ACCESSIBILITY RESEARCH GROUP

Working paper

Investigation of the appropriate slope gradient for humps on railway platforms

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Abstract

Gaps between the train and the platform are a major safety concern for railway users, especially those who are disabled, and London Underground will introduce platform humps to solve this problem. In order to realise properly designed platform humps, it is necessary to investigate the effects of the design factors of the hump. As an initial attempt to understand the complexity of the design factors of humps, this study focused on the slope and backfall gradients. A series of experiments was conducted in the Pedestrian Accessibility Movement and Environment Laboratory (PAMELA) at University College London. In total, 45 participants with various types of disabilities were asked to walk on simulated slopes and to board or alight from the simulated train from or onto the slope. The tested slope gradients were 3.0% (1:33), 5.2% (1:19) and 6.9% (1:14) with the backfall gradients 1.5% (1:67), 2.0% (1:50) and 2.5% (1:40). It was found that the slope gradient did not largely affect performance and subjective evaluation of the participants' longitudinal walking on slopes, but would add additional difficulty for them to board/alight from the train from/onto a slope. This suggests that train doors should not stop next to the slope. There was little evidence as to the effects of the backfall gradient. The results will be used in the development of the design guidelines of platform humps.

Keywords: Platform hump, Gap, Ramp, Slope, Slope gradient, Backfall gradient

1. Introduction

Gaps between the train and the platform are a big hazard in railway systems. The issue is significant in old railways still in use. There is always a risk of passengers tripping or falling into the gap. Gaps especially affect disabled passengers, and are one of the main barriers that deter disabled and elderly passengers from using railways. In the UK the regulations stipulate that if the gap between the edge of the door sill and the edge of the platform is more than 75 mm horizontally or more than 50 mm vertically, a boarding device is required for wheelchair users (Stationary office, 1998). There has been research which concluded that when the gap height and width are added together, the value should not exceed 200mm (Atkins, 2004).

The gap can be divided into two components: horizontal component and vertical component. The main cause of the horizontal component is curvature of the track (see figure 1), and its elimination requires a mechanical solution (such as a device to fill the gap while the train is stationary) or manually bridging the gap with a portable ramp. On the other hand, the main cause of vertical gaps is the platform regulations according to which existing platforms were built. Because the platform regulations were written a long time ago, they do not match the specifications of current trains and did not consider the importance of level access between the train and the platform. The springs of the carriage which change the train floor level according to the load (the number of passengers) and the process of rounding wheels during carriage maintenance also make it difficult to achieve level access, but they are not the main factors. The vertical component can be reduced by relatively simple solutions: lowering (or raising) the train floor level or raising (or lowering) the platform level. It is, however, almost impossible to retrospectively change the floor level of existing carriages and a certain floor level may suit some stations but not other stations. Raising or lowering the platform can be a solution, but raising (or lowering) the whole platform may be costly. Therefore, London Underground has decided to introduce humps on the platform across its network so that level access can be achieved at a certain part of the train at any station.

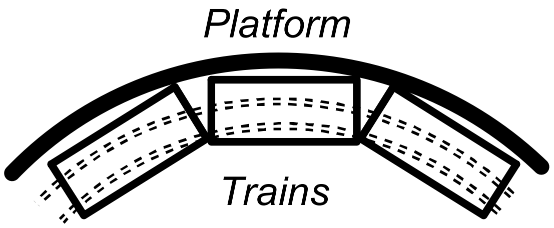

Figure 1. Curvature of the track and the platform. Because the carriage shape is rectangular whereas the platform edge is circular, gaps at some parts of the carriage (the middle of the carriage in this case) are unavoidable.

Humps may be a solution to achieve level access between the platform and the train. However, railway platforms are usually flat (except that platforms usually have a small lateral gradient for safety or drainage reasons, which is described later). Adding a hump to a platform would cause safety problems. Improperly designed humps could lead to serious accidents not only on the platform but also involving trains. Because platform humps have been seldom used in busy railway systems, it is necessary to investigate appropriate hump designs so that passengers can safely and comfortably use them. Commissioned by London Underground, we conducted a series of experiments in order to examine the design factors of the hump, such as the slope gradient, from the viewpoint of passenger safety and comfort. The results will be addressed in the design guidelines of platform humps.

Humps consist of several design factors, including the slope gradient, the slope width and the length of the top level part (upper landing), and the design factors affect each other. For example, a wider ramp width may compensate a short length of the top level part for wheelchair users. This complex nature of humps makes it difficult to empirically investigate the acceptable level of each design factor. In order to solve the problem, we first divided the factors into three groups. One group includes the dimensions of slopes, such as the slope gradient. Another group includes the dimensions of the top level part, which mainly concerns the size and manoeuvrability of wheelchairs. There may be a group that includes the visibility of humps, lighting and surface materials, which mainly concerns passengers with visual impairment. As an initial attempt to understand the complexity, this study focuses on the first group: the dimensions of slopes because the dimensions of slopes affect most passengers and thus are important. It should be note that, other than design factors which are under the control of designers, congestion may affect safe and comfort use of the hump, but this study did not consider congestion because its primary focus is the effects of the design factors of the hump. Surface materials may affect the use of humps, but this study does not look into this because the inclusion of surface materials in the experiment would significantly increase experiment variables.

2. Existing studies

There have been several studies on the gradient of slopes. Templer (1992) concluded that slopes steeper than 1:8 (12.5%) are inaccessible or difficult to use from the viewpoint of elderly and disabled users. He recommended a maximum slope of 1:10 (10%) for a height greater than three inches (7.6 cm) and 1:12 (8.3%) for a height greater than 6 inches (15.2 cm) but less than 9 feet (2.74m). He also pointed out that if a slope between the pavement and the carriageway at pedestrian crossings is lower than 1:16 (6.3%), visually impaired people with a long cane on the pavement cannot detect the change of the surface, and therefore may stray into the carriageway. Indeed, 1:12 (8.3%) has been set as the maximum gradient of slopes according to the standards of some countries including the United States and the United Kingdom (Access Board, 1990; Office of Deputy Prime Minister, 2004). This value was re-examined by Stanford et al. (1997), who concluded that the value should remain. Based on interviews and observations, Leake et al. (1991) concluded that for wheelchair users a gradient in excess of 1:50 (2.0%) should be avoided where possible, and for ambulatory disabled people the threshold can be increased to 1:25 (4.0%). Ishida et al. (2006), who studied pavements from the viewpoint of wheelchair users, found that when the slope gradient exceeds 1:50 (2.0%), the subjective discomfort and the gradient have a linear relation. Canale et al. (1991) recommended 1:6.7(14.9%), whereas Steinfeld et al. (1979) concluded that people with limited stamina, hemiplegics and quadriplegics may have difficulty with slopes steeper than 1:20 (5.0%). As Stanford et al. (1997) pointed out, one reason for the variance among these acceptable limits of the gradient may be because different studies employ different samples.

In the UK, there are several regulations regarding the slope gradient in railway stations and buildings. Railway Safety Principles and Guidance (Health and Safety Executive, 1996) requires that the slope gradient not be steeper than 1:20 (5.0%). In case of difficulty, however, and where slopes are not regularly used by disabled people, they may be 1:12 (8.3%). Train and Station Services for Disabled Passengers (Strategic Rail Authority, 2005) also suggests the same requirement. Building Regulations (Office of Deputy Prime Minister, 2004) stated that the maximum gradient should be 1:20 (5%) for 10m; 1:15 (6.7%) for 5m; and 1:12 (8.3%) for 2m. As for the backfall gradient, London Underground Standards (London Underground, 2005) stated that all platform surfacing should have a cross-fall (backfall) not steeper than 1:40 (2.5%) or shallower than 1 in 70 (1.4%) away from the back edges of the nosing slab, whereas Train and Station Services for Disabled Passengers (Strategic Rail Authority, 2005) suggests that the backfall be between 1.0 and 2.0 % (max 2.5%).

