# Exploring the Effect of Train Design Features on the Boarding and Alighting Time by Laboratory Experiments

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**Abstract** The objective of this work is to study the effect of design features such as door width, vestibule setback and vertical gap on passengers' boarding and alighting time (BAT) at metro stations. Simulated experiments were performed at University College London's Pedestrian Accessibility Movement Environment Laboratory (PAMELA). The mock-up included a hall or entrance to the train and a relevant portion of the platform in front of the doors. Different scenarios were tested based on existing stations. Results were compared to observations at Green Park Station of the London Underground (LU). Results from PAMELA showed that wider doors (1.80 m), larger vestibule setback (800 mm) and smaller vertical gap (50 mm) reduced the average boarding time. However, the average alighting time presented no significant differences due to other phenomenon such as congestion or formation of lines of flow at doors. The observation at LU presented a reduction of the BAT when a small vertical gap (170 mm) was presented. More experiments are needed at PAMELA to test the effect of the design features for different densities and types of passengers.

**Keywords** Train design · boarding · alighting · laboratory experiment

# 1 Introduction

The interface between the vehicle and the platform at stations is considered the zone where the most interactions occur. In the case of metro or rail systems, this space is called the platform train interface (PTI) by Seriani and Fernandez [1]. For example, according to RSSB [2] more than 3 billion interactions take place within the UK national train network each year, during which 21 percent of the safety risks (injuries and fatalities) and 48 percent of the fatality risks to passengers are produced at the PTI zone.

Interactions are also related to the dwell time, which is the time each vehicle remains stationary at the station when transferring passengers [3]. The dynamic part of dwell time is defined as the boarding and alighting time (BAT), whilst the static part includes the time of opening and closing of doors. The dwell time depends on the number of passengers boarding and alighting, and their flow. The speed of passengers depends on different design variables such as the difference in height and distance between the vehicle and the platform, the number and width of doors, and the layout inside the vehicle. In addition, the speed of passengers is influenced by operational variables such as the fare collection method, the density of passengers on the platform and inside the vehicle, the behaviour of passengers (e.g. interactions), etc. Moreover, the dwell time affects the capacity of stations, delays and queues of vehicles, which in turn impacts on the frequency and regularity of the services, and therefore on the delays caused to passengers at the PTI.

To reduce interactions at the PTI, various recommendations can be modelled and then compared to design thresholds [4]. One of the most common measures to represent the degree of congestion is the Fruin's Level of Service or LOS [5], which categorizes walkways, stairs and queues from a Level A (free flow) to a Level F (over the capacity). However, the LOS is based on unidirectional flows and average values (e.g. number of passengers divided by the platform area), and it is therefore difficult to identify which part of the PTI is more congested. In addition, few manuals and recommendations have addressed the problem of design of vehicles and stations. As a consequence, the design of the PTI is inadequate. Therefore, the decision making has been based on particular cases or has used the method of "trial and error".

To show or provide evidence, a line of research has been developed based on laboratory experiments and observations at University College London's Pedestrian Accessibility Movement and Environment Laboratory (PAMELA).

The main question of this research is how the train design features such as door width, vestibule setback (distance between the train doors and the seats) and vertical gap (height between the platform and the train) affects the passengers' boarding and alighting time (BAT). At stations, design standards have focused on accessibility [6]; however, is level access the best solution to reduce the BAT? The hypothesis of this research is that a larger gap size would lead to a slower speed, increasing the BAT. The specific objectives are: a) to review the literature related to the design of vehicles and stations, and their effect on BAT; b) to simulate the boarding and alighting process at PAMELA; c) to compare the BAT from the laboratory experiments with London Underground (LU) stations.

In this work, only horizontal and vertical gaps (e.g. less than 300 mm) were studied based on observation in existing metro stations (i.e. urban railway systems). Bigger

differences in height and distance between the vehicle and the platform (e.g. between 200 and 600 mm) are considered as further research to represent other railway systems (e.g. commuting or long-distance trains).

This paper is composed of five sections. The next section describes existing studies that have measured the BAT, followed by a section that explains the methods of this work. The fourth section presents the laboratory and observed results. Finally, a discussion and future work of the laboratory experiments and observations at LU stations is then provided.

## 2 Literature Review

At the PTI the BAT has been studied by different authors, showing the well-known linear relationship between the average time it takes for each passenger to board and alight, and the numbers of passenger boarding and alighting reported in the Highway Capacity Manual [7]. If the BAT is added to the time taken to open and close the doors, then the dwell time (td) is obtained. Based on this linear relationship Fernandez et al. [8] calibrated td for the case of Transantiago in Chile, in which the average boarding time was 40 percent higher than the alighting time in the metro system. Similarly, Tirachini [9] calibrated td using multiple regression models for the case of buses, in which td was influenced by the payment method, steps at doors, types of passengers (e.g. age) and the crowding situation. With respect to non-linear models, some authors have used the well-known LU Train Service Model to describe the BAT as part of the station stop time (SS) [10, 11]. The SS depends on the number of passengers boarding and alighting, the number of doors per car, the peak door/average door factor, the number of seats per car, the number of through passengers, and the door width factor [12, 13].

