for R = 4 and R = 1, therefore H_0 cannot be rejected, i.e. in these two cases (R = 4 and R = 1) the use of PEDs had no statistical difference in relation to $\overline{D}_a$ compared to the case without PEDs. However, in the case R = 0.25 the presence of PEDs had a significant impact on the distance between passengers alighting compared to the situation without PEDs. This impact (R = 0.25) reached a difference of 5.93 cm in favour of the case without PEDs.

Table 4-3: Average distance (cm) between passengers alighting with PEDs and without PEDs at PAMELA

Scenario	PEDs	No-PEDs	p-value
R = 4	66.01	72.56	0.062
R = 1	67.34	71.02	0.177
R = 0.25	68.72	74.65	0.003

4.5.2 Boarding

Table 4-4 shows the number of observations to compare the distance between passengers boarding. In the case with PEDS, a total of 2418 observations were compared, while in the case without PEDs, a total of 2604 observations were analysed.

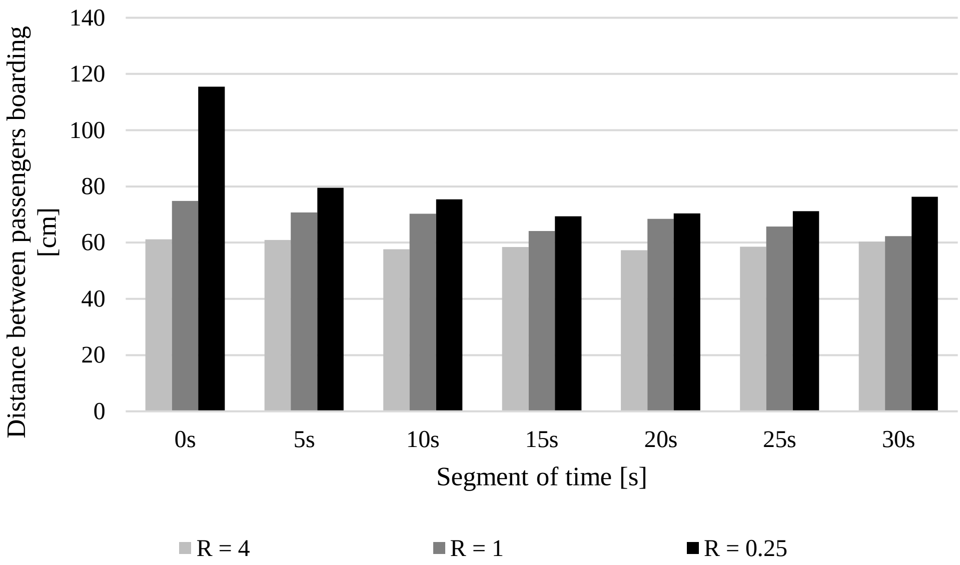
Table 4-4: Number of observations to compare the distance between passengers boarding with PEDs and without PEDs at PAMELA for each scenario of R

Scenario	**Observations between passengers boarding**	
	PEDs	NoPEDs
R = 4	1386	1378
R = 1	734	794
R = 0.25	298	432
Total	2418	2604

Figure 4-14 shows the average distance between passengers boarding ($\overline{D_b}$) 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 0^{th} seconds), the distance between heads almost doubled compared to R = 4 or R = 1 due to the available space on the platform (i.e. R = 0.25 had four times less boarding passengers than with R = 4). Therefore, passengers in the case of R = 4 or R = 1 presented higher interaction compared to those passengers in the scenario of R = 0.25.

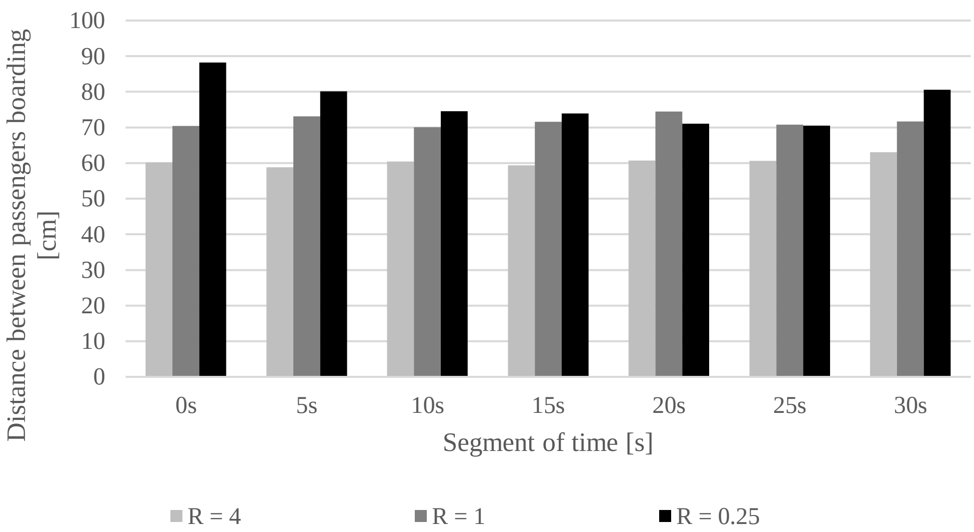
An ANOVA test single factor was used with a significance level of 5% ($\alpha = 0.05$ or 95% of confidence level) to see whether, for $\overline{D_b}$, there is a significant difference between different R (i.e. compare groups R = 4 vs R = 1 vs R = 0.25). The results of the ANOVA showed that the p-value was lower than 0.05, therefore H_0 is rejected, i.e. there is significant difference for the distance of passengers boarding between each case of R. In particular, it is obtained that there are significant differences for the distance of passengers boarding comparing each pair of R (R = 4 vs R = 1; R = 4 vs R = 0.25; R = 1 vs R = 0.25).

Figure 4-14: Average distance between passengers boarding with PEDs at PAMELA



Similarly, for the case without PEDs, the results of the ANOVA showed that in absence of PEDs there is significant differences for the distance of passengers boarding between each case of R. In particular, when comparing each pair of R (R = 4 vs R = 1; R = 4 vs R = 0.25; R = 1 vs R = 0.25), significant differences for the distance of passengers boarding are obtained. Figure 4-15 shows $\overline{D_b}$ in segments of 5 seconds without PEDs at PAMELA.

Figure 4-15: Average distance between passengers boarding without PEDs at PAMELA



As there are significant differences between different R, from both figures (Figure 4-14 and Figure 4-15) it could be observed that a situation with high interaction (R = 4) is reached when $\overline{D_b}$ is less or around 60 cm, while a low interaction (R=0.25) is obtained when $\overline{D_b}$ is around or more than 80 cm (and could reach up to 115 cm in case with PEDs). A medium interaction (R = 1) is reached in between the other two cases.

To compare the observations with and without PEDs, a t-Test (two-sample assuming unequal variances with $\alpha = 0.05$) was performed for different R. A total of 2418 observations with PEDs were compared to a total of 2604 observations without PEDs (see Table 4-4). The results in Table 4-5 presented a p-value higher than 0.05 for the case R = 4 and R =1, therefore the presence of PEDs have no significant differences in terms of distance between boarding passengers compared to the case without PEDs in these two cases of R. However, a p-value lower than 0.05 was reached when R = 0.25, in which the difference between with and without PEDs is significant reaching a value of 6.0 cm in favour of PEDs.

Table 4-5: Average distance (cm) between heads of passengers boarding with PEDs and without PEDs at PAMELA

Scenario	PEDs	No-PEDs	p-value
R = 4	59.11	60.27	0.093
R = 1	68.71	71.15	0.075
R = 0.25	80.57	74.57	0.011

4.6 Density by layer

4.6.1 Before doors open

Figure 4-16 shows the variation of maximum density by layer (k_L) in the PCA before the PEDs started to open (segment of time 0 s) for R = 4, R = 1, and R = 0.25, respectively. The table shows that the number of passengers per layer remain stable over time, i.e. even if passengers change their position in the PCA from one run to another, this change is not dramatic. For example, the second layer (50-100 cm) presented fluctuations of density for each run, but in the last layer (250-300 cm) the density smoothly varied for each run. This situation happened for each case of R.

Figure 4-16: Variation of the maximum density by layer (pass/m^2) for each run before PEDs open at PAMELA when R = 4

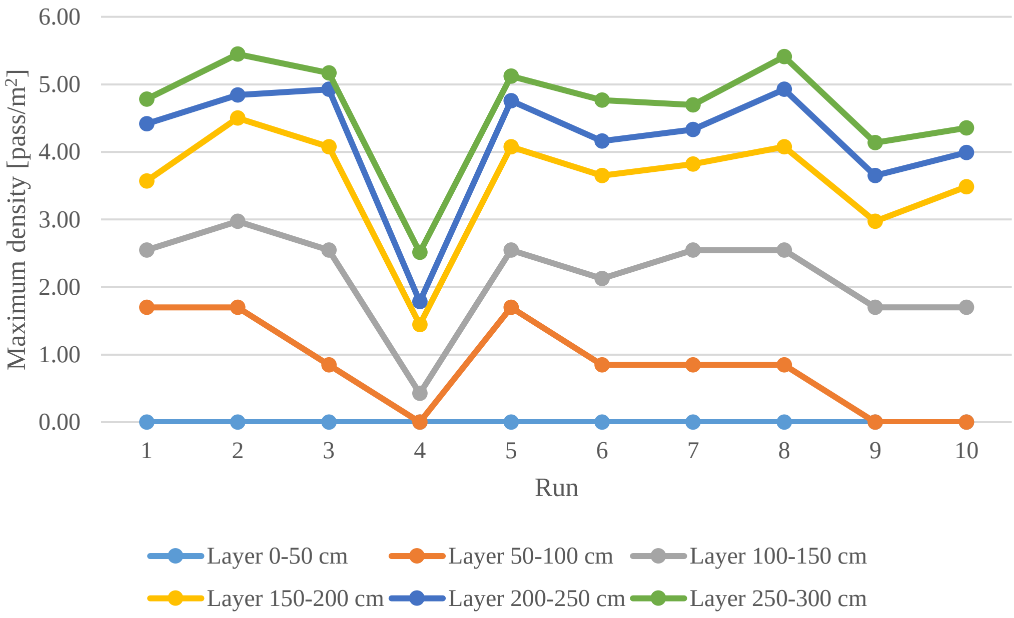


Figure 4-17: Variation of the maximum density by layer (pass/m^2) for each run before PEDs open at PAMELA when R = 1

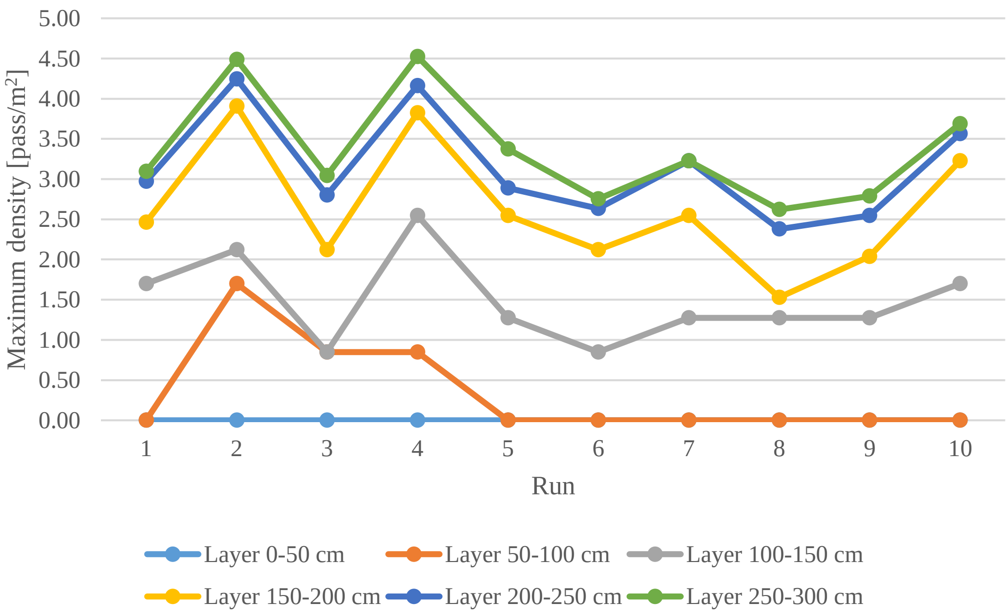
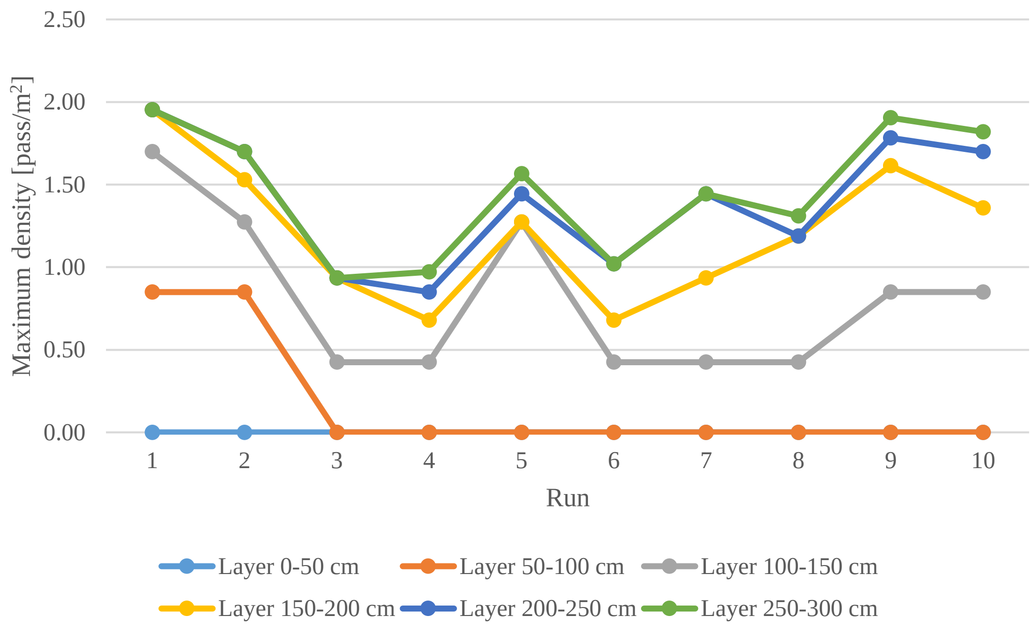
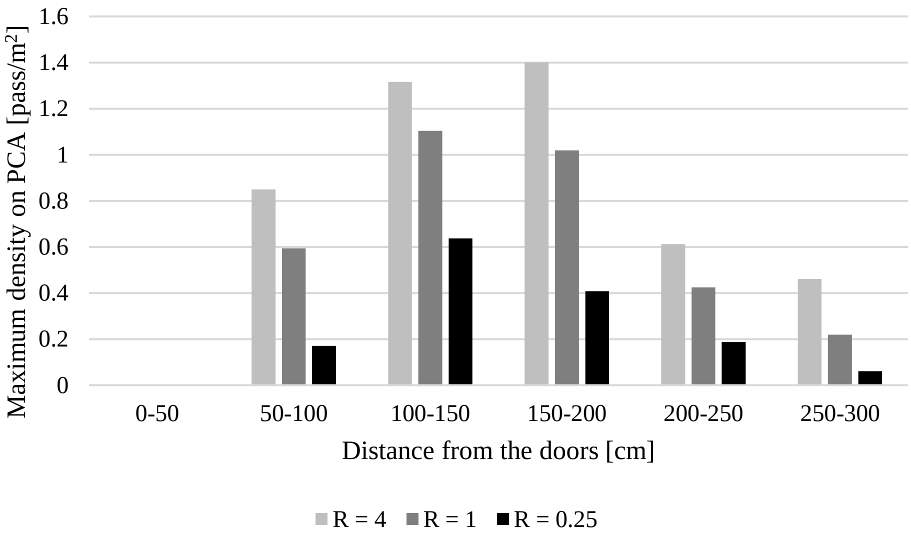


Figure 4-18: Variation of the maximum density by layer (pass/m^2) for each run before PEDs open at PAMELA when R = 0.25



From Figure 4-16, Figure 4-17, and Figure 4-18 it could be obtained the average maximum k_L just before PEDs started to open (which is presented in Figure 4-19). When R = 4, a high density (and therefore a high interaction) was presented on average compared to R = 0.25 and R = 1, due to the higher number of passengers boarding, reaching a maximum of 1.40 pass/m^2 in the fourth layer (150 – 200 cm). In the case of R = 1, the maximum density reached 1.10 pass/m^2 (third layer 100 – 150 cm), which is 74% more than the situation with R = 0.25 (0.63 pass/m^2 ≈ 0.60 pass/m^2 in third layer).

Figure 4-19: Average maximum density by layer on the PCA just before PEDs started to open at PAMELA



A Kruskal–Wallis one-way (or one-way ANOVA on ranks) was performed with a significance level of 5% ($\alpha = 0.05$ or 95% of confidence level) to see whether, for k_L, there is a significant difference between different R (i.e. compare groups R = 4 vs R = 1 vs R = 0.25). The null hypothesis (H_0) was defined as the medians of the samples are equal for each layer. It is assumed that the outcome is not normally distributed due to the small sample size (n = 10 for each scenario of R in the segment of time 0^{th} seconds). In the case without PEDs, the results of the Kruskal–Wallis one-way test presented always a p-value lower than 0.05 for each layer, i.e. there are significant differences in terms of maximum k_L between different R. The same results (i.e. p-value < 0.05) are obtained in the case with PEDs between different R, however the only exception that presented a p-value > 0.05 (p-value = 0.0760) was the layer 2 (50-100 cm) when R = 4.

The average maximum overall density (k_O) was obtained at the laboratory experiment before doors opened with and without PEDs (see Table 4-6). In the case of k_O 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 4-6: Maximum overall density (pass/m^2) before doors opened with and without PEDs

Run	With PEDs			Without PEDs		
	R = 4	R = 1	R = 0.25	R = 4	R = 1	R = 0.25
1	1.13	0.87	0.27	1.93	1.27	0.53
2	1.40	1.00	0.33	1.67	0.93	0.33
3	1.40	0.87	0.20	1.53	1.07	0.67
4	1.20	1.00	0.40	1.67	0.87	0.60
5	1.40	0.93	0.33	1.67	0.80	0.60
6	1.40	0.93	0.27	1.60	1.20	0.60
7	1.27	0.93	0.47	1.40	1.07	0.47
8	1.60	0.87	0.33	1.67	1.13	0.53
9	1.33	0.87	0.47	1.73	0.87	0.47
10	1.33	0.87	0.47	1.60	0.67	0.67
Average	1.34	0.91	0.35	1.65	0.99	0.55

The average maximum density by layer (k_L) was compared to the average maximum overall density (k_O). In the case with PEDs, Table 4-7 shows that the variable k_L was more representative to measure interaction than k_O which is used in the Level of Service – LOS (Fruin, 1971), reaching 80% greater density when R = 0.25.