From the observations of the existing literature and regulations, we concluded that there have been studies on the slope gradient in the longitudinal direction. However, as explained in Section 1, platform humps are a complex structure, which has been seldom built. There are several issues that need to be examined in order to fill a gap between the practice of introducing platform humps and existing literature, which has tended to simplify problems. The issues that lie in the gap are as follows

1. Users of platform humps are not uniform but vary. They include passengers with various disabilities and those with temporal mobility-difficulties, such as passengers with a pram.
2. Railway platforms often have a lateral gradient (for safety or drainage reasons). We call it the backfall gradient. When a slope is built along the platform (which means that the longitudinal direction of the slope is parallel to the track), the slope would have not only a longitudinal gradient (slope gradient) but also a lateral gradient (backfall gradient).
3. Suppose a hump is to be introduced in a station where the vertical difference between the train and the platform levels is large. The upper landing is located next to a certain door(s) of the train. If the train has many doors, which means that the distance between two adjacent doors is small, the lower end of the slope may reach a door adjacent to the one at the upper landing (see figure 2). In this case, designers need to choose between 1) increasing the gradient of the slope so that the slope does not reach adjacent doors; 2) keeping the slope gradient but admitting that passengers need to board/alight from/onto a sloped platform; or 3) inserting a middle landing to the slope so that the landing is at the door (see figure 3). The information regarding the effects of the sloped platform on the boarding and alighting of passengers would be valuable because trains sometimes do not stop at the suggested point for various reasons and in this case passengers would be accidentally forced to board/alight the train from/onto the slope, which could lead to serious accidents. In any case, passengers should be able to safely and comfortably board/alight the train.

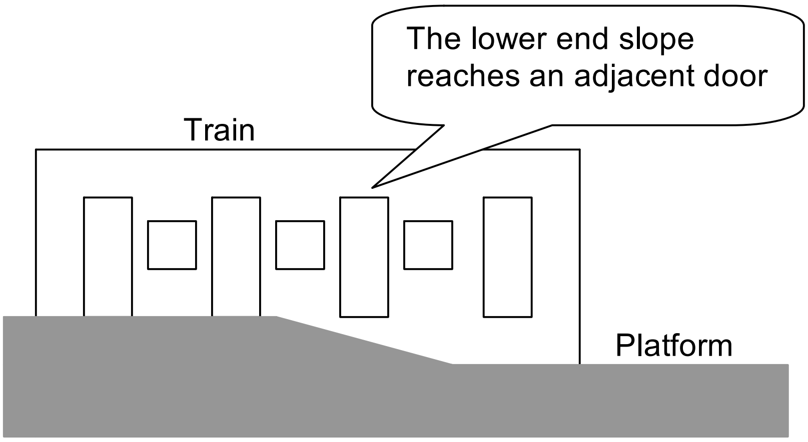

Figure 2. Schematic representation of the situation where the lower end of a slope reaches an adjacent door

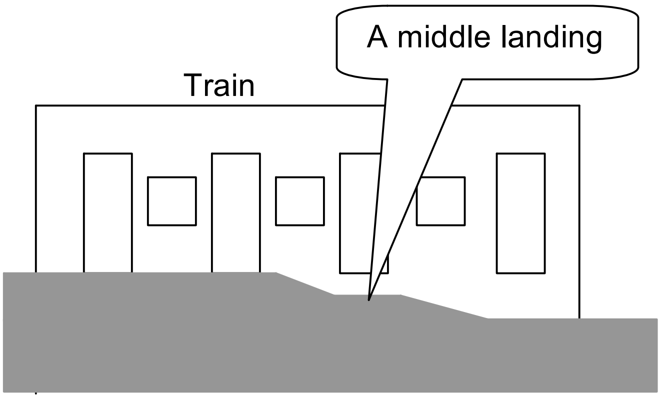

Figure 3. Schematic representation of a middle landing at a door

These issues have not been investigated but are essential in the practice. Therefore, we conducted experiments to investigate the issues.

3. Experiment

The experiment consisted of two parts. The first part looked into the longitudinal walk on slopes with both longitudinal and backfall gradients, and the second looked into boarding/alighting the train from/onto the slope. The empirical work took place in the Pedestrian Accessibility and Movement Environment Laboratory (PAMELA) at University College London. PAMELA is a laboratory used to test existing and proposed pedestrian environments under controlled conditions. The laboratory includes a computer-controlled paved platform which can be varied in terms of layout, topography and surface type (Childs et al., 2007).

3.1 Experiment 1: Longitudinal walk on slopes

In the first experiment, we tested the following three slopes:

Slope 1: Slope gradient 3.0% (1:33), Horizontal length: 8.40m, Vertical ascent: 0.25m

Slope 2: Slope gradient 5.2% (1:19), Horizontal length: 4.80m, Vertical ascent: 0.25m
Slope 3: Slope gradient 6.9% (1:14), Horizontal length: 3.60m, Vertical ascent: 0.25m

Each slope has a backfall gradient of 1.5%, 2.0% or 2.5%. The backfall gradient was changed in the course of the experiment. Participants were tested with each backfall gradient for each slope. This means there were nine types of slope/backfall gradients (three slope gradients x three backfall gradients). These gradient values were chosen according to the expected vertical gap at the train-platform interface, existing regulations and the capability of the PAMELA platform. There is a 1.20m long flat landing space next to each end of the slope. The width of each slope was 2.40m. Using video cameras on the ceiling of the laboratory, we recorded the behaviour of the participants. We placed marks 0.60m beyond each end of the slope and participants were asked to start and stop walking at a mark, rather than at the beginning or end of the slope. This was to prevent acceleration for starting or finishing a walk from taking place on the slope.

For each type of slope, all the participants except those with visual impairment made two round trips from the mark at the lower landing to the mark at the upper landing space and to the mark at the lower landing. Those with visual impairment made one round-trip only. If a participant was about to walk off the side of the slope, the experimenter asked him/her to stop and verbally suggested the correct direction. After completing the walk on each slope, we asked each participant about his/her subjective evaluation of the slope regarding their perception of danger. The platform surface consists of 0.40m square concrete blocks. Each participant was asked to choose one of the following options: 1) I felt entirely safe; 2) I felt safe but needed to be a bit careful; 3) I felt a little unsafe; needed to be quite careful; 4) I felt unsafe; or 5) I felt frightened about my own safety. The question and the analyse method were the same as the ones used in Atkins (2004).

There were 20 participants, consisting of five groups, namely “wheels” (5 participants), “Visually impaired people (VIP)” (8), “Mobility restrictions” (4), “Shoes” (2) and “wheelchair” (1). “Wheels” consisted of two participants with a pram and three with a suitcase with wheels. Participants in this group were healthy and able-bodied. “VIP” included two participants with a guide dog, three with a long cane and three with mid-range visual impairment. Those with a guide dog or a long cane were totally or almost-totally blind. Those with mid-range visual impairment were those who could walk around by themselves with a cane but not at night. “Mobility restrictions” included two people who usually use a crutch when going out and two who limp when walking. “Shoes” included two people with high-heel shoes. “Wheelchair” included a person with a manually self-propelled wheelchair.

3.2 Experiment 2: Boarding/alighting the train from/onto the slope

Experiment 2 was designed to investigate the safety and comfort of passengers boarding/alighting the train from/onto the sloped platform. We set up three slopes with different gradients: 3.0% (1:33), 5.2% (1:19) and 6.9% (1:14). At the side of each slope, we placed a wooden platform, which had three boarding/alighting (stepping) places: one where the vertical difference between the platform and the slope was

50mm, another 150mm and the other 250mm. This means that we set nine stepping places. At each stepping place, we set a measurement line on the slope 0.30m away from the slope edge, and another on the platform 0.30m away from the platform edge. These lines were marked so it was possible to see them on the video recorded by the cameras on the ceiling of PAMELA. At each stepping place, we located a mark at a point 1.20m away from the platform edge and another 1.20m away from the slope edge, and participants were asked to start and stop walking at a mark, rather than on a measurement line. At each stepping place, there was a horizontal gap with a width of 75mm between the slope and the platform, but in the course of the experiment the width was changed to 150mm and then 225mm. Figure 4 explains the experiment settings. Because there were nine stepping places, we were able to test 3 x 9=27 types of steps. The reference values of 50mm for vertical differences and 75mm for horizontal differences were set according to the Stationary Office (1998) (see Introduction). Note that there was no backfall gradient on any slope.