Models have also been used to represent the boarding and alighting process. For example, according to Rudloff et al. [14] the social force model could predict the BAT. The authors found that the BAT decreased as the door width increased, reaching a minimum overall value of 24.93 secs for a door 185 cm wide. Other studies proposed a dwell time model based on smart card data [15] and using time-series based methods [16]. For Qi et al. [17], the BAT is influenced by the perception and behaviour of passengers. The authors found that perception is influenced by the visual information captured by each passenger, the angle of movement, speed and density, whilst the behaviour depends on the distance, speed and time to get to the "target". With respect to cellular automata models, each passenger boarding or alighting is represented within a square cell and their movement is recorded according to their negotiation and competition for positions/space. Zhang et al. [18] and Davidich et al. [19] studied the BAT, including the formation of lines of flow and the behaviour of passengers in waiting areas.

Different field studies have been carried out to support the different models in order to study the BAT at the PTI as reported by Li et al. [20]. In relation to the width of doors, Wiggenraad [21] found that wider doors decreased the BAT by 10 percent. The author studied five door widths in existing Dutch trains: 800 mm, 900 mm, 1100 mm, 1300 mm, and 1900 mm. However, Harris et al. [22] reported that the relationship between door

width and capacity is not linear, as the flow rate at doors is influenced by the available space on the platform and inside the train. In addition, Heinz [23] concluded that the BAT may be increased when the number of vertical steps is increased. The authors studied 18 different entrance designs at Swedish trains with level access, 2 steps, and 3 steps.

However, field studies are limited to the type of vehicles and stations existing at the time of study. It would be difficult to change the layout of the station or buy new vehicles to calibrate the models and to identify their effect on the BAT. In addition, it is impossible to control all the factors that influence the boarding and alighting for each observation. These factors are classified into four groups: people (e.g. density on the platform), physical aspects (e.g. platform width), information (e.g. on-board displays), and environmental influences (e.g. weather) [24].

To solve this, various laboratory experiments have been done at PAMELA. These experiments have been very useful in singling out the influence of a particular variable because only one particular variable could be changed while keeping the other variables the same. One of the first laboratory studies done by Fernandez et al. [25] showed that the BAT is influenced by the door widths (0.80 m and 1.60 m) and the different fare collection systems. The authors simulated the boarding and alighting in a bus and they found that wider doors (1.60 m) reduced the alighting time by 40 percent, while the boarding time was reduced by up to 45 percent by payment being made outside the vehicle (using a ticket vending machine on the platform). That study was followed by an experiment done by Seriani and Fernandez [26] to simulate the boarding and alighting in a train at the Human Dynamics Laboratory (HDL) in Universidad de los Andes, in which the BAT was influenced by the vertical handrails, waiting areas on the platform, and the use of one-way doors. Recent experiments performed by De Ana Rodriguez et al. [27] showed that the use of platform edge doors (PEDs) has no relevant impact on the BAT, however, passengers change their behaviour by queuing at the side of the doors rather than waiting in front of them. Following the study of PEDs, Seriani et al. [28] explored the Level of Interaction (LOI) at PAMELA, where passengers reached a high LOI near the doors, which decreased as the distance from the doors increased. This study was expanded by Seriani and Fujiyama [29] to calculate the space used by each passenger alighting at PAMELA when PEDs were installed.

In relation to steps, Holloway et al. [30] simulated laboratory experiments at PAMELA in which the use of steps was considered an obstacle for passengers boarding and alighting. In this case the authors simulated 60 passengers boarding and alighting with one single door and three different steps: 20 mm (zero step), 350 mm (2 steps), and 510 mm (3 steps). The authors found that boarding passengers spent more time (4.13 seconds on average) than those who were alighting (3.68 seconds on average), and 40 percent of the total passengers found it difficult to use steps when they were boarding and alighting. In the same line of research, experiments at TU Delft done by Daamen et al. [31] reported that steps can influence the capacity of doors. In this experiment the authors tested four steps: 50 mm (zero step), 200 mm (1 step), 400 mm (2 steps), and 600 mm (3 steps); and three horizontal gaps: 50 mm, 150 mm, and 300 mm. The authors found that the capacity of the doors decreased from 0.91 passengers per second (pps) to 0.81 pps when changing the step from 50 mm to 400 mm. In this case the horizontal gap was 50 mm and the

door width 80 cm. However, the authors also found that for a horizontal gap of 300 mm and the same door width (80 cm), the capacity increased from 0.85 pps to 0.88 pps when changing the step from 50 mm to 200 mm.