Table 4-7: Difference between average maximum overall density (rectangular space) and density by layer (semi-circular space) before PEDs opened on the PCA at PAMELA

R (board/alight)	Average max. k_O (pass/m^2)	Average max. k_L (pass/m^2)	Diff.* (pass/m^2)
4.0	1.34 (LOS E)	1.40 (LOS E)	+0.06
1.0	0.91 (LOS D)	1.10 (LOS E)	+0.09
0.25	0.35 (LOS B)	0.63 (LOS C)	+0.28
*Diff. = Average max. k_L – Average max. K_O			

To identify if the use of PEDs influenced the density of passengers by layer before the doors opened, a Mann-Whitney U test was used with a significance level of 5% (α = 0.05) to compare each group (PEDs and No-PEDs) for each layer. It is assumed that the outcome is not normally distributed due to the small sample size (n = 10 for each scenario of R in the segment of time 0 s). The null hypothesis (H_0) was defined as the two medians being equal.

The results of the Mann-Whitney U test showed that, except for the layer 200-250 cm when R = 4 and the layer 100-150 cm when R = 0.25, 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 4-8). This means that H_0 is accepted for the majority of the cases, however, due to the exception cases (layer 200-250 cm when R = 4 and 100-150 cm when R =0.25), it is not possible to assume that the use of PEDs caused no significant difference in relation to the density by layer compared to the case without PEDs.

Therefore, there could be an impact of PEDs with respect to the passengers' position in the PCA from the doors. The use of PEDs could change the behaviour of passengers as they would know exactly where the train doors would open and therefore organize themselves more efficiently on the platform. This is in concordance with results of section 4.4.

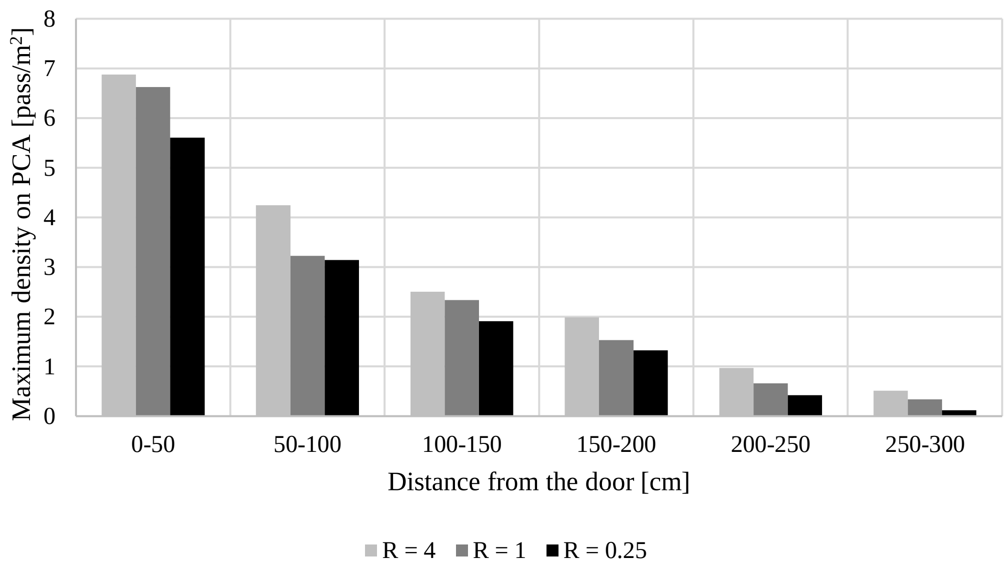
Table 4-8: Average maximum density (pass/m^2) before doors started to open with PEDs and without PEDs at PAMELA

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	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-
50-100	0.85	1.44	27.50	0.59	0.51	44.00	0.17	0.17	50.00
100-150	1.32	1.83	27.50	1.10	1.10	49.50	0.64	1.15	12.50
150-200	1.40	1.61	37.00	1.02	1.20	35.50	0.41	0.66	31.00
200-250	0.61	0.88	18.50	0.42	0.53	34.50	0.19	0.19	47.50
250-300	0.46	0.44	49.00	0.22	0.25	43.00	0.06	0.12	32.50

4.6.2 After doors open

The maximum density by layer or k_L in the PCA after the doors started to open was obtained for the case with and without PEDs. For all values of R (ratio between boarding and alighting), the k_L in the PCA followed a Logarithmic distribution with a coefficient of correlation between 0.97 and 0.99 (see Equation 4.1 and Table 4-9). This means 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 (see Figure 4-20). Considering that space used by passengers is the inverse of density, layers in the 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.

Figure 4-20: Average maximum density by layer in the PCA after PEDs started to open at PAMELA



$$k = -C_1 \cdot ln(x) + C_2 \qquad \text{for x = distance from the doors [cm]} \qquad (4.1)$$

Table 4-9: Coefficients in the interaction model of density by layer in the PCA after PEDs opened at PAMELA

R (board/alight)	C1	C2
4.0	3.56	6.75
1.0	3.43	6.21
0.25	3.06	5.44

An ANOVA test single factor was used with a significance level of 5% ($\alpha = 0.05$ or 95% of confidence level) to see whether, for k_L, there is a significant difference between different R (i.e. compare groups R = 4 vs R = 1 vs R = 0.25). The null hypothesis (H_0) was defined as the samples having the same mean (i.e. $k_{L\_R=4} = k_{L\_R=1} = k_{L\_R=0.25}$ in each layer). In the case with PEDs, the results of the ANOVA presented significant differences for different R, except for the comparison between R = 1 and R = 0.25 in layers 1 to 5 (i.e. 0-50 cm, 50-100 cm, 100-150 cm, 150-200 cm, 200-250 cm). The same results (i.e. p-value < 0.05) are obtained for different R in the case without PEDs, however the only exception that presented a p-value > 0.05 was the comparison between R = 1 and R = 0.25 in layer 1 to 4 (i.e. 0-50 cm, 50-100 cm, 100-150 cm, 150-200 cm).

In Table 4-10 the density by layer or k_L was compared to the LOS of Fruin (1971), in which the overall density or k_O was obtained by counting the average maximum number of passengers in the PCA with and without PEDs (see Table 4-11). However, in this case (k_O) 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.

In the case with PEDs, Table 4-10 shows that this rectangular area reached a maximum k_O of 1.82 pass/m^2 in the case R = 4, which is equivalent to a LOS E, obtaining up to 3.7 times less density than the method of PCA divided into layers. Therefore, the method of layers in the PCA was more representative of the interaction between passengers boarding and alighting than the LOS with respect to density.

Table 4-10: Difference between maximum overall density (rectangular space) and density by layer (semi-circular space) after PEDs opened on the PCA at PAMELA

R (board/alight)	Max. k_O (pass/m^2)	Max. k_L (pass/m^2)	Diff.* (pass/m^2)
4.0	1.82 (LOS E)	6.87 (LOS F)	+5.05
1.0	1.30 (LOS E)	6.62 (LOS F)	+5.32
0.25	0.99 (LOS D)	5.60 (LOS F)	+4.61
*Diff. = Max. k_L – Max. K_O			

Table 4-11: Maximum overall density (pass/m^2) after doors opened with and without PEDs

Run	With PEDs			Without PEDs		
	R = 4	**R = 1**	**R = 0.25**	**R = 4**	**R = 1**	**R = 0.25**
1	1.80	1.13	0.93	2.27	1.53	1.00
2	1.93	1.13	0.93	1.87	1.33	0.80
3	1.80	1.07	0.73	2.00	1.53	1.20
4	1.60	1.40	1.20	1.93	1.27	1.13
5	1.87	1.33	1.00	1.87	1.27	1.13
6	1.67	1.40	1.13	1.93	1.53	1.13
7	1.87	1.27	0.93	1.73	1.40	1.00
8	1.93	1.53	1.07	2.13	1.47	0.93
9	1.80	1.40	1.13	2.00	1.33	0.93
10	2.00	1.33	0.87	1.93	1.00	1.33
Average	1.82	1.30	0.99	1.97	1.37	1.06

To identify if the use of PEDs influenced k_L after the doors opened, a t-Test (two-sample assuming unequal variances) was used with a significance level of 5% (α = 0.05) to compare each group (PEDs and No-PEDs) for each layer (i.e. PEDs vs No-PEDs for each layer when R = 4, PEDs vs No-PEDs for each layer when R = 1, and PEDs vs No-PEDs for each layer when R = 0.25). Therefore, it was compared 3600 observations in total (i.e. 600 observations with PEDs were compared with 600 observations without PEDs for each case of R). The null hypothesis (H_0) was defined as the samples having the same mean for each case of R. The results of the t-Test showed that the use of PEDs had no significant difference in relation to the density by layer compared to the case without PEDs, except for the layer 250-300 cm in the situation R = 0.25.

4.7 Passenger space and instantaneous speed

Table 4-12 shows the average longitudinal dimension of the asymmetrical ellipse for each passenger alighting (A_i) in the different scenarios of ratio between boarding and alighting (R) at PAMELA. All cases (total tracked of 450 alighters) of R presented smaller longitudinal back radius than the longitudinal front radius, reaching up to a

22.4% difference when R = 0.25. The standard deviation of the longitudinal front radius was about 26 cm for all cases of R, whilst the longitudinal back radius reached a standard deviation in the range of 14 cm to19 cm.

Table 4-12: Average longitudinal radii of asymmetrical ellipse for each alighter (A_i)

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

A t-Test (two-sample assuming unequal variances) was used with a significance level of 5% (α = 0.05 or 95% of confidence level) to see whether, for each R, there is a significant difference between the longitudinal back radius and longitudinal front radius. The null hypothesis (H_0) was defined as the samples having the same mean. The results of the t-Test showed that the p-value was lower than 0.05 for each R. This means that the null hypothesis is rejected, i.e. there is significant difference between the longitudinal front radius and the longitudinal back radius in each case of R.

An ANOVA test single factor was used with a significance level of 5% (α = 0.05 or 95% of confidence level) to see whether, for each of longitudinal front radius and longitudinal back radius, there is a significant difference between different R. The results of the ANOVA presented p-value lower than 0.05 (significant differences) for the longitudinal front radius, but not for the longitudinal back radius in which the p-value was equal to 0.65.

With respect to lateral radii, Table 4-13 shows that passengers alighting maintained more distance from the right side than from the left side, reaching up to 13% in difference when R = 0.25. This was produced in all scenarios of R (a total of 1464 passengers tracked around the total of 450 passengers alighting). The standard deviation of the lateral left radius was around 25 cm; whilst the lateral right radius in R = 1 reached almost 10 cm lower standard deviation compared to R = 0.25 and R = 4.

Table 4-13: Average lateral radii of asymmetrical ellipse for each alighter (A_i)

R	Number alighters A_i tracked	Lateral right radius (cm)		Lateral left radius (cm)		Diff. Lat.*
		Average	Standard Deviation	Average	Standard Deviation	
4	227	89.02	36.66	78.86	24.21	-11.41%
1	523	85.35	25.36	77.46	23.75	-9.24%
0.25	714	95.05	36.27	82.41	26.01	-13.29%
* Diff. Lat. = Average lateral left radius – Average lateral right radius						

A t-Test (two-sample assuming unequal variances) was used with a significance level of 5% ($\alpha = 0.05$ or 95% of confidence level) to see whether, for each R, there is a significant difference between the lateral right radius and lateral left radius. The results of the t-Test showed that the p-value was lower than 0.05 for each R. This means that the null hypothesis is rejected, i.e. there is significant difference between the lateral right radius and the lateral left radius in each case of R.

An ANOVA test single factor was used with a significance level of 5% ($\alpha = 0.05$ or 95% of confidence level) to see whether, for each of lateral right radius and lateral left radius, there is a significant difference between different R. The results of the ANOVA presented significant differences for the lateral right radius, but not for the lateral left radius in which the p-value was equal to 0.063.

The longitudinal and lateral radii can be plotted for each scenario of R (see Figure 4-21, Figure 4-22 and Figure 4-23). The coordinate (0,0) represents the alighting passenger A_i, who is surrounded by passengers X_i (who were boarding or alighting). The shape of the passenger space changed with respect to each value of R.

Figure 4-21: Maximum, minimum and average asymmetrical ellipse for R = 0.25 at PAMELA

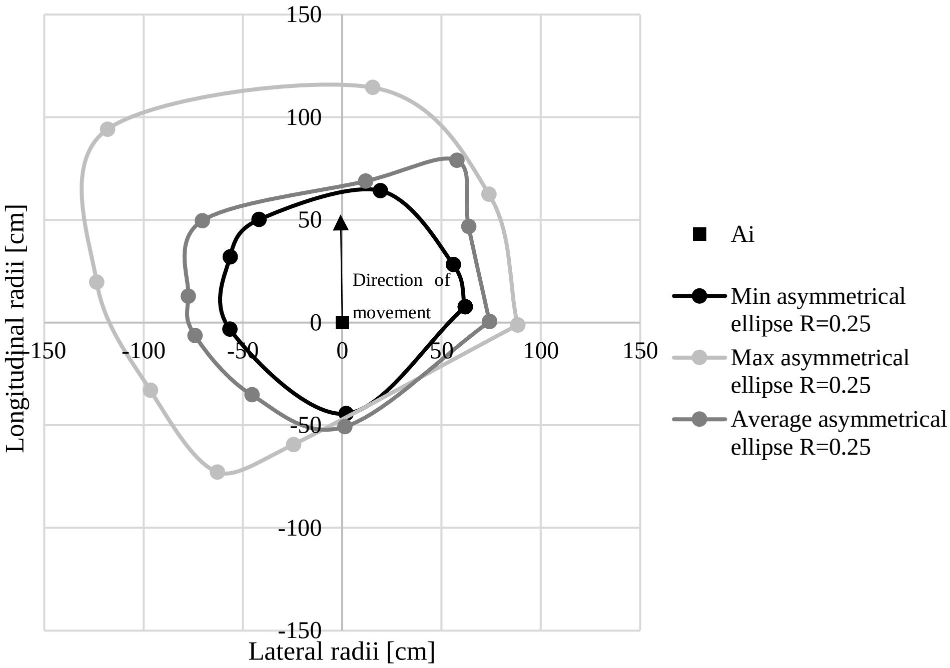


Figure 4-22: Maximum, minimum and average asymmetrical ellipse for R = 1 at PAMELA

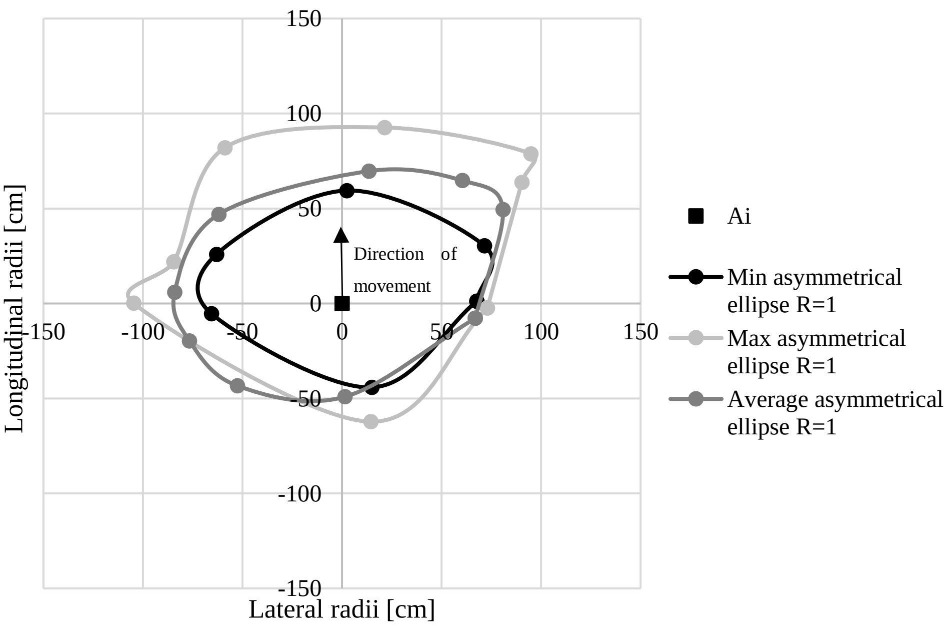


Figure 4-23: Maximum, minimum and average asymmetrical ellipse for R = 4 at PAMELA

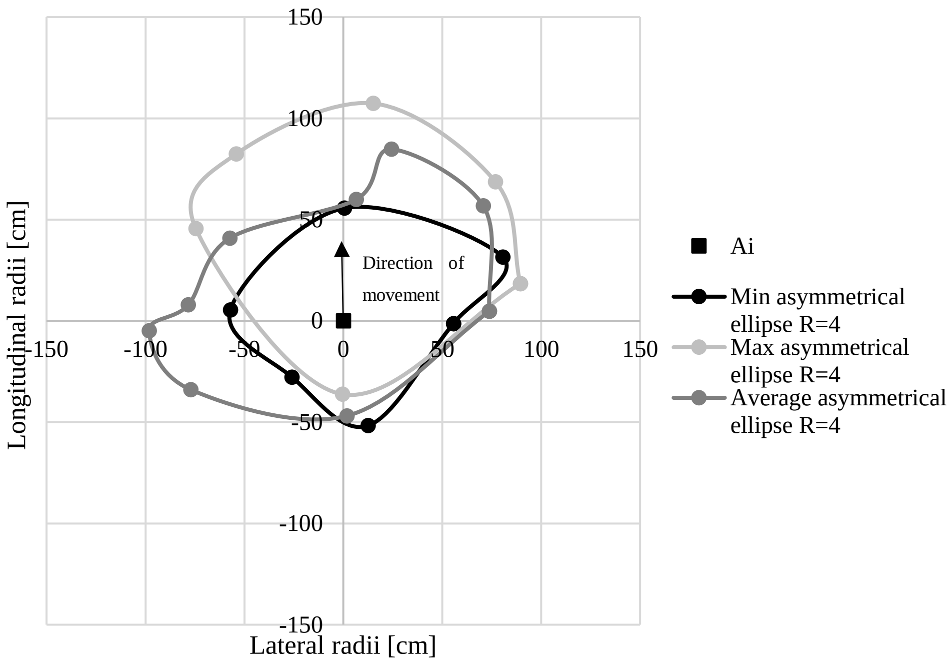


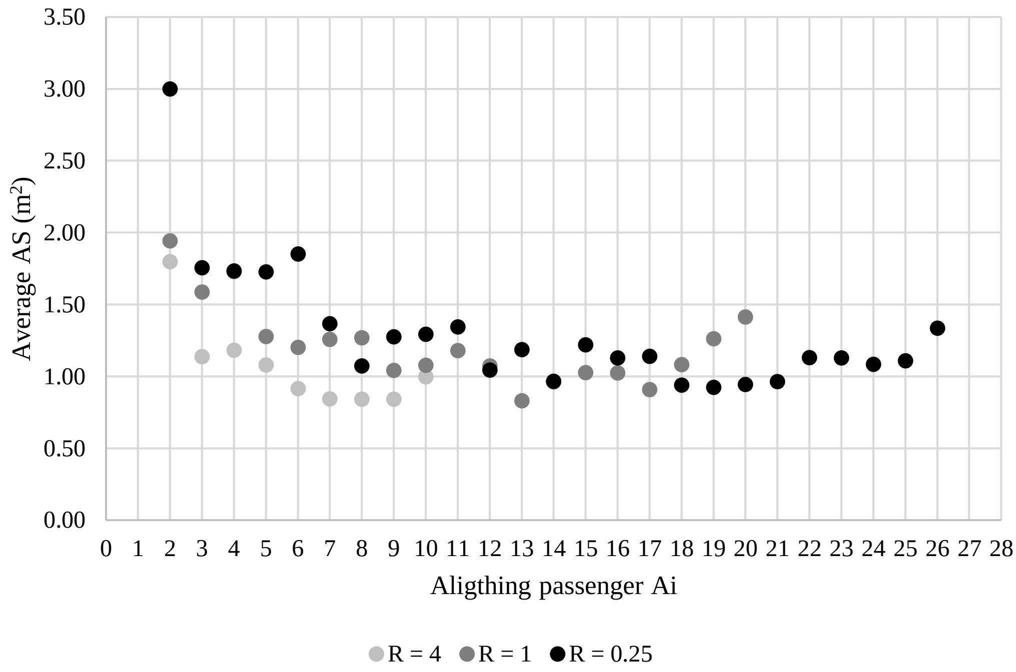
Figure 4-24 shows the average asymmetrical space (AS) for each passenger alighting (A_i) using Equation 3.2 (section 3.5.5). In total 450 alighters were tracked and the three scenarios of R were simulated at PAMELA. The x-axis shows the number of passengers alighting when they came out from the doors (i = 2,..,N_a). The variable AS followed a "U" shape.

