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Train design features affecting boarding and alighting of passengers

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SUMMARY

Accurately predicting train dwell time is critical to running an effective and efficient service. With high-density passenger services, large numbers of passengers must be able to board and alight the train quickly – and within scheduled dwell times. Using a specially constructed train mock-up in a pedestrian movement laboratory, the experiments outlined in this paper examine the impact of train carriage design factors such as door width, seat type, platform edge doors and horizontal gap on the time taken by passengers to board and alight. The findings illustrate that the effectiveness of design features depends on whether there are a majority of passengers boarding or alighting. An optimum door width should be between 1.7 and 1.8 m. The use of a central pole and platform edge doors produced no major effects, but a 200 mm horizontal gap could increase the movement of passengers. There is no clear effect of the type of seats and neither the standbacks between 50, 300 and 500 mm. Further research will look for the relationship between the dwell time and the characteristics of passengers such as personal space. Copyright © 2017 John Wiley & Sons, Ltd.

KEY WORDS: commuter rail; flow; passenger movement; train dwell time; transport and pedestrian studies; transportation engineering

1. INTRODUCTION

The duration of time when a train stops in a station (dwell time) is critical to train scheduling. This duration has implications right across a service. When train dwell time can be predicted accurately, it can improve the punctuality of service and enables modellers to forecast run times and service capacity [1]. This is especially valuable for complex train systems and high-density stations. When delays occur to a single train departing from a station, this can result in a knock-on effect across the whole of the service. This has been shown not only in freight services in which delays are associated to loading/unloading, train connections or fueling [2], but also in passenger services [3–5]. For passenger train services, delays can be caused not only by external factors such as weather, track or signal failure but also on dwell time at the station. This dwell time is dependent not only on the number of passengers boarding or alighting but additionally on the gap between the train and platform as well as the design and layout of the train itself.

Every day circa 4.25 million trips are taken using the London Underground, with 400 000 people alone starting their journey between 8 am and 9 am [6]. One of the busiest stations, Oxford Circus has 125 000 people enter and 136 000 exit it each day. Many London Underground lines operate one train every 2–3 min during peak time. Given the amount of people needing to board or alight the train at each station and the length of time a train can stay in the station to maintain the line frequency, the movement of passengers needs to be as fast and as efficient as possible.

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The dwell time is a key variable that alters service frequency, and reliability. The occupancy time within a station is calculated using the train unblocking, doors opening, passenger boarding and alighting, doors closing and train dispatching dwell [7]. The time it takes passengers to board and alight from a train makes up a significant proportion of the time a train spends at a station and therefore has great impact on train frequency and capacity of the network. Much of the time, a train spends at a station is due to passenger boarding and alighting, which could be observed directly on the platform [8–10]. This is particularly true in busy metro and suburban stations. The faster and more efficient passenger movement on and off the train can be made, the faster the end-to-end run times that can be achieved. This will increase the capacity of the line. When the required capacity is low, trains are generally programmed to stop at a station for a fixed amount of time, more than what is required for passengers to board and alight. When required capacity increases, additional dwell time is often required depending on the direction and amount of boarding and alighting movements as well as internal train layout [11]

Research has been completed looking at the speed and behaviour of passengers on trains and within stations [12–18] but little research to date has examined the impact that train carriage design plays on passenger movement. In a study of boarding and alighting, Lin and Wilson [10] reported that knowledge of crowding and congestion on board the train would improve flow rate models. To manage crowds on platform, [19] found that platform edge doors (PEDs) had no important impact in the boarding and alighting times, but the behaviour of passengers changed by queuing at the side of the doors rather than in the front. Research into rail and metro train dwell times shows that a step height between train and platform of 50 mm increases the number of passenger movements, reaching a maximum flow of 1.42 pass/s for a door 1.8 m width [20]. Moreover, [21] reported that a small step height reduces the dwell time in 8%. This is particularly key for those passengers encumbered by luggage or pushchairs, in which passengers boarding (4.13 s) spent more time than passengers alighting (3.68 s) [22].

Boarding and alighting time is usually calculated using regression models.

