Experimental study on luggage-laden pedestrian movement in narrow seat aisle

Shenshi Huang\textsuperscript{1,2}, Ruichao Wei\textsuperscript{1,2}, Siuiming Lo\textsuperscript{2}, and Shouxiang Lu\textsuperscript{1}

1 State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, China
2 Department of Civil and Architectural Engineering, City University of Hong Kong, Hong Kong
E-mail: kermit@mail.ustc.edu.cn

Abstract. The experiment of one-dimensional luggage-laden pedestrian movement in narrow seat aisle were performed in this study, to investigate the hindrance effect of seat configuration on pedestrian flow. In a seat arrangement similar to a vehicle carriage, experiments of individual walking and single-file pedestrian flow were carried out respectively. The result shows that carrying luggage has little effect on pedestrian walking ability. However, Carrying large luggage such as trolley case can significantly increase the distance headway of pedestrians. It is also found that, although the pedestrian dynamic pattern in narrow seat aisle was similar to that in open environment, the randomness of narrow seat aisle environment shows obviously greater.

1. Introduction
The topic on safe evacuation of high-speed train car has received widespread attention. As for the passenger evacuation progress inside the car, luggage-laden passenger and narrow seat aisle are the two important obstructive factors. Previous studies \cite{1, 2} had pointed out that the pedestrians with luggage tend to walk slower and occupy a larger space when boarding and alighting, and this impact will be more serious when passengers passing through the narrow seat aisle.

Present studies on pedestrian evacuation of seat area mostly focused on the evacuation time, egress rate, and occupant density. The pedestrian dynamic is rarely of concern. In the past years, researches on pedestrian dynamics used to concern about the pedestrian walking ability \cite{3, 4} and the interaction between individual pedestrian \cite{5, 6}. It is pointed out that the pedestrian individual walking speed can be affect by many factors such as particularity of individuals, and environment. Also, when there are pedestrians walking, they will usually keep a certain distance between each other, meanwhile the movement speed will be affected by others. In order to better understand pedestrian evacuation of seat area, it is necessary to analyse the pedestrian dynamic parameters in such environment.

This study focuses on the movement of luggage-laden pedestrian. Experiments of individual walking and single-file pedestrian flow are carried out in the narrow seat aisle, and the pedestrian walking speed and distance headway are analysed. Based on the discussion of luggage impacts on pedestrian movement in the narrow seat aisle, this study will give the useful benchmark for evacuation simulation of similar scenarios as well as provide reference to safety design of new train cars.

2. Experimental conditions
The experimental set-up was similar to our previous studies \cite{7, 8}. The impact of luggage on pedestrian movement was investigated by rearrange the seat and luggage configurations. Experiment
was carried out in the multi-function room, and the aisle was set up using six seat rows with spacing of 1.0 m. The aisle width was fixed as 0.5 m, which is the most common width in vehicle cars. Pedestrians were asked to walk through this 5-meter-long seat aisle, carrying different kinds of luggage. All the trolley cases weight no more than 10 kg and all the bags weight no more than 5 kg. Normal walking and fast walking conditions were designed, to simulate Cameras were set up to record the whole experiment process. By using the PeTrack [9, 10] software, the position of each pedestrian and the trajectories could be extracted, as illustrated in Figure 1. Based on the measured position, the pedestrian walking speed, distance headway, and other parameters can be obtained.

![Figure 1](image)

**Figure 1.** (a) The camera shots of luggage-laden pedestrian movement in this experiment; (b) Illustration of the pedestrian motion in seat aisle and distance headway.

This experiment includes two parts: individual pedestrian walking and single-file pedestrian movement. In the individual walking part, the pedestrian individual walking behaviours were measured. In the single-file pedestrian movement part, a “stop” instruction and a “go” instruction were designed, and the interaction between luggage-laden pedestrians were observed. The detail of experimental conditions have been list out in Table 1. Moreover, two repetitions of each test case were performed, in order to reduce the randomness of results.