With respect to minimum values of AS in Figure 4-24, when R = 1 there are 0.83 m^2/pass or LOS E (passenger A_{13} from a total of 20 alighters). When R = 4 and R = 0.25 the minimum values were slightly higher, reaching 0.84 m^2/pass (passenger A_7 from a total of 10 alighters) and 0.92 m^2/pass (passenger A_{19} from a total of 26 alighters), respectively. In all the cases of R, the minimum values of AS presented a LOS = E.

Regarding maximum values of AS, Figure 4-24 shows that passengers alighting reached a LOS C in the case of R = 1 (1.94 m^2/pass) and R = 4 (1.80 m^2/pass). However, in the case of R = 4 a LOS B was obtained with 3.0 m^2/pass on average, which is 70.45% higher with respect to the following passenger alighting.

In terms of alighting time (t_a), Figure 4-24 shows that the minimum values of AS are reached on average at 11.79 s when R = 1 (equivalent to the 73% of the total average ta = 16.15 s). However, when R = 4, the minimum AS is obtained at 6.38 s which is 77% of the total average t_a = 8.26 s, whilst in the case of R = 0.25 it is reached at 17.05 s (equal to 67% of the total average t_a = 25.37 s).

Figure 4-24: Average asymmetrical space (AS) of each passenger alighter (A_i) according to each R



Similar "U" curves were found in the case without PEDs. To identify if the use of PEDs influenced AS after the doors opened, a t-Test (two-sample assuming unequal variances) was used with a significance level of 5% (α = 0.05) to compare for different R each group (PEDs and No-PEDs). The results show that the only case that presented significant differences were the cases R = 0.25 and R = 1, in which p-value was lower than α = 0.05. In the case of R = 4 there were no significant differences between the scenario with and without PEDs (p-value = 0.31).

The AS can be compared to the overall passenger space (OS), obtained using Equation 3.3 from section 3.5.5 (see Table 4-14).

Table 4-15 shows that, on average, the AS for alighters presented a LOS D for all cases of R, however, the OS reached up to LOS E for R = 4. In other words, the AS reached 0.57 m^2/pass difference compared to the OS when R = 4. In the case of R = 1, this difference is slightly lower, reaching 0.41 m^2/pass, whilst in R = 0.25 the difference is reduced to 0.05 m^2/pass.

Table 4-14: Average asymmetrical space (AS) and overall space (OS) for each run

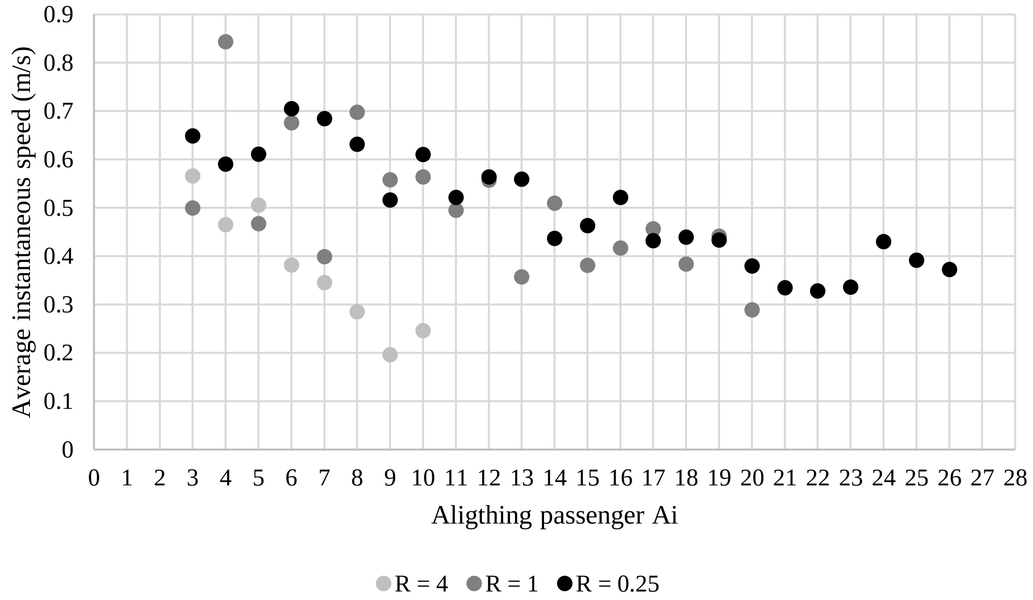
R	Run	1	2	3	4	5	6	7	8	9	10
4	AS	0.75	0.90	1.58	1.97	0.83	1.37	1.10	0.97	1.02	0.99
	OS	0.62	0.54	0.59	0.63	0.58	0.62	0.58	0.53	0.57	0.57
	Dif.	0.13	0.36	0.99	1.34	0.26	0.76	0.51	0.45	0.45	0.42
1	AS	1.02	1.05	1.36	0.85	0.91	1.22	1.70	1.59	1.64	0.96
	OS	0.85	0.92	0.99	0.77	0.74	0.80	0.81	0.77	0.75	0.83
	Dif.	0.18	0.13	0.37	0.08	0.17	0.41	0.89	0.82	0.89	0.13
0.25	AS	1.52	1.54	1.48	1.41	1.00	1.06	1.67	1.43	0.97	1.00
	OS	1.27	1.32	1.84	1.11	1.23	1.14	1.16	1.22	1.05	1.23
	Dif.	0.25	0.21	-0.37	0.31	-0.23	-0.08	0.51	0.20	-0.07	-0.22
Dif. = Average AS - Average OS											

Table 4-15: Average asymmetrical space (AS) and overall space (OS) for 10 runs

R	Average AS (m^2/pass)	Average AS LOS	Average OS (m^2/pass)	Average OS LOS	Dif. (m^2/pass)
4	1.15	D	0.58	E	0.57
1	1.23	D	0.82	E	0.41
0.25	1.31	D	1.26	D	0.05
Dif. = Average AS - Average OS					

In addition, Figure 4-25 shows the average instantaneous speed v_{Ai} of each passenger alighting for each case of R at PAMELA. The average v_{Ai} is obtained for all runs using Equation 3.4 in section 3.5.5. In the case of R = 4, the first alighters reached a higher value than the rest of the passengers alighting, however, this did not occur in the case of R = 0.25 and R = 4. In all cases a linear approximation can be obtained, but not "U" curves as the AS.

Figure 4-25: Average instantaneous speed of each passenger alighter (A_i) according to each case of R



4.8 Discussion

The experimental analysis conducted at PAMELA revealed that the presence of PEDs and level access compared to a stepped PTI was linked to a reduction of approximately 1.4 seconds in the BAT. At the same time, the variability of the BAT was found to increase very slightly (0.8 seconds) in the scenario with PEDs. The magnitude of these changes is small but it can be confidently concluded that when PEDs are present they do not have a detrimental effect on the BAT. In addition, there seem to be few differences in the relative boarding and alighting profiles for the scenarios with and without PEDs, thus suggesting that the fundamental boarding and alighting dynamics (majority of alighters first followed by boarders) are only marginally altered, albeit enough to ease platform flows.

It should be noted as a limitation that, due to cost restrictions, this study could not run a scenario in the PAMELA experiments that investigated PEDs independently of level access. The decision was discussed in detail and it was considered better to test the two practical PTIs than to include a PTI that would not be seen in practice on the LU. However, this does not limit the conclusions as it can be stated that a PEDs PTI shows a minimal improvement on the BAT when compared to a traditional (no PEDs) interface but it cannot be categorically affirmed that PEDs alone are the reason for this.

In this chapter a new method is presented to represent and evaluate the behaviour and interaction of passengers who are boarding and alighting a train and which includes a new space defined as the platform conflict area (PCA). The PCA consists of a semi-circular shape of radius L and a square cell grid to measure the behaviour and density by layers, showing interaction to be higher near the doors and decreasing as the distance from the door increased. Therefore, the PCA is more representative of passengers' interaction and behaviour than other fixed shapes used in the literature such as Shen (2001; 2008), Lu and Dong (2010) and Seriani and Fernandez (2015b).

It is suggested that this method could help traffic engineers and policy makers to evaluate behaviour and interaction for the design of spaces in metro systems. This new method is based on eight variables: the level of demand, BAT, types of queue, formation of lines, distance between passengers, density by layer, passenger space, and instantaneous speed.

As part of the method, based on London Underground stations, 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.

The PAMELA experiments showed an important relationship between R (ratio of passengers boarding to those who are alighting) and the interaction of passengers.. When R was equal to 4, more passengers wait in front of the doors and 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 waited beside the doors until alighting was almost finished to board the train, creating a lower interaction. In addition, when R increased, the number of lines of flow for alighting was reduced, creating a narrow single line when R = 4 (reaching a higher interaction compared to the other two cases of R = 0.25 or R = 1). These results show that the formation of lines of flow in the PTI zone depends not only on the width of the bottleneck at 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).

In relation to the distance between passengers, according to an ANOVA test, the distance between passengers boarding presented significant differences between the scenarios of R. This could be caused due to the differences in the level of demand (e.g. R = 4 had four times more boarding passengers than with R = 0.25) and there was enough space available on the platform for passengers to move. The lack of space produced a high interaction when the distance between passengers boarding reached 60 cm or less, which is 40% lower than the distance of 100 cm (i.e. 50 cm plus two times half the body depth as reported in Fruin, 1971) reported by Hall (1966), Sommer (1969) and Pushkarev and Zupan (1975) when pedestrians felt as 'intimate'. However, the distance between passengers alighting presented no significant differences for the different scenarios of R. This could be caused because the PTI was always packed and little space was available for passengers to alight the train.

In addition, a t-Test was performed to compare the distance between passengers for each scenario of R with and without PEDs. Only the case R = 0.25 presented significant differences. The distance between passengers alighting presented a difference of 5.93 cm in favour of the case without PEDs. In the case of the distance between passengers boarding the difference reached 6.0 cm in favour of PEDs. This mean that the use of PEDs could reduce the distance between passengers alighting when R = 0.25, but could help passengers boarding to maintain a larger distance. A more detailed study would be needed to better understand these differences and their impact on the behaviour and interaction of passengers at the PTI.

At PAMELA, the density by layer or k_L was obtained in the PCA before and after the doors opened. In this first case, the maximum density by layer reached a higher value for R = 4 compared to the other two scenarios of R (R = 1 and R = 0.25). This is caused because when R = 4 there are four times more passengers boarding than in the case of

R = 0.25, and twice the number of passengers of R = 1. The Kruskal–Wallis one-way test supported these results as there was significant differences (p-value < 0.05) in all the cases, except the second layer (50-100 cm) in scenario R = 4 when PEDs were used. In addition, the Mann-Whitney U test presented no significance differences between the case with and without PEDs, except for the layer 4 (200-250 cm) when R = 4 and the layer 3 (100-150 cm) when R = 0.25. Therefore, more runs are needed to better understand if the use of PEDs could present an impact on the maximum k_L.

Before the doors opened, the k_L is more representative of the interaction between passengers boarding than the overall density or k_O (rectangular space) defined by Fruin (1971) and TRB (2000; 2013). When R = 4 and R = 1, there was not a big difference between the maximum value of density by layer or k_L (in which the PCA is divided by layers) and k_O due to the high number of passengers waiting to board the train (≥ 20 passengers). However, in the case of R = 0.25 the value of k_L was 80% more than the maximum k_O due to the few passengers waiting to board the train on the platform (≤ 10 passengers). In static movement (before doors open), a high interaction is obtained when the density by layer is more than 1.10 pass/m^2, which is almost five times less than the value of 5.0 pass/m^2 or Level of Service F (LOS F) reported in Fruin (1971) and TRB (2000; 2013). Nevertheless, the k_L uses the PCA and therefore helps to identify which part (layer) of the platform is more congested, rather than average values of density used in the LOS.

After the doors opened, the k_L 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 in the case with PEDs. 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 1.82 pass/m^2 (3.7 times less than the density by layer).

In relation to statistical analysis, the ANOVA test showed that there is no significant differences with the density by layer when comparing each scenario of R, except for the cases between R = 1 and R = 0.25 in layers 1 to 5 (with PEDs) and layers 1 to 4 (without PEDs). This could be caused by the less number of passengers boarding in R

= 1 and R = 0.25 compared to the case of R = 4 (when R = 4 there are 4 times more passengers boarding than alighting). In addition, the t-Test presented that the use of PEDs have no significant differences with the density by layer, except for the layer 250-300 cm in the case R = 0.25. To better identify if the use of PEDs have an impact on the density by layer, future experiments are needed at PAMELA.

With respect to the passenger space, significant differences in the dimensions of the asymmetrical ellipse were reached for each scenario at PAMELA. The average values for all the three cases of R (4, 1, and 0.25) showed that the lateral left radius was smaller than the lateral right radius. The difference between them could be caused because passengers preferred to maintain a certain distance to avoid collision. This distance can be considered as intimate when a value lower than 100 cm is reached between the heads of two passengers (2 times the body depth defined in Fruin, 1971, plus 0.5 m defined in Hall, 1966; Sommer, 1969; Pushkarev and Zupan 1975). Therefore, the results of this work showed that, on average, the lateral distance between passengers alighting and boarding (pair A_i - B_i) was around 80 cm. However, this distance could be influenced by the behaviour of passengers boarding and the location of the exit gate on the platform, which could be considered as further research.

Similarly, it seems that passengers alighting preferred to maintain a greater distance in front of them than behind them due to collision avoidance techniques. This could be caused because the longitudinal radii are obtained just when each passenger alighting exited the PTI zone, and therefore they have less space from behind as there are more passengers alighting in a reduced space (congested door) compared to the space they have in front (passengers waiting to board give space for those passengers alighting). On average, the longitudinal front and back radii reached a value lower than 100 cm. The results also showed that the value of R had an impact on the longitudinal front radius. In contrast, in all the cases of R passengers maintained a similar distance from behind.

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

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

To avoid situations in which a LOS higher than E (capacity) is reached, the platform width needs to be re-calculated. To obtain the optimum platform width a OS = 0.93 m^2/pass is recommended by LU (2012), while the AS could be used in further research to identify the optimum dimensions of the PTI zone.

In relation to the instantaneous speed, it was expected that "U" curves would be obtained with a correlation to AS, but it was only possible to reach linear approximations. In general, the speed of the first passengers alighting was higher than the rest of the passengers. This can be caused by the fact of the first passengers who alighted having more AS in the PCA than the rest of the passengers. In addition, towards the end of alighting, alighters could have more space between themselves as the supply of alighters from the seating sections of the carriage decreases, however their speed did not increase, which led to the conclusion that not always more space means more speed. This could be related to the field of vision of each passenger, which was not covered in this work. However, further experiments can be carried out at

PAMELA and the results can be compared to existing laboratory studies (Kitazawa and Fujiyama, 2010), in which participants used an eye camera to identify their space.

Chapter 5 Results from LU observations

5.1 Introduction

The objective of this chapter is to develop a framework to study the effect of crowd management measures (CMM) such as platform edge doors (PEDs) on the behaviour and interaction of passengers at existing stations. Firstly, the impact on boarding and alighting time (BAT) is analysed between PEDs with level access and NoPEDs with 170 mm gap in relation to the demand and profiles (section 5.2). Secondly, the effect of BAT is studied between PEDs with level access and NoPEDs with platform hump (section 5.3). Thirdly, the behaviour of passenger is described according to the interaction time (IT), overlap, type of queue and formation of lines of flow (section 5.4). Fourthly, a new framework is proposed based on the London Underground (LU) observations (section 5.5). Fifthly, some recommendations to reduce interaction problems are discussed (section 5.6). Sixthly, these results are discussed in section 5.7.

5.2 Impact on BAT with PEDs and 170 mm gap

In this section the results between having PEDs with level access (WMS) are compared to the results without PEDs and with a vertical gap of 170 mm (GPK). The platform with PEDs presents an average BAT of 23 s (standard deviation of 7.1 s) which is 0.3 seconds shorter than the platform without PEDs (23.3 s and standard deviation of 8.5 s), when calculated from a corrected BAT. Although these differences are small in real terms and could be considered negligible, there could be an influence on the level of demand.

The relative boarding and alighting profiles for the LU observations are shown in Figure 5-1 and Figure 5-2, respectively. They have been constructed as relative profiles to isolate the effect of demand and get the boarding and alighting patterns out of the shape of the curves. To calculate the relative boardings (alightings) at each 5 s segment, the number of boarders (alighters) is divided by the total number of boarders (alighters) in that boarding (alighting) process.