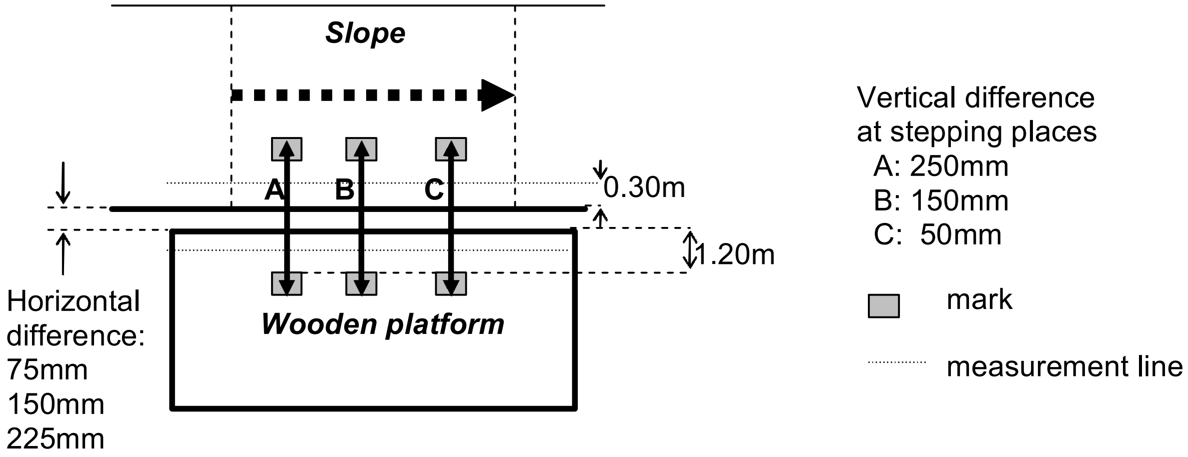

Figure 4. A schematic representation of the setting of Experiment 2

At each stepping place, participants were asked to walk from the mark on the slope to the mark on the platform and then back to the mark on the slope. Participants except those in the “visually impaired people” group were asked to complete the walking trial twice. Those in the “visually impaired people” group were asked to complete it once. We also asked each participant about his perception of danger after completing the walk at each step in the same manner as in Experiment 1.

There were 25 participants, consisting of four groups, namely “wheels” (6 participants), “Visually impaired people (VIP)” (12), “Mobility restrictions” (4), and “Shoes” (3). “Wheels” consisted of two participants with a pram and four with a suitcase with wheels. “VIP” included three participants with a guide dog, six with a long cane and three with mid-range visual impairment. “Mobility restrictions” included three people who usually use a crutch when going out and one who limps. “Shoes” included three people with high-heel shoes. The degree of the disability of each group is the same as in Experiment 1.

4. Data analysis

4.1 Experiment 1

For each type of slope, we measured the time taken by each participant to walk on the slope. Using the videos captured by the cameras on the ceiling of PAMELA, we calculated the difference between the two timings: when the centre of the participant's body passed one end of the slope and when it passed the other. For video analysis, we used the software Observer version 5.0. It is professional software used for the study of behavioural processes. By dividing the time difference by the horizontal length of the difference, the walking speed is calculated. For each group, we calculated the average walking speeds by backfall gradient. We performed two-tailed paired t tests on the average speeds. Note that in the t tests the alpha level is divided by three, which is the number of the backfall gradients tested, based on the Bonferroni correction.

We also calculated the deviation of each participant at each type of slope. We set deviation measurement lines every 1.20m from the beginning to the end of the slope. On the video, we measured how much the centre of each participant's body deviated from the previous deviation measurement line.

$$d_i = \left| D_i - D_{i-1} \right|$$

where d_i = Deviation on deviation measurement line (i) (unit: meter)
D_i= Lateral distance from the centre of the slope to the centre of the body on deviation measurement line (i) (unit: meter)

The measurement of deviation was conducted by identifying the nearest measurement point on the line to the point where the centre of the body passed. Measurement points were either the centre or an edge of the concrete block on the platform. Because the size of the concrete block is 0.40m square, there are measurement points every 0.20m on the deviation measurement line, thus deviation readings are {0.00m, 0.20m, 0.40m, 0.80m…}.

We calculated the average deviation for each type of slope by

$$\bar{d} = \frac{\sum_i d_i}{L}$$

where L : Horizontal length of the slope

4.2 Experiment 2

Using the videos, we calculated the difference between the two timings: when the centre of the participant's body passed the measurement line on the slope and when it passed the other mark on the platform. For each group, we calculated the average time. We performed paired t tests on the average times in the same way as we did in Experiment 1.

In the experiment, participants sometimes got stuck at the step or refused to try because he/she perceived the gap was too large. In these cases, we recorded the trial as a "failure". Participants sometimes managed to board but could not alight. In that case, we recorded the trial as a failure. Note that all the participants except the visually impaired were asked to make two trials at each stepping place. If a participant could not complete in both trials, we recorded "failure" for each trial.

5. Results

5.1 Experiment 1

Figure 5 shows the average ascending walking speeds of each participant group by backfall gradient. Figure 6 shows that of descending. The effects of the backfall gradient are not clear for all the participant groups in the figures. Paired t tests were conducted between the speed of 1.5% and 2.0%; 2.0% and 2.5%; and 1.5% and 2.5% for all the groups, and a significant difference ($p<0.05$) was observed only between 2.0% and 2.5% in the ascending speed of the visually impaired group. Overall, the effects of the backfall gradient are not tangible in the figures.

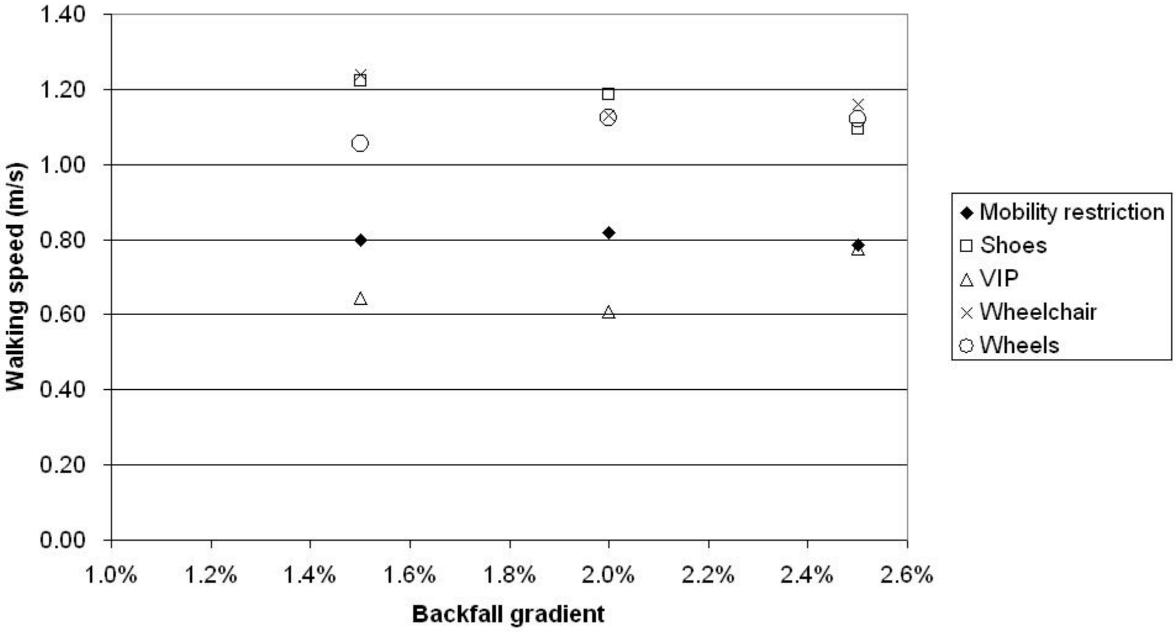

Figure 5. Average ascending walking speeds of each participant group by backfall gradient

