Evacuation characteristics of preschool children through bottlenecks

Jun Zhang, Hongliu Li, Yanghui Hu, Weiguo Song
State Key Laboratory of Fire Science, University of Science and Technology of China
Jinzhai Road 96, Hefei, Anhui, P. R. China
junz@ustc.edu.cn; wgsong@ustc.edu.cn

***Abstract* -** Pedestrian movement through bottlenecks have been widely studied from various aspects to understand the effects of bottlenecks on the pedestrian flow. However, few attentions have been paid to the movement characteristics of preschool children, who show obvious differences behaviour compared to adults due to the poor balance and understanding of danger especial under emergencies. In this study, we focus on the evacuation characteristics of preschool children through bottlenecks with laboratory experiments. From all the experiment, we do not observe clear lane formation process from the trajectories diagrams. It is found that the first arrive first out principle does not work in the situation with competition. Compared to adults, children are more likely to fall and hard to be controlled during movement, which is very dangerous in emergencies. The highest speed for the preschool children can beyond 3 m/s and is depend on the location in the crowd for each individual. For a given number of evacuees, the total evacuation time firstly decreases a linear with the increasing the bottleneck width and then keeps a constant if nobody falls down during the movement. Falling down of children will increase the evacuation time incredibly. The findings will be beneficial for the evacuation drill design in kindergarten as well as the facility design for young children.

***Keywords*:** bottleneck, pedestrian flow, competition, preschool children evacuation

1. Introduction

It is reported that 26.1% of the population in the world are children aged from 0 to 14 years and 17.85% are kids aged 0-9 [1]. There are of great difference between children and adults in movement behaviours as well as psychological characteristics. Children prefer to behave with temporary feelings and desires instead of rational thinking. Especially for kids, their behaviours are usually not purposeful and easily affected by the surrounding environment. For example, kids aged 2-5 years are forming their control scheme of their own bodies and prefer to open their arms to keep balance. Most of them do not follow the desired direction [2]. Under emergencies, children face higher risks and might need more assistance than adults do due to their poor balance ability and poor understanding of danger. Besides, with the developed society, more and more children stay in kindergartens or day-care centres for both parents have to work outside. Thus, it is significant to consider the children evacuation dynamics when designing buildings for kids like kindergartens or children's amusement parks in order to reduce the risk of casualties.

Bottleneck is a common geometry in most of pedestrian facilities. When a large group of discrete bodies passes through a narrow exit, they might accumulate in front of the exit since the narrow exit restrict their movement [3]. Several stamped disasters happened because of the congestion in front of bottleneck. Hence, pedestrian flow through bottleneck has attracted increasing attention from researchers and several well-controlled experiments have been performed in the last decades [4-11]. Pedestrian movement through bottleneck is influenced by several factors including the geometry of the bottleneck (length, width and location), the initial distribution of pedestrians and sociological effects [8]. The impact of bottleneck lengths, widths and shapes on the flow has been investigated widely with different objects such as pedestrians, sheep herds or mice [3]. It is found that appropriate bottleneck shape can improve the traffic effectiveness and the wider the bottleneck the greater the flow [8, 11]. There is a linear decline of the specific flux with increasing width when only one person can pass the bottleneck at a time and a constant value for larger bottleneck widths [6, 7, 9, 12, 13]. The bottleneck width shows strong influence on the density and velocity inside the bottleneck but less on them in front of the bottleneck [6]. There are severe differences between upstream and downstream of a bottleneck. Pedestrians' movements upstream are guided by the traffic state information of bottleneck ahead while their movements downstream are ruled by the physical restrictions of local conditions [14]. Different opening width, population composition and light intensity show influence on capacity of emergency doors [15]. Paradoxical phenomena like faster-is-slower effect can be observed from flow through bottlenecks [3, 5, 16-18]. Some researchers study pedestrian counterflow through bottlenecks and point out that bottleneck width has clear influence on the process of lane formation and wider bottleneck width can reduce passing time [19]. While some researchers thought that wide bottlenecks have few impacts on formation of lanes inside the bottleneck and the number of lanes does not show clear impact on the relations between flow and bottleneck width [4].

Even though there are studies on pedestrian flow through bottlenecks, most of data is related to the movement of adults. Up to now, very few studies on the children movement can be found, especially for preschool children [2, 20, 21]. Some researchers found that the speed of 3-5 years old children on the stairs was low and tended to grow when they can use handrails or walk hand in hand [2]. When kids are familiar to surroundings, they show higher walking speeds in spiral stairs and lower speeds on horizontal plane. During evacuation, they are keen to run and their speed can be higher than that of adults [21, 22]. Compared to adults, higher densities and flow of children through doors were observed [20, 21]. Lack of data and special behaviour characteristics of kids determines the necessity to study children's evacuation characteristics through bottlenecks.