Figure 5-1: Average relative boarding profiles with PEDs and level access (Westminster - WMS) and without PEDS and with a 170 mm vertical gap (Green Park - GPK)

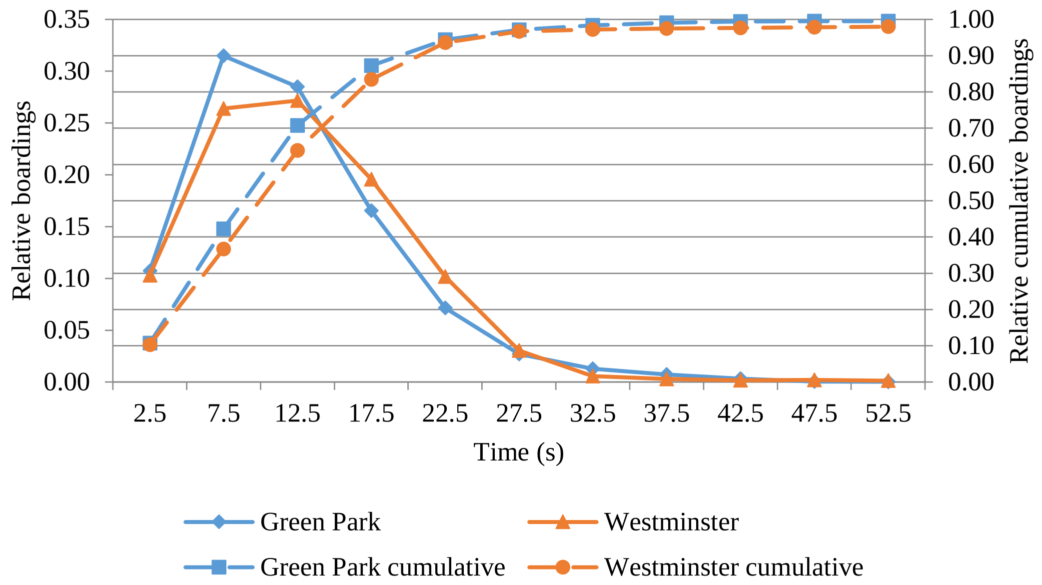
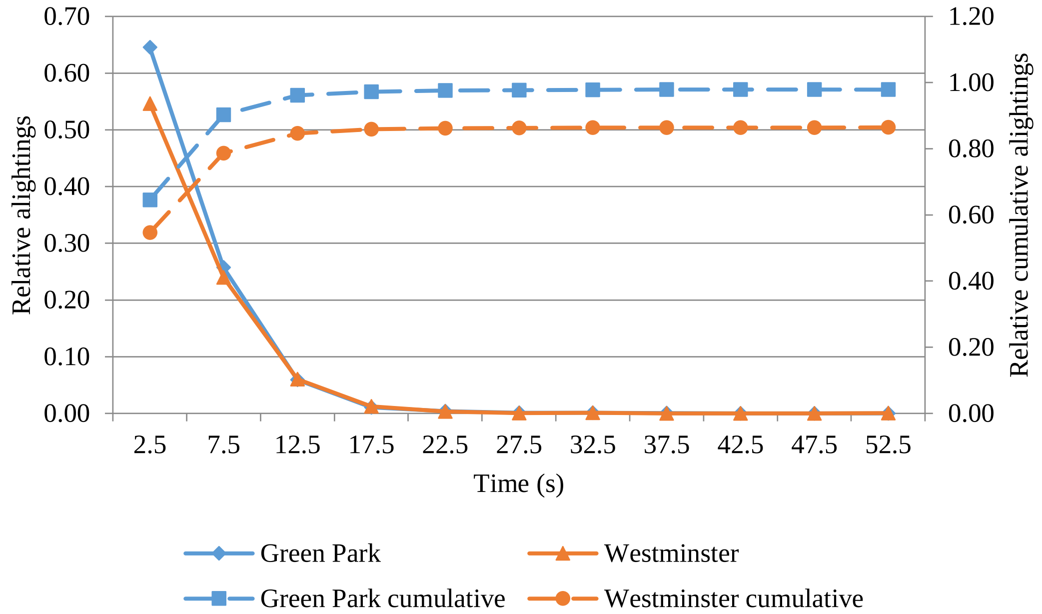


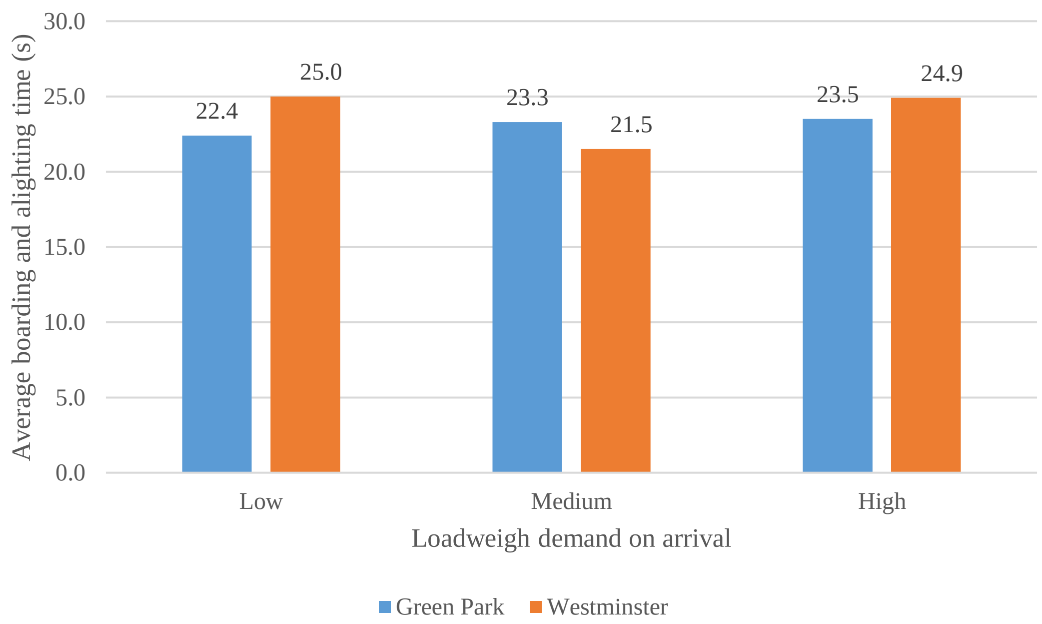
Figure 5-2: Average relative alighting profiles with PEDs and level access (Westminster - WMS) and without PEDS and with a 170 mm vertical gap (Green Park - GPK)



It can be seen that, in general, the profiles are very similar with and without PEDs both for boardings and alightings. Looking more closely at the boarding profile in Figure 5-1, it is clear that there is a higher and earlier peak of boarders at GPK, but then the curve gets closer to zero earlier, whereas at WMS the peak of boarders occurs a bit later (probably due to people giving way to alighters) and the curve approaches zero later, in such a way that these two opposing effects balance each other and, overall, the boarding process is completed at approximately the same time, as shown by the cumulative boardings profile. This pattern was consistently repeated across a range of different boarders' proportions and using the corrected numbers of boarders and alighters, therefore it is considered to be generic.

With respect to the train demand on arrival (Figure 5-3), PEDs reduce BAT in 1.8 s for medium on-train demands, which is in accordance with the PAMELA experiments (section 4.3), but increase BAT in 2.6 s and 1.4 s on low and high train demands, respectively.

Figure 5-3: BAT with PEDs and level access (Westminster - WMS) and without PEDS and with a 170 mm vertical gap (Green Park - GPK) with respect to demand on arrival



However, it is important to acknowledge some limitations of the data presented in Figure 5-3. First, the accuracy of the low-medium-high classification is rather low, and secondly there does not seem to be a clear advantage or disadvantage of PEDs since BAT does not increase or decrease consistently with demand at each station.

In terms of the total number of boardings and alightings, it can be seen in Figure 5-4 that the higher this number is, the longer the BAT. However, the difference between PEDs and no PEDs is not consistent and favours no PEDs in the two first categories (+2.5 s and +2.7 s mean BAT), but PEDs (-0.4 s mean BAT) when total boardings and alightings exceeded 25.

Figure 5-4: BAT with PEDs and level access (Westminster - WMS) and without PEDS and with a 170 mm vertical gap (Green Park - GPK) with respect to the total number of boardings and alightings

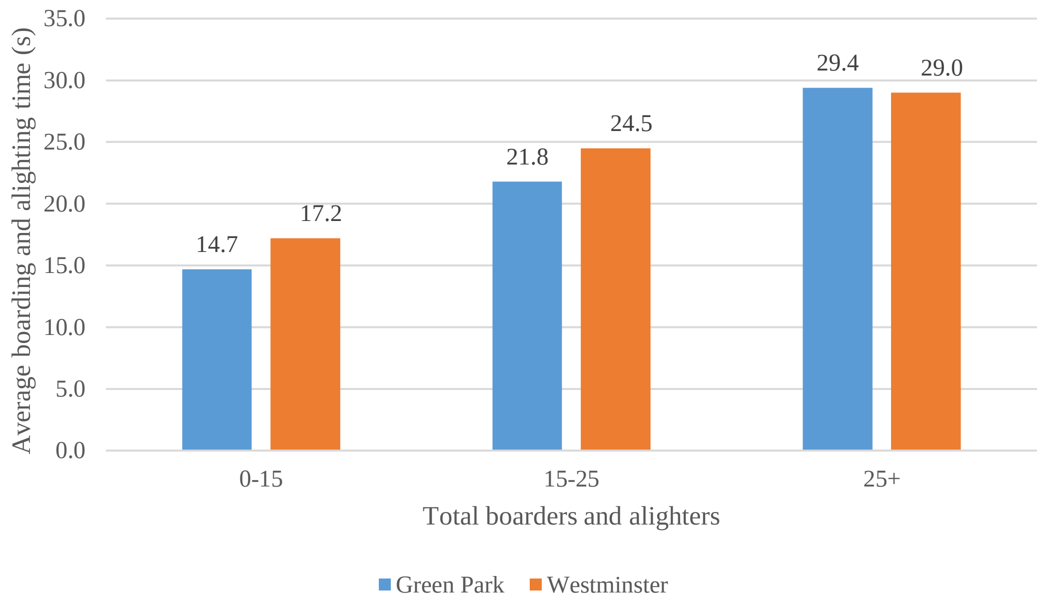


Table 5-1 shows the number of observations and standard deviation of the corrected BAT with respect to the train demand on arrival and total boardings and alightings. In the case of GPK 1610 observations were analysed, while at WMS 1703 observations were studied. The standard deviations presented low values and in any case reached two or more times the average BAT presented in Figure 5-3 and Figure 5-4. The difference in the standard deviation between GPK and WMS was in the range between -3 s and +2 s, which is not consistent and did not favours PEDs.

Table 5-1: Number of observations and standard deviation of the corrected BAT with PEDs and level access (Westminster - WMS) and without PEDs and with a 170 mm vertical gap (Green Park - GPK) with respect to demand metrics

Metric	Level	Number of observations		Standard deviation of corrected BAT (s)		
		GPK	WMS	GPK	WMS	Diff.
Train demand on arrival	Low	61	10	10.1	9.4	-0.7
	Medium	928	945	9.7	6.9	-2.8
	High	621	748	6.0	7.0	+1.0
Total boardings and alightings	0-15	333	554	5.4	5.8	+0.4
	15-25	646	809	5.9	5.4	-0.5
	25+	631	340	7.4	5.8	-1.6
Note: Diff. = Difference						

5.3 Impact on BAT with PEDs and level access

Table 5-2 shows summary statistics of the average BAT and numbers of boarders and alighters at the two stations, with and without PEDs when level access was used (i.e. between the two double doors at WMS and the double door with platform hump at GPK). At face value, the case without PEDs presents an average BAT which is 16% lower than in the case with PEDs.

Table 5-2: Observed average BAT with PEDs and level access (Westminster) and without PEDs and platform hump (Green Park)

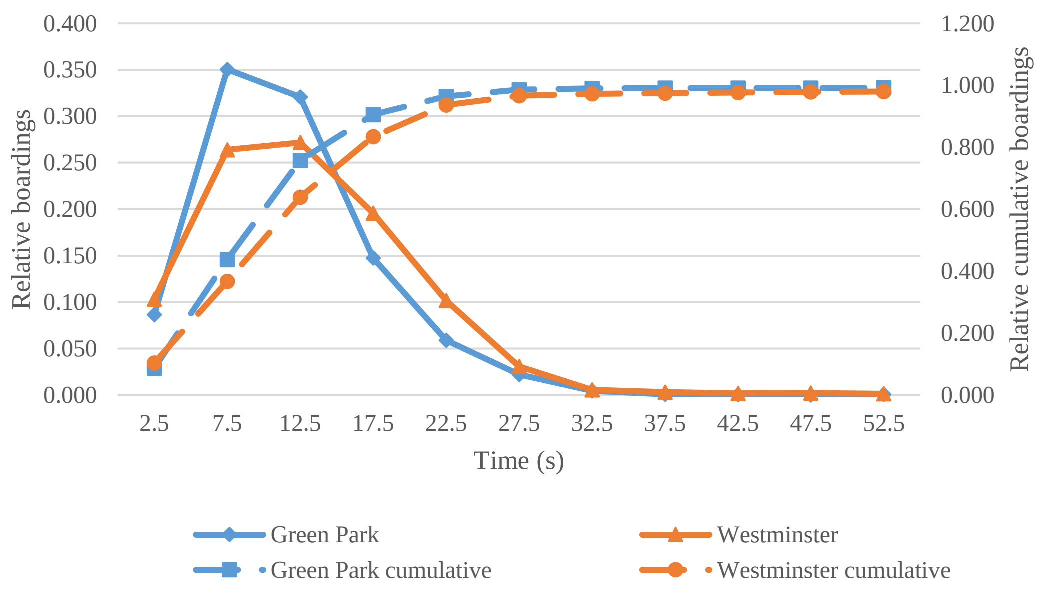
Variable (average over observations)	Westminster (1)	Green Park (2)	Difference to PEDs (2 with respect to 1)
BAT (s)	23.0	19.4	-16%
P_a (passengers)	6	5	-16%
P_b (passengers)	12	7	-42%
$P_a + P_b$ (passengers)	18	12	-33%
$R = P_b/P_a$	4.8	1.8	-63%

However, it is difficult to draw simple conclusions about the BAT from Table 5-2 because it is influenced by demand, and, as it can be seen, the case without PEDs

(GPK) has an average number of passengers boarding and alighting ($P_a + P_b$) which is 33% lower than in WMS, where there are PEDs, and a much greater difference between boarders and alighters, as given by the different ratios (R).

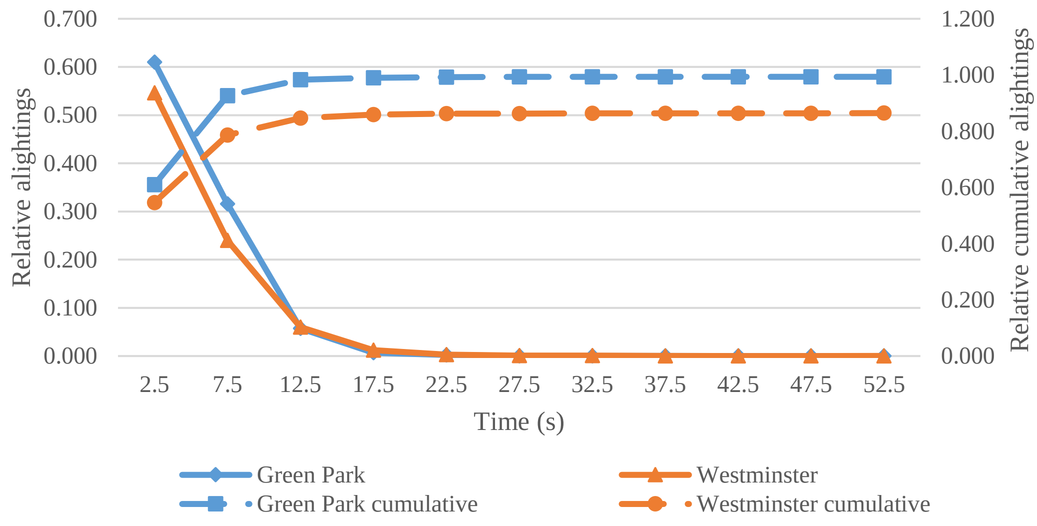
Figure 5-5 and Figure 5-6 show the average boarding and alighting profiles, respectively. These profiles are constructed using the same criteria explained in section 5.2. It can be seen in Figure 5-5 that the case without PEDs (GPK) has a higher and earlier peak value in the boarding profile as compared to the case with PEDs (WMS). However, even if boarding peaks later in the case of PEDs (probably due to people giving way to alighters), the boarding profiles then converge to zero at almost the same time, so that in both cases most passengers have boarded before 32.5 s. In other words, the earlier peak is compensated by a quicker drop to zero. The largest difference in the cumulative boarding profiles occurs after 12.5 s, where on average 11% more passengers boarded at GPK compared to WMS, but this difference fades away at 32.5 s.

Figure 5-5: Average relative boarding profiles with PEDs and level access (Westminster - WMS) and without PEDS and platform hump (Green Park - GPK)



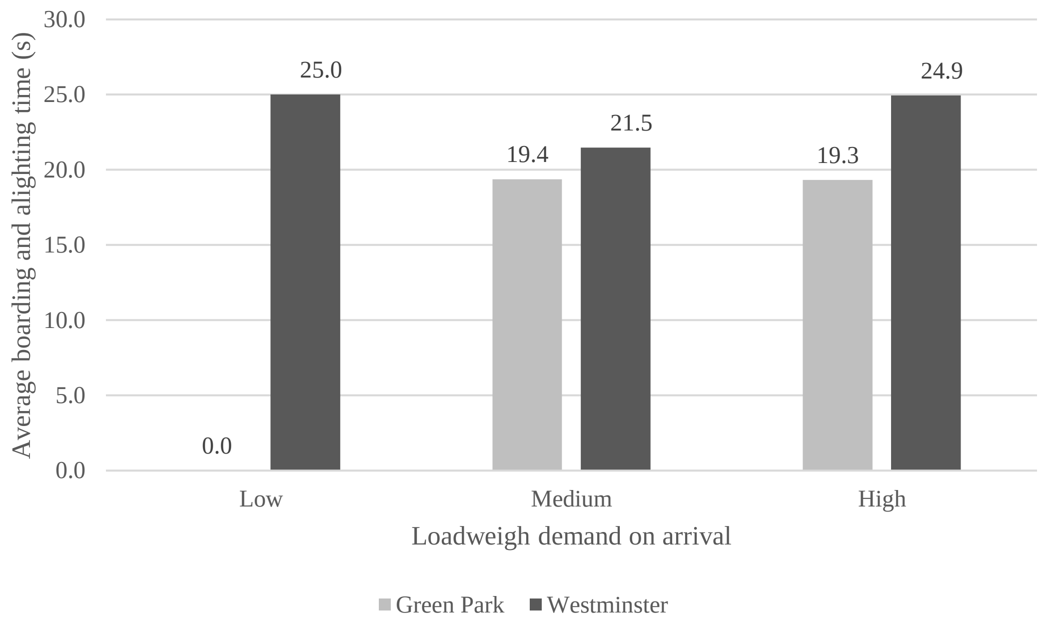
The alighting pattern is much more consistent, and a similar cumulative alightings profile have been plotted in Figure 5-6, in which the largest difference between PEDs and no PEDs would have occurred after 7.5 s and been approximately 14% more passengers alighting at GPK (no PEDs) compared to WMS (PEDs), but the difference virtually disappears after 12.5 s.