It is generally thought that to improve accessibility at the PTI the difference in height (vertical) and distance (horizontal) between the vehicle and the platform should be reduced to their minimum. Some studies performed by Atkins [32] recommend that the sum between the horizontal and the vertical gap should not exceed 300 mm, and that an optimum value for design would be 200 mm. If the vertical gap is more than 50 mm and the horizontal gap more than 75 mm, then a boarding device is needed for passengers with restricted mobility (e.g. wheelchairs) [6]. When these values are not in place along the complete platform, Tyler et al. [33] propose to build platform humps, by which only a part of the platform is raised to be level with the vehicle. The authors tested different slopes and cross-fall gradients at PAMELA, in case the vehicle should not stop directly in front of the ramp.

Although the vertical gap could be considered as a negative aspect in providing accessibility, in some cases it could improve the boarding and alighting process. Recently laboratory studies at HDL showed that a small vertical gap can decrease the BAT. Fernandez et al. [34] found that for a door width of 1.65 m the best vertical gap may be 150 mm, allowing an alighting flow of 1.6 passengers per second. In this experiment only alighting was simulated, considering three scenarios of vertical gap: 0 mm, 150 mm, and 300 mm. From another study at PAMELA, Fujiyama et al. [35] simulated bidirectional flows (i.e. boarding and alighting) and suggested that the PTI should be designed with a vertical gap of 50 mm, allowing a maximum flow of 1.42 passengers per second. From these results a model was proposed by Karekla et al. [36] to predict the dwell time was proposed, in which a small vertical gap reduced the dwell time by 8 percent.

Other authors have studied bottlenecks to simulate the movement of pedestrians through a single door by laboratory experiments. In the case of Kretz et al. [37] examined different door width (40, 50, 60, 70, 80, 90, 100, 120, 140 and 160 cm) and found that if the bottleneck is 90 cm or above then two or more participants were able to pass. The author also reported that a competitive scenario presented smaller evacuation time compared to the non-competitive scenario. Hoogendoorn and Daamen [38] studied the effect of the width of the bottleneck and the wall surface. The authors found that pedestrian followed the pedestrian directly in front and when the distance between them is about 45 cm then the zipper effect is reached (e.g. pedestrian are overlapped forming two lines of flow). This is caused because pedestrian need more space to move forward than to move in lateral way. However, Seyfried et al. [39] also used unidirectional flow in a bottleneck cantered of a corridor (similar to [37]) and found that the density in front of the bottleneck has a major impact on the flow, in which the zipper effect (overlapped pedestrians) began to act when the door reached 70 cm width. Recently, Adrian et al. [40] did 2 runs per group and studied the width of the bottleneck for different scenarios: 1.2 m, 2.3 m, 3.4 m, 4.5 m, and 5.6 m. The authors reported that the demand level affects the behaviour of pedestrians in the bottleneck (e.g. pushing).

In spite of different research having being carried out to study the layouts of vehicles and stations, more detailed research was needed to identify the effect of design features

on the BAT. The observations made from the results of the experiments presented in this paper would fill gaps and reconfirm important points in relation to existing studies. In particular, it could be interesting to compare the results from laboratory experiments at PAMELA with real data observed at LU stations.

# 3 Methods

The methods used in this research were based on one period of observation at Green Park Station of the LU and real-scale laboratory experiments at PAMELA. The main variables used in these methods were selected according to three groups reported by Seriani and Fernandez [1]: physical (i.e. vertical and horizontal gap, width of doors, width and length of platforms), spatial (i.e. number of seats, setback), and operational (i.e. density of passengers, BAT, time for each passenger to board and alight).

## 3.1 Set-up of experiments

In experiments at PAMELA, the laboratory (or the experimental setting) consisted of a mock-up of a vehicle and the relevant portion of the platform in front of the doors. According to Childs et al. [41] the use of laboratory experiments could help to separate the effect of external factors that influence the movement of passengers, such as social interactions, activities and safety constraints. In addition, the laboratory environment is an ideal space to change one variable and keep the rest fixed. Therefore, PAMELA represent an ideal opportunity for researchers to test "what if" scenarios. However, this does 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 be observed afterwards in existing stations.

The set-up at PAMELA consisted of a half-carriage mock-up of a train with one double door. The platform was 3.60 m wide and 10.80 m long, whilst the train was 2.50 m wide and 10.00 m long. The doorway width of 1.30 m, 1.50 m and 1.80 m were based on the existing and proposed rolling stock as well as the results of a field study on the existing Thameslink stations (see Fig. 1).

