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 Londons 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 speed. 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 Fruins 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 Londons 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, the differences in height and distance between the vehicle and the platform can be divided into two groups: steps (e.g. between 200 and 600 mm) and vertical/horizontal gaps (e.g. less than 300 mm).

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 1.85 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: 800mm, 900mm, 1100mm, 1300mm, and 1900mm. 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 Universidad de los Andess Human Dynamics Laboratory (HDL), 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. This is an interesting result, which led us to think that there would be a benefit (i.e. to reduce BAT) to having small vertical gaps (lower than 300 mm), which is different from having steps (which are around 300 mm and 600 mm).

It is generally thought that to increase 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.

To represent similar conditions, some 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 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 (see Fig. 1).

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 tested afterwards in existing stations.

Experiments 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 1.50 m, 1.65 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.

In total 120 participants were recruited at PAMELA (on average 55 percent male and 45 percent female, mostly under 40 years old) and a combined bidirectional flow of boarding and alighting was simulated (45 alighting / 5 boarding, and 45 boarding / 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

PAMELA.jpg PAMELA.jpg

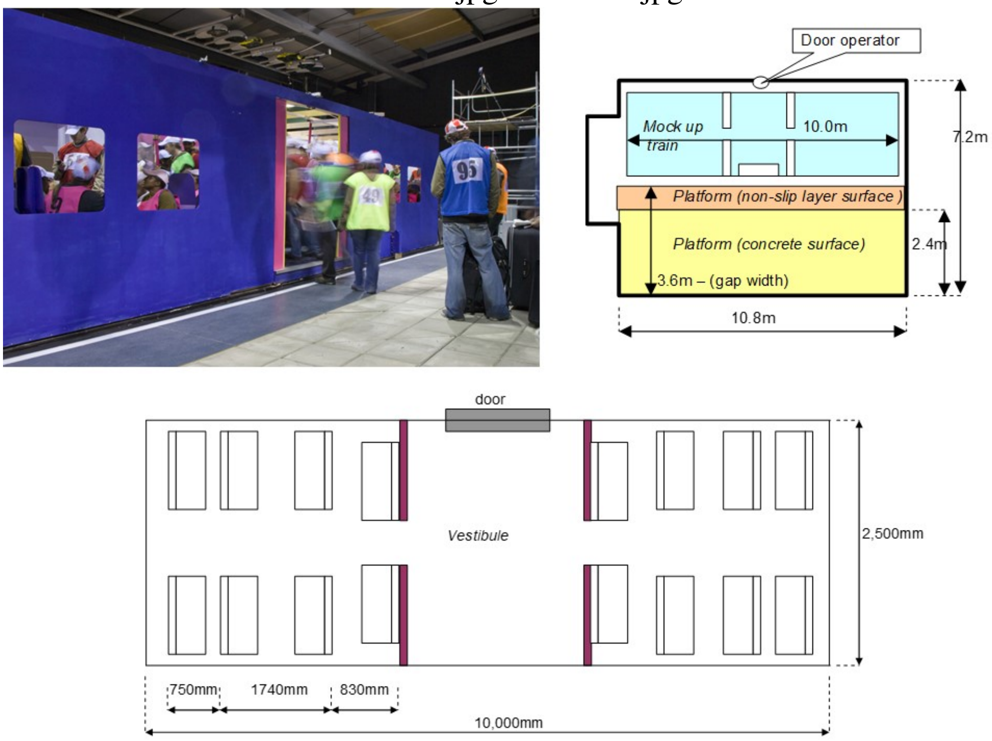

Figure 1 Different views of the mock-up at PAMELA

were asked to get on/off but we did not record. Participants familiarised themselves with the experiment environment within these dry runs.

