THE COMBINED EFFECT OF PLATFORM EDGE DOORS AND LEVEL ACCESS ON THE BOARDING AND ALIGHTING PROCESS IN THE LONDON UNDERGROUND

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ABSTRACT

Platform edge doors (PEDs) are used in metro stations to improve passengers' safety and comfort, whilst a step-free access with minimum gap between the train and the platform is desirable on the grounds of accessibility.

There is little research focused on the effect of PEDs on the boarding and alighting time (BAT) and passenger behaviour patterns. On the other hand, many authors have treated the impact of vertical and horizontal gaps in passengers' boarding and alighting.

On London Underground (LU), there is always step-free access between the train and the platform when there are PEDs; but even at some platforms without PEDs there may be level access provided by platform humps.

The objective of this paper is to study the combined effect of PEDs and level access on the boarding and alighting process. To this aim two LU platforms, both with level access, one with PEDs and one without PEDs, have been compared. This was done analysing bespoke video footage. The results show that PEDs on their own have no overall negative impact on the BAT and that in most situations they encourage passengers to wait beside the doors. It was also found that demand (number of boarders, alighters, and passengers on the train) is more important on the BAT and passenger behaviours than the presence of PEDs.

Keywords: dwell time; boarding, alighting, passenger behaviour, platform edge door, level access.

INTRODUCTION

Platform edge doors (PEDs) are used in metro systems around the world mainly to improve passengers' safety (*1, 2, 3*). Currently, the London Underground (LU) network has PEDs in nine stations on the Jubilee Line, all of which provide level access to the trains from the whole platform. However, at many other LU stations, there is a certain gap between the train and the platform. The vertical gap typically varies with the type of rolling stock, whilst the horizontal gap is usually most influenced by the platform design (e.g. curved platforms generate wider horizontal gaps). It is recommended that vertical gaps should not exceed 50 mm, and that horizontal gaps be lower than 75 mm (*4*).

To reduce these gaps at the platform train interface (PTI), platform humps have been retrofitted at some stations to provide equal accessibility to all users and ease the boarding and alighting of passengers with mobility impairments or encumbrances such as heavy luggage or buggies. They are located in front of some doors and cover the whole platform width, with gentle access slopes on either side and specific signage. However, the implementation of platform humps is limited by the need of consistency in train stopping and the different types of rolling stock (*5*).

There is a common presumption that the presence of PEDs increases both the static and dynamic components of dwell time, which is defined as the time that the train remains on a platform from the moment the wheels stop to the time when they start rolling again. The static component of dwell time is related to the door opening and closing times, as well as to the duration of other mechanical movements and of safety delays, whilst the dynamic compoment relates to passenger movements and is mainly the boarding and alighting time (BAT), which is the focus of this paper.

However, recent studies (*6*) have shown that PEDs have no important impact on the BAT, although these elements change waiting passengers' behaviour, whereby queuing or clustering beside the doors rather than in front of them happens more often when there are PEDs. For that study, the authors used a mock-up train and PTI in a controlled environment at University College London's Pedestrian Accessibility Movement Environmental Laboratory (PAMELA) and conducted observations from video footage at two LU platforms. For both the experiments and observations in (*6*), they compared a PTI with PEDs and level access with another PTI without PEDs and a 170 mm high vertical gap. However, due to a technical fault in the automatic video recording and lack of resources, the authors could not consider a PTI without PEDs and with level access, therefore the results obtained left the question of the effect of PEDs under equal vertical gap unresolved for further research.

The aim of this work is thus to fill that knowledge gap and to expand the analysis and results obtained in (*6*), studying the effect of PEDs on the BAT and on passengers' behaviour when level access is provided. In this work behaviour is defined as the way passengers interact with each other at the PTI (*7*).

This paper comprises six sections, including this one. The second section is the literature review. In the third, the method is explained. The fourth section presents the results. In the fifth, these are further discussed, and finally in the sixth section the conclusions are explained.

LITERATURE REVIEW

The boarding and alighting time (BAT) has been studied by different authors. Here, only a few contributions are discussed.

The Highway Capacity Manual and Transit Capacity and Level of Service Manual (*8, 9*) propose a linear relationship to determine dwell time. The time to open and close the doors is considered the static component, whilst the dynamic component or BAT is defined as the product of the average time it takes each passenger to board or alight and the number of passenger boarding and alighting.

However, some field studies (*10*) show that the BAT depends not only on the number of passengers boarding and alighting but also on other factors such as the door width, where wider doors may reduce the BAT by up to 10%.