| Case No. | seat aisle width | pedestrian type | luggage          |
|----------|------------------|-----------------|------------------|
| D1       | 0.50 m           | individual      | none             |
| D2       | 0.50 m           | individual      | bag              |
| D3       | 0.50 m           | individual      | trolley case     |
| D4       | 0.50 m           | single-file     | none             |
| D5       | 0.50 m           | single-file     | bag              |
| D6       | 0.50 m           | single-file     | trolley case     |
| D7       | 0.50 m           | single-file     | trolley case and bag |
| D8       | 0.50 m           | single-file     | G1 none + G2 bag |
| D9       | 0.50 m           | single-file     | G1 trolley case + G2 bag |
| D10      | 0.50 m           | single-file     | G1 trolley case + G2 none |

G1: 50% of all participants, with the Pedestrian No. of 1, 3, 5, 7, 9, 12, 14, 16, 18, 20, 22, 24, 26;
G2: the other 50% of all participants, with Pedestrian No. of 2, 4, 6, 8, 10, 11, 13, 15, 17, 19, 21, 23, 25.
Similar to our previous studies, different methods were applied to the analysis of different pedestrian types. The individual walking parameters were measured as spatial mean values, representing the basic attributes of the pedestrians. On the other hand, the single-file walking parameters were described by instantaneous values, in order to present the whole process of pedestrian movement under the action of instructions.

3. Results and discussions

3.1. Individual pedestrian movement

The average walking parameters of each individual in each test case is described in Figure 2, where the mean values are shown as scatter points and the distributions are present by box chart. It is clearly observed that, the bag has little impact on walking behaviours, no matter on walking speed, step size, and step frequency. Under normal walking condition, the pedestrians were able to walk at the speed about 1.5 m/s in average, with about 0.7 m per step. Under fast walking condition, the pedestrian can walk at about 1.7 m/s, and the average step size increases to about 0.8 m. This result is not very different from that of open space[8]. However, in the case of pedestrian carrying large luggage, the walking parameters would be much different. The statistical mean value of waking speed decreases and the variance increases significantly. Due to the obstructive effect of narrow aisle, pedestrians cannot easily carry the trolley case. The average walking speed was observed to be 1.2 m/s for normal walking and 1.6 m/s for fast walking cases. Besides, with carrying trolley case, the mean step size reduces to about 80% while the step frequency slightly increases. It indicates that carry large piece of luggage has a significant impact on pedestrian’s walking ability.

![Figure 2. Distribution of (a) average walking speed, (b) mean step size, and (c) step frequency of individual luggage-laden pedestrian walking through the seat aisle.](image)

3.2. Single-file pedestrian movement

The x-t curve of typical single-file pedestrian movement cases are shown in Figure 3, where the instantaneous moving speed is represent by the slope and the distance headway of each pedestrian can be indicated by the difference in height of curve clusters. As seen from Figure 3, the x-t curves are quite similar, which includes three movement phase corresponding to the designed instructions. In the first and the third phase, when the pedestrian queue was moving smoothly, the walking parameters such as maximum speed, distance headway were observed. In the second phase, when the pedestrians were lining up and waiting, the safety margin can be measured. Moreover, the propagation velocity of the action speed can also be calculated based on the curve offsets. The summary of walking speed and distance headway have been listed out in Table 2. The result shows that, when pedestrian queue moves through the narrow seat aisle (width = 0.5 m), they are able to walk at 1.33-1.51 m/s at normal speed condition and 1.63-1.77 m/s at fast speed condition respectively. It is found that the luggage has little effect on reducing the walking speed, no matter it is a bag or a trolley case. On the contrary, significant differences can be observed in distance headway.
When pedestrians are walking down the aisle one by one, they used to keep a distance of about 1.25 m to their predecessor. Due to the fact that the size of bag is small, the increase in pedestrian spacing is not obvious. However, in the tests with large luggage (trolley case), the distance headway of each pedestrian individual increases by 0.4-0.5 m. This phenomenon can be more clearly observed in the cases of fast walking. In addition, it is also obtained from the curve that, when the pedestrians stop or start to walk, the average acceleration is about 0.62 m/s$^2$ for normal walking condition and 0.85 m/s$^2$ for fast walking condition respectively. Carrying luggage is found to have little impact on acceleration.