[11, 13, 14], as a function of the layout of the train (e.g. door width), distribution and number of passengers, and the behaviour of boarding and alighting. More recently, laboratory experiments have been carried out to understand how different variables such as door width, platform width and layout of trains impact upon boarding and alighting times [23–26]. In particular, [25] stated that a vertical gap of 150 mm could reduce the boarding and alighting times. These results could be considered as going in the opposite direction with [22] in relation to accessibility. Similarly, [24] reported that the optimum door width should be 1.8 m with a vestibule setback of 800 mm, which is different from the optimum door width of 1.65 m in [25].

Despite of the research performed to optimize the vehicle and platform designs, London Underground commissioned University College London (UCL) to carry out a series of experiments using a specially constructed mock up tube train carriage installed at the UCL Pedestrian Accessibility Movement and Environment Laboratory (PAMELA). The mock up carriage permits a variety of configurations that can be tested. The aim was to design a more effective train. The questions which this study aimed to answer were (i) would a 1.6, 1.7 or 1.8 m door width be best for passenger boarding and alighting rates? (ii) Does the vestibule standback affect passenger boarding, alighting rates and passenger distribution in the carriage? (iii) Does the type of seating affect passenger boarding and alighting rates and passenger distribution in the carriage? (iv) Does the presence of a central vestibule pole affect passenger boarding and alighting rates? (v) Do the presence of PEDs and an increased horizontal gap affect passenger boarding and alighting rates?

This paper is composed of five sections, including this one. In the second Section, the method of this paper is described. Next, in the third Section, the scenarios of simulation are presented. In the fourth Section, a complete discussion is provided. Finally, in the fifth Section, the conclusions are delivered.

2. METHOD

The method consisted of four stages. Firstly, the variables were selected according to one of the three groups reported in [27]: physical (e.g. door width), spatial (e.g. seat type) and operational (e.g. demand). The selected variables were based on the new rolling stock for the London Underground

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trains obtained as part of a complete research project in collaboration with Transport for London (Table I).

The features tested were door width, standback, seat type, central grab pole, PEDs and horizontal gap (Table I). The door widths tested were 1.6, 1.7 and 1.8 m. Standback refers to the area between the edge of the doors and the end of the vestibule as illustrated in Figure 2. The standback lengths tested were 50, 300 and 500 mm. The seat types tested were tip-up seats and perch seats. A horizontal gap of 75 mm was tested across all the other design features but an additional test of a horizontal gap of 200 mm was also tested. The presence or absence of a central pole was tested across ass door widths and with a standback of 300 mm. The effect of PEDs were tested with a horizontal gap of 75, 150 and 200 mm Table II.

Secondly, the experiments took place at the PAMELA facility at UCL. PAMELA is a multisensory pedestrian environment laboratory, consisting of a large pedestrian area, controlled to provide different topographies, vertical and horizontal obstacles, different lighting and noise conditions. Full-scale mock-ups of vehicles with surround sound and multi angle recording can be built inside the lab and movement on the platform can be filmed and tracked in real time.

For this experiment, a full-size mock-up of a single carriage of the proposed two-double door train was constructed, based on drawings supplied by London Underground and designed to permit the changes in the features to be tested (Figure 1 and Figure 2). A horizontal gap between the train and the platform could be altered and PEDs could be added. An ambisonic sound environment was created for the experiments to mimic station sounds including the sound of a train arriving at the station, public

Table I. Selected variables for the experiments.

	Width (m)	Standback (mm)	Seat type	Horizontal gap (mm)
Door width	1.6, 1.7 & 1.8	300	Tip-up	75
Standback	1.7	50, 300 & 500	Tip-up	75
Seat type	1.7	50	Tip-up & Perch	75
PED and horizontal gap	1.7	50	Tip-up	Without PED: 75 & 200 With PED: 75, 150 & 200
Central pole	1.6, 1.7 & 1.8	300	Tip-up	75 & 200

Table II. Preferred design option by passenger scenario.

	Equal boarding/alighting	Majority boarding	Majority alighting
Door width	1.7	1.8	1.7
Standback	300 or 500	300	50
Seat type	Tip-up	Perch	Tip-up
Central pole	No difference		
PEDs with horizontal gap	Only affected with 200 mm horizontal gap		

Figure 1. Sample images of the mock-up train carriage at the PAMLEA facility with Platform Edge Doors (PEDs).