In total 120 participants were recruited at PAMELA, in which on average 55 percentage were male and 45 percentage were female, and mostly under 40 years old. Two load conditions were tested: a) 45 alighting and 5 boarding; b) 45 boarding and 5 alighting. A complete sound system was provided in order to make the environment seem more familiar to the participants. The sound simulated the train movements, i.e. included the train arriving, braking, door opening alarm, door closing alarm and departure. In addition, cameras were installed at a height of 4.0 m in the laboratory ceiling. The boarding/alighting did not require any particularly skilful actions but just walking and getting on/off the step. Before the first experiment of each day, we ran a couple of dry runs where participants were asked to get on/off but we did not record. Participants familiarised themselves with the experiment environment within these dry runs.
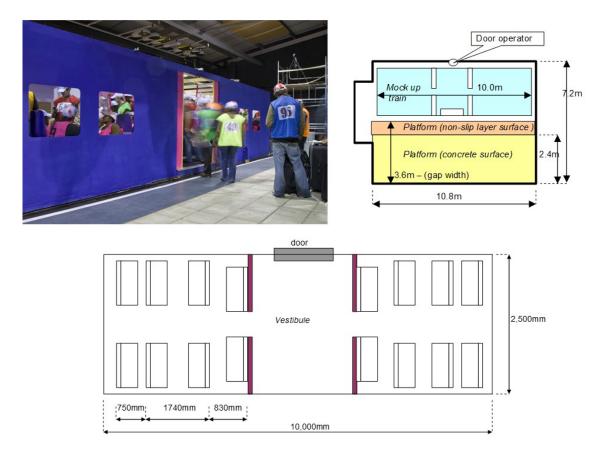
**Figure 1**    Different views of the mock-up at PAMELA

To achieve a high frequency, each train would be able to stop at a station for a maximum of 45 seconds. This means that there would be only 27 seconds for doors to be fully open. At the maximum, the 50 passengers are supposed to alight or board at the double door. Therefore, those passengers needed to alight or board within the 27 seconds door-fully-open time.

In total, 68 runs, representing train arrival, dwell and departure, were completed at PAMELA. Three door widths were simulated: 1.30 m, 1.50 m, and 1.80 m. The vestibule setback changed from 0 mm to 400 mm, and from 400 mm to 800 mm.  In total, 27 scenarios were performed.  In this experiment, the vestibule setback is defined as the distance between the train doors and the seats, which is also known as the standback space. These scenarios were repeated for three vertical gaps: 50 mm, 165 mm, and 250 mm. The experiments were always performed in the same order, increasing the step size from one to the next experiment. In all cases the horizontal gap was 275 mm.

The experiment at PAMELA lasted three days. The first day all the experiments were simulated with the step height of 50 mm, the second day 165 mm and the third day 250 mm. Some people participated in all three days while others in only one or two. It might be possible that in the third day people were familiar with the step height of 250 mm, but we think this is not a major factor because such familiarity would have more impact on experiments within the same day.

Each session consisted of several runs representing the boarding and alighting process involved with a single train at the station (some sessions included 4 runs, others included 6 runs). In runs 1, 3 and 5, the number of the alighting participants was 45 whereas that of the boarding participants was 5. In runs 2, 4 and 6, the number of the alighting participants was 5 whereas that of the boarding participants was 45. Before runs 1, 3 or 5, the train was loaded so that it was full of participants. For each run it was decided to maintain the same number of passengers on the loaded train so it was designed that 70 participants would be on the train before runs 1, 3 or 5 started and after runs 2, 4, 6.

In order to keep the platform density the same for each run, experiment organisers asked the participants on the platform to crowd together to maintain the density. The set density varied slightly according to the experiment day because the number of participants was slightly different across the experiment days. Each participant was given a unique ID for each day. This was used to instruct participants in terms of boarding and alighting. Because the number of participants was around 120 whereas the number of movements (alighting/boarding) was 50 in each run, some participants needed to stay where they were. However, all the participants had the same number of alighting/boarding in each session. Participants were unaware until the instructions were given whether or not they would be required to board or alight.

The basic procedure of each run started with the sound system (e.g. train approaching). Then, an experimenter announced was made to mention who should alight/board when the door opened by means of announcing the boarding and alighting participant IDs. After this announcement, the run was started. Except in the cases where we allowed the doors to remain open until the last passenger movement had taken place, we opened/closed the door with the fully opening duration being 27 seconds. After closing the door, and allowing the participants to settle in the new arrangement, we opened the door again in order for any non-completed passenger movements to be completed. This ensured that the right number of participants were in the right place for the succeeding run and provided observers with a quick check of ongoing performance.

The experiment was recorded by eight video cameras set up at various points on the ceiling of PAMELA and one was set up at ground level to view participant performance over the horizontal gap. Each ceiling-mounted camera had a viewing area of 3.2 m by 4.0 m at the floor level, so that distortion was as small as possible. In addition a manual count was taken by observers of the camera outputs to ensure that the correct numbers of passenger movements were included.