Figure 5-6: Average relative alighting profiles with PEDs and level access (Westminster - WMS) and without PEDS and platform hump (Green Park - GPK)



In relation to the train demand on arrival, Figure 5-7 shows that PEDs seem to increase BAT for medium and high on-train loads in 2.1 s and 5.6 s, respectively. However, there are no “low” loads reported for the hump door (no PEDs). This could be because those demand levels are actually not reached. However as explained in section 5.2 it is important to emphasise the limitations of these data, which firstly are not very accurate in their distinction among low-medium-high and secondly come from a separate dataset which has to be matched to the observations, which could have introduced some mismatch errors. Therefore, any conclusions in this regard should be treated with circumspection.

Figure 5-7: BAT with PEDs and level access (Westminster - WMS) and without PEDS and with platform hump (Green Park - GPK) with respect to demand on arrival



With respect to the total number of boarders and alighters, Figure 5-8 shows that the BAT increases with the number of total passengers, as is expected. In general, there do not seem to be big differences in the BAT between the doors with and without PEDs in any of the categories. In the first two categories, these differences are lower than 1 s and favour the absence of PEDs. However, in the third category (when the total boardings and alightings exceed 25 passengers) the average difference of 1.96 s favours PEDs.

Figure 5-8: BAT with PEDs and level access (Westminster - WMS) and without PEDS and platform hump (Green Park - GPK) with respect to the total number of boardings and alightings

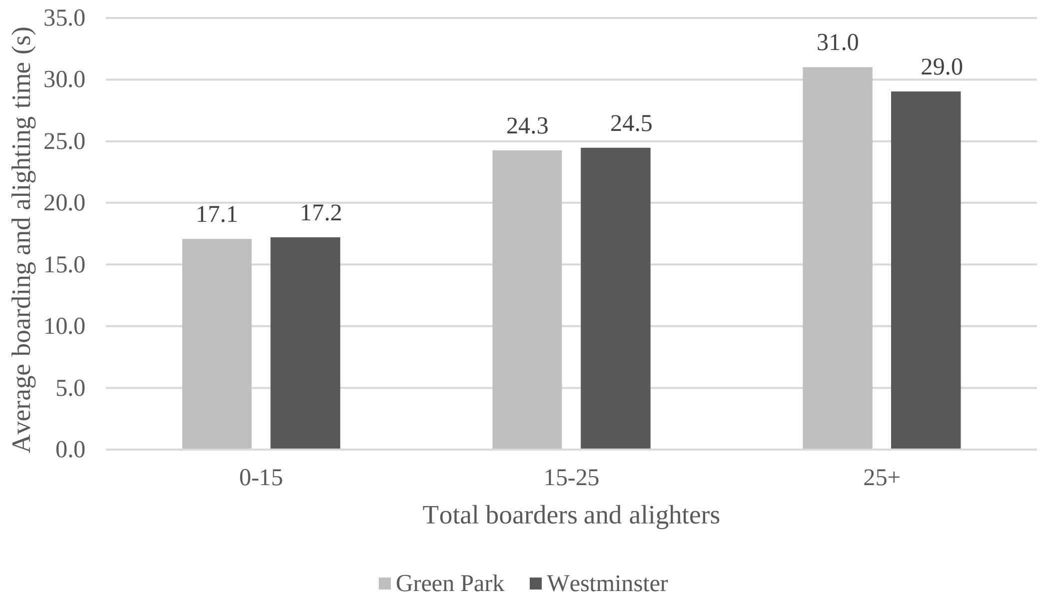


Table 5-3 shows the number of observations and standard deviation of the corrected BAT in relation to the train demand on arrival and total boardings and alightings. In the case of GPK 615 observations were analysed, while at WMS 1703 observations were studied. Similar to the results in section 5.2 the deviation standard reached a low value and in any case represented two or more times the average BAT obtained in Figure 5-7 and Figure 5-8.

The low number of observations at GPK in Table 5-3, in particular only 5 cases for the group 25+ passengers, could be deemed as a limitation to these initial conclusions. However, the platform hump door used for the study was the only door at that station with level access and access arrangements comparable to those at WMS, and the only one for which data are available. For some reason, that door did not receive high levels of demand, which is not the case with other doors at GPK (without hump). It is beyond the scope of this thesis and would require further research to explore whether the hump itself is the reason why demand levels of more than 25 passengers are so rarely observed at that door or whether it is down to other factors or is even random.

Table 5-3: BAT with PEDs and level access (Westminster - WMS) and without PEDs and platform hump (Green Park - GPK) with respect to demand metrics

Metric	Level	Number of observations		Standard deviation of corrected BAT (s)		
		GPK	WMS	GPK	WMS	Diff.
Train demand on arrival	Low	-	10	-	9.43	-
	Med-ium	286	945	6.44	6.88	+0.45
	High	329	748	6.37	6.96	+0.60
Total boardings and alightings	0-15	422	554	5.69	5.85	+0.16
	15-25	188	809	4.76	5.42	+0.65
	25+	5	340	4.18	5.82	+1.63
Note: Diff. = difference						

5.4 Impact on IT, types of queue and formation of lines

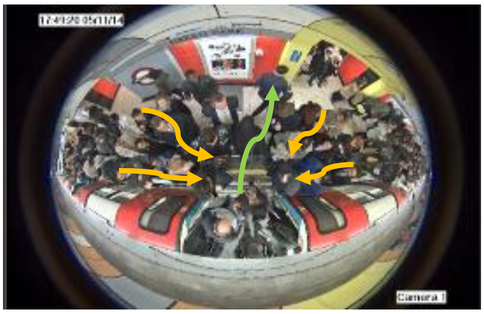
The interaction time (IT) and platform behaviour (types of queue and formation of lines) was obtained with and without PEDs when level access was used (i.e. between the two double doors at WMS and the double door with platform hump at GPK).

From the observation at GPK and WMS stations, the typical patterns of behaviour between boarding and alighting were identified (see Figure 5-9). Three types of interaction were identified between the opening and closing of doors: only alighting (when boarding passengers were waiting on the platform), overlap (when boarding and alighting occurred simultaneously), and only boarding (when alighting was complete). The process started when the first passenger entered the PTI (step 1). When the train doors commenced opening, passengers started to form queues (step 2). Then between one and two alighting lines of flow were produced (step 3). When the alighting process was complete, up to 3 lines of flow were formed for boarding (step 4). Then the last passenger exited the PTI (step 5), and the process ended when the doors closed (step 6).

Figure 5-9: Typical pattern of behaviour between boarding and alighting at Green Park

1. Train arrival; 1st passenger enter PTI

2. Train door opening; formation of queues



3. Alighting first (1 line); wait at side of doors

4. Alight completed; 3 lines formed for boarding

5. End boarding; last passenger exit PTI

6. Train door closes

In the case of WMS, the use of PEDs helped passengers to know where the doors were located on the platform. Thus, when a high-density situation was reached passengers formed an “arch” (see Figure 5-10). This “arch” shape is created by tracking the head of each passenger waiting to board the train and then drawing some lines to connect each of these heads. The “arch” in Figure 5-10 registered 35 passengers on the platform, forming different layers that inspired the idea of platform conflict area (PCA) defined in section 3.5.

Figure 5-10: Arch behaviour of passengers waiting to board at Westminster

The lines of flow in Figure 5-9 are the spaces created that enable passengers to move on or off the train. 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, resulting in less interaction between passengers boarding and alighting. When R = 1, passengers waited until segment 10-15 s to start boarding the train, reaching a medium interaction. In the case of R = 4, passengers started to board earlier (from the segment 5-10 s) 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, resulting in more interaction between passengers boarding and alighting.

Figure 5-11 shows the frequency of events at both stations with respect to five categories of the ratio R (passengers waiting to board/passengers alighting). 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 5-11: Frequency of events by category of R (B/A) at GKP and WMS

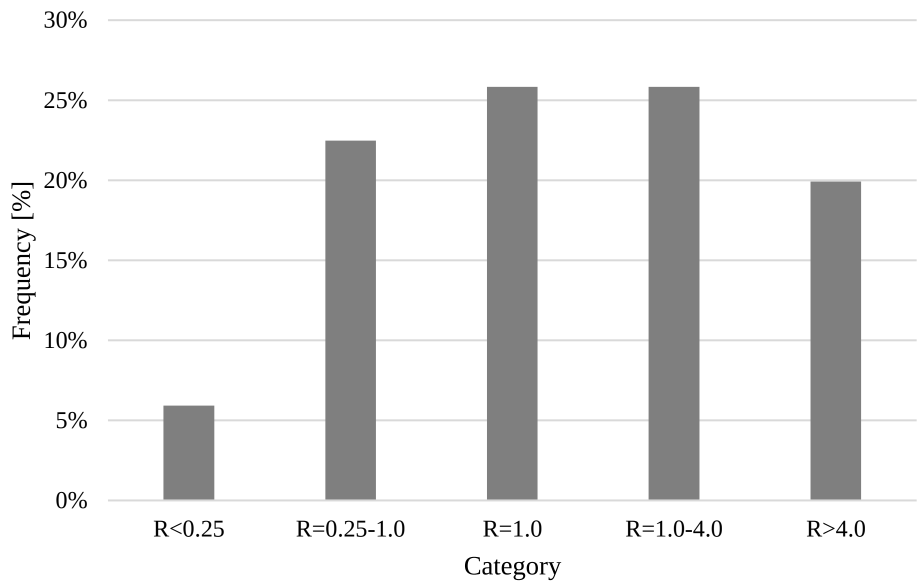
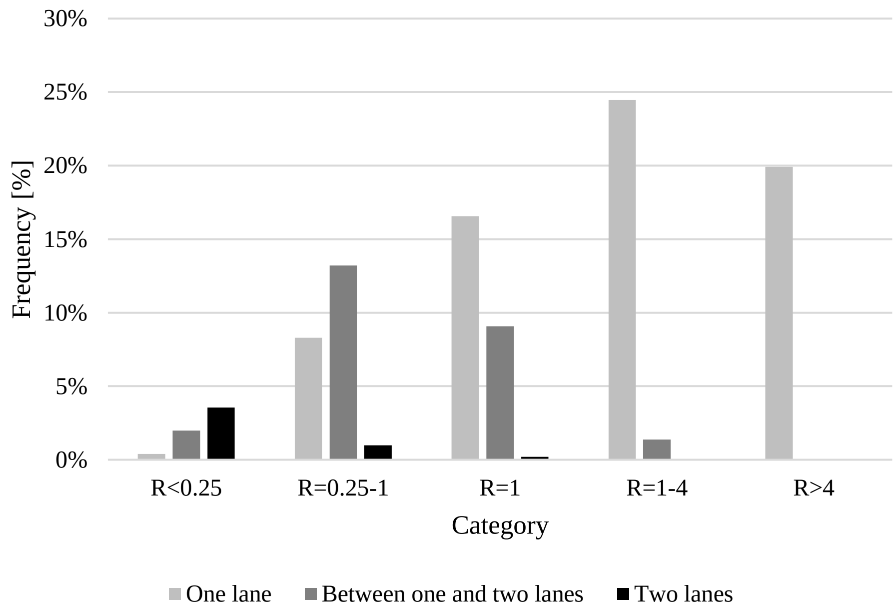


Figure 5-12 shows the relationship between the number of lines of flow formed for alighting and the ratio R (B/A) at both stations. For low R (R < 0.25) up to two lines for alighting are formed, reaching 60% of the cases in that category, whilst the other 40% of the cases presented between one and two lines for alighting. The two lines are formed due to the available space on the platform. When this space is reduced, then the number of lines is reduced, too. When there are between one and two lines, 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 line for alighting.

As the value of R increases, the number of lines is reduced. In Figure 5-12, within the category R = 1, 64% of the cases show only one line for alighting, whilst the rest of the observations in that category present between one and two lines. In this category (R = 1), virtually no events showed two lines for alighting.

For high values of R (4 or more), Figure 5-12 shows that only one line 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 line is formed for alighting.

Figure 5-12: Relationship between number of lines and R (B/A) at GKP and WMS



With respect to the location of passengers, Figure 5-13 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 = 8 passengers are distributed in six layers in the platform conflict area (PCA) defined in section 3.5. The first layer (0-50 cm) is not used, due to the yellow safety line, which is respected by passengers. 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 (see Figure 5-14).

Figure 5-13: Average location of passengers on the platform waiting to board the train at GPK in the AM and PM peak hours

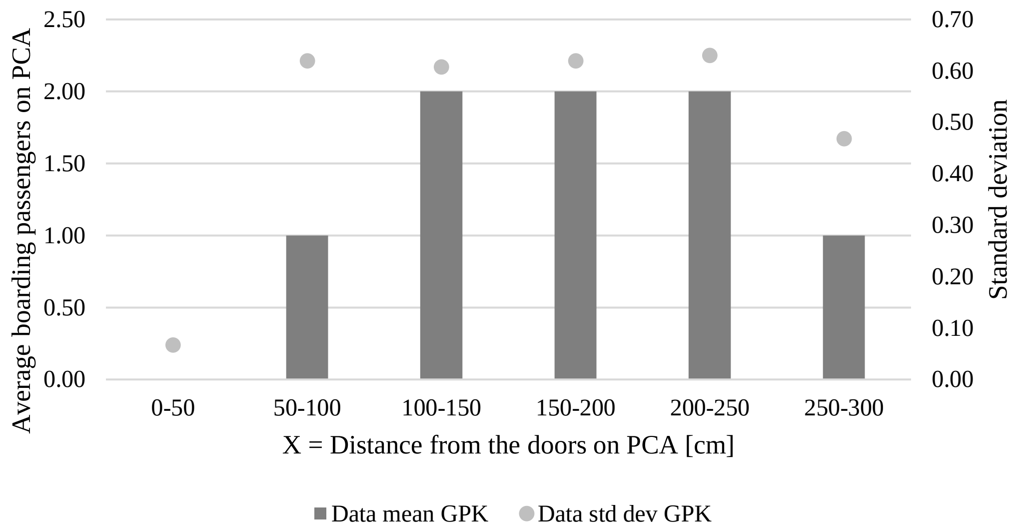
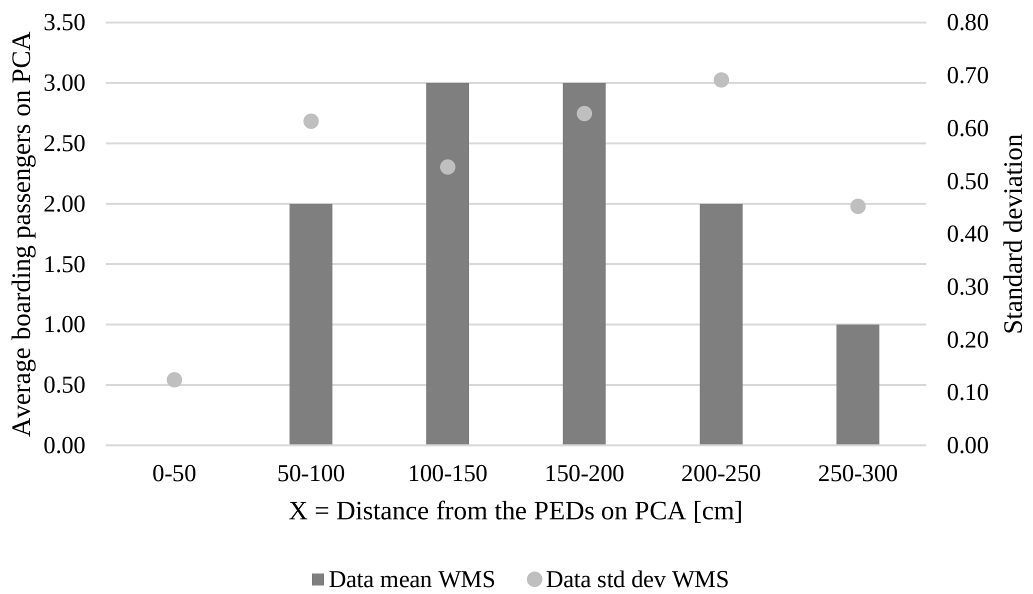


Figure 5-14: Average location of passengers on the platform waiting to board the train at WMS in the AM and PM peak hours



As a complementary visualisation tool of the distribution of passengers on the platform by layers, Figure 5-15 shows the occupation 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, as a consequence of the occupation at the PTI zone, interaction problems can be reached based on the density of passengers and potential risks such as agglomeration, high pressure, “crossing of flows”, collision and “confined flow”. The green colour represents a low occupation area, whilst the red colour denotes high occupations. Medium occupations are symbolised by an amber colour.

Figure 5-15: Average occupation maps on the platform at WMS and GPK

Platform with PEDs

	1	2	3	4	5	6	7	8	9	10	11	12
A	1	0	0	1	1	2	1	1	1	1	1	2
B	2	1	2	3	2	1	2	2	3	2	2	4
C	3	3	3	3	3	4	3	4	4	4	4	3
D	3	5	5	7	5	5	5	5	6	4	5	4
E	4	7	6	8	6	4	3	6	7	7	7	5
F	2	7	7	9	6	3	3	6	7	6	6	5
G	2	5	7	12	15	3	3	9	16	7	7	4
					D	O	O	R				
	Train											

Platform without PEDs

	1	2	3	4	5	6	7	8	9	10	11	12
A	2	1	2	2	1	1	1	1	1	1	1	2
B	2	2	2	2	3	3	2	3	3	3	5	4
C	3	2	2	3	2	2	1	3	3	2	3	3
D	3	4	3	4	3	5	4	4	4	4	3	3
E	5	6	5	6	6	5	5	4	6	4	7	6
F	6	7	7	8	9	8	8	7	11	5	8	5
G	0	1	1	1	2	1	1	2	2	1	1	1
					D	O	O	R				
	Train											

Key:
Low
Medium
High

In Figure 5-15 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 with 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 (without PEDs), Figure 5-15 shows that passengers are more evenly distributed on the platform and 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 with the same cells at WMS (with PEDs), 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 with WMS, in which all the platform width is used.

The standard deviation of the number of times each cell is used was also calculated for the 5 days sample (AM and PM). In both cases (GPK and WMS) the standard deviation resulted in a range between 0 to 4. The standard deviation decreases as the distance from the doors increases, i.e. those cells closer to the doors presented a higher standard deviation than those cells near the platform wall.