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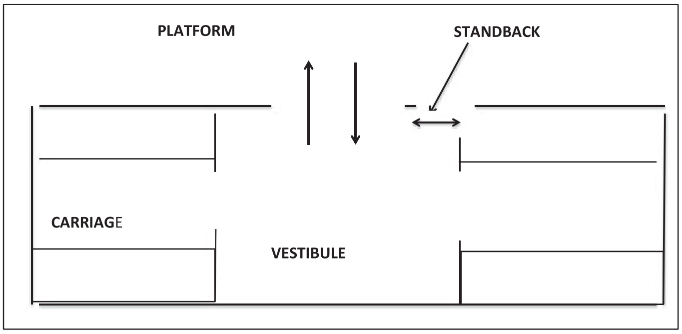

Figure 2. Birds Eye View of a train carriage showing vestibule standback.

address announcements and the sounds of the doors opening and closing. Cameras were positioned directly above the carriage doors, as well as in positions so that the inside of the whole carriage was captured as well as the whole of the station platform. This was so that the movement of any of the participants could be captured during the whole experiment regardless of where they were, or moved to, on the train or the platform.

Thirdly, for the different scenarios, a total of 110 participants were recruited, with a mix of ages and gender. A convenience sample was used of people of self-reported being regular tube users. Participants were given a number, a bid colour and a red hat and a white hat. Before each experiment, there was an announcement telling participants who should alight, board or stay on board the train based on their assigned numbers. Participants wore their red hat when boarding and their white hat when alighting to make the visual aspect of the data extraction and analysis easier. Variations of the number of people boarding and alighting were made across the experiments. An experiment 'run' consisted of the participants being assembled in their starting positions, and the doors of the train closed. The sound system was started, which initiated the clock time for the run, and the passengers heard the train arriving, decelerating and stopping. The doors were opened, the passengers boarded/alighted as per their instructions, the doors were closed and the train was heard to leave the station. Routine passenger announcements were made during the run according to normal practice on London Underground. A combined total of 465 experimental runs were carried out with the various train configurations (totaling 92 design parameter combinations) and scenarios resulting in 20 000 individual passenger movements. The mock-up carriage was modelled after a potential new design carriage with two doors. The crush load capacity for this carriage was 109 people, giving an average of seven people per metre squared inside the train.

The experiment runs were based on a set of scenarios, which represented different boarding/alighting conditions; equal boarding and alighting, majority boarding and majority alighting (Figure 3). Three passenger movement scenarios are presented here. (i) Equal Passenger Boarding and Alighting. In this scenario 40 people boarded, 40 people alighted and 30 people remained on the train. (ii) Majority of Passengers Alighting. In this scenario 20 people boarded, 80 people alighted and 10 people remained on the train. (iii) Majority of Passengers Boarding. In this scenario consisted of 80 people boarding, 20 people alighting and 10 people remaining on the train.

Fourthly, the data was extracted from the video footage using Observer (version 9.0) and analysed using Java analysis tools. Each of the experimental runs was analysed to measure when the doors began opening, when each person boarded or alighted the carriage, when the doors were fully opened, when the doors began closing and when they were fully closed. The Door Open Times was calculated from the moment the doors began to open until the moment they were fully closed. Passenger flow rates were obtained over 2.5 s periods between these times.

Each scenario was compared in terms of number of passengers boarding or alighting, and the flow throughout doors. In addition, the Level of Service (LOS) [28] was used. The LOS is a qualitative indicator to measure the degree of congestion and conflict of passengers in walkways, stairs and queue areas. In walkways, the LOS goes from a Level A (free flow lower than 0.38 passengers per second per metre) to a Level F (flow higher than 1.36 pass/s-m), where LOS = E is equal the capacity (flow between 1.1 pass/s-m and 1.36 pass/s-m). Therefore, if the change in design

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Figure 3. View of the mock-up train carriage showing participants boarding and alighting.

improved the LOS, then it could be considered a better design. A LOS = F should be avoided in all situations.