The average boarding time per passenger (tb) was obtained as the ratio between the total boarding time (Tb) and the total number of boarding passengers (Pb) each time the train arrived. Tb is defined as the difference in time between the last passenger boarding and first passenger boarding. For example, if only 35 passengers could board the train, in which the first passenger board the train in t = 1 s and the last passenger board the train in t = 27 s (time when doors are closed), then Tb = 26 s and tb = 0.74 s per passenger. The same calculation was done for the average alighting time (ta = Ta/Pa). In this case Ta is obtained by the difference in time between the last passenger alighting and the first passenger alighting. In terms of load conditions, tb is obtained for the case when 45 passengers are boarding and 5 passengers are alighting. Similarly, ta is calculated in the

situation when 45 passengers are alighting and 5 passengers are boarding.

To compare the mean between samples at PAMELA, a MANOVA was performed, taking into consideration that the door width, vestibule setback and vertical gap were changed. For the statistical test it was used a significance level of 0.05 and the null hypothesis (H0) was that the door width, vestibule setback and vertical gap will have no significant effect on the average alighting time (ta) or average boarding time (tb). This non-parametric test was used considering the small sample size and assuming that the data is not normally distributed.

## 3.2 Observations in existing stations

The results of the laboratory experiments at PAMELA were then compared with a complete CCTV footage analysis at Green Park Station on the Jubilee Line during the morning and afternoon peak hours: 8:15 am to 9:15 am and 5:15 pm to 6:15 pm. During these time periods the train frequency was around 30 trains per hour (2 min headway on average). In total, two weeks of videos were observed with the software Observer XT 11 [42].

At Green Park Station three double doors were observed. The first door was subject to a higher demand as it was located in front of an exit gate on the platform, whilst at the second door passengers needed to walk along the platform to reach the exit gates. In both doors the vertical gap was equal to 170 mm and the horizontal gap was 90 mm, which was within the range of the laboratory simulations at HDL and PAMELA. The third door had a vertical gap of 0 mm as a platform hump had been installed to produce level access for passengers (see Fig. 2). This hump had a total length of 27.00 m and the same width as the platform (3.00 m). Therefore, it covered four train doors (two double doors and two single doors) in the second and third carriages of the train. The double doors at the trains in Green Park Station were 1.60 m wide.

Similar to the experiments at PAMELA, to record the BAT in LU observations, the number of passengers boarding (Pb) and alighting (Pa) was counted every five seconds. The counting period was between the time when the doors started opening and the time when the doors were completely closed.

However, in the observations at Green Park Station, the Ta and Tb were combined, obtaining a BAT of 5 second slices. Similar to previous studies at PAMELA and London Underground [27–29] the time slices were used as a corrected metric of the BAT because, as opposed to the conditions in a controlled laboratory experiment, in existing stations a corrected metric is needed to isolate the BAT from external factors such as operational delays due to signal failures or congestion down the line, and stems from the impossibility of controlling the boarding and alighting processes under actual operation. In addition, Pb and Pa at Green Park Station were corrected to eliminate those 5 second time slices in which "late runners" were recorded (i.e. passengers boarding the train after the main group had already boarded). A criterion for precise observations was that those passengers who boarded the train after two or more time slices in which no passengers were observed, were not considered in the BAT.

To further explore the differences in the boarding and alighting process, the average boarding and alighting profiles were analysed. In order to get results that were directly

**Figure 2** Platform hump door at Green Park Station

comparable, relative profiles have been used, which isolate the shape of the curve from the demand. Thus, the relative profiles for each observation are obtained by dividing the number of boardings (alightings) in each 5 seconds interval by the total number of boardings (alightings) in that boarding (alighting) process. The profiles presented are formed by averaging over all observations for each interval. Therefore, they represent the average proportion of boardings (alightings) in any given interval.

For the LU observations, only descriptive statistics were provided. The BAT at Green Park Station was obtained as an expanded study of [27–29], in which the authors stated that the data did not satisfy the requirements for parametric tests (e.g. ANOVA) or even non-parametric tests (e.g. Mann-Whitney). There was no normal distribution and the distribution within each group was not similar.

# 4 Results

## 4.1 Experiments at PAMELA

Tab. 1 - 6 show the effect of train design features on the average alighting time (ta) and the average boarding time (tb) at PAMELA experiments.