Moreover, other authors (*11, 12*) use the LU Train Service Model to describe the BAT as part of the station stop time, where the BAT is given by a non-linear relationship between the number of passengers boarding and alighting, the number of doors per car, the number of seats per car, the number of through passengers, and two adjustment factors: the peak door/average door factor and the door width factor. They found that wider doors, larger stand-backs, and more seats can reduce the BAT. In particular, the BAT is determined by the total alighting time, total boarding time and total interaction time at the busiest door (*11*), where the interaction time is defined as the overlap time when boarding and alighting occurs simultaneously at the busiest door.

According to laboratory experiments, the BAT depends on the vertical gap, door width, fare collection method, internal vehicle layout, and vehicle occupancy (*13*).

In relation to platform edge doors (PEDs), the work in (*6*) was expanded in (*14*) to study the Level of Interaction between passengers boarding and alighting in a space defined as platform conflict area, which is divided in layers. The authors found that the interaction between passengers was higher near the PEDs and decreases as the distance from the PEDs increases (*14*). These studies (*6, 14*) are considered the first that identify a relationship between PEDs, BAT and behaviour in normal conditions.

On the contrary, some authors had studied the presence of PEDs in emergency situations, when the platform evacuation time increases whith the presence of these elements (*15*). For these authors the use of PEDs is limited by the inconsistency on the train stopping positions along the platform or by the fragility of their materials (e.g. delays are incured because of a broken PED or cracked glass). In addition, PEDs can be very sensitive and produce delays when the door closing is interrupted, especially in situations when passengers are trapped between the PEDs and the train doors (*16*). On LU these problems have been addressed with more robust materials and by limiting the use of PEDs to stations where the differences in doors spacing between new and old trains are adequate (*17*).

Another factor that affects the BAT is the height difference between the train and the platform, which is considered an obstacle for passengers' boarding and alighting. Experiments at PAMELA (*18*) measured the average time per passenger to board or alight at one single door with three different steps (20 mm vertical gap with no steps, 350 mm for one step, and 510 mm for two steps), finding that boarding (4.13 s) takes on average more time than alighting (3.68 s). In addition, up to 40% of the passengers felt that it was difficult to negotiate steps, and especially those who carried luggage took longer to board or alight. This research is in accordance with some field studies (*19*) which used cameras to study the boarding and alighting in Swedish trains. This author identified three different situations (level access, 2 steps, and 3 steps) and the BAT increased with the number of steps.

Vertical gaps at the PTI are an accessibility barrier for people with reduced mobility. To solve this problem, platform humps can be installed, but the trains should not stop in front of the ramps, which have to take into account the best combination of slopes and crossfall gradients (*20*).

Although vertical gaps could be deemed negative for equal accessibility, recent laboratory studies show that a small vertical gap can actually reduce the BAT (*21*). However, that study only considered alighting passengers in a laboratory experiment, but in (*22*) it is stated that for a bidirectional flow (boarding and alighting) the PTI should be designed with a vertical gap of 50 mm, reaching a maximum flow of 1.42 passengers per second (for a door width of 1.80 m and setback of 800 mm). In the same line of research, in (*23*) it was found that a small vertical gap can also increase doors' capacity when the horizontal gap is increased. Moreover, (*24*) proposed a model to predict dwell time where a small vertical gap could reduce the dwell time in 8%.

Regardless of the research around PTI safety and accessibility, little research has been done to identify the combined effect of PEDs and level access on the BAT and passenger behaviour. Therefore this paper, which extends the study in (*6*), analyses the BAT and passenger behaviour on LU stations, which is expected to be insightful for other metro systems, too.

METHODS

The analysis of the boarding and alighting processes is based on observations 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 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 the aim of this study is to analyse the impact of PEDs when the vertical gap is the same, it was necessary to get footage from doors at GPK and WMS which would satisfy this condition. As was pointed earlier, 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 at a platform hump where there is no vertical gap between train and platform. Therefore these were the only doors at GPK that could be used for this study. The platform hump at GPK has a total length of 27 m and extends over the whole platform width, therefore covering the second and third cars and a total of four doors (two doubles and two singles).

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 pm), 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 which was obtained for the previous study (*6*). Those videos are from November 2014, i.e. at 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 analysis compares:

- 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

At both stations the double doors are 1.60 m wide and the horizontal gap at the PTI is 90 mm.