3. RESULTS

3.1. Door width

In the equal passenger boarding scenario, the door width of 1.7 m performed best. This is illustrated in Figure 4. All passengers had boarded and alighted in less than 40 s. After 20 s, the 1.7 m door width had resulted in 10 more people having boarded or alighted than the 1.6 or 1.8 m door widths. In addition, all cases presented a LOS lower than F. In the case of 20 s, the 1.7 m reached a flow of 0.66 pass/s-m (LOS C), whilst the 1.6 and 1.8 m reached a flow of 0.53 pass/s-m (LOS B) and 0.47 pass/s-m (LOS B), respectively. Therefore, the 1.7 m presented a higher flow without affecting negatively the congestion and conflicts of passengers.

In the majority alighting scenario, there was a consistent number of passenger movements every 10 s between 0 and 30 s of approximately 30 people, which was only slightly lower in the first 10 s (Figure 5). After 40 s, all the passenger movements had reduced for all door widths. The widest door (1.8 m) performed worst in this scenario. After the doors had been open for 30 s, five more people had boarded/alighted than under the other door widths. This resulted in an approximate dwell time excess of 3 s for the 1.8 m door width for 100 passenger movements. In relation to the LOS, all cases presented a LOS = D (lower than F) for the period of time 30 s. The 1.8 m reached a flow of 0.87

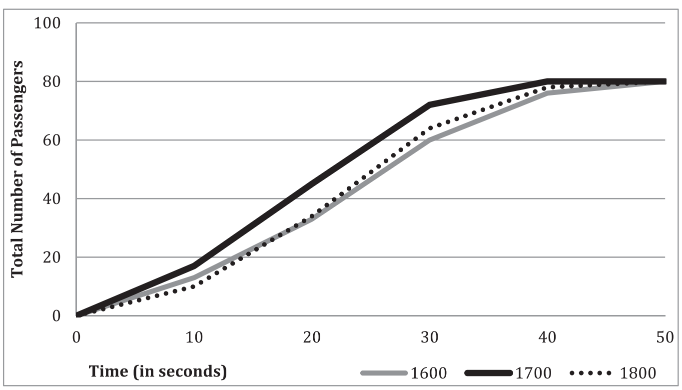

Figure 4. Cumulative number of passengers boarding or alighting throughout door open time.

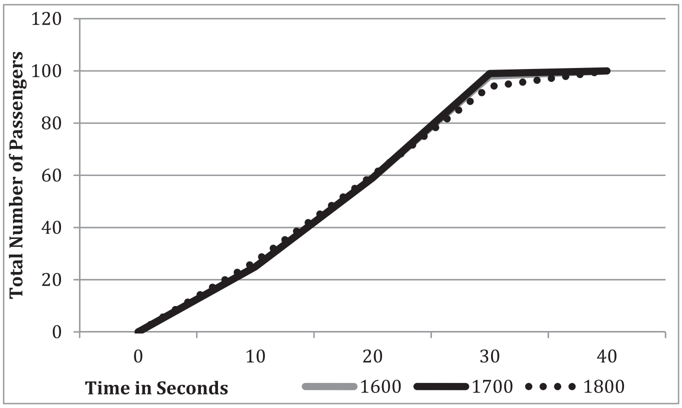

Figure 5. Cumulative number of passengers boarding or alighting throughout door open time, majority alighting scenario.

pass/s-m, whilst the other door widths presented a flow between 1.03 pass/s-m (1.6 m) and 0.97 pass/s-m (1.7 m).

In the majority boarding scenario, increasing door width increased the number of passenger movements in any given time period across this scenario (Figure 6). After the doors have been open for 20 s, the 1.8 m width door resulted in five more people having boarded or alighted than the 1.7 m width door and 10 more people than the 1.6 m width door. The 1.8 m door width had a dwell time of 46 s. Therefore, with each 0.1 m increase of door width the dwell time was reduced by 3 s for every 100 passenger movements. In terms of flow, the 1.8 m reached 0.76 pass/s-m (LOS C) for the period of 20 s, whilst the other width doors presented a flow between 0.85 pass/s-m (LOS D) and 0.73 pass/s-m (LOS C). However, for the 30 s there were no differences between 1.8 and 1.7 m in terms of flow performance.

