Pedestrian flow characteristics upstream of bottleneck: An empirical evaluation using fundamental diagrams

ボトルネック上流における歩行者交通流特徴：基本図に基づく実験的評価

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Introduction

As a basic tool to explore pedestrian flow characteristics, pedestrian fundamental diagrams (PFDs) have been investigated by a considerable number of previous studies. However, whether a PFD for an area upstream of a bottleneck differs according to the bottleneck properties (e.g., width, passing rule, and capacity), and how the PFD represents the unique characteristics of the corresponding walking behaviors of the crowd are not yet comprehensively understood. Through a series of laboratory experiments, this study derived new findings on pedestrian flow characteristics and walking behavior upstream of a bottleneck through the comparison of PFDs derived using a simplified Voronoi diagram method.

Experiment & Measurement Method of PFD

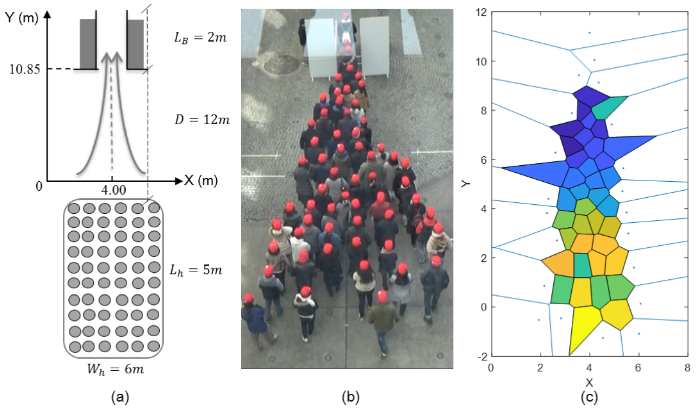


Fig. 1 (a) Experiment configuration, (b) snapshot from experiment site
(c) Example of Voronoi diagrams produced from experiment data

- **Experiment Scenarios**

  4 conditions combined with 3 bottleneck widths (0.8m, 1.0m and 1.2m)

  (a) Uncontrolled (UC)
  (b) Departure Control Slow (DS)
  (c) Departure Control Fast (DF)
  (d) Stairway (SW)

- **Voronoi Diagram Approach**

  This approach was reported to be able to reduce the density scatter and at the same time improve the resolution of data with higher sampling rate. The basic idea is that at each frame or during a short enough time period a bounded Voronoi cell area, A_i, can be obtained for each person i. Then, the density and velocity for a measurement area can be defined as:

$$\rho_i = 1/A_i \qquad \vec{v}_i = \vec{v}_{\Delta t,i}(t) = \frac{\vec{x}_i(t+\Delta t/2) - \vec{x}_i(t-\Delta t/2)}{\Delta t}$$

$$\langle\rho\rangle_v = \frac{1}{n}\sum_{i=1}^{n}\rho_i \qquad \langle v\rangle_v = \frac{1}{n}\sum_{i=1}^{n}\|\vec{v}_i\| \qquad \langle q\rangle_v = \langle\rho\rangle_v \cdot \langle v\rangle_v$$

ρ_i is the density in cell A_i, $\vec{v}_i$ is the instantaneous speed of person i during Δt

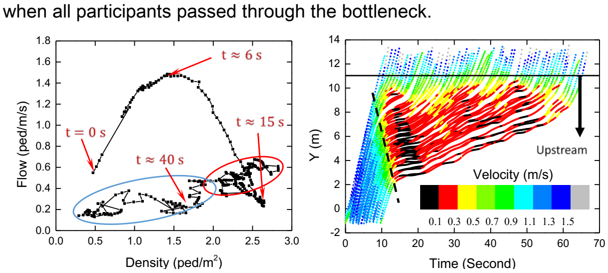
$\langle\rho\rangle_v$, $\langle v\rangle_v$ and $\langle q\rangle_v$ are Voronoi density, speed and flow of pedestrians group

Analysis Results

- **Whole-period PFD**

  Here, each point in Fig. 2(a) represents the average density and flow of the moving crowd at each time instant (0.2 s intervals). From this experiment, three states of crowd movement (i.e., loading, unsteady and unloading) were observed upstream of bottleneck.

  PFD was approximately linear when density was lower than 1 ped/m^2. The flow reached the maximum at density around 1.5 ped/m^2 ($t \approx 6$ s). When the shockwave reached the tail of the queue ($t \approx 15$ s), most pedestrians in the upstream totally stopped. Then, stop-and-go behaviors became prevalent and flow condition became unsteady. Finally, density gradually decreased to zero when all participants passed through the bottleneck.



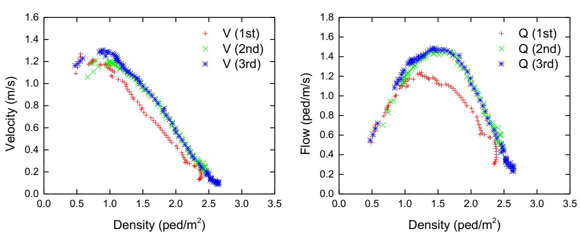
(a) Density-flow relation (b) Y direction time-space diagram

Fig. 2 Whole-period PFD & corresponding time-space diagram of 0.8 m UC scenario (third run).

- **Impact of Experimental Repetition**

  For the same bottleneck it was found that during the first repetition (e.g. red plots in Fig. 3), velocity and flow at the same density were significantly smaller than the second and third repetitions. This can be interpreted as an adaptation process or learning effect of pedestrians to the new experiment scenario.

  As a suggestion for the planning and design of public walking spaces, under the same traffic demand, pedestrian facilities that mainly serve newcomers (e.g., tourists) may require larger capacities than those that serve mainly daily users.



(a) 0.8 m UC velocity-density relation (b) 0.8 m UC flow-density relation

Fig. 3 Examples of PFDs from three repetitions of the same scenario

- **Impact of Bottleneck Type & Width**

  PFDs were separately compared between different scenarios to explore the impact of bottleneck type and width. Findings can be concluded as:

  - Pedestrians behaved more aggressively when they faced a bottleneck without a clear first-in-first-out passing rule.
  - In addition to prejudging the passing rule of the bottleneck, pedestrians also adjusted their walking speeds based on the recognition of the bottleneck width.

- **Comparison with previous studies**

  Findings from the comparison can be summarized as:

  - Pedestrians participating experiment would be less likely to form a crowd as congested as in other activities, like commuting.
  - Pedestrians preferred walking faster and maintaining a larger personal space when walking in an open area.
  - The existence of lateral boundaries alleviates drastic drop in pedestrian walking speed

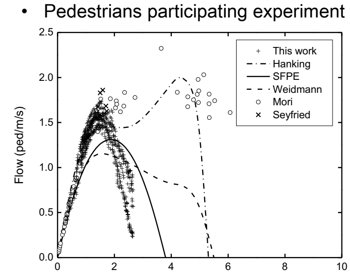


Fig. 4 Comparison of PFDs with other empirical works