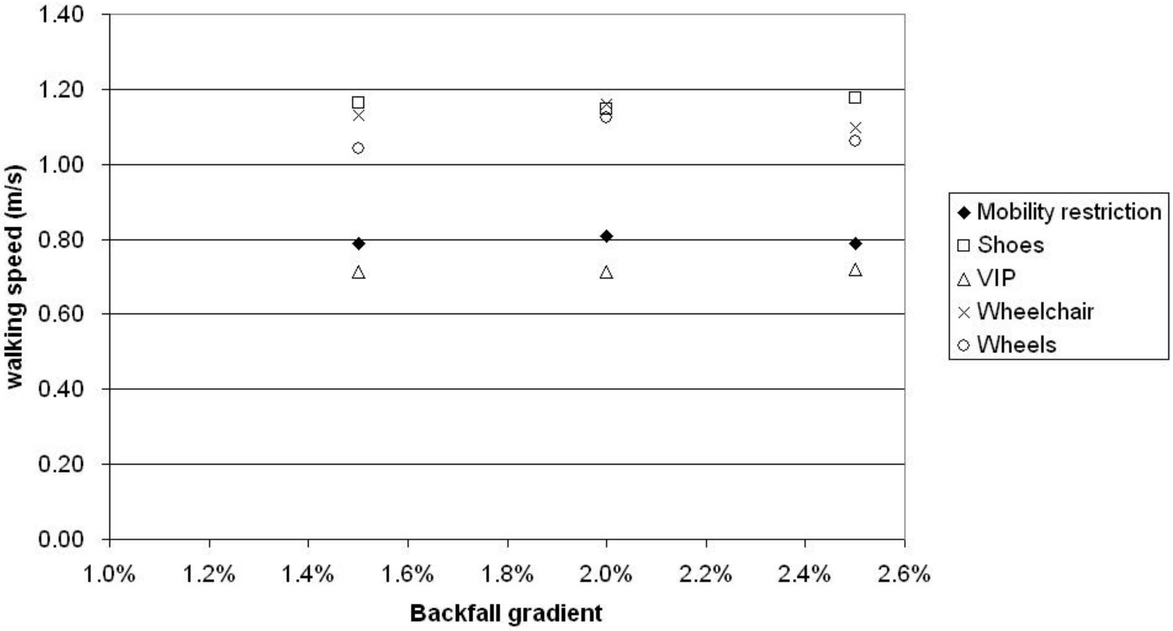

Figure 6. Average descending walking speeds of each participant group by backfall gradient

In the experiment, each participant was asked to evaluate their perception of danger for each type of slope (see Section 3.1). Figure 7 shows the percentages of the participants in each participant group who scored 3 or more in the answer to the question regarding the perception of danger to the total number of participants by slope gradient. The wheelchair group shows an increase in the perception when the gradient increases from 5.2% to 6.9%. Because the answer keys to the questions are in one dimension (the perception of danger), we calculated the average of the participants' scores. Figure 8 shows the average scores of answers to the question regarding perception of danger of the slope by slope gradient. Figure 8 shows that for the visually impaired group and the shoes group, there may be a slight increase in the average scores when the gradient increases from 5.2% to 6.9%. However, two-tailed paired t test results show no significant difference.

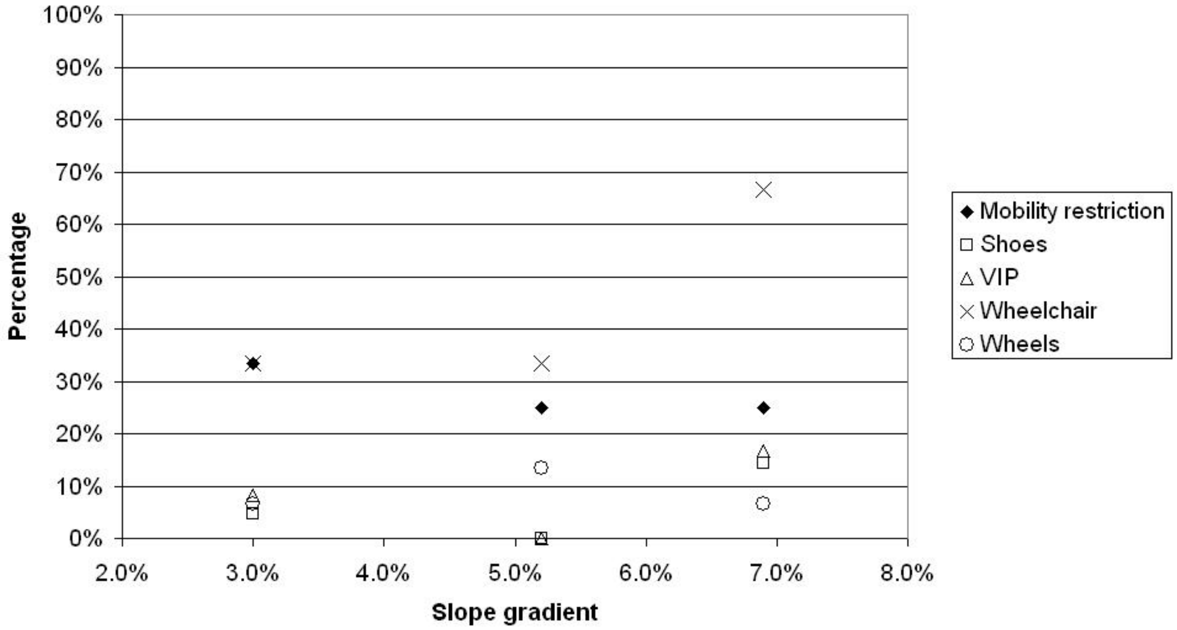

Figure 7. Percentages of the participants in each participant group who scored 3 or more to the question regarding perception of danger by slope gradient

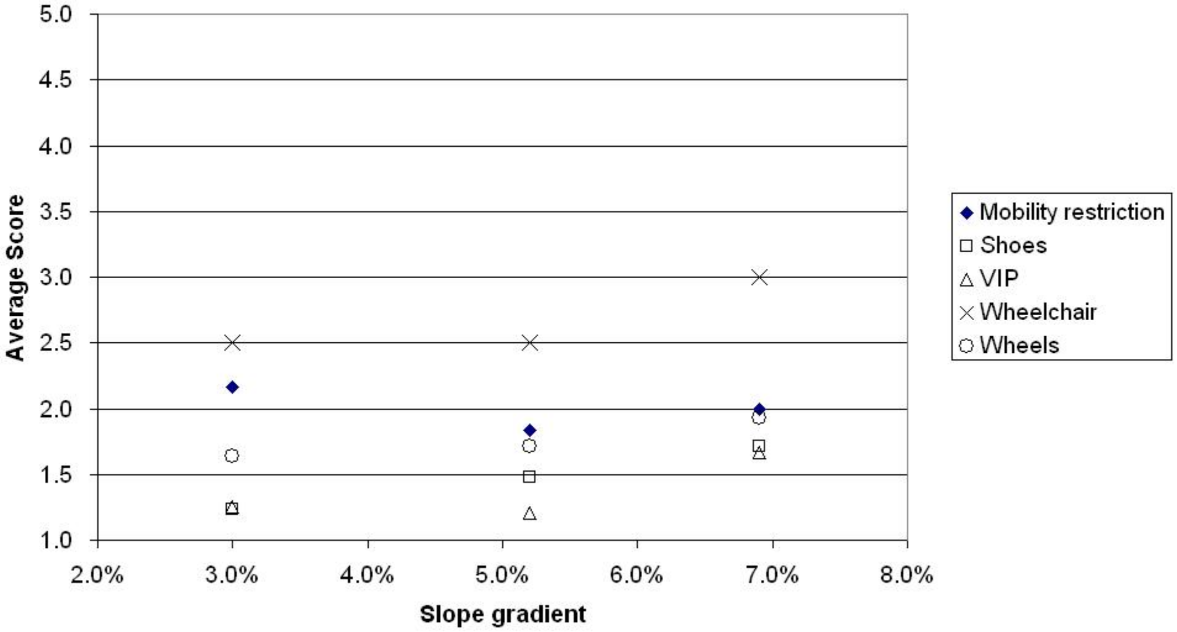

Figure 8. Average scores of answers to the question regarding perception of danger of the slope by slope gradient

Figure 9 shows the percentages of the participants in each participant group who scored 3 or more to the question regarding the perception of danger by backfall gradient. Effects of the backfall gradient are not clearly seen in the figure.