As a consequence of the three scenarios, the door width 1.7 m presented a better performance compared with 1.6 and 1.8 m in terms of number of passengers boarding/alighting, flow and LOS for the given conditions at PAMELA. This width was considered in the following sections when testing the standback, type of seats and use of PEDs with horizontal gap.

3.2. Standback

In the equal passenger boarding scenario, the 50 mm standback resulted in the lowest number of passenger movements but there was no difference in the number of passenger movements between the 300 and 500 mm standback (Figure 7). Passenger movements were at their greatest for all standbacks between 10 and 30 s. Passenger flow does not reach its fastest until passengers in the

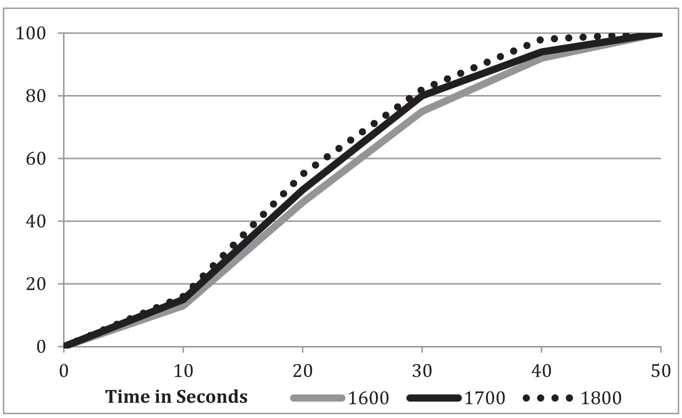

Figure 6. Cumulative number of passengers boarding or alighting throughout door open time, majority boarding scenario.

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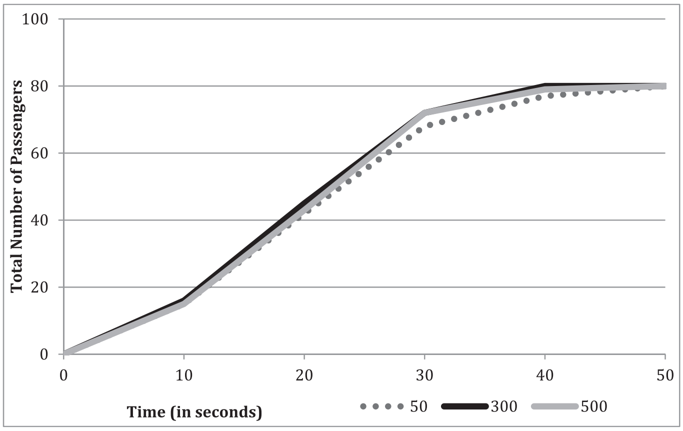

Figure 7. Cumulative number of passenger movements during the door-open time, according to standback, equal boarding/alighting scenario.

vestibule who are not leaving the train have created space for boarding and alighting passengers to move easily through the doors. The 300 and 500 mm presented a flow of 0.70 pass/s-m (LOS C) in the period of time 30 s, whilst the 50 mm reached 0.66 pass/s-m (LOS C).

In the majority alighting scenario, the 500 mm standback resulted in fewer passenger movements at each of the time intervals up to 30 s after the doors opened (Figure 8). There was no noticeable difference between the 300 and 500 mm standback for passenger movements during this time, reaching 0.82 pass/s-m (LOS D). Whilst the 50 mm presented a higher flow of 0.88 pass/s-m with the same LOS = D in the segment 30 s.

In the majority boarding scenario, the largest standback (500 mm) performed best where boarding passengers formed the majority of passenger movement. This improvement is shown in Figure 9, which shows that after 10 s the 500 mm standback had allowed five more passenger movements (flow of 0.61 pass/s-m or LOS C) than either the 300 mm standback or the 50 mm standback (flow of 0.47 pass/s-m or LOS B). However, after 30 s, there was no difference between the 500 and 300 mm standbacks. At 40 s, the 300 mm standback (flow of 0.69 pass/s-m or LOS C) had outperformed the 500 mm standback (flow of 0.66 pass/s-m or LOS C). However, this is likely to be because after 40 s fewer people in total were boarding or alighting. It is always the case that the final few passengers take the longest to board/alight and due to amount of passenger movement that had already occurred only the final few passengers were left in the 500 mm standback scenario.