In this study, preschool children experiments were performed to investigate the impact of the width of bottlenecks on children's evacuation process. The remainder of the paper is as following. In section 2, the experiment setup is briefly described. Section 3 shows the main results from the experiment analysis and the concluding remarks are made in section 4.

2. Experiment Setup

Totally 16 runs of experiment were performed in a kindergarten in Yueyang City, Hunan Province in China in Jan. 2018. The participants were 32 preschool children in the kindergarten with the age of 3-5 years old: 14 girls and 18 boys. The height of them ranges from 0.95m to 1.25m with the average of 1.06m, while their weight is from 14.8kg to 33.1kg with a mean value of 19.3kg. Fig. 1 shows the sketch of the experimental scenarios and two snapshots during the experiment. Two types of bottleneck, normal and funnel-shaped exit, were considered to study the influence of the shape of bottleneck on pedestrian flow. For each type of bottleneck, eight runs were performed by changing the width of exit from 0.4m to 1.1m at 0.1m intervals. Especially for the funnel shaped bottleneck, the cone angle α was fixed as 45° and only the width of outer edge of the bottleneck was changed. The geometry of the experimental scenario was built with plastic security fences (height: 75cm) and tables (size: 120×60×50 cm). In this case, the effective width of the bottleneck is larger than expected value especially for narrow situations, since both the fences and tables are shorter than the children. The upper part of the body can move outside the bottleneck, which can be seen from the snapshot.

Each child was given a yellow or blue hat during the experiment for quick extraction of their trajectories automatically afterward. Before each run of the experiment, all the children assembled orderly in the waiting area 5m far away from the bottleneck and were told to leave the exit like in an evacuation drill when the experiment start, which was organized by the kindergarten teachers. When everything was ready, one of our managing staff gave command "Ready! Go!" and the experiment started. During the experiment we asked the children to leave the bottleneck as fast as they can. As a result, competitive behaviours were observed and some children always wanted to leave the exit firstly. Especially in front of the bottleneck nobody let others overtake them and they always tried their best to leave the exit, even push-and-pull behaviour occurred sometimes. Since we considered several safety issues and prepared well in advance, the experiment was performed safely and smoothly finally. The whole experiment was recorded by two cameras (a HD camera with the resolution of 1920 x 1080 pixels, frame rate of 25fps and a sports camera GoPro Hero 4) mounted on the roof of a three-floor building. Before and after the experiment, we calibrated the camera and the whole scenario twice based on the operation instruction of the software PeTrack to extract the trajectories precisely. Finally, we extracted all the trajectories from video recordings of HD camera. Moreover, all quantitative analysis following is based on these trajectories.