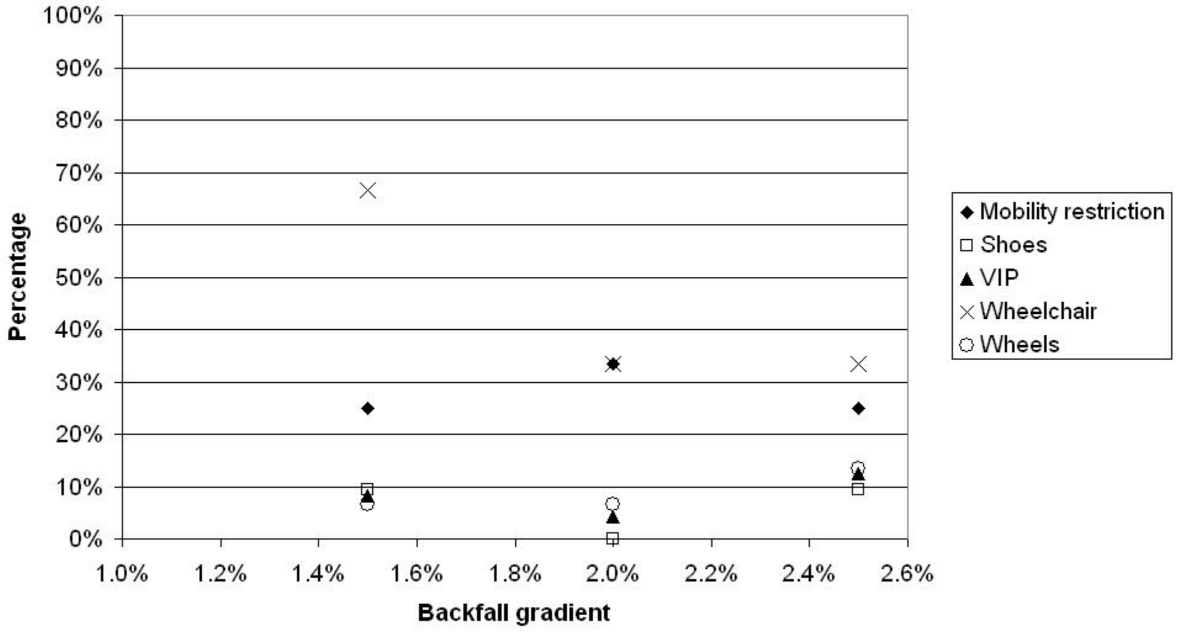

Figure 9. Percentages of the participants in each participant group who scored 3 or more in the answer to the question regarding perception of danger by backfall gradient

Figure 10 shows the average deviations of each participant group divided by backfall gradient when ascending. Figure 11 shows the results when descending. The group of visually impaired people shows a high value of deviation, but from the figures the effects of the backfall gradient are not clear.

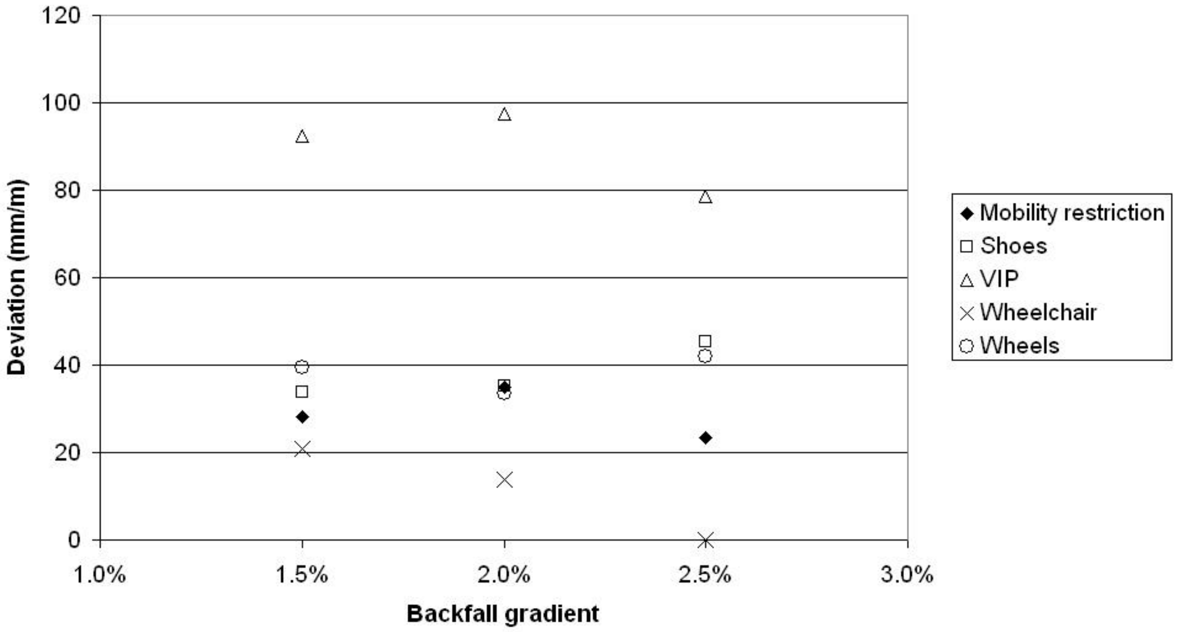

Figure 10. Average deviations of each participant group by backfall gradient when ascending

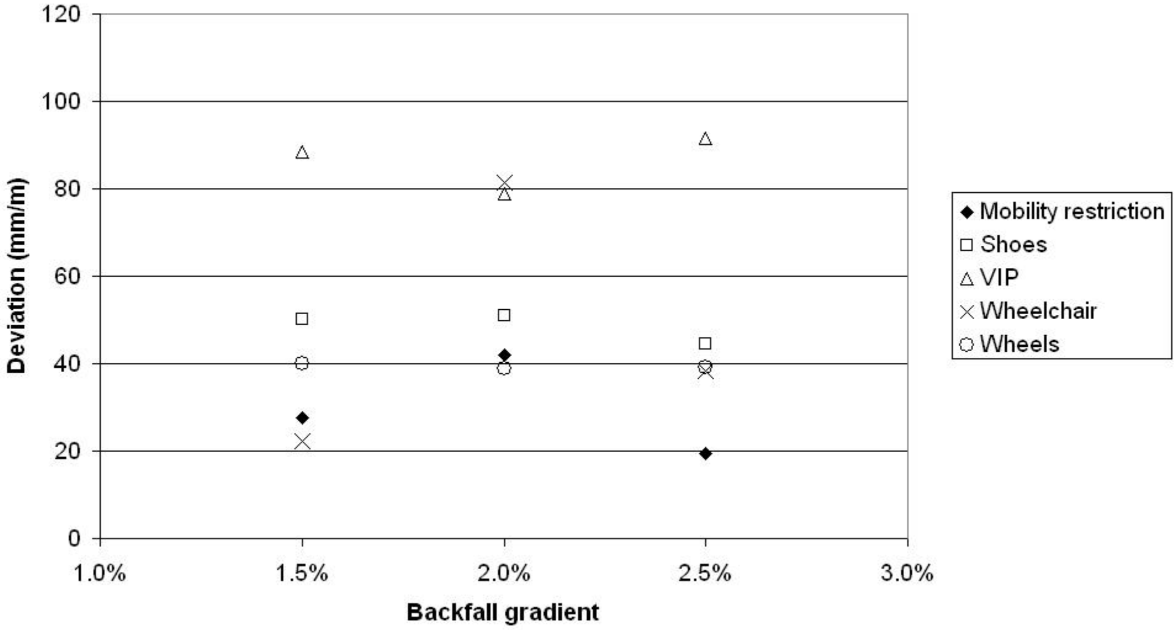

Figure 11. Average deviations of each participant group by backfall gradient when descending

5.2 Experiment 2

Figure 12 shows the average times taken to board by the participant groups. Figure 13 shows the times taken to alight. The figures show that for the mobility impaired group, the time increases according to the slope gradient. Table 1 shows the results of paired t tests on differences in speeds in relation to different slope gradients. For the mobility restriction group, significant differences were observed in the comparisons between 3.0% and 5.2% or between 3.0% and 6.9%. We checked the video in order to examine the reason why the visually impaired group shows a high value for 3.0%, and found that some participants with a guide dog spent a long time to board due to the hesitation of the dog.