From the different scenarios, it is not clear which is the best design for the standback. In the case when there are more passengers alighting than boarding, the best performance was obtained with 50 mm. Whilst in the other cases (more boarding than alighting or equal number of boarding and

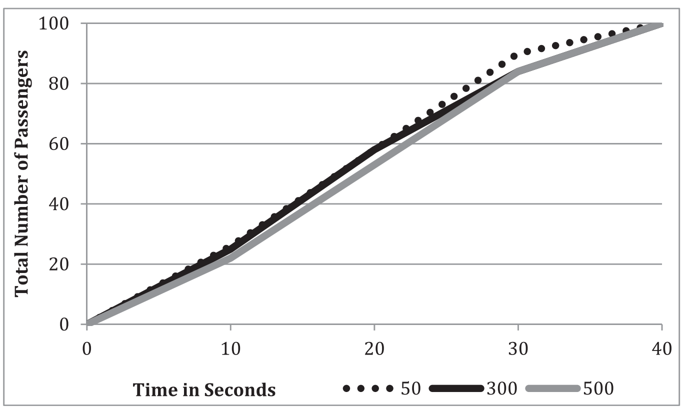

Figure 8. Cumulative number of passenger movements during the door-open time, according to standback, majority alighting scenario.

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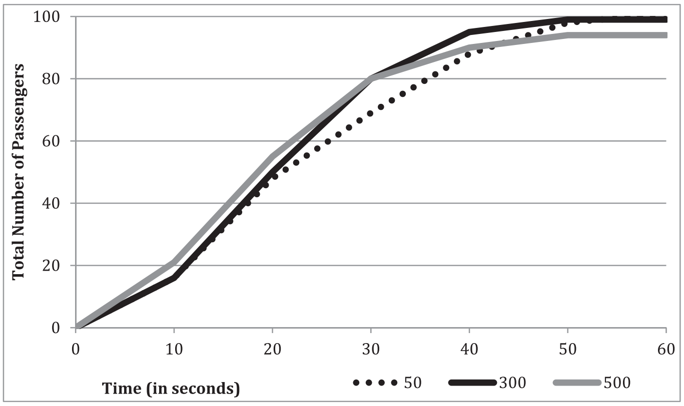

Figure 9. Cumulative number of passenger movements during the door open time for different standback arrangements, majority boarding scenario.

alighting), the best situation resulted between 300 and 500 mm. All cases presented a LOS lower than F. Because of the resources involved in this research, it was not possible to select the three standback to test the following scenarios. Therefore, a 50 mm was used to test the seat type and the PEDs with horizontal gap, whilst a 300 mm was considered for the scenario to test the central pole.

3.3. Seat type

In the equal passenger boarding scenario, tip-up seats performed better than perch seats across all time intervals and resulted in a dwell time reduction of almost 9 s. This difference peaked at 30 s when tip-up seats had resulted in nearly 70 passenger movements and perch seats had only resulted in 55 passenger movements.

In the majority alighting scenario (Figure 10), tip-up seats performed better than perch seats resulting in a reduced dwell time of nearly 7 s. At each time interval tip-up seats had greater passenger movement than perch seats with this difference peaking at 30 s after the doors open. In this period of time (30 s), the tip-up seats presented a flow of 0.88 pass/s-m (LOS D), whilst the perch seats reached 0.76 pass/s-m (LOS C).

In the majority boarding scenario, perch seats performed best in this scenario where dwell time was reduced by 9 s when perch seats were present instead of tip-up seats. However, the relationship between passenger movements and seat types is a little more complicated than a simple parameter can describe; this is illustrated in Figure 11.

Figure 11 shows that perch seating results in two extra passenger movements up to 20 s after the doors have opened. This figure increases to eight extra passenger movements after 30 s, in which

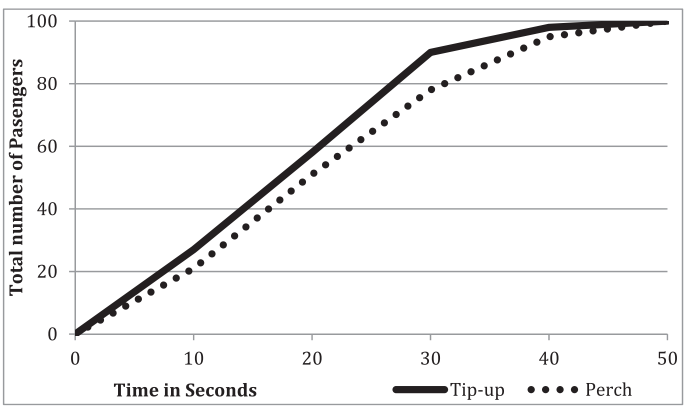

Figure 10. Cumulative number of passenger movements during the door open tim.e for different seat types, majority alighting scenario.

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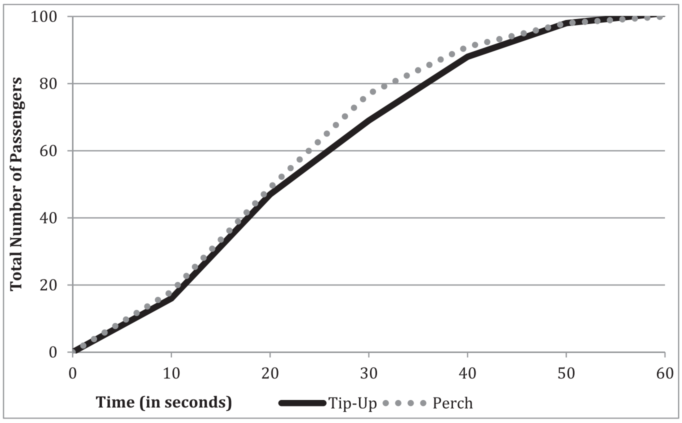

Figure 11. Cumulative number of passenger movements during the door open time for different seat types, majority boarding scenario.

the perch seats presented 0.75 pass/s-m (LOS C), whilst the tip-up seats reached 0.67 pass/s-m (LOS C). However, the passenger movements are reduced to three after 40 s and there is no difference after 50 s. Therefore, while the perch seating is more advantageous than tip-up seats overall it is clear that it is most beneficial at around 30 s. The 30 s point occurs between 60 and 80 passenger movements and it is here that perch seats appear to offer their greatest advantage.

3.4. Effect of central pole

In neither the equal passenger boarding scenario, the majority alighting scenario or the majority boarding scenario were any differences were found in passenger movements between the presence and absence of a central vestibule pole.

3.5. Platform edge doors and horizontal gap

In the equal passenger boarding scenario, a smaller horizontal gap resulted in more passenger movements in any given time period and also a 4 s reduction in dwell time. After the doors had been open for 20 s nearly 60 passengers had boarded or alighted when the gap was 75 mm (flow of 0.88 pass/s-m or LOS D) compared with only 50 passengers boarding or alighting when there was a 200 mm gap (flow of 0.73 pass/s-m or LOS C). When PEDs were introduced with a 75 mm gap, the rate of passenger movements decreased to a level similar to that when there was a 200 mm gap with no PEDs. However, there were no important differences in the overall passenger flow with a 200 mm gap between the experiments with a platform edge door and without a platform edge door.

In the majority alighting scenario, the smaller horizontal gap of 75 mm resulted in more passenger movements than the larger gap of 200 mm. Identical to the equal boarding and alighting scenario when PEDs were introduced with a 75 mm gap the number of passenger movements decreased to a level similar to when there was a 200 mm gap with no PEDs. However, there were no important differences in overall passenger flow with a 200 mm gap between the experiments with a platform edge door and without a platform edge door.

In the majority boarding scenario, a larger horizontal gap resulted in more passenger movement across all time periods as well as a 4 s reduction in dwell time. For both horizontal gap sizes, there was a reduced flow initially up to 10 s after the doors opened, followed by a faster flow between 10 and 30 s after the doors opened. After 30 s the flow rate dropped considerably.