In the case of the average boarding time (tb) the lowest value is found for a vertical gap of 50 mm with a door width of 1.80 m and a vestibule setback of 800 mm, giving 0.65 s/pass on average (see Tab. 1, 2 and 3). For the same door width and vestibule setback, if

| Vestibule setback (mm) | V=50 mm | V=165 mm | V=250 mm |
| --- | --- | --- | --- |
| 0 | 1.10 | 1.07 | 1.02 |
| 0 | 0.86 | 0.85 | 1.38 |
| 0 | 0.87 | 1.09 | |
| 0 | 0.95 | | |
| 400 | 0.96 | 0.91 | 0.76 |
| 400 | 0.84 | 1.11 | 1.00 |
| 400 | | 0.99 | 1.01 |
| 800 | 0.79 | 0.92 | 0.83 |
| 800 | 0.73 | 0.85 | 0.91 |
| 800 | | 0.78 | 1.27 |

**Table 1**  Average boarding time (tb) in seconds for a door width of 1.30 m at PAMELA

| Vestibule setback (mm) | V=50 mm | V=165 mm | V=250 mm |
| --- | --- | --- | --- |
| 0 | 0.78 | 1.43 | 1.88 |
| 0 | 0.92 | 0.91 | 1.18 |
| 0 | | | 0.97 |
| 400 | 0.90 | 0.82 | 0.90 |
| 400 | 0.79 | 0.86 | 0.96 |
| 800 | 0.77 | 0.79 | 0.84 |
| 800 | 0.74 | 0.77 | 0.84 |

**Table 2**  Average boarding time (tb) in seconds for a door width of 1.50 m at PAMELA

| Vestibule setback (mm) | V=50 mm | V=165 mm | V=250 mm |
| --- | --- | --- | --- |
| 0 | 0.72 | 1.12 | 0.79 |
| 0 | 0.76 | 0.93 | 0.76 |
| 0 | | 0.77 | 1.05 |
| 400 | 0.66 | 0.74 | 0.74 |
| 400 | 0.66 | 0.77 | 0.71 |
| 400 | | 0.66 | 0.78 |
| 800 | 0.68 | 0.71 | 0.78 |
| 800 | 0.62 | 0.79 | 0.81 |
| 800 | | 0.71 | 0.91 |

**Table 3**  Average boarding time (tb) in seconds for a door width of 1.80 m at PAMELA

the vertical gap is increased to 165 mm and 250 mm, then tb also increased by 13 percent (0.74 s/pass on average) and 27 percent (0.83 s/pass on average), respectively.

The MANOVA (with a significance level of 0.05) showed that the three variables (door width, vertical gap and vestibule width) presented significant differences. The null hypothesis (H0) for the statistical test was that the door width, vestibule setback and vertical gap will have no significant effect on the tb. Therefore, it is recommended to have wider doors, larger vestibule setback and smaller vertical gaps to reduce tb. This is also supported by Fig. 3, in which a high number of cumulative passengers are reached for a door width of 1.80 m, a vestibule setback of 800 mm and a vertical gap of 50 mm. In addition, for the case of a door width of 1.80 m the correlation became non-linear above 30 boarders. This could be related to the formation of lines of flows of passengers boarding, which is described in [37–40]. More experiments should be done to better explain the differences between each scenario. In particular, it could be interesting to understand why in the case of a door width of 1.30 m there appears to be a separation between the 400 mm setback, which is not produced in the other two cases (door width of 1.50 m and 1.80 m).
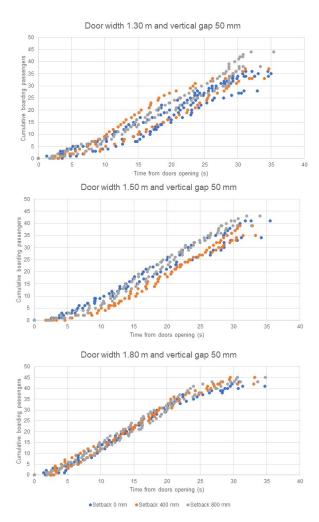


**Figure 3** Effect of the vestibule setback and door width on the cumulative boarding passengers when the vertical gap is 50 mm

| Vestibule setback (mm) | V=50 mm | V=165 mm | V=250 mm |
|---|---|---|---|
| 0 | 1.63 | 2.61 | 2.77 |
| 0 | 1.14 | 1.59 | 1.56 |
| 0 | 2.40 | 1.30 | |
| 0 | 1.78 | | |
| 400 | 0.98 | 1.27 | 1.41 |
| 400 | 1.18 | 1.41 | 1.24 |
| 400 | | 1.00 | 1.22 |
| 800 | 1.41 | 1.50 | 2.19 |
| 800 | 1.08 | 1.33 | 1.05 |
| 800 | | 1.22 | 0.90 |

**Table 4**　Average alighting time (ta) in seconds for a door width of 1.30 m at PAMELA

| Vestibule setback (mm) | V=50 mm | V=165 mm | V=250 mm |
|---|---|---|---|
| 0 | 1.04 | 1.59 | 1.34 |
| 0 | 1.40 | 1.49 | 1.38 |
| 0 | | | 1.58 |
| 400 | 1.26 | 1.49 | 1.25 |
| 400 | 1.40 | 1.09 | 1.46 |
| 800 | 1.07 | 1.34 | 1.38 |
| 800 | 1.12 | 1.36 | 1.31 |