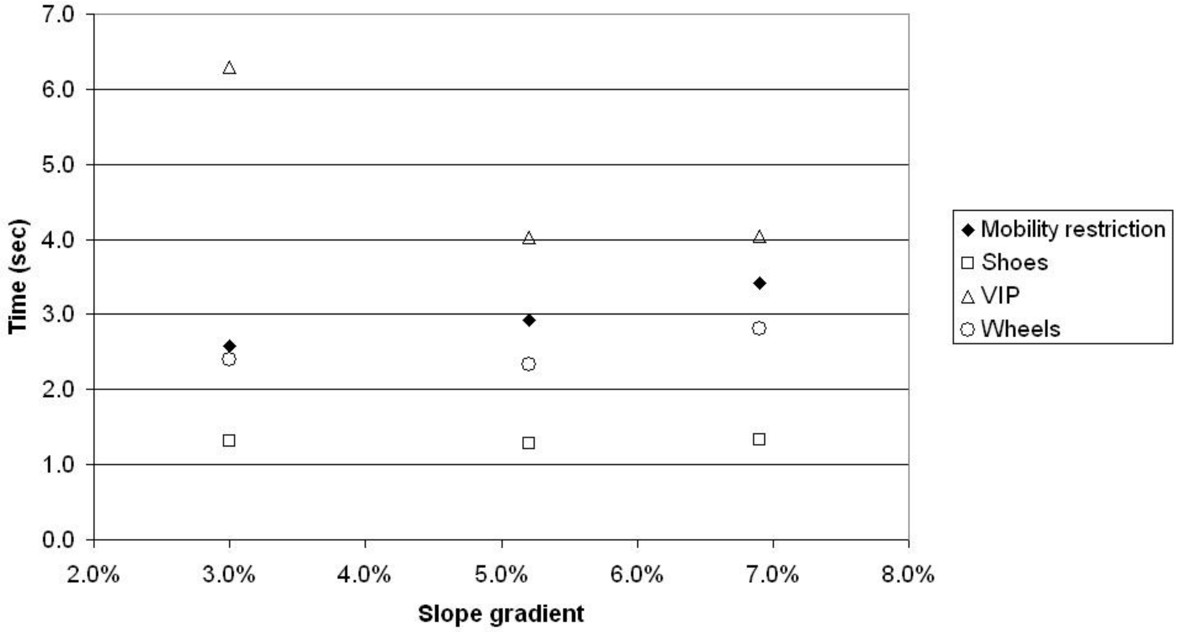

Figure 12. Average times taken to board by each participant group

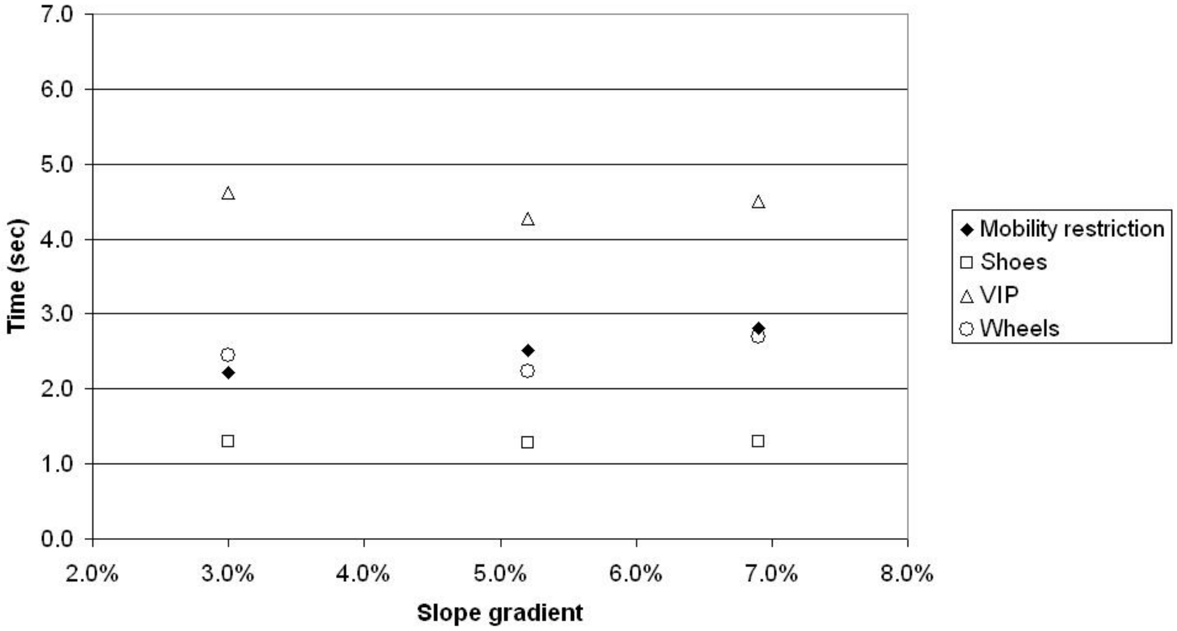

Figure 13. Average times taken to alight by each participant group

Table 1. Result of paired t tests results on the times taken by slope gradient and participant group

Slope Gradient	Mobility restriction	Shoes	VIP	Wheels
3.0% - 5.2%	$p<0.05$	1.58	$p<0.001$	0.69
	$p<0.05$	0.89	0.98	1.61
5.2% - 6.9%	2.20	2.48	0.36	1.70
	1.88	1.34	0.51	$p<0.05$
3.0% - 6.9%	$p<0.05$	0.72	$p<0.001$	1.51
	$p<0.01$	0.47	0.40	1.54

Above: Boarding
Below: Alighting

Figure 14 shows the percentages of the participants in each participant group who scored 3 or more to the question regarding the perception of danger by slope gradient. The figure shows that the effects of the slope gradient are not clear except for the participants with different shoes who show an inverse trend. In comparison, figure 15 shows the percentages by vertical difference. Interestingly, the figure clearly shows, in contrast, that an increase of vertical difference contributes to a higher score.

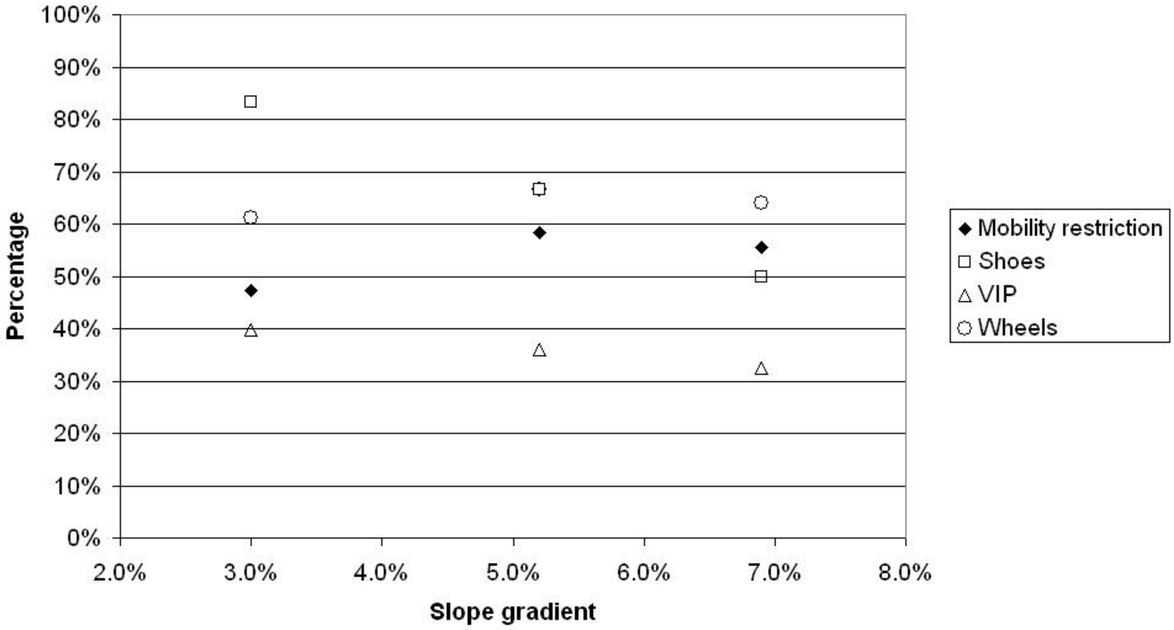

Figure 14. Percentages of the participants in each participant group who scored 3 or more to the question regarding the perception of danger by slope gradient

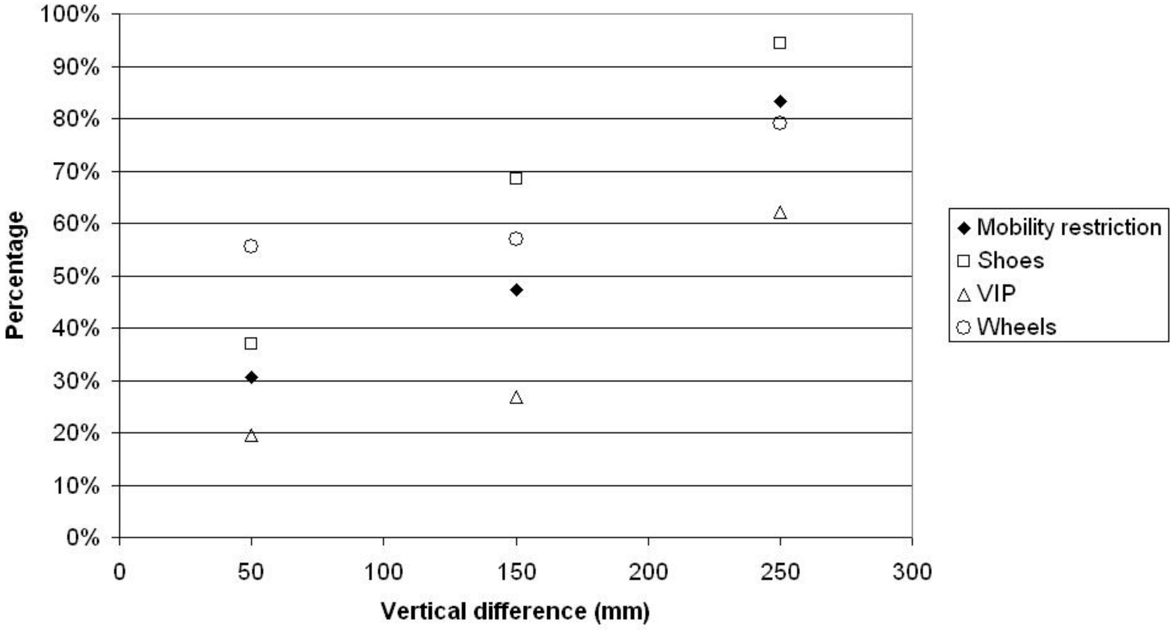

Figure 15. Percentages of the participants in each participant group who scored 3 or more to the question regarding the perception of danger by vertical difference