In relation to the types of queue, Figure 5-16, Figure 5-17 and Figure 5-18 compares boarding passengers' behaviour between the situation without PEDs (GPK) and the case with PEDs (WMS) for low, medium and high demand levels, respectively. The percentages quoted are calculated as the frequency of each behaviour in each category (0-15, 15-25, >25 of passengers boarding) divided by the total number of observations in that category. For example, Figure 5-16 shows the percentage of observations with respect to low demand levels (0-15 passengers boarding), in which from the total observations at WMS, 20% of passengers wait in front of the doors, 56% of the passengers wait beside the doors, and the rest wait in front and beside the doors. In the case of GPK, Figure 5-16 shows that 4% of passengers wait in front of doors, 45% of passengers wait beside the doors, and the rest wait in front and beside the doors. The data are binned according to the total number of boarders, because people place themselves in positions on the platform based on the number of passengers surrounding them, which has been seen to have an impact on behaviour, and this seems to be the best way of capturing that.

From Figure 5-16 (0-15 passengers), the case with PEDs (WMS) presents more passengers waiting in front of the doors than at GPK (no PEDs). This behaviour did not change when the demand increased, so that for medium (15-25 passengers in Figure 5-17) and high (more than 25 passengers in Figure 5-18) demand levels there were more passengers waiting in front of the doors at WMS (PEDs) than at GPK (no PEDs). In addition, PEDs seem to encourage passengers to wait beside the doors for low (Figure 5-16) and high (Figure 5-18) demand levels, thus reducing the conflict at the PTI, but not for the medium demand situation.

In the case of special situations when there are passengers everywhere around the doors, the case with PEDs in Figure 5-16 (low demand levels) presents fewer passengers waiting in front and beside the doors than the case without PEDs. However, this behaviour changed when the level of demand reached medium levels (Figure 5-17), when no relevant differences were found between WMS and GPK.

Figure 5-16: Passengers' behaviour with respect to low demand level (0-15 passengers boarding)

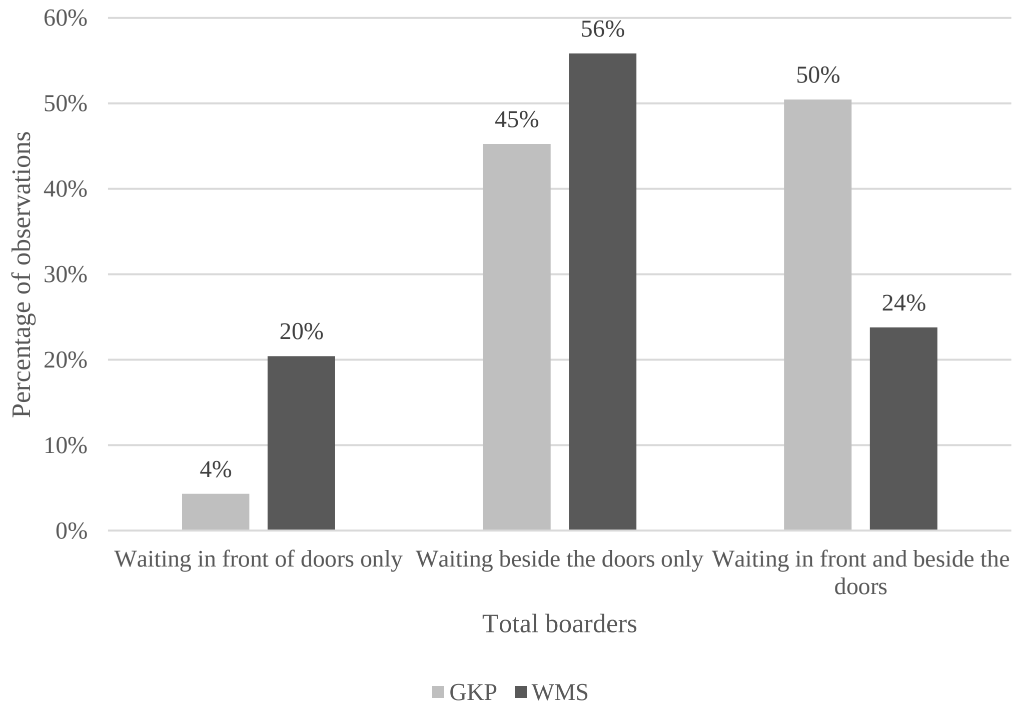


Figure 5-17: Passengers' behaviour with respect to medium demand level (15-25 passengers boarding)

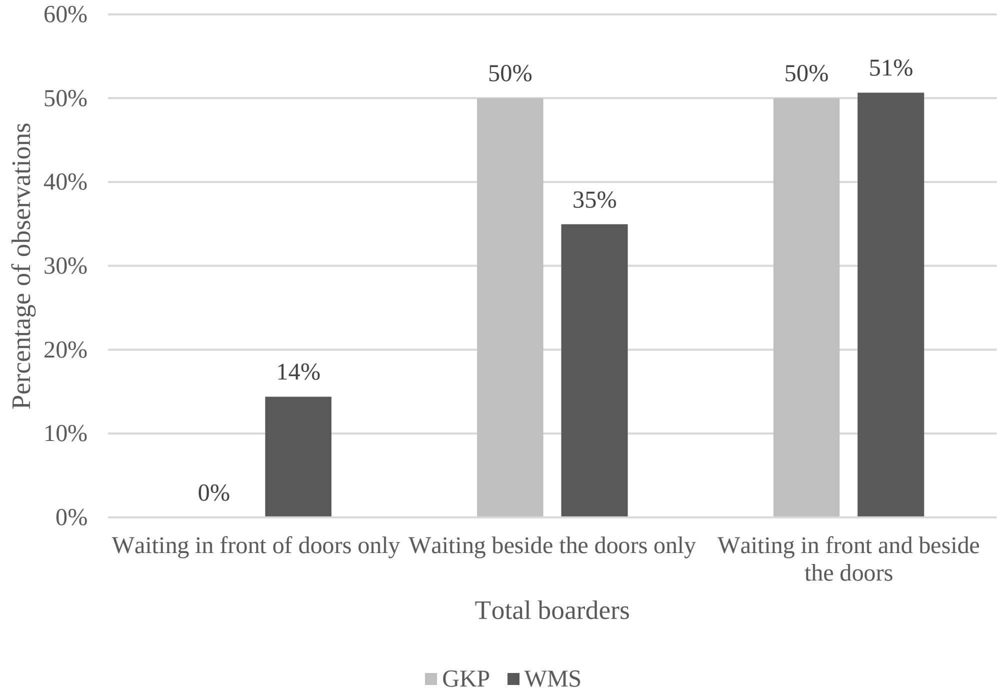
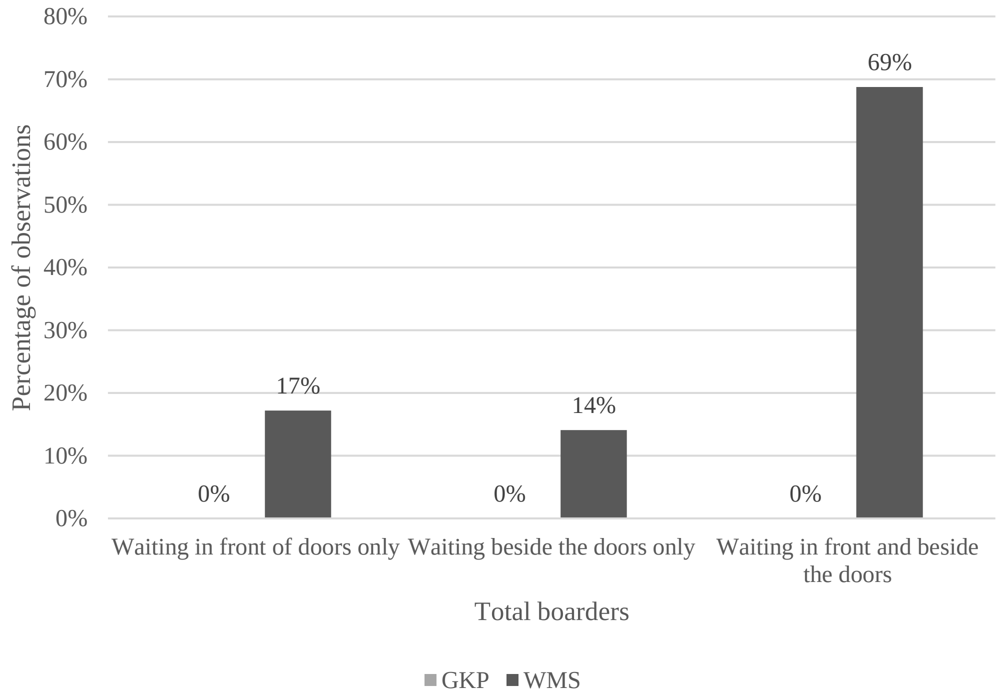


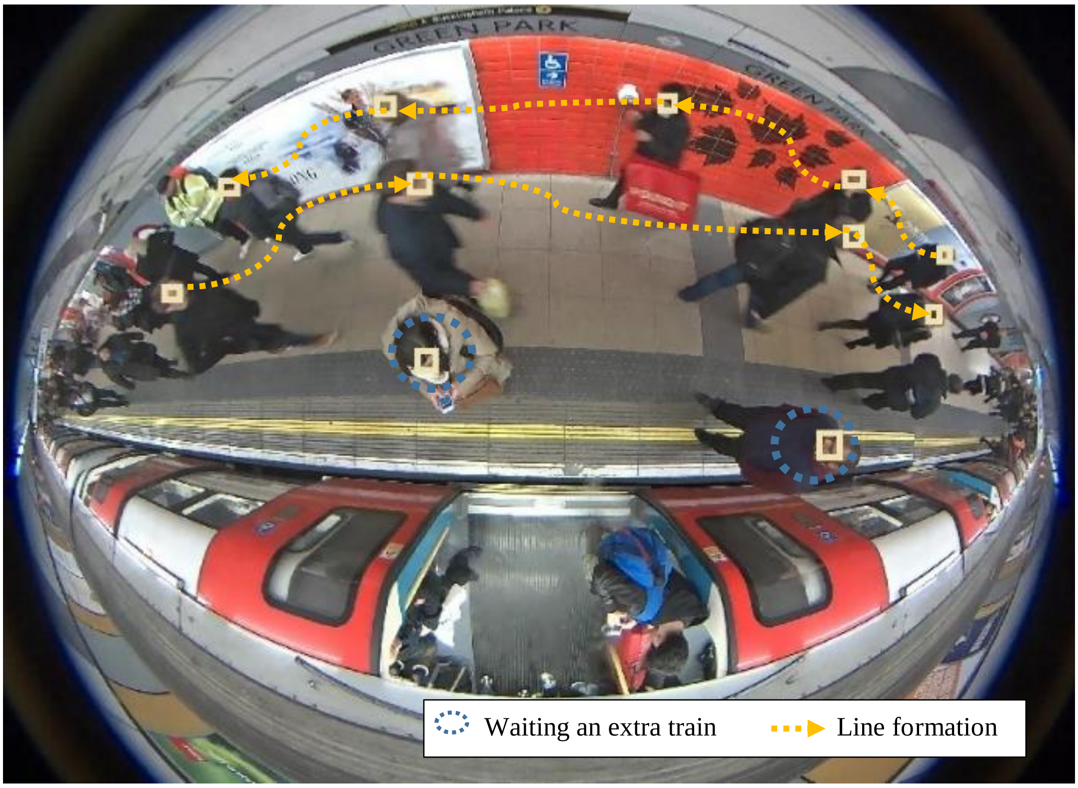
Figure 5-18: Passengers' behaviour with respect to high demand level (>25 passengers boarding)



When the boarding and alighting finishes, another behaviour pattern was observed at the hump door in GPK (Figure 5-19). In 22% of the observed trains, passengers preferred to stand on the platform and wait for the next service (135 out of a total of 615 trains). There are two main reasons why a person would decide not to board the train that is currently on the platform. One is that there is not enough space available inside for them to feel comfortable and willing to board, and the other is that their destination station may not be served by the current train, which happens at GPK because some southbound Jubilee line services short-trip a few stations before the last one. However, with the available data, it is impossible to determine what the true reason in each case is.

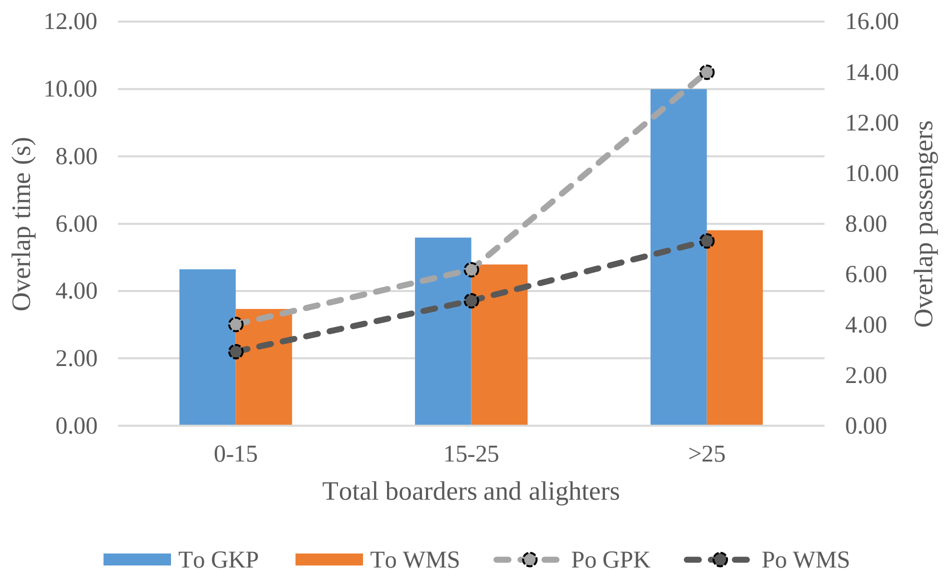
At the same time, a circulation space was formed between the platform wall and the standing passengers on the platform, where passengers naturally form flow lines to avoid collisions with people coming in the opposite direction (Figure 5-19).

Figure 5-19: Passenger behaviours at the hump door (Green Park, no PEDs)



The amount of overlap in the boarding and alighting process is another indicator of passengers' behaviour and interactions. At an aggregate level, there seem to be no major differences between PEDs and no PEDs in terms of overlap. However, Figure 5-20 shows that the average interaction time (IT) and the average number of overlapping passengers (P_o) changed with respect to the total boarders and alighters. For low (0-15 passengers) and medium (15-25 passengers) demand levels the difference in IT is about 1 s in favour of PEDs, however, this difference reached up to 4 s for the high demand situation. Similarly, with respect to P_o no major differences are presented between PEDs and no PEDs for low and medium demand levels, but for the high demand situation this difference reached up to 6 passengers in favour of PEDs.

Figure 5-20: Average interaction time (To) and overlap passengers (Po) with (Westminster - WMS) and without PEDs (Green Park - GPK) with respect to total number of boarders and alighters



5.5 BAMBI framework

From the results obtained in the LU observation (GPK and WMS) 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.

5.5.1 Conceptual model

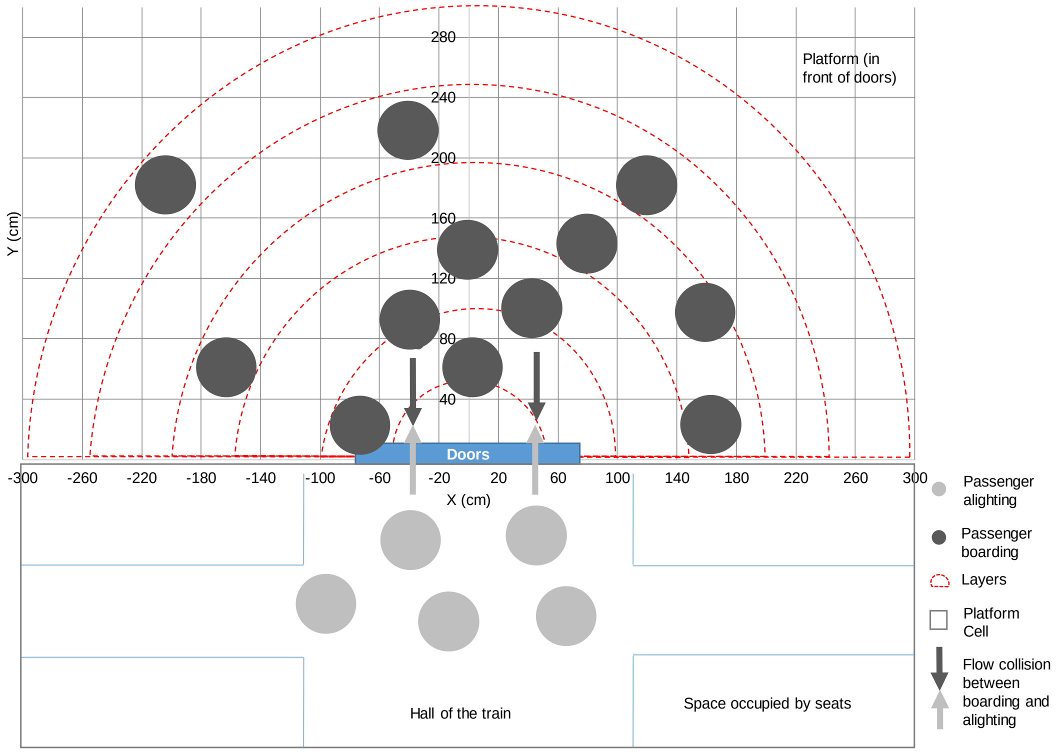
Firstly, a conceptual model is created to represent the interaction problems observed in GPK and WMS (see Figure 5-21). Rectangles are used to represent the main infrastructure and arrows to show the direction of passenger flows. The main infrastructure is classified into three elements of circulation: 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 conceptual 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. As explained in section 3.5 the use of cells to represent the platform area helps to obtain the density in terms of 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 conceptual 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 defined as the platform conflict area (PCA) divided into concentric layers of 50 cm each, using the method proposed in section 3.5. 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 5-21, 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.

According to the results obtained in the LU observations, passengers' interaction in Figure 5-21 can be classified into three categories (type of users): interaction between passengers boarding (only boarding), between passengers boarding and alighting (when there are simultaneous movements), and between passengers alighting (only alighting).

Figure 5-21: Conceptual model divided in concentric layers of 50 cm each to measure behaviour and interaction on platforms formed of 40 cm square cells



5.5.2 Variables

Secondly, the variables that affected the behaviour and interaction of passengers in the LU observations (GPK and WMS) are classified according to the elements of circulation defined in the conceptual model (see Table 5-4). The classification according to the type of infrastructure will help to create a matrix (see section 5.5.4), in which all the problems of interaction are described.

The variables were observed at GPK and WMS during the morning and afternoon peak hours as explained in section 3.4. In addition, Table 5-4 shows the unit and code of each variable.

