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Measuring the steady state of pedestrian flow in bottleneck experiments

Weichen Liao [a,b,*], Antoine Tordeux [b], Armin Seyfried [b], Mohcine Chraibi [b], Kevin Drzycimski [b], Xiaoping Zheng [c], Ying Zhao [d]

[a] Beijing University of Chemical Technology, College of Information Science and Technology, Beijing 100029, China
[b] Forschungszentrum Jülich GmbH, Jülich Supercomputing Centre, Jülich 52425, Germany
[c] Tsinghua University, Department of Automation, Beijing 100084, China
[d] Beijing University of Chemical Technology, Centre for Information Technology, Beijing 100029, China

HIGHLIGHTS

- A modified Cumulative Sum Control Chart (CUSUM) algorithm is proposed and rigorously calibrated to detect steady states from bottleneck experiments.
- Comparing with the manually selected steady states, the CUSUM detected ones are more objective, robust and reproducible.
- The criterion to judge the difference between the flows in all states and in steady states is the ratio of pedestrian number to bottleneck width.
- The critical value of the ratio is approximately 115 persons/m.
- The conclusion applies not only for the analysis of existing bottleneck experiments but also for the design of new bottleneck experiments and the validation of evacuation models.

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ABSTRACT

Experiments with pedestrians could depend strongly on initial conditions. Comparisons of the results of such experiments require to distinguish carefully between transient state and steady state. Thus a modified version of the Cumulative Sum Control Chart algorithm is proposed to robustly detect steady states from density and speed time series of bottleneck experiments. The threshold of the detection parameter in the algorithm is calibrated using an autoregressive model. Comparing the detected steady states with manually selected ones, the modified algorithm gives robust and reproducible results. For the applications, three groups of bottleneck experiments are analysed and the steady states are detected. The results reconfirm that the specific flow is constant as bottleneck width changes. Moreover, we proposed a criterion to judge the difference between the flows in all states and in steady states, which is the ratio of pedestrian number to bottleneck width. The critical value of the ratio is found to be approximately 115 persons/m. This conclusion applies not only for the analysis of existing bottleneck experiments but also for the design of new bottleneck experiments and the validation of evacuation models. Furthermore, the range of steady

* Corresponding author at: Forschungszentrum Jülich GmbH, Jülich Supercomputing Centre, Jülich 52425, Germany.
E-mail address: w.liao@fz-juelich.de (W. Liao).

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state in time series of pedestrian characteristics could be effectively controlled by adjusting the value of the ratio.

1. Introduction

In recent years, several experiments under well-controlled laboratory conditions were carried out to explore pedestrian dynamics in bottlenecks. Some of the experiments focused on collective phenomena such as jamming and oscillations [1]. Others concentrated on transport characteristics of pedestrian dynamics [2,3].

Many bottleneck experiments studied the relationship between bottleneck width and pedestrian flow [2–16]. The flow was shown to be linearly dependent on bottleneck width [2,4–7]. The slope of the linear function is approximately 1.9 $(\mathrm{m\ s})^{-1}$ with bottleneck width ranging from 0.7 to 5.0 m [2,4,5]. Different types of participants were chosen for the experiments (students, soldiers and employed), therefore this value seems typical for European adults without disabilities. When bottleneck width is smaller than 0.7 m, the slope of the linear function decreases with increasing bottleneck width [3,7,16]. Other bottleneck geometrical factors were also investigated. Shorter bottlenecks provide higher flow than longer ones [5,6,12,13]. Wider width of the passage in front of the bottleneck leads to higher flow [5,8]. The flow also increases with increasing distance between bottleneck and holding area [5]. Usually the bottleneck geometry was made up of boards higher than 2.0 m to prevent pedestrians' bodies overlapping the boundaries. Nagai et al. [11] used desks with the height of approximately 0.8 m, which was pointed out to actually represent wider bottleneck widths with regard to flow [4]. Helbing et al. [17] and Yanagisawa et al. [18] studied the influence of an obstacle in front of the bottleneck. They found that in the case of pushing crowds or test persons advised to rush, the existence of the obstacle leads to higher flow especially when shifted from the centre. Furthermore, the influences of non-geometrical factors were studied [11,14,17, 19,20]. Nagai et al. [11] changed the initial density of the participants in the holding area. The flow was found to increase with increasing initial density, but the rate of the increase decreases. Daamen et al. [14] considered different compositions of the participants. The experiment with mainly children had the highest flow and that with disabled pedestrians had the lowest flow. Most experiments were conducted under normal situations, in which the participants were asked to walk through the bottleneck with normal speed. Only a few experiments were conducted under competitive [21], hurried [20], pushing [17] or stressful [14] situations. Unfortunately, no coincident result has been made considering the influence of different situations.

As a scientific method, these experiments are performed to study the influence of one single parameter of interest and to exclude external unwanted influences as much as possible. To enable a variation of the parameter of interest, the experiments are usually organized in different runs. Each run has a start time with unique initial conditions, which are often artificial. Moreover, to avoid the feeling of tedium for the participants and due to limited resources typical experiments with pedestrians are short in time. Thus, how strong the quantity of interest depends on the initial conditions and observation time is uncertain. For example Figure 8 in Ref. [2] providing the time series of speed in the bottleneck of a typical pedestrian experiment shows strong dependence. A good indicator to reveal the system is no longer influenced by the initial conditions is the steady state of the quantity of interest [4]. With this mind the values measured in steady states have a more general validity. Therefore, defining a uniform method to select steady states is important and necessary to the investigation and comparison of such experiments, for example to compute the flow through bottlenecks. Some indications of the relevance distinguishing transient and steady states are provided by the following examples. Cepolina [22] showed the time series of pedestrian flow. The flow changes significantly in a transient state (at the beginning and at the end) but keeps in average constant in a steady state. Yet she did not further analyse the flow in steady states. Seyfried et al. [2] used regression analysis to calculate the stationary values for the density and speed, but the flow in steady states was not considered. Rupprecht et al. [5] found that the flows with all participants and with specified participants have different trends. However the specified participants were selected arbitrarily without considering steady states. Liao et al. [4] selected steady states manually from the density and speed time series of the experiments. The flows in all states and in steady states both show a linear dependence on bottleneck width but with different slopes. Nevertheless, the duration of steady states was determined according to the "small fluctuations" in the time series, but the demarcation of the "small fluctuations" is ambiguous. Up to now, the specific relationship between steady state and pedestrian flow is unknown. Moreover, no generally accepted method was used to detect steady states in bottleneck experiments. Manually selected steady states can be used, but the result varies from different researchers [5].

In this paper, the parameter of interest is bottleneck width and the quantity of interest is pedestrian flow. We propose a robust and reproducible method of steady state selection for pedestrian flow. The method, based on a modified Cumulative Sum Control Chart (CUSUM) algorithm, allows to robustly detect steady states in bottleneck experiments and to objectively analyse pedestrian flow in such experiments. The remainder of the paper is organized as follows. In Section 2 the CUSUM algorithm is modified and improved to reproducibly detect steady states; the threshold of the detection parameter in the algorithm is calibrated using an autoregressive model. Section 3 applies the modified CUSUM algorithm to three groups of