When PEDs were introduced, the passenger flow rate was only improved for the 200 mm gap. However, the effect of the PEDs did not reduce the number of passenger movements for the 75 mm gap.

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4. DISCUSSION

It is not enough to use dwell time to measure the effectiveness of designs on passenger movement. The findings from this research show that passenger flow changes across the period of time in which the doors are open. There is a distinctive dynamic which surrounds the boarding/alighting process which indicates that there should be a point during the door-open time after which the board/alighting flow rate is characteristically much slower. This means that an additional passenger joining the passenger movement process after this point will take longer than a passenger who completed their manoeuvre earlier. Thus, passenger service time is not directly proportional to the number of passengers, but depends on when during the door open time the passenger movement is being attempted. It is thus nonlinear over time. This constitutes a risk to train service reliability due to extended door-open times causing disproportionate delays to the current and subsequent trains. This gives rise to questions around transport planning and service planning issues (for example, train frequency) in order to make the best use of the dwell time for system performance as a whole.

In general, all flow rates dropped after 30 s. When there were an equal number of boarders and alighters or when there was a majority of boarders, a reduction in flow rate in the first 10 s after the doors opened occurred. Therefore, optimal dynamics of passenger boarding and alighting movements occur between 10 and 30 s after the doors have opened.

Where there was a majority of passengers moving in one direction and it was possible for them to create two streams, the dwell time was reduced. This occurred more frequently when there was not an initial mixed period of boarding and alighting. In the case of an alighting majority, when passengers were standing by the doors when they opened but were not due to alight, how they navigated a seat often affected the alighting process. This was independent of standback distance or seat type in as much as no clear pattern could be identified.

5. CONCLUSION

Depending on whether there is a majority of passengers either boarding or alighting, different design features are optimal. None of the scenarios showed consensus on any of the design features tested. This clearly proposes a problem as different train stations and different times of day will have different numbers of passengers boarding or alighting. Operational decision making, particularly if operators have specifications as to how long the door open time will be, will determine what design features will be optimal because of the implications of operation within the station.

In terms of door width, an increased door width produced an increase in passenger flow rate. For all scenarios, the narrower 1.6 m door width offered the worst performance in terms of dwell time. Where there was a majority passenger movement (in either direction), the 1.7 m door width was optimal. The mock-up used is one configuration amongst the many possibilities. In other train designs door width may have a significant effect.

Whilst there was no consensus on an optimal standback size to give a reduction in dwell time, it was clear from the scenarios tested that the only size which was not the least effective for any of the scenarios was 300 mm. Whilst a larger standback of 500 mm did perform well when there was equal boarding and alighting and when there was a majority of boarding, its poor performance and the loss of seats that would occur reduces its advantages. Therefore, a 300 mm standback would be most effective across all scenarios.

Tip-up seats will result in reduced dwell times provided the limiting factor on service provision is not a station where there are consistently high numbers of alighting passengers in comparison to boarding passengers; in which case, perch seats would be recommended. The evidence for PEDs was mixed. Two of the scenarios found the smaller 75 mm horizontal gap with PEDs to be most effective, whereas the final scenario found the wider 200 mm gap with platform edge door to be most effective. When PEDs are not present then the horizontal gap should be limited to 75 mm.

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6. FURTHER RESEARCH

Further work would allow a fuller understanding of why delays in dwell times occur when there are high numbers of people on board the train. These conditions result in considerable variability due to the nature of people avoiding each other as they attempt to board or alight the train. The role the type of seating plays in dwell time could be better understood with further, more detailed experiments and analysis. The initial investigation into passenger distributions within the carriage showed that perch seating tended to cause higher densities of people directly in front of the perch seating compared with the densities found in front of the tip-up seating. There was a consistent number of people in between the fixed seating for both tip-up and perch cases; however, this number is always smaller than elsewhere in the carriage.

In addition, new laboratory experiments should be conducted at PAMELA to study the effect of passengers' characteristic such as gender, personality, stress, culture and personal space on the boarding and alighting times.

7. LIST OF ABBREVIATIONS

PEDs	Platform Edge Doors
UCL	University College London
PAMELA	Pedestrian Accessibility and Movement Environment Laboratory
LOS	Level of Service

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