Table 5-4: Variables that affect the behaviour and interaction of passengers boarding and alighting on the PTI area

Space	Variable	Unit	Code
Vehicle	Passengers alighting	Pass	V1
	Passengers on-board	Pass	V2
PTI	Platform edge doors (PEDs) as door positions indicators	unitless	V3
	Existence of a vertical and horizontal gap	mm	V4
	Boarding and alighting time (BAT)	s	V5
	Overlap time or interaction time (IT)	s	V6
	Overlap of passengers	pass	V7
	Formation of lines of flow	unitless	V8
Platform	Type of queue	unitless	V9
	Passengers waiting to board the train	pass	V10
	Presence of a platform humps	unitless	V11

5.5.3 Assessment of risk

Thirdly, the degree of interaction between passengers is defined as high, medium or low based on the density and perception of risk observed in GPK and WMS. This is based on the concept of critical density defined by Fruin (1971), LUL (2012) and Still (2013), which is related not only to the number of passengers per square metre of physical space, but also to the risk of accidents presented at the PTI. The authors (Fruin, 1971; LUL, 2012; and Still, 2013), state that a high risk will be obtained when there is more than 2 passenger per square metre in walkways, or more than 4 pass/m^2 for static movement of passengers. With respect to the risk, five factors can be observed at the PTI following the classification reported in RSSB (2015): slips/trips/fall (e.g. misjudged the vertical gap), encumbrances (e.g. encumbered by suitcases, pushchairs, bikes, or other baggage), rushing or running (e.g. ran too near the platform edge), intoxication (e.g. be struck by a train while on the platform due to a drunk passenger), and hazard on platform (e.g. walked on cracked pavement).

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 position of passengers). A medium interaction (amber colour) is considered when the risk of accidents is reduced (but still should 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 5-5 shows the degree of interaction as a combination between perception of risk and density between passengers boarding and alighting in 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. A degree more than 5 is considered a critical degree.

Table 5-5: Degree of interaction between passengers boarding and alighting on the PTI area

Perception of risk	**Density**			**Key**
	Low	Medium	High	
Low	1	2	4	Increase of interaction
Medium	2	3	5	
High	4	5	6	Critical degrees

5.5.4 Matrix

Fourthly, a matrix is created. The results of assigning each variable (from Table 5-4) one degree of interaction (from Table 5-5) 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 (see Table 5-6).

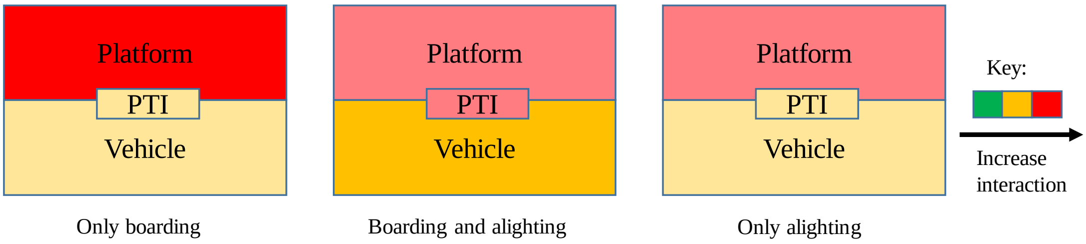
The way of displaying the results in Table 5-6 helps to communicate the interaction problems to the relevant decision makers more effectively. For example, if interaction problems arise in the vehicle, then the manufacturing company that designed the vehicle should be contacted. On the other hand, if high interactions happen on the platform, then 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 in Table 5-6 (types of users), the framework helps to look for the correct action in terms of information. For example, if high interactions are affecting alighters only, 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.

Table 5-6: BAMBI framework matrix applied to GPK (variables from Table 5-4 within parenthesis)

User / Area	Only boarding	Boarding and alighting	Only alighting
Vehicle	Although trains have 20 seats per carriage and a setback of 200-300 mm, in some cases it was not sufficient to allocate space to passengers boarding (V10) in the hall or entrance of the train, reaching a medium density and a low perception of risk.	Passengers on-board (V2) affected the BAT (V5). In some cases passengers cannot board or alight from the train. Pressure on passengers being stuck at the doors. This situation produced medium density and medium perception of risk.	Although the vertical pole in the train hall is displaced from the centre, it produced on-board passengers (V2) agglomeration, being in some cases an obstacle for those who are alighting (V1), reaching a medium density and a low perception of risk.
	Degree: 2	Degree: 3	Degree: 2
PTI	Although vertical and horizontal gaps (V4) are small, a few boarders presented reduced mobility (V10), reaching low density and medium perception of risk for passengers boarding.	Although double doors are 1.6 m wide, the high density produced only one line of flow (V8) for alighting and two lines of flow (V8) for boarding. Pressure and “confined flow”, reaching a high density and a medium perception of risk.	Although vertical and horizontal gaps (V4) are small, a few alighters presented reduced mobility (V1). This situation presented low density and medium perception of risk for passengers alighting.
	Degree: 2	Degree: 5	Degree: 2
Plat-form	Without PEDs (V3) passengers did not know where the doors are, so they were located (V9) in front of the doors rather than beside them. In addition, passengers can slip/trip/fall if platform humps (V11) are no installed to achieve level access, reaching a high density and high perception of risk.	The lack of markings on the ground (V3) means passengers did not identify which parts of the platform should be used as waiting or circulation areas. This affected the interaction time (V6) and overlap passengers (V7), producing high density and medium perception of risk for passengers boarding and alighting.	The high density (V10) on the platform means that boarding passengers were considered an obstacle for alighting, affecting the BAT (V5) and the formation of lines of flow (V8) for alighters. Pressure and “confined flow”, reaching high density and medium perception of risk.
	Degree: 6	Degree: 5	Degree: 5

The framework could be used as a diagnostic tool to identify potential problems that could be addressed with the application of crowd management measures (CMM). After this initial diagnosis, problems that affect behaviour and interaction can be studied in more detail. Another way to represent interaction problems at GPK is shown in Figure 5-22. According to the type of users, boarding and alighting represent the most critical situation of interaction reaching a total degree of 13 points (obtained as the sum of the scores in the second column of Table 5-6). With respect to the type of infrastructure, the platform reached the highest degree of interaction problems with 16 points (obtained as the sum of the scores in the third row of Table 5-6).

Figure 5-22: Interaction maps by category of user and type of infrastructure at GKP

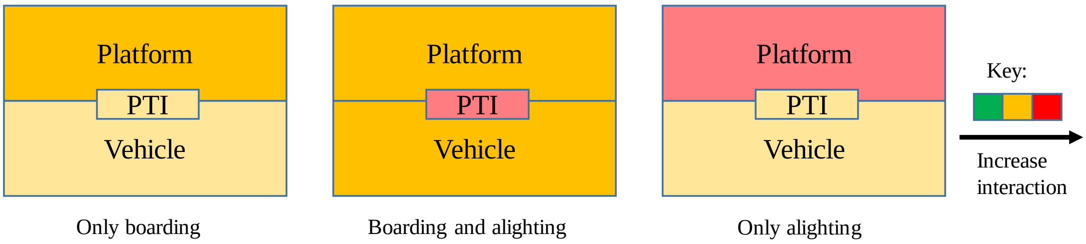


The same framework was applied to WMS (see Table 5-7). This station presents the same problems of high interactions as GPK. The only difference is that the use of PEDs at WMS reduced the density and perception of risk, as PEDs work as sliding barriers that prevent passengers from falling onto the tracks. In addition, these elements serve as door positions indications on the platform, and therefore the behaviour of passengers changed to waiting beside the doors rather than in front of them. With respect to the vertical and horizontal gaps, at WMS there is level access, and therefore a very low risk of slips/trips/fall. However, the risk of using PEDs could be increased as passengers can be stuck in between these elements and the train doors. Similar to GPK, another way to represent interactions problems at WMS are presented in Figure 5-23. AT WMS less interaction is reached compared to GPK, but boarding and alighting represent the most critical interaction score with respect to the type of users reaching a total degree of 11 points (obtained as the sum of the scores in the second column of Table 5-7). With respect to the type of infrastructure, WMS presented less interaction compared to GPK, however the platform reached the highest degree of interaction problems with 11 points (obtained as the sum of the scores in the third row of Table 5-7).

Table 5-7: BAMBI framework matrix applied to WMS (variables from Table 5-4 within parenthesis)

User / Area	Only boarding	Boarding and alighting	Only alighting
Vehicle	Although trains have 20 seats per carriage and a setback of 200-300 mm, in some cases it was not sufficient to allocate space to passengers boarding (V10) in the hall or entrance of the train, reaching a medium density and a low perception of risk.	Passengers on-board (V2) affected the BAT (V5). In some cases passengers cannot board or alight from the train. Pressure on passengers being stuck at the doors. This situation produced medium density and medium perception of risk.	Although the vertical pole in the train hall is displaced from the centre, it produced on-board passengers (V2) agglomeration, being in some cases an obstacle for those who are alighting (V1), reaching a medium density and a low perception of risk.
	Degree: 2	Degree: 3	Degree: 2
PTI	Although there is level access (V4) on the PTI, passengers boarding (V10) can be stuck between the PEDs (V3) and the train doors, reaching low density and medium perception of risk for passengers boarding.	Although double doors are 1.6 m wide, the high density produced only one line of flow (V8) for alighting and two lines of flow (V8) for boarding. Pressure and "confined flow", reaching a high density and a medium perception of risk.	Although there is level access (V4) on the PTI, passengers alighting (V1) can be stuck between the PEDs (V3) and the train doors, reaching low density and medium perception of risk for passengers boarding.
	Degree: 2	Degree: 5	Degree: 2
Plat-form	The use of PEDs (V3) changed the behaviour of passengers boarding (V10), so they are located (V9) beside the doors rather than in front of them, reaching a medium density and medium perception of risk.	PEDs included a grey line as markings on the ground (V3) means passengers identified which parts of the platform should be used as waiting or circulation areas. This reduced the interaction time (V6) and overlap passengers (V7), producing medium density and medium perception of risk for passengers boarding and alighting.	The high density (V10) on the platform means that boarding passengers were considered an obstacle for alighting, affecting the BAT (V5) and the formation of lines of flow (V8) for alighters. Pressure and "confined flow", reaching high density and medium perception of risk.
	Degree: 3	Degree: 3	Degree: 5

Figure 5-23: Interaction maps by category of user and type of infrastructure at WMS

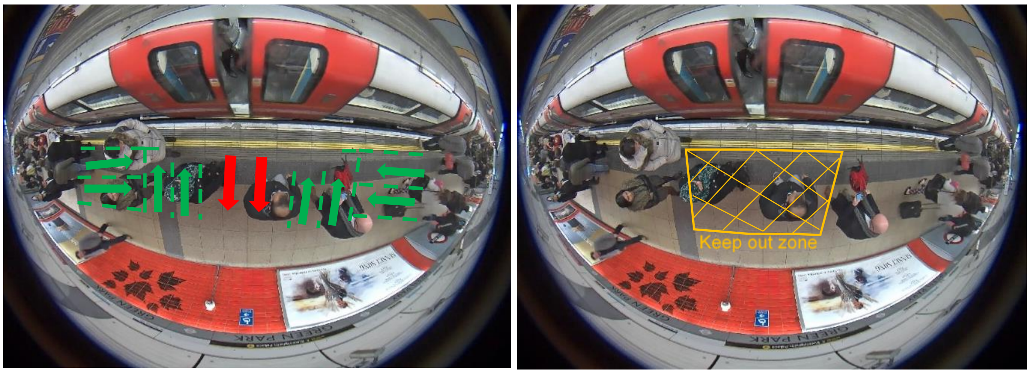


5.6 Recommendations to reduce interaction problems

In this section, recommendations to reduce problems of 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 CMM on platforms (Loukaitou-Sideris et al., 2015; Lim, 2015; WMAT, 2015).

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 platform. Figure 5-24 shows a possible application of CMM 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 (2015b), 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 occupation maps from Figure 5-15 (section 5.4), which represent 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 (see Figure 1-4 in section 1.1).

Figure 5-24: "Keep out zone" (right) and queue lines (left) to reduce interaction at GPK



Another crowd management measure proposed in Figure 5-24 is the use of queue lines. In the case of GPK, queue lines 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 5-15 (section 5.4), 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 lines for alighting are formed, therefore only two queue lines need to be marked on the ground for these passengers. In addition, according to Figure 5-15 (section 5.4), a minimum of four queue lines 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 lines and the wall on the platform. Both types of queues are similar in size to queue lines for alighting (i.e. 1.2 m long by 0.4 m wide).

5.7 Discussion

A complete observation of peak hours during three weeks were performed by means of CCTV footage to understand the effect of CMM such as platform edge doors (PEDs) on the behaviour and interaction of passengers boarding and alighting at existing London Underground (LU) stations.

With respect to the boarding and alighting time (BAT) at LU stations, the case without PEDs and platform hump (GPK) presents an average BAT which is 16% lower than in the PEDs with level access case (WMS). This could be interpreted as PEDs increasing the BAT but that would overlook the impact of demand. When demand is taken into account, PEDs do not always induce a higher BAT than the case without PEDs. In fact, PEDs with level access only present a BAT that is approximately 1% higher than the case without PEDs and platform hump for the first two demand categories of total boarders and alighters (0-15 and 15-25 passengers), but for high demand levels, when the total number of boarders and alighters exceeds 25 (third category), PEDs have a BAT that is 7% lower than the case without PEDs, i.e. PEDs seem to be more effective in dealing with high levels of crowding. These results are different from the comparison with the case without PEDs and with a 170 mm vertical gap, in which the first two categories presented a difference of 2.5 s and 2.7 s in favour of the absence of PEDs, however, the third category presented a variation of 0.4 s in favour of PEDs. Although these differences can be caused by the presence of a vertical gap (170 mm), it seems that PEDs can improve the BAT in crowded situations (over 25 passengers).

In relation to profiles, in the case of GPK (both cases with platform hump and with a 170 mm vertical gap) the average relative boarding profile presents an earlier and higher peak compared to WMS (PEDs), and in both stations the profiles converge after 32.5 s, which is the time when most of the boarding is finished. Something similar occurs with the average relative alighting profiles. Therefore, from the point of view of these profiles, there is no impact of PEDs on the BAT.

All in all, and bearing in mind the methodological limitations, there seems to be no overall negative impact of PEDs on the BAT, which contradicts the preconceived concern described in the literature review in which some authors (Allen, 1995; Coxon et al. 2010) state that PEDs could increase the BAT. In fact, there seems to be a minor advantage of PEDs in crowded situations.

With regards to passenger behaviour at the platform, there seem to be two distinct zones: a circulation and a waiting area.

The circulation area appears at the back of the platform, near the wall and parallel to it, where passengers form flow lines to avoid collisions with people coming in the opposite direction. It is interesting that collision avoidance techniques such as formation of flow lines are not only presented in public spaces when pedestrians auto-organise themselves (Oeding, 1963; Fruin, 1971; Still, 2000) but also presented at the PTI zone. Further research is needed to study the relationship between collision avoidance and the presence of PEDs.

The behaviour in waiting areas is dominated by the boarding passengers who are waiting on the platform. The presence of PEDs does not always change passenger behaviour. PEDs seem to have an important effect in encouraging passengers to wait beside the doors for low (less than 15 boarders) and high (more than 25 boarders) demand levels, but not for medium levels. Conversely, PEDs have a positive impact on preventing passengers from waiting in front of and beside the doors for high demand levels, which could be used to control crowded situations. These results are different from Wu and Ma (2013), in which no differences were found between the case with PEDs and without PEDs, as passengers were always waiting in front of the doors rather than beside the doors, due to the high-density situation. To correctly interpret this analysis, it should be noted that the results are influenced by the ratio (R) between boarders and alighters. Therefore, the detailed level of demand and the exact position of each passenger should be included in further research as factors that influence behaviour.

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 WMS (with PEDs), passengers knew where the train was going to stop on the platform and therefore the phenomenon of arching was formed in high density situations, which is similar to the effect observed in bottlenecks by Guy et al. (2010).

This formation of “arches” motivated the definition of the PCA used at PAMELA, in which passengers were waiting beside the doors rather than in the front just before boarding when PEDs were used.

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 could cause high interaction between passengers. The occupation maps (divided by 40 cm square cells) help to identify which part of the PTI zone is more congested, and therefore where problems of interactions (e.g. high density and risk or hazards) are occurring. However, further research should analyse the relationship between the door positions indicators and other factors that affect the location of passengers on the platform such as the position of the platform exit at their destination station, the search for the least crowded carriage, how crowded the platform is, and random variables (e.g. meeting with a friend) (Krstanoski, 2014).

With respect to the formation of lines, as the ratio R between passengers waiting to board the train and those who are alighting increases, the number of lines for alighting decreases. When R = 0.25 (or less), 60% of the observations presented two lines for alighting. These two lines 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 when waiting to board and therefore only one narrow line for alighting can be formed. In the case R = 1, 35% of the observations had between one and two lines for alighting. These results show that the formation of lines in the PTI depends not only on the width of the bottleneck at train doors (Hoogendoorn and Daamen, 2005; Harris, 2006; Daamen et al., 2008; Seyfried et al., 2009) but also on the ratio between passengers boarding to those who are alighting (R).

Another behaviour was observed whereby some passengers stayed on the platform even when there was a train, and waited for the next one. This could be due to either overcrowding on the train at the boarding point or because the train destination does not match the passenger’s destination. However, there are not enough data to assess this impact in detail.

In relation to the passenger dynamics, alighting occurs before boarding, first at a higher speed and then slowed down due to the increasing interaction with boarding passengers. This interaction (or overlap) in the case with PEDs was found to be negligible for the low and medium demand levels. In the high demand situation the case with PEDs reached 42% less interaction time and 48% fewer overlap passengers than the case without PEDs. The presence of PEDs is related to less overlap, possibly because PEDs induce a more organised boarding and alighting process with less friction, where boarders tend to give way to alighters more often.

This chapter also proposed a new framework to analyse the behaviour and interaction of passengers at the PTI area. Even though this framework was created from the case of study at GPK and WMS, it could help to identify potential problems at an early stage in similar stations. The problems are described in each cell of the framework matrix to help professionals in decision making (e.g. choosing the best crowd management measure). This matrix is different from existing studies (Still, 2013; 2014) as it is applied to metro stations in normal operations with high densities to evaluate CMM such as platform edge doors (PEDs). In addition, this framework used interaction maps, and therefore gives more information compared to existing indicators such as the Level of Service or LOS in (Fruin, 1971). The LOS is based only on average values of overall density; however this framework uses the density and the perception of risk to identify the interaction between passengers boarding and alighting at the PTI.

The new framework is named BAMBI (Boarding and Alighting Matrix on Behaviour and Interaction), and consists 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) at a specific station. Existing frameworks (Shi et al., 2012; D'Acierno et al., 2013; Li et al., 2017) do not include these stages as they are focused on evacuation scenarios at metro stations and do not considered the use of PEDs at the PTI or any other crowd management measure.

In summary, the empirical analyses lead to the conclusion that in the presence of PEDs there is a small reduction of BAT in crowded situations and passengers behave differently, tending to a more organised boarding and alighting process.