**Table 5**　Average alighting time (ta) in seconds for a door width of 1.50 m at PAMELA

| Vestibule setback (mm) | V=50 mm | V=165 mm | V=250 mm |
|---|---|---|---|
| 0 | 0.95 | 1.02 | 0.90 |
| 0 | 1.35 | 1.95 | 0.91 |
| 0 | | 1.00 | 0.85 |
| 400 | 1.10 | 0.95 | 1.25 |
| 400 | 1.12 | 1.30 | 1.46 |
| 400 | | 0.81 | 1.00 |
| 800 | 0.90 | 0.82 | 0.92 |
| 800 | 0.93 | 1.20 | 1.09 |
| 800 | | 0.94 | 0.73 |

**Table 6**　Average alighting time (ta) in seconds for a door width of 1.80 m at PAMELA

In the case of ta (see Tab. 4, 5 and 6), the best layout for the lowest ta is represented by a vertical gap of 250 mm with a door width of 1.80 m and a vestibule setback of 0 mm, giving 0.89 s/pass on average.

However, the MANOVA results (with a significance level of 0.05), showed no significant differences for the vertical gap (p-value higher than 0.05). The null hypothesis (H0) for the statistical test was that the door width, vestibule setback and vertical gap will have no significant effect on ta. Possible causes are due to other phenomenon such as congestion inside the train and formation of lines of flow to alight, which were out of the scope of this study.

Although the vertical gap presented no significant differences, the door width and vestibule setback presented a p-value lower than 0.05. The ta is reduced up to 60 percent on average when increasing the door width and vestibule setback. Therefore, it is recommended to have wider doors (1.80 m) and larger vestibule setback (800 mm) to reduce ta.

## 4.2 Observation at Green Park Station

In the case of the LU observations, the ratio (R) of passengers boarding to those alighting was obtained at Green Park Station for the total video recordings at each door. Door 1 and Door 2 (both with a vertical gap of 170 mm) presented an average value of R 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 and vertical gap between Door 1 and Door 2, the boarding and alighting time (BAT) was calculated as an average between both doors (henceforth termed Door 1&2).

Two types of codes were used with the software Observer (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. The PTI was defined in consultation with Transport for London as the space between the yellow line on the platform edge and the train doors.

Fig. 4 shows the average boarding and alighting profiles for the selected doors at Green Park Station. 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 (10th - 15th s), whilst boarding started at the second time slice (5th - 10th s) and ended almost at the fifth time slice (20th - 25th s). Door 1&2 (vertical gap 170 mm) presented a slightly lower cumulative boarding profile compared to 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 Station 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 to 15 passengers; b) 15 to 25 passengers; c) more than 25 passengers. Fig. 5 shows that the BAT increased as
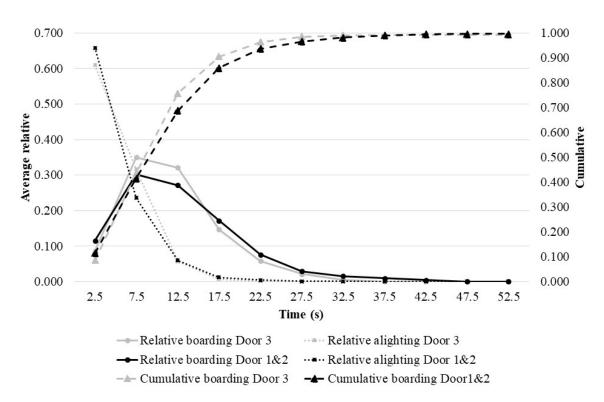
**Figure 4**   Average boarding and alighting profiles at Green Park Station

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 percent lower BAT than Door 3 (level access). The minimum difference was reached in the category more than 25 passengers, reaching a difference of 1.6 s, while the maximum difference was obtained in the category 15 to 25 passengers, reaching a difference of 2.4 s. Therefore, it seems that level access is not always the best scenario to reduce the BAT. A possible explanation would be that in presence of a small vertical gap passengers need to do an impulse to board or alight, and therefore their speed increases, reducing the BAT. Further experiments at PAMELA are needed to measure the impulse of passengers, and therefore verify this behaviour.

In this study it was not possible to identify the effect of on-board passengers on the BAT. The demand on arrival could not be derived from the variables observed from the videos. Instead, the network management information system at Transport for London provides a level of demand, which only says if this demand is low, medium or high. Therefore, this study is limited only to the analysis of the BAT and the boarding and alighting passengers. To obtain an exact value of passengers on-board and calibrate the system further research is needed.