![Figure 3. The x-t curves of the luggage-laden single-file pedestrian movement in each test cases.](image)

3.3. Impact of narrow seat aisle

The experiment tests in this study can be well compared with the previous study [7, 8], as the main difference is the environment. This study focuses on the pedestrian movement in narrow seat aisle (width = 0.5 m), so that the movement is more hindered. Table 2 compares the results of pedestrian movement behaviour under the condition of narrow seat aisle and open environment. Not surprisingly, it is found that in the narrow seat aisle, the pedestrians tend to walk at a slower speed. For normal walking condition, there is a 4% drop on velocity; for fast walking condition, there is a 9% drop. By comparing the result of distance headway, it can be concluded that pedestrian in seat aisle prefer to keep slightly large distance to their predecessors in the seat aisle. And it can be observed by comparing each case pair that, trolley case has a much greater impact on distance headway. It means that when the pedestrians with large luggage are walking in the seat aisle, they might feel more crowded and uncomfortable, so that they prefer to keep a larger distance and safe margin headway.

By analysing the instantaneous data of each pedestrian, a fundamental diagram can be obtained using the mean value of each experiment test case. The fundamental diagram can graphically show the relationship between pedestrian walking speed and occupant density.
Table 2. Summary of maximum walking speed and distance headway of pedestrians in seat aisle (width = 0.5 m) and open environment.

| Case No. | maximum speed (m/s) | distance headway (m) | Case No. | maximum speed* (m/s) | distance headway (m) |
|---------|---------------------|----------------------|---------|----------------------|----------------------|
|         | normal   | fast    | normal  | fast    | normal | fast | normal  | fast |
| D4      | 1.42     | 1.77    | 1.24    | 1.25    | E4     | 1.48  | 1.84    | 1.26  | 1.35 |
| D5      | 1.41     | 1.73    | 1.29    | 1.29    | E5     | 1.49  | 1.77    | 1.28  | 1.31 |
| D6      | 1.51     | 1.65    | 1.68    | 1.68    | E6     | 1.46  | 1.85    | 1.51  | 1.59 |
| D7      | 1.33     | 1.67    | 1.74    | 1.79    | E7     | 1.42  | 1.91    | 1.47  | 1.65 |
| D8      | 1.35     | 1.72    | 1.21    | 1.32    | E8     | 1.55  | 1.84    | 1.31  | 1.35 |
| D9      | 1.38     | 1.71    | 1.46    | 1.59    | E9     | 1.44  | 1.91    | 1.34  | 1.48 |
| D10     | 1.47     | 1.63    | 1.56    | 1.56    | E10    | 1.43  | 1.95    | 1.28  | 1.54 |
| Average | 1.41     | 1.70    | 1.45    | 1.50    | Average| 1.47  | 1.87    | 1.35  | 1.47 |

As illustrated in Figure 4(a), the average safety margin of the pedestrians in such seat aisle is about 0.7 m. It means that the pedestrians are willing to move forward only when there is 0.7 m distance free ahead. The slope of deceleration and acceleration phase curve is approximately 2.5 s⁻¹, which means that the pedestrians may walk 2.5 m/s faster with every meter distance greater headway. It is sound that when the distance headway is larger enough, the speed will stabilize at the maximum. The critical distance can be 1.3 m for normal walking condition and 1.5 m for fast walking condition. Figure 4(b) shows the relationship of average walking speed and linear density, compared with previous study in open environment [8]. Based on the fact the curves are almost overlapping, it can be conclude that the pedestrian dynamic pattern of these cases are similar. The scatter point of seat aisle experiment are distributed more discrete, indicating that the randomness of pedestrian behaviour is greater.

Figure 4. The (a) speed-distance plot and (b) speed-density plot of single-file pedestrian movement in seat aisle (width = 0.5 m) and previous study in open environment.

4. Conclusion
The luggage-laden pedestrian dynamic pattern in narrow seat aisle is investigated in this study. By conducting a series of pedestrian walking experiment. The pedestrian walking speed and distance headway are analysed. It is found that the individual pedestrian walks at about 1.5 m/s for normal walking condition and 1.7 m/s for fast walking condition. When there is a single-file pedestrian walking through the seat aisle, they used to keep a distance of about 1.25 m to their processor.
Carrying large luggage such as trolley case will significantly increase the distance headways, about 0.4-0.5 m. By drawing the fundamental diagram and making comparison with previous study, pedestrian dynamic pattern in narrow seat aisle is found to be similar to that in open environment. Nevertheless, the hindrance effect of seat configuration make the randomness of pedestrian behaviour obviously greater.

5. Reference
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