The intuitive idea that the BAT is longer when more passengers need to board and alight was also confirmed, which is in line with some papers reported in the literature review. It was also observed that there is a clear positive correlation between BAT and the proportion of overlap but no causality can be established.

In light of these results, it is considered that the BAT should not be a cause of major concern in future debates about the suitability of PEDs on a particular platform as the evidence gathered in this study does not point to detrimental impacts.

The results in this study were obtained in particular for the case of LU. However, they could be considered as a starting point to study the use of PEDs as door positions indicators in other transport systems.

Chapter 6 Conclusions

6.1 Introduction

In this chapter, the conclusions of this thesis are delivered. Firstly, a conclusion on the achievements are presented (section 6.2). Secondly, the application of the developed framework is discussed (section 6.3). Thirdly, the limitations are presented (section 6.4). Finally, further research is proposed (section 6.5).

6.2 Achievements of this thesis

One of the main achievements of this thesis is the development of a framework to study the effect of CMM such as platform edge doors (PEDs) on the behaviour and interaction of passengers at existing stations. As discussed in section 5.7, this framework represented successfully the problems of interactions at two existing stations in the LU. The framework was divided into four stages: conceptual model, variables, risk assessment, and matrix. The results from the LU observations and laboratory experiments supported BAMBI framework. In particular, the pattern of movement of passengers boarding and alighting gives further insight to identify the type of user and area used by passengers, which is the main structure for the matrix. In addition, as reported in section 2.5, few frameworks have been developed from the perspective of passengers as individuals at the PTI. Therefore, this new framework will contribute to fill the gap in the existing literature. The BAMBI framework also helps to identify which CMM is more effective, which could be used as a tool to answer the third research question, and therefore validates de third hypothesis (see section 1.2).

Another important achievement is the creation of a new method to represent and evaluate the behaviour and interaction of passengers boarding and alighting at the PTI area, in which a new space is defined as platform conflict area (PCA) divided by layers of 50 cm each and 40 cm square cells (see section 3.5). The new method is influenced by eight variables: the level of demand, boarding and alighting time (BAT), types of queue, formation of lines, distance between passengers, density by layer, passenger space, and instantaneous speed. Results are presented in Chapter 4. As discussed in section 4.8, this method was more representative of the interaction problems than the traditional method of calculating average values of densities on the platform used in the Level of Service or LOS (Fruin, 1971) to design and manage the PTI area. In the case of LU observations only three variables were studied using this new method (BAT, types of queue, and formation of lines) due to the lack of a tracking tool (see Chapter 5). These results answered the second research question, and therefore validated de second hypothesis defined in section 1.2.

In relation to the results presented in Chapter 4 and Chapter 5, it is important to highlight that the presence of PEDs has a relevant impact on the types of queues and distribution of passengers on the platform. These elements are used as door positions indicators, and therefore change the behaviour of passengers by encouraging them to wait beside the doors rather than in front of them, reducing the problems of interaction. The common assumption that PEDs could have an impact on the BAT was refuted. Results showed that no relevant impact is observed on the BAT when these elements are used at the PTI, which answered the first research question and reject the first hypothesis in section 1.2.

In addition, with respect to the first hypothesis (in section 1.2) Chapter 4 showed that the presence of PEDs have no relevant impact in the formation of lines, density by layer and distance between passenger. These variables are more influenced by the level of demand expressed as a ratio (R) between passengers boarding (or waiting to board) with respect to those who are alighting. As discussed in section 4.8, when R increased, the number of lines of flow for alighting was reduced, creating a narrow single line when R = 4 (reaching a higher interaction compared to the other two cases of R = 0.25 or R = 1). These results show that the formation of lines of flow in the PTI zone depends not only on the width of the bottleneck at train doors (as stated in existing literature) but also on the ratio R.

In the new method, in which the platform conflict area (PCA) is divided by layers, results from Chapter 4 showed that the density by layer was more representative of the interaction of passengers boarding and alighting than average values of densities used in the Level of Service or LOS in Fruin (1971) to design and manage the PTI area.

Finally, the results from Chapter 4 showed that passenger space is represented as an asymmetrical ellipse, which varied over time. This could be used as an input to calibrate existing pedestrian models (presented in section 2.3.4) which use a circle with constant radius or a fixed square cell to represent each passenger. In addition, as discussed in section 4.8, different from existing literature, not always more space means a higher speed. These results could help to answer the second research question in section 1.2

6.3 Application of the developed framework

As described in section 5.5, the new framework BAMBI was applied to evaluate interaction problems in existing stations. This framework could help engineers and transport planners in decision making to identify the dimensions of crowd management measures (CMM). The way the matrix is configurated helps to channelize and communicate these problems to the driver, train manufacturer or station manager. For example, if the problem is produced inside the vehicle, then is the driver who needs to provide some announcement to users and solve the problem. Similarly, if the problem is located on the platform, then is the station manager who needs to look for the solution.

BAMBI was applied to two stations (with and without PEDs) in the LU. The new framework successfully described the phenomena of high interactions between passengers boarding and alighting. The conceptual 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, which was more representative of the interaction problems than using average values as reported in the literature. Variables such as door position indications on platforms (e.g. the use of PEDs, markings on the floor), density (e.g. number of passengers boarding and alighting), types of queue, and formation of lines appeared to be the most important variables that produced high interaction problems at both stations.

Potential commercialisation of this framework could be linked to the prediction of accidents at existing stations. The relation between number of accidents, risk of accidents and exposition to the risk, typically used in urban areas can be applied to passengers at the PTI. From the framework it could be obtained the risk of accidents, and the exposition to the risk could be represented as the number of passengers boarding and alighting. Therefore, the number of accidents would be obtained by multiplying both variables (risk of accident and exposition to the risk).

Although the framework was applied to existing LU stations, 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, by 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 CMM are more effective, considering each condition and their effect on platforms. Other limitations on the framework and suggestions for further research are presented in section

6.4 Limitations

As explained in section 6.2 this thesis has met the objectives. However, some limitation is suggested considering the approach based on observation and experiments.

This thesis is focussed on the behaviour, specifically on how the number of boarders and alighters on the LU affects the passenger interactions when CMM are used. This was chosen 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.

The observation is based on two LU stations. However, they could be considered as a starting point to study the use of CMM such as PEDs in other transport systems. It is important to notice that the purpose of this thesis is to highlight some of the results obtained by comparing two stations for which they have extensive and very detailed observations via CCTV footage that allow a thorough interpretation and comparison of the results, rather than a panel comparison across several metro systems of very different nature where measurements and conclusions would have been limited even more by the lack of a common ground to compare against.

In addition, the results from LU observations could be very contextual; i.e. culture could have an impact upon patrons’ propensity to move away from doors and the density to which people are prepared to stand next to each other. In terms of demand, a limited number of observations were recorded for the category of more than 25 passengers when platform humps are used at GPK station. It is out of the scope of this thesis to understand why platform humps were not crowded. However, this situation could be deemed as a limitation to the conclusions.

With respect to the definition of late runners, the 10 seconds (2 x 5 second segments) cut-off for the correction of the BAT relates to the limitation of the data whereby the number of boarders and alighters is given in 5 second bins. This was a practical limitation imposed by the time and resources available to undertake the manual review of the footage. Provided that this limitation exists, the 10 seconds interval used to define later movements as “outliers” seemed like the most reasonable number. Three segments (15 s) would have been too much and included a lot of “late runners/boarders” in the BAT. On the other hand, using only one segment (5 s) seemed too restrictive because there are times when such a pause in the boarding and alighting may occur naturally, for instance in very crowded situations, where an alighter needs to push through the crowd on the train to reach the door; or when a person with reduced mobility (e.g. pushing a buggy) is manoeuvring to get on or off the train.

To measure the BAT at GPK and WMS it would be preferred to use rates. However, there were technical reasons not to do so. Given the limitation on the data collection whereby 5 second bins had to be used to count the number of boarders and alighters, using rates meant dividing multiples of 5 seconds by the number of passengers (an integer number), which lead to a discontinuous and very unstable distribution of "times per passenger" that was not representative not easier to analyse, hence it was decided to make aggregate comparisons by demand level.

In the case of PAMELA experiments, volunteers' demographics are not representative of the whole population that use the LU. The objective of these experiments was to simulate the boarding and alighting when one variable changed (e.g. use of PEDs) while the rest keep fixed, i.e. the laboratory experiments could help to study the behaviour and interaction of passengers in a controlled environment, in which the effect of external factors that influence the movement of passengers such as social interactions, activities and safety constraints are separated. Therefore, PAMELA represent an ideal opportunity for researchers to test "what if" scenarios. However, this do not mean that the behaviour of passengers during the experiments is the same as the behaviour of passengers at existing stations. Thus, the experiments help to select the "best scenario", which would then need to be tested afterwards in existing stations. In addition, more experiments are needed to study other type of passengers (e.g. wheelchairs).

Other limitations on the LU observations and PAMELA experiments, and suggestions for further research are presented in section 6.5.

6.5 Further research

6.5.1 Effect of PEDs on BAT, IT and platform behaviour

Two future types of research can be proposed:

Firstly, further research should look at the relationship between the BAT and different vertical/horizontal gaps at the PTI. As a preliminary result, the BAT can be compared at different doors at Green Park (GPK) station. From Chapter 3, Door 1 and Door 2 (both with a vertical gap of 170 mm) presented an average value of R (passengers boarding to those alighting) equal to 3.4 and 3.8, respectively. However, in the case of Door 3 (level access) the ratio R gave 1.8 on average, i.e. Door 3 presented a value of R half that of the other doors. Because of the similarities in R between Door 1 and Door 2, the boarding and alighting time (BAT) can be calculated as an average between both doors (henceforth termed Door 1&2).

Figure 6-1 shows the average boarding and alighting profiles for the selected doors used in Chapter 3 at GPK. In all three cases passengers get off first and then other passengers get on. The alighting process started at 0 s and finished almost at the third time slice (10^{th} - 15^{th} s), whilst boarding started at the second time slice (5^{th} - 10^{th} s) and ended almost at the fifth time slice (20^{th} - 25^{th} s). Door 1&2 (vertical gap 170 mm) presented a slightly lower cumulative boarding profile compared with Door 3. However, the cumulative boarding profiles tend to compensate their differences and converge to zero at 22.5 s, finishing the process at 32.5 s. In relation to the alighting profile there were no marked differences between the three doors.

The profiles at Green Park were also influenced by the total number of passengers boarding and alighting. Therefore, to identify the effect of a vertical gap on the BAT, the demand was classified into three categories for each door: a) 0 – 15 passengers; b) 15 – 25 passengers; c) more than 25 passengers. Figure 6-2 shows that the BAT increased linearly as the number of passengers boarding and alighting went up. However, the BAT was also influenced by the vertical gap. Door 1&2 (vertical gap of 170 mm) presented between 5% and 13% lower BAT than Door 3 (level access). The minimum difference was reached in the category >25 passengers, reaching a difference of 1.6 s, while the maximum difference was obtained in the category 15-25 passengers, reaching a difference of 2.4 s.

Figure 6-1: Average boarding and alighting profiles at Green Park (GPK)

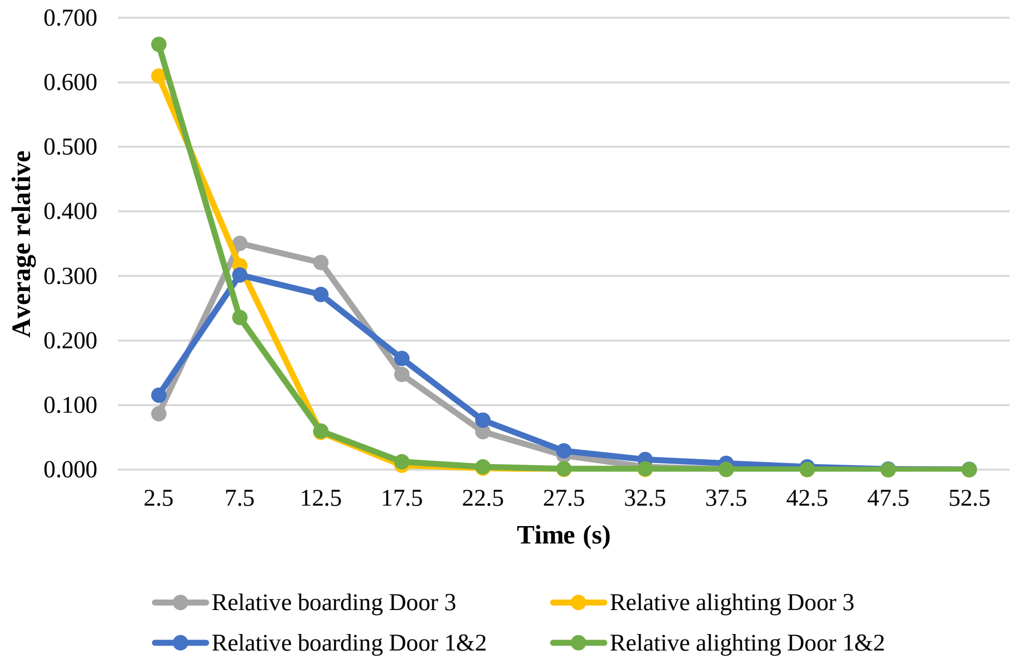
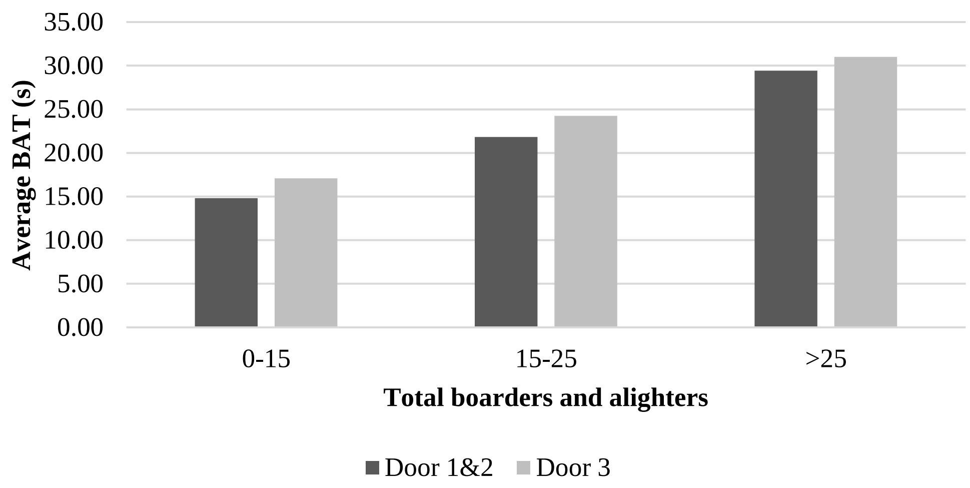


Figure 6-2: Boarding and alighting times by total boarders and alighters at Green Park (GPK)



Secondly, future studies to assess the impact of PEDs on the train door opening time are needed to expand the number of doors that are used for the comparison. However, any doors used for this type of analysis must have similar characteristics in terms of the station layout, demand levels and passenger profiles (cultural norms, passenger mix by journey purpose, etc.). As a preliminary result, from videos of Westminster and Green Park stations, Table 6-1 shows that the use of PEDs slows down the train doors opening time, reaching on average 2.83 s (which is 36% more than the case without PEDs). However, the use of these elements helped to reduce the number of incidences due to passengers boarding at the end of the process ('late runners') or passengers being stuck at the doors. This reduction is from 128 events (without PEDs) to 67 events (with PEDs), i.e. a decrease of 48%. In terms of BAT the incidences represent between 24 s and 30 s on average (standard deviation between 12 s and 17 s). These results were obtained from a total of 3427 events (each event representing one train arriving at the station).

Table 6-1: Train door opening time with and without PEDs

Train doors opening time (s)	Events	Average (s)	Standard Deviation (s)
Without PEDs	1703	2.08	0.39
With PEDs	1724	2.83	0.36

6.5.2 Methods to evaluate interaction problems in boarding and alighting

Five future paths of research can be proposed:

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

Secondly, it would also be interesting to collect more data to identify the impact of passengers on-board and with encumbrances (luggage, shopping, buggy) or mobility aids (wheelchair, pram) on the level of interaction. In particular, further research is needed to identify the relationship between the level of demand and the door in which platform hump is used (e.g. it is because of the platform hump that the demand levels of more than 25 passengers are so rarely observed or whether it is down to other factors or is even random). In addition, future research could identify the combined effect of PEDs and CMM (e.g. queue lines or waiting areas) on platform behaviour considering these types of passengers.

Thirdly, the asymmetrical ellipse can be used in further research to calibrate the space used by passengers in existing and new pedestrian models, and therefore to obtain the optimum width of platforms. In addition, new experiments are needed to determine what other factors can influence the space of passengers at the PTI. For example, it would be interesting to study the relationship between the formation of lines, passenger space and platform layout (e.g. number and location of exit gates). In addition, further research is needed to better understand the relationship between the speed and passenger space at the PTI. Following the research of Gérin-Lajoie et al. (2005; 2008), a possible future study could be to test if the distance between passengers is a function of the smaller personal space in his/her domain side (e.g. if right handed passengers need less space to overpass another passengers from the right compared to the same situation from the left side). Further experiments can also be simulated at PAMELA to expand existing laboratory studies (Kitazawa and Fujiyama, 2010), in which participants used an eye camera to identify their space.

Fourthly, it could be also interesting to study in more detail the relation between the instantaneous speed and the space used by passengers at the PTI. These could be transformed into Fundamental Diagrams in which the behaviour and interaction of passengers is described according to the flow, density and speed. The following question could be answered: It is always true that more space available means more speed of passengers?

Finally, PAMELA presents a limitation of space and resources. In this thesis the analysis was focused on the period between the train doors opening and closing (i.e. after the train arrived). If more space and resources are available different studies can be tested to identify different patterns of behaviour that are out of the scope of this thesis such as the way in which passengers are distributed over the length of the platform, the difference in culture between passengers, the psychology of passengers when deciding their destination (or “next step”), the experience of passengers when traveling in groups or single, which are the most frequent door used to board and alight, etc.

6.6 Conclusions

This thesis presented the problems of interaction between passengers boarding and alighting at the platform train interface (PTI) in metro stations. As a conclusion, crowd management measures (CMM) such as platform edge doors (PEDs) have no relevant impact on the boarding and alighting time (BAT) but could change the platform behaviour. The new method based on observation in existing stations on London Underground (LU) and laboratory experiments at UCL’s PAMELA, divided the platform conflict area (PCA) into semi-circular layers, starting from the train doors. Results were more representative than average values of density. The behaviour and interaction was influenced by the type of queues, formation of lanes, distance between passengers, density by layer, passenger space and instantaneous speed. Finally, the framework BAMBI represented and evaluated successfully the problems of interaction between passengers boarding and alighting at the PTI in metro stations.

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