The results of the observation at Green Park Station should be treated carefully as there could be other factors affecting the behaviour of passengers, which were out of the scope of this study such as the location of staircases, level of demand and type of passengers.
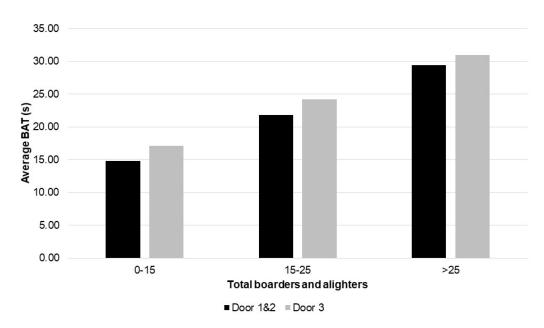
**Figure 5**   Boarding and alighting times by total boarders and alighters at Green Park Station

# 5  Discussion

This work studied the effect of train design features on the boarding and alighting time (BAT). The approach was based on similar studies done previously by [26–30], in which laboratory experiments were performed at the Pedestrian Accessibility Movement Environment Laboratory (PAMELA) in University College London and observation was done using a complete CCTV footage analysis of two weeks (morning and afternoon peak hours) at Green Park Station in London Underground.

The results of the laboratory experiments showed the importance of the door width, vestibule setback and vertical gap on the BAT. The combination of wider doors (1.80 m), larger vestibule setback (800 mm) and smaller vertical gap (50 mm) presented the lowest tb, reaching 0.65 s/pass on average. Our hypothesis had been that a larger gap size would lead to a lower tb, and this phenomenon was in concordance to our hypothesis. However, in the case of ta the statistical test showed no significant differences (even if larger vertical gaps reached a lower ta). It should be noted that this phenomenon was observed in some runs with a door width of 1.50 m and in many runs with a door with of 1.80 m. It is assumed that, in alighting, a major factor which decides the number of alighting passengers within a given time could be the train's internal layout, and it has been observed in the experiment runs with a door width of 1.80 m that two parallel streams (or lines of flow) of alighting passengers often (but not always) emerged at the door, while for 1.30 m there was only one stream. In these cases, the impact of the vertical gap can become relatively less important and thus in some cases a larger vertical gap gave a lower ta. In the case of boarding experiments, usually no congestion inside the train occurred (as boarding started when alighting completely or almost finished), and thus the step becomes a factor that determines tb. These results are supported by the MANOVA analysis, in which the vertical gap, the door width and the vestibule setback has an impact

on tb (i.e. p-value less than 0.05).

Similarly to in the laboratory experiments, the results from the observations at Green Park Station can be interpreted as the BAT being influenced by the vertical gap. A small vertical gap of 170 mm could reduce the BAT by up to 13 percent. We thought that this result could also be affected by the types of passengers (e.g. passengers with restricted mobility were more attracted to use Door 3 than other doors over the length of the platform). Nevertheless, in terms of the total passengers that boarded and alighted at Door 3, only 0.5 percent used wheelchairs/prams and 2.8 percent carried luggage.

It must be noted, however, that the objective of our experimental work is not to recommend the ultimate design features, but to shed light onto the magnitude of changes on BAT as a consequence of variations in the door width, vestibule setback and vertical gap. In addition, values of vertical gaps different to zero may cause inaccessibility for people with permanent or temporary disabilities (e.g. pushchair, trolley bag, or encumbrances). In such cases, some parts of the platform may have special facilities, for instance platform humps, as in the case of Green Park Station. In this sense, to compare the laboratory experiments and obtain an "optimal" design feature or "best scenario", further research is needed. More runs would help to reduce possible errors and differences between results at PAMELA. However, in this study the resources were limited, and therefore between 2 and 3 runs per scenario were performed at PAMELA. In addition, further research is needed to examine if the impulse of passengers is influenced by the interaction between flow size (number of passengers), type of passengers and gap size at the PTI. For instance, it could be interesting to obtain the speed of passengers and compared to some studies such as Weidmann [43], in which the author obtained relationship between density and speed for different type of passengers (shoppers have a free-flow speed of 1.04 m/s, commuters 1.45 m/s, and tourists 0.99 m/s). For the further studies, we would like to first do field studies and then laboratory experiments to test the same cases or even new situations not seeing at the existing stations. This approach would be recommended to better connect the experiments with the field studies.

In conclusion, the use of laboratory experiments helped to test different situations ("what if" scenarios) in a controlled environment. This would be difficult to do in a real situation due to the different variables affecting the layout and vehicles of existing public transport systems. In addition, few laboratories such as PAMELA have been built in the world, which has led us to be in a privileged position and be able to perform new research. Currently, new experiments are simulating the use of a waiting area or a "stay clear" to avoid alighting being blocked by passengers waiting in front of the doors. This research will include more observation and experiments to better understand the effect of other variables such as staircases, level of demand and type of passengers on the behaviour of passengers.

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