Figure 16 shows the percentages of failed trials to the total trials of different participant groups by slope gradient. The percentage of the visually impaired participants increases according to the slope gradient. Table 2 shows the percentages of failed trials to the total divided by participant group, vertical difference and horizontal difference. The table suggests that for people with mobility restriction, the increase of vertical difference contributes to the increase of the percentage of failed trials, whereas for visually impaired people it is the horizontal difference that contributes to the increase.

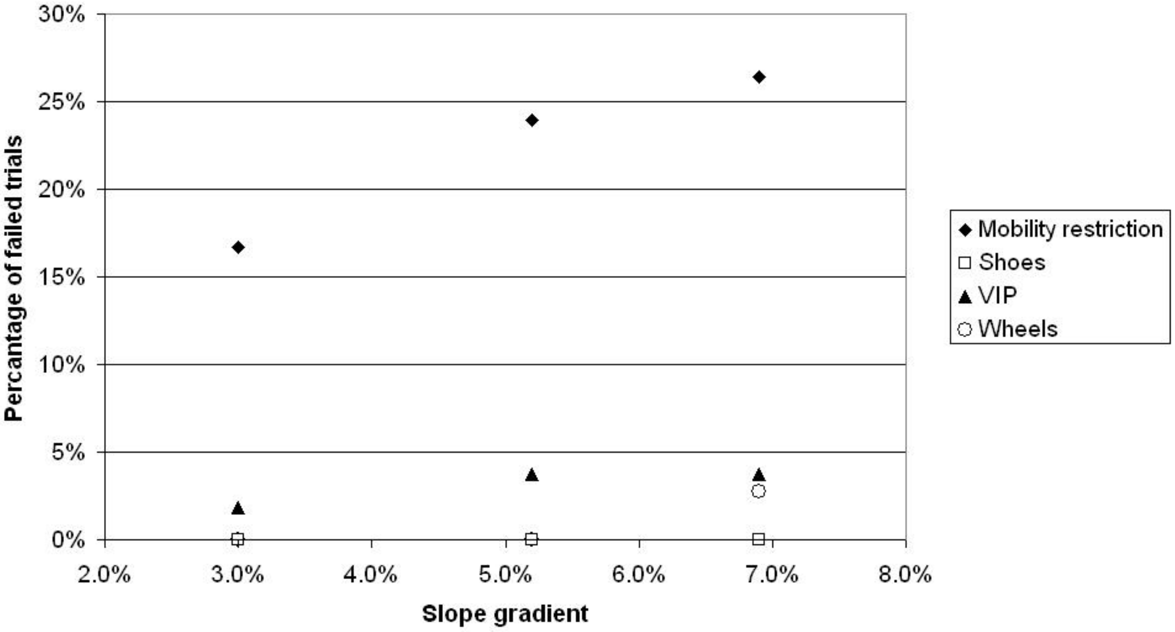

Figure 16. Percentage of the failed trials to the total trials of each participant group by slope gradient

Table 2. Percentage of the failed trials to the total divided by participant group, vertical difference and horizontal difference

Vertical Difference (mm)	Participant groups and horizontal differences (mm)											
	Mobility restriction			Shoes			VIP			Wheels		
	75	150	225	75	150	225	75	150	225	75	150	225
50	0%	0%	0%	0%	0%	0%	0%	0%	6%	0%	0%	0%
150	17%	17%	21%	0%	0%	0%	0%	0%	6%	0%	0%	0%
250	50%	50%	48%	0%	0%	0%	0%	6%	11%	3%	6%	0%

Figure 17 shows the percentages of failed trials to the total of the mobility restriction group trials by slope gradient and vertical difference. The figure suggests that, for the vertical height of 150mm, an increase of the slope gradient contributes to an increase of the percentage.

Figure 18 shows the percentages of failed trials to the total of the visually impaired participants' trials by slope gradient and vertical difference. The figure shows that, for the horizontal gap of 225mm, if the slope gradient increases from 3.0% to 5.2% or 6.9%, the percentage increases.

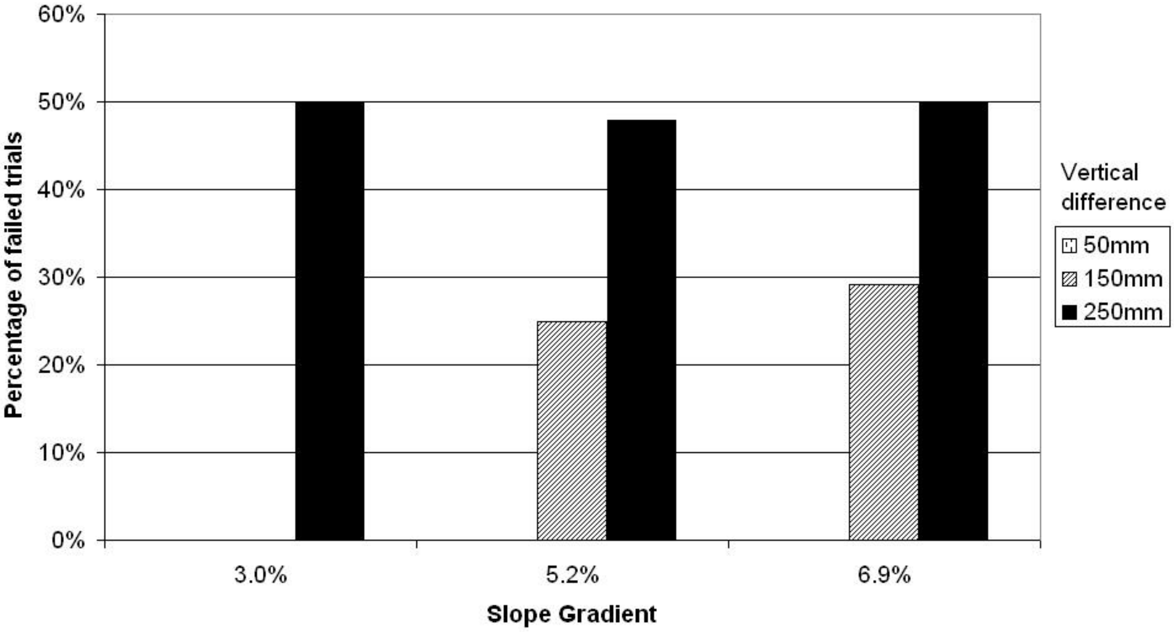

Figure 17. Percentage of failed trials to the total of the mobility restriction group trials by slope gradient and vertical difference