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 five seconds from the time the doors opened until they closed or after 120 s, whichever the greatest.

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 to do with 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 overlap time (T_o) 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, the 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:

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

From these factors, only the demand on arrival could not be obtained from the videos. As an alternative, it was obtained from NetMIS, TfL's network management information system, which provides a level of demand (low-medium-high) for each arriving train.

In addition to the BAT analysis, the behaviour of passengers waiting to board the train was also studied. To this aim, two types of behaviour were recorded when trains stopped at the platform:

- Passengers waiting beside the doors;
- 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).

Finally, and similarly to the analysis of actual observations in (*6*), this work is limited to descriptive statistics, without formal statistical significance tests. This is because the data do not satisfy the assumptions of any statistical tests, either parametric (e.g. ANOVA) or non-parametric (e.g. Mann-Whitney).

RESULTS

Impact on the BAT

High level statistics

Table 1 shows summary statistics of the average BAT and numbers of boarders and alighters at the two stations, with and without PEDs. At face value, the case without PEDs presents an average BAT which is 16% lower than in the case with PEDs. However, it is difficult to draw simple conclusions about the BAT because it is influenced by demand, and as it can be seen, the case without PEDs (GKP) 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 different split between boarders and alighters, as given by the different ratios (R).

TABLE 1 Observed Average BAT With (WMS) And Without PEDs (GPK)

Variable (average over observations)	WMS (1)	GKP (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%

Boarding and alighting profiles

Figure 1 shows the average boarding and alighting profiles for each case. 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 or alightings at each 5 s segment, the number of boarders or alighters is divided by the total number of boarders and alighters in that boarding and alighting process. But the profiles in Figure 1 are the average of all the profiles so built of all recorded boarding and alighting processes.

It can be seen 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 have boarded at GKP compared to WMS, but this difference fades away at 32.5 s.

The alighting pattern is much more consistent, and a similar cumulative alightings profile could have been plotted (not done for clarity), in which the largest difference between PEDs and no PEDs would have occurred after 7.5 s and been approximately 14% more passengers alighted at GKP (no PEDs) compared to WMS (PEDs), but the difference virtually disappears after 12.5 s.

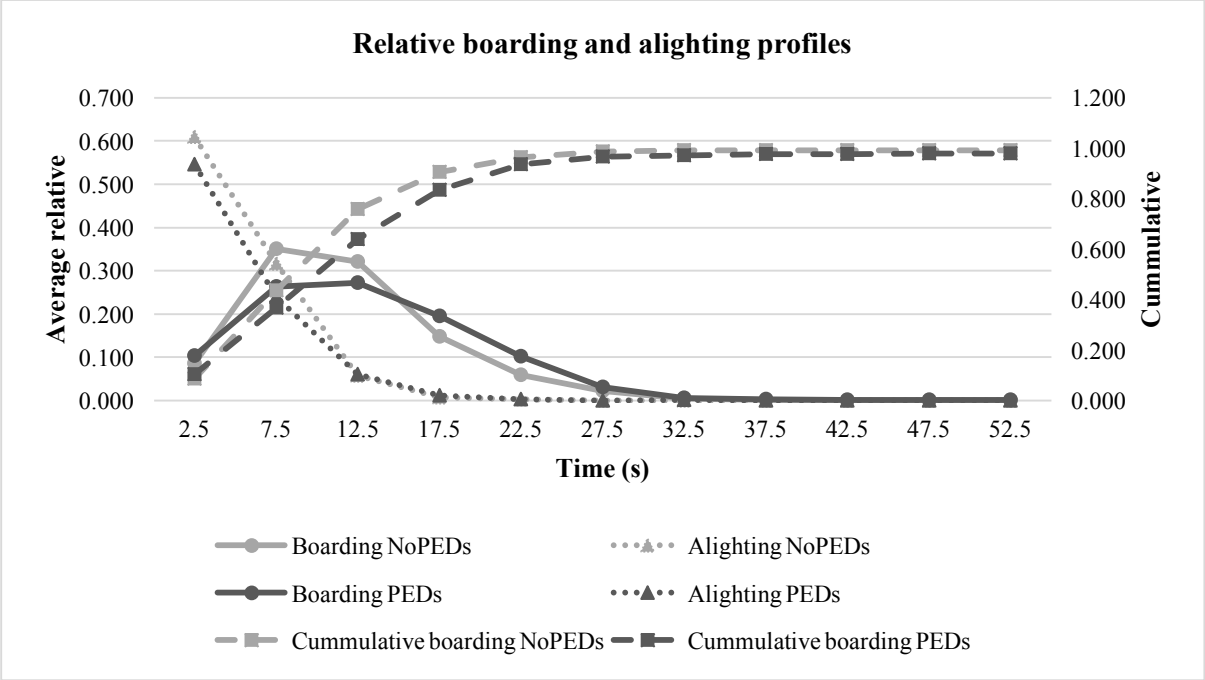

FIGURE 1 Average relative boarding and alighting profiles with (WMS) and without PEDs (GPK).

Demand

This section looks at the impact of PEDs on BAT for the different demand categories, to decouple their influence on the BAT.

In relation to the train demand on arrival, Table 2 shows that PEDs seem to increase BAT for medium and high on-train loads. However, there are no "low" loads reported for the hump door (no PEDs). This could be caused because those demand levels are actually not reached, but it is important to insist on 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.

With respect to the total number of boarders and alighters, Table 2 shows that the BAT increases with the number of total passengers, as is intuitive. 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. On 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.

TABLE 2 BAT With (WMS) And Without PEDs (GPK) With Respect To Demand Metrics

Metric	Level	Number of observations		Mean corrected BAT (s)			Standard deviation of corrected BAT (s)		
		GPK	WMS	GPK	WMS	Diff.	GPK	WMS	Diff.
Train demand on arrival	Low	-	10	-	25.00	-	-	9.43	-
	Medium	280	945	19.38	21.47	+2.09	6.44	6.88	+0.45
	High	329	748	19.33	24.94	+5.61	6.37	6.96	+0.60
Total boardings and alightings	0-15	422	554	17.09	17.20	+0.11	5.69	5.85	+0.16
	15-25	188	809	24.26	24.46	+0.20	4.76	5.42	+0.65
	25+	5	340	31.00	29.04	-1.96	4.18	5.82	+1.63

Impact on passenger behaviours

Observed behaviour frequencies

Figure 2 (right) shows the formation of queues at the hump door in GKP when the train is stopped at the station. Queues beside the doors help passengers alight, reducing the conflict at the PTI.

When the boarding and alighting finishes, another behaviour pattern was observed at the hump door in GKP. 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 just on the platform. One is that there is not enough space available inside for them to feel comfortable, 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 is the true reason in each case.

At the same time, a circulation space was formed between the platform wall and the standing passengers on the platform, where naturally passengers form flow lanes to avoid collisions with people coming in the opposite direction (Figure 2 left).

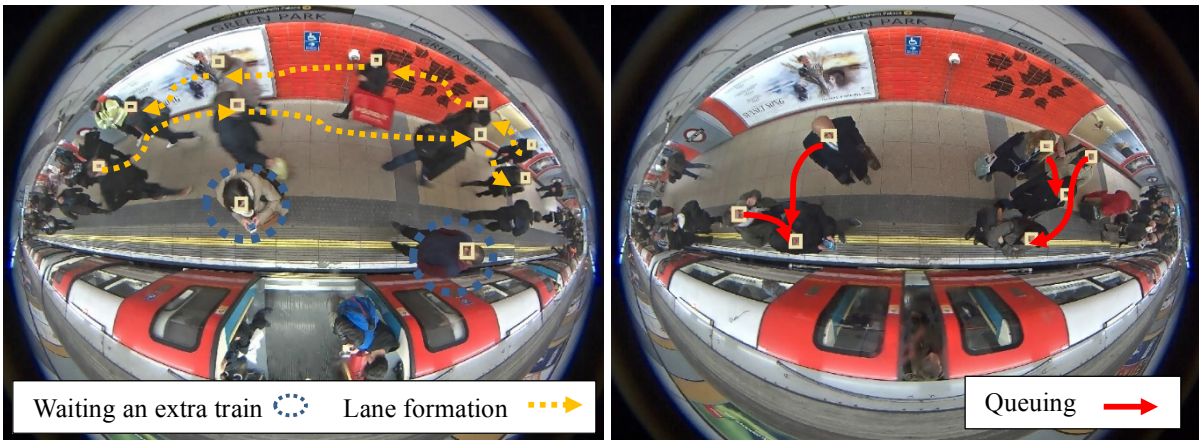

FIGURE 2 Passenger behaviours at the hump door (GPK, no PEDs).