Between 2 and 3 runs per scenario were simulated at PAMELA, reaching a total of 68 runs. 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, 9 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. In summary the scenarios (S) where labelled as the following:

- S1: vertical gap of 50 mm and vestibule setback of 0 mm.
- S2: vertical gap of 50 mm and vestibule setback of 400 mm.
- S3: vertical gap of 50 mm and vestibule setback of 800 mm.
- S4: vertical gap of 165 mm and vestibule setback of 0 mm.
- S5: vertical gap of 165 mm and vestibule setback of 400 mm.
- S6: vertical gap of 165 mm and vestibule setback of 800 mm.
- S7: vertical gap of 250 mm and vestibule setback of 0 mm.
- S8: vertical gap of 250 mm and vestibule setback of 400 mm.
- S9: vertical gap of 250 mm and vestibule setback of 800 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.

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. 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.

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.

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 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. The relative average number of passengers boarding and alighting was plotted against time, showing different profiles at each door. 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

Figure 2 Platform hump door at Green Park Station

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.

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

In experiment at PAMELA, Tab. 1 show the effect of train design features on the average alighting time (ta). Nine different scenarios were simulated. The best layout for the lowest ta is scenario 7 (S7), which represented 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. 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.

Door width (m)	S1	S2	S3	S4	S5	S6	S7	S8	S9
1.30	1.74	1.08	1.24	1.84	1.23	1.35	2.17	1.29	1.38
1.50	1.22	1.33	1.09	1.54	1.29	1.35	1.43	1.36	1.34
1.80	1.15	1.11	0.91	1.32	1.02	0.99	0.89	0.91	0.91

Table 1 Average alighting time (ta) for the 9 different scenarios (s) simulated at PAMELA

Door width (m)	S1	S2	S3	S4	S5	S6	S7	S8	S9
1.30	0.94	0.90	0.76	1.00	1.00	0.85	1.20	0.92	1.01
1.50	0.85	0.85	0.76	1.17	0.84	0.78	1.34	0.93	0.84
1.80	0.74	0.66	0.65	0.94	0.72	0.74	0.87	0.74	0.83

Table 2 Average boarding time (tb) for the 9 different scenarios (s) simulated at PAMELA

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 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.

In the case of the average boarding time (tb) the lowest value is found for the scenario S3, which represented 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 (see Tab. 2). For the same door width and vestibule setback, if the vertical gap is increase to 165 mm (scenario S6) and 250 mm (scenario S9), then tb also increase by 13 percent (0.74 s/pass) and 27 percent (0.83 s/pass), respectively. In contrast to ta, 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 (1.80 m), larger vestibule setback (800 mm) and smaller vertical gaps (50 mm) to reduce tb.

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).

Fig. 3 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

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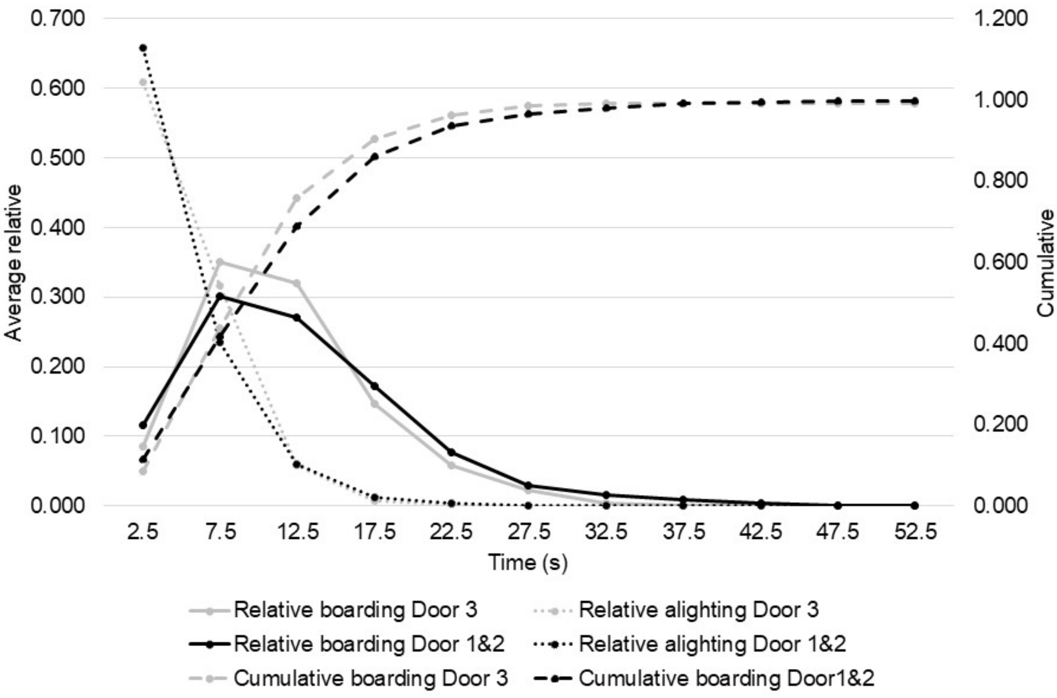