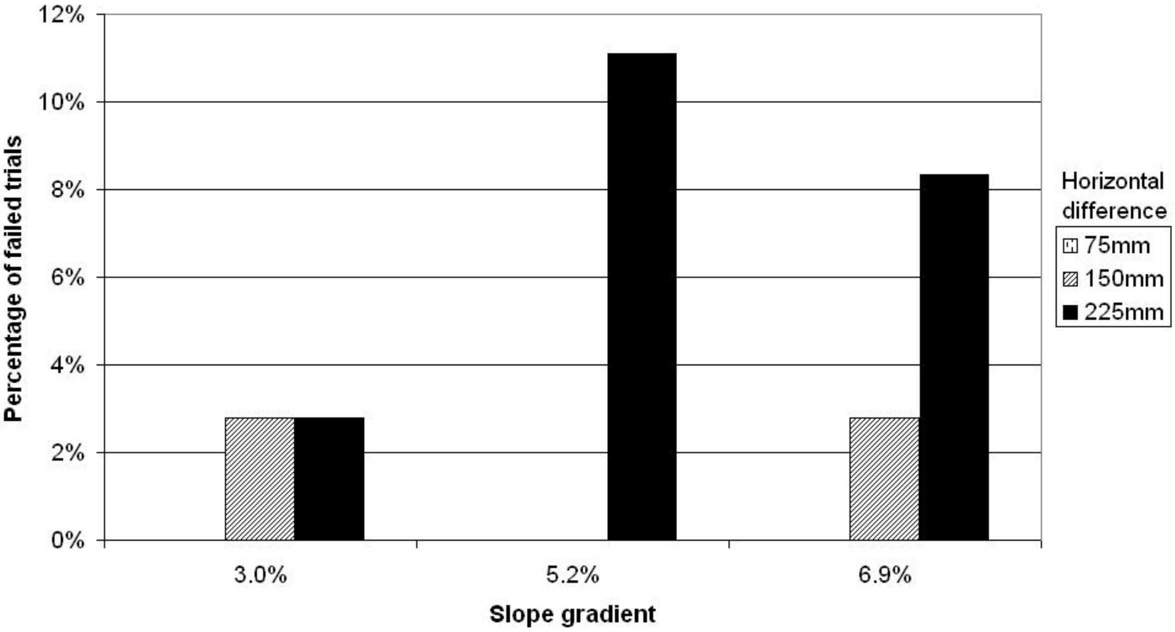

Figure 18. Percentage of failed trials to the total of the visually impaired participants' trials by slope gradient and horizontal difference

6. Discussion

This study was to examine the slope and backfall gradient of the platform hump. Because platform humps will be introduced in stations, the design factors should be properly assessed from the viewpoint of safety. Firstly, we looked into the slope gradient. The results of the question about perception of danger in Experiment 1 (figures 7 and 8) show that overall, the effects of the slope gradient were not clearly seen and the averages scores are 3 or less. Score 3 represents "I felt a little unsafe; needed to be quite careful". These suggest that an increase of the slope gradient does not greatly contribute to an increase of perception of danger.

In Experiment 2, it was observed that for the mobility impaired group, when the slope gradient increased, time to board or alight increased (figures 12 and 13 and table 1). On the other hand, the perception of danger does not change according to the slope gradient (figure 14) as much as it does for the vertical difference (figure 15). However, the percentage of failed trials in Experiment 2 suggests that an increase of the slope gradient affected the mobility impaired group (figure 16). A detailed analysis leads us to notice that the percentage increased for the vertical height of 150mm (figure 17). For the other vertical heights, an increase of the slope gradient did not affect the percentage. Indeed, because no participant failed at the 50mm height and half of the trials were failed at the 250mm height, the 150mm height can be considered at the threshold between "easy" and "difficult" barriers. This means that the slope gradient increased the percentage of failed trials for the vertical height that is at the threshold. Also, figure 18 shows that for the horizontal gap of 225mm, if the slope gradient increases from 3.0% to 5.2% or 6.9%, the percentage increases. These results suggest that the slope gradient is, by itself, not the main factor that affects performance and perception of danger, but it adds additional. When physically less capable people are stretching their capability to board or alight, the slope gradient would affect their performance.

An implication of the results above is that it could be recommended that doors should not stop next to a slope (figure 2) because boarding or alighting the train to/from the slope would add additional constraints for physically less capable people, whereas the results of Experiment 1 suggest that, within the range of the tested gradients, an increase of the slope gradient did not largely affect the perception of danger (figure 7). This suggests that, even though the slope gradient becomes steep, the slope length should not be so long that the slope would not reach an adjacent door. Note that it is possible to insert a middle landing when the slope reaches an adjacent door (figure 3), but one concern of the middle landing is that having two separated slopes would confuse visually impaired people. This issue was not investigated in this study and further research would be necessary.

Regarding the backfall gradient, figures 5 and 6 show that the effects of the backfall gradient on walking speeds in Experiment 1 were not clear. The perception of danger did not greatly vary according to the backfall gradient (figure 7). We also did not observe an increase of deviation relative to the backfall gradient (figures 10 and 11). In fact, in some cases, the amount of the deviation decreased. These results suggest that, for the range of the tested gradient, the backfall gradient did not affect the performance or perception of danger of the participants. In Experiment 2, we did not include the backfall gradient as an experiment variable because there were already many variables, and the backfall gradient may have increased difficulty and perception of danger when people boarded/alighted the train from/onto the slope.

Before the experiment, we expected an increase of deviation of visually impaired participants relative to the backfall gradient in Experiment 1. However, the results (figures 10 and 11) did not show such a proportionate relationship. One reason could be that the backfall gradients were not very steep and therefore the effects were negligible, which suggests that, even in their normal walking, visually impaired people show a similar deviation to the ones observed in the experiment. Another reason could be that the surface of the experiment site is covered by 40cm-square concrete blocks, so that the participants were able to detect the edges of the blocks thereby avoiding large deviation. This suggests that it would be useful to have some indication along the edge of platform to enable visually impaired people to walk safely along the platform. Nowadays, many stations have tactile paving about 1m away from the platform edge, whose main function is to prevent visually impaired people from falling onto the track, rather than being a guidance measure to walk along the platform. In fact, it is not safe to walk where the edge of the platform is just around 1m away. However, it is necessary to walk along the platform because of the location of an exit, lift or staircase. It may be necessary to have a guidance measure on humps as well as on other parts of the platform for visually impaired people to walk safely along the platform.

Figure 16 shows that generally the mobility impaired group had the highest failure rates in Experiment 2, whereas the results of Experiment 1 (figures 12 and 13) as well as Experiment 2 (figures 5 and 6) show that visually impaired group has the longest boarding/alighting time and the least walking speed. It was also observed that for some participants in the visually impaired group in Experiment 2, it took more than 20 seconds to board or alight. It is essential to remove barriers for mobility impaired people, but it is also important, especially for high-frequency lines, to provide environments where visually impaired people feel safe and comfortable and can smoothly board or alight without hesitation.

As for the limitations of this study, one would be the choice of the samples. As Stanford et al. (1997) mentioned, the selection of samples may affect the results. One approach would be to choose samples that represent the population. However, as the primary target of platform humps is disabled people, who are not the majority, this approach would be not appropriate for this study. Another approach would be that the samples consist mainly of those who are disabled, but it is expected that the more severe the disability of people is, the more their performance is affected by environments, such as the slope gradient. It is true that using the underground requires a certain level of mobility capability, and those with severe disability would not take the underground on their own (Stanford et al., 1997). For example, reaching the platform from the station entrance requires walking a certain distance, and those who cannot walk such a distance would not use the underground by themselves. It is difficult to identify the underground users with the least mobility capability who should be considered in the design of platform humps, because platform humps, which would enable more disabled people to use the underground, have not yet been introduced and therefore there is no knowledge about their user profile. Thus, a careful approach would be required to reach a conclusion about the acceptable limit of design factors, such as the maximum gradient of slope. However, it may be possible to examine the effects of each design factor, and this study can be regarded as such a preliminary investigation, which should be followed by more detailed investigations to determine the exact acceptable limits of design factors.

7. Conclusion

This study has investigated the effects of the design factors of platform humps. Platform humps are consists of several design factors and factors affect each other. As an initial attempt to understand the complexity, the presented study focused on the slope gradient and backfall gradient. The study found that the tested slope gradients and backfall gradients did not largely affect the performance of the participants' longitudinal walking on slopes. However, it is speculated that the slope gradient would add additional difficulty to board/alight the train from/onto a slope. Therefore, it should be avoided that the lower end of the slope reaches an adjacent door when the distance between doors is short. As the slope within the range of the tested gradients, which is 6.9% (1:14) or less, did not largely affect the performance and perception of danger of the participants, one solution is to increase the slope gradient so that the slope finishes before reaching the adjacent door.

The presented research was to bridge the gap between the practice of introducing platform humps and existing literature on slopes. It was necessary to understand the complexity of design factors of platform humps. As this study did not cover the design factors that are particularly related to wheelchair users (i.e. dimensions of the upper landing of the hump) or to visually impaired passengers (i.e. lighting and visibility), further research is necessary to address such design factors, so that it is possible to design platform humps that can be safely and comfortably used by various passengers.

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