Figure 3 compares boarding passengers' behaviour between the situation without PEDs (GKP) and the case with PEDs (WMS). The percentages quoted are calculated as the frequency of each behaviour in each category divided by the total number of observations in that category. The data are binned according to the total number of boarders, because people place themselves on the platform based on their surroundings passengers, which has been seen to have an impact on behaviours and this seems to be the best way of capturing that.

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

In the case of crowded situations when there are passengers everywhere around the doors, the case with PEDs presents fewer passengers waiting in front and beside the doors for low demand levels. However, this behaviour changed when the level of demand reached medium levels, in which no relevant differences were found between WMS and GKP.

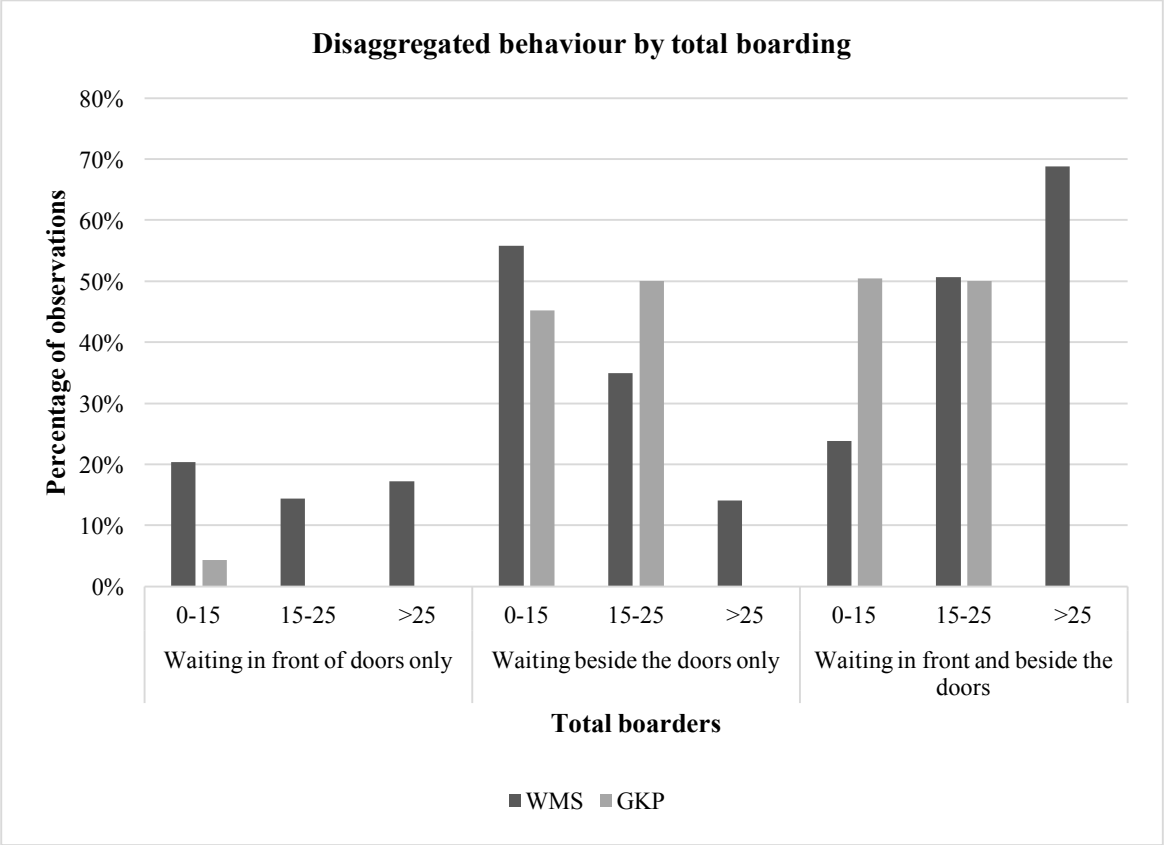

FIGURE 3 Passengers' waiting behaviours with respect to total number of boarders.

Overlap

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 4 shows that the average overlap time (T_o) and the average number of overlaping 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 T_o 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.

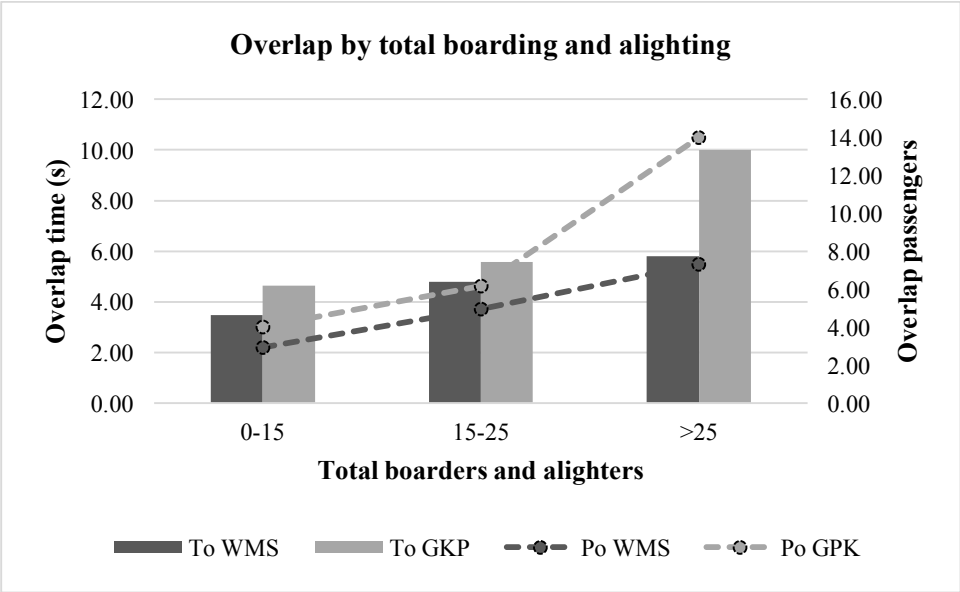

FIGURE 4 Average overlap time and passengers with (WMS) and without PEDs (GPK) with respect to total number of boarders and alighters.

DISCUSSION

With respect to the boarding and alighting time (BAT), the case without PEDs (GKP) presents an average BAT which is 16% lower than in the PEDs 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, and similarly to what was found in (*6*), PEDs not always induce a higher BAT than the case without PEDs. In fact, PEDs only present a BAT that is approximately 1% higher than the case without PEDs 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, 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.

Although at GKP (no PEDs) the average relative boarding profile presents an earlier and higher peak compared to WMS (PEDs), in both cases 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, in line with what was found in *(6)* and opposed to the preconceived concern. 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 regions: a circulation and a waiting area.

The circulation area appears at the back of the platform, near the wall and parallel to it, when passengers form flow lanes to avoid collisions with people coming in opposite direction. Further research is needed to study the relationship between the formation of lanes and the presence of PEDs.

The behaviour in waiting areas is dominated by the boarding passengers who are waiting on the platform. As opposed to what was found in (*6*), 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 a medium levels. Conversely, PEDs have a positive impact on preventing passenger to wait in front and beside the doors for low demand levels, which could be used to control crowded situations.

To correctly interpret this analysis, it should be noted that the results are influenced by the ratio between boarders and alighters, which in the case without PEDs is 63% smaller than in the case

with PEDs. Therefore, the detailed level of demand and the exact position of each passenger should be included in further research as factors that influence behaviour.

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 done to either overcrowding on the train at the boarding point or because the train destination does not match the passenger's destination. However, we lack data to assess this impact in detail.

In relation to the boarding and alighting dynamics, the results are in accordance with (*11*), where 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) was found to be smaller in the case with PEDs in *(6)*, but in this study the reduction was found to be negligible for the low and medium demand levels. In the high demand situation the case with PEDs reached 42% less overlap time and 48% fewer overlap passengers than the case without PEDs. These results are in line with what was found in (6), whereby 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.

CONCLUSIONS

This paper has studied the combined effect of platform edge doors (PEDs) and level access on the boarding and alighting time (BAT) and passenger behaviour by means of observation at two LU stations. The results show that there is no clear advantage or disadvantage of PEDs versus no PEDs in terms of BAT, where demand plays a more important role. In any case, there seems to be no clear negative impact of PEDs on BAT (as opposed to what is normally believed) and even PEDs could be minorly beneficial in crowded situations.

With respect to passenger behaviour, the results show that the presence of PEDs influences passenger behaviour and encourages waiting beside the doors rather than in front of them, probably because passengers can see where the doors are. However, this only happens at certain levels of demand.

Further research should deepen the analysis of the combined effects of demand and the PTI characteristics and also look at the relationship between the BAT and different vertical/horizontal gaps, because in this case two situations with level acess have been compared. It would also be interesting to collect more data to identify the impact of passengers with encumbrances (luggage, shopping, buggy) or mobility aids (wheelchair, pram) on the BAT.

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