Figure 3 Average boarding and alighting profiles at Green Park Station

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. 4 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 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 increase, Green Park.jpg Green Park.jpg

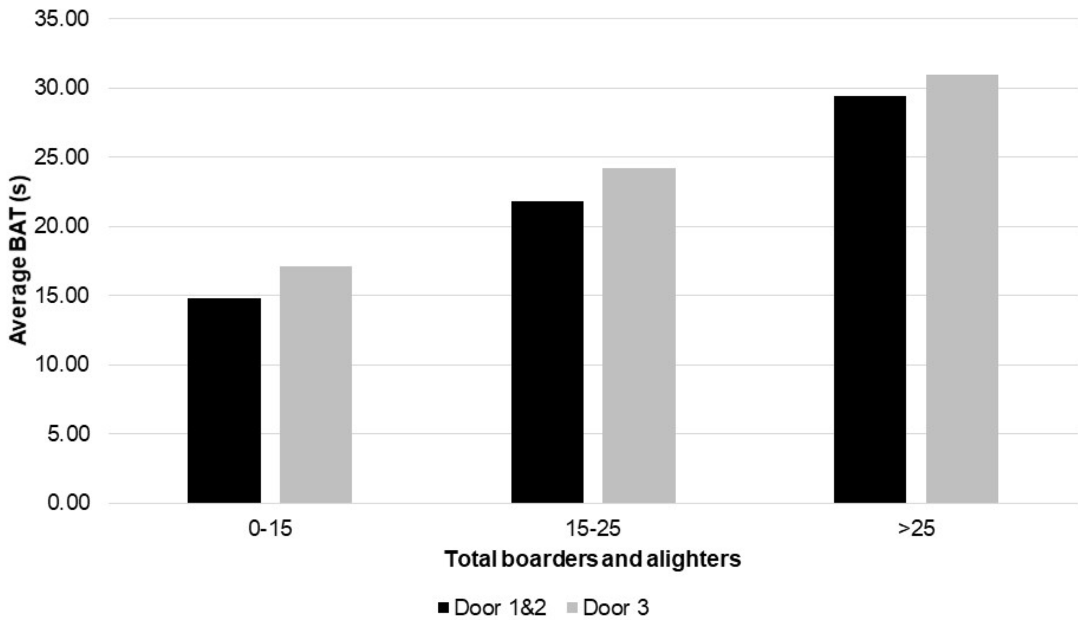

Figure 4 Boarding and alighting times by total boarders and alighters at Green Park Station

reducing the BAT. Further experiments at PAMELA are needed to measure the impulse of passengers, and therefore verify this behaviour.

5 Discussion

This work studied the effect of train design features on the boarding and alighting time (BAT). The approach was based on laboratory experiments at University College Londons Pedestrian Accessibility Movement Environment Laboratory (PAMELA) and observation using a complete CCTV footage analysis of two weeks (morning and afternoon peak hours) at London Undergrounds Green Park Station.

The results of the laboratory experiments showed the importance 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. 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 speculated that, in alighting, a major factor which decides the number of alighting passengers within a given time could be the trains 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.

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.

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.

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