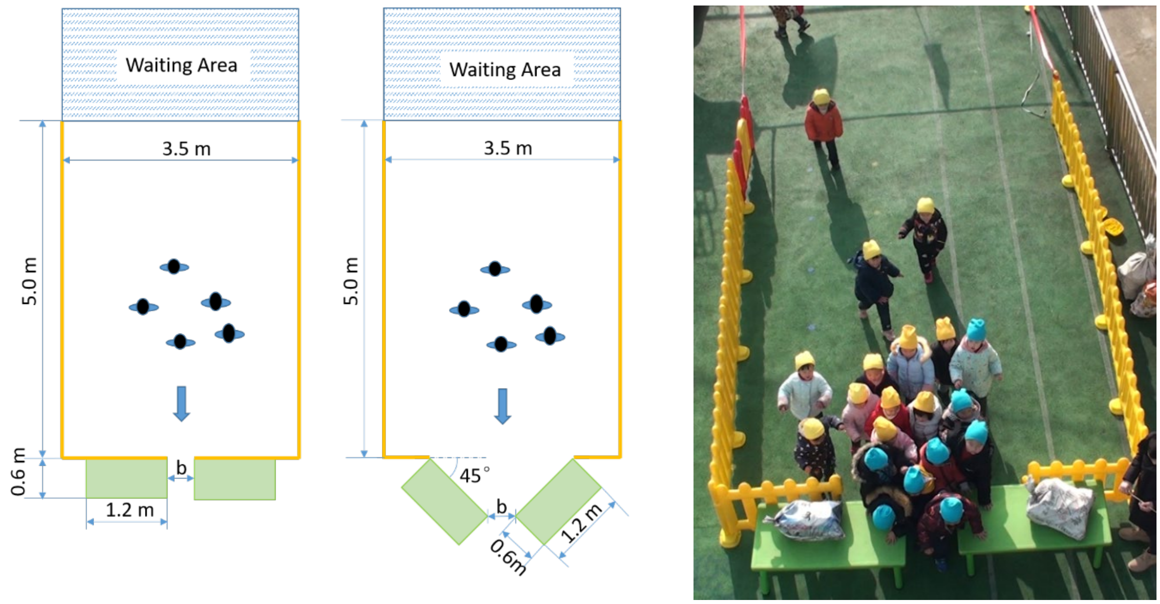

Fig. 1: Illustration of the experiment scenarios and a snapshot.

3. Results and Analysis

3.1. Trajectories

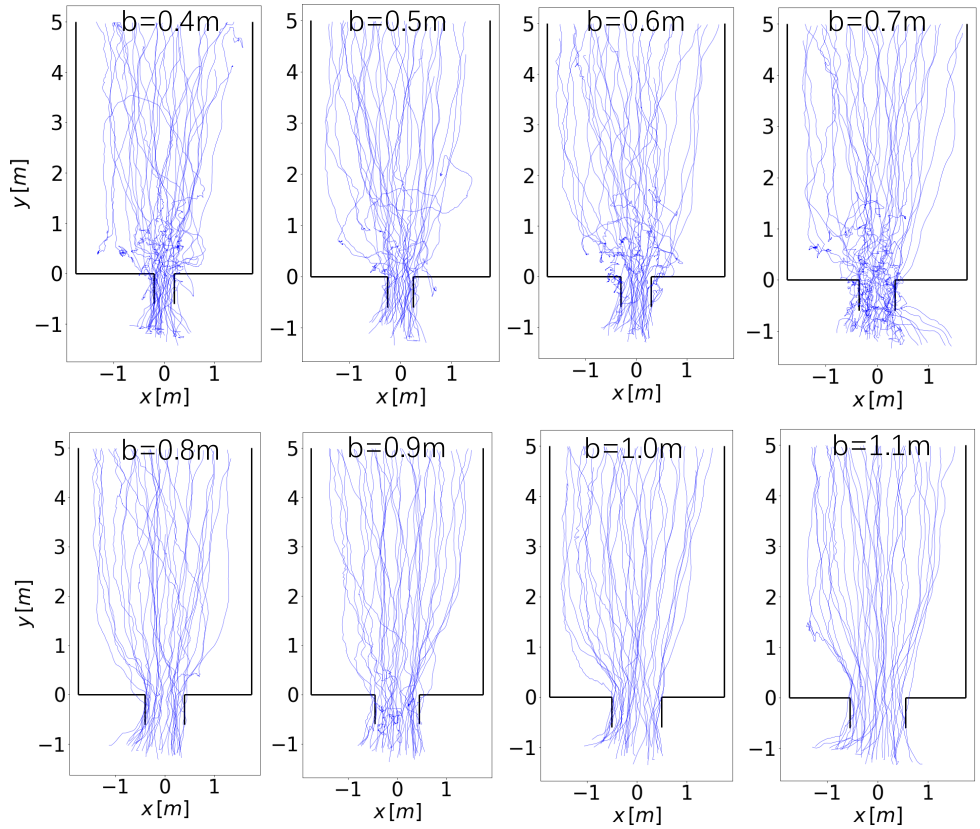

Fig. 2: Trajectories of all children in the experiment.

In Fig. 2 all paths taken by the children passing through bottlenecks of varying widths are overlaid. Firstly, we can examine the process of lane formation, which is considered as a typical self-organization phenomenon and is often discussed in previous experiments for pedestrian movement in narrow corridors. However, unlike the results in [8], the process is not apparent from the trajectories in this experiment. The motivation of the movement can be one main reason for the difference. Pedestrians in other experiments move in normal speed with collaborative and gentle way. However, children tried to leave the bottleneck as soon as possible by run and competitive behaviours exist in this experiment. In this case, they less consider to follow the behaviours or paths of others around them. For b<0.8m, serious congestion formed very quickly after the experiment started and children movement at bottleneck is chaotic. The trajectories near the bottleneck oscillate obviously due to the strong competition. Some child squeeze through the boundary of the bottleneck with the upper body on the table. That is the reason why some trajectories are out of boundary in the figure. Especially for the scenario with b = 0.7m, the trajectories inside bottleneck also show strong oscillations. That is because some children fall down outside the bottleneck and become obstacles. For b > 0.8m, less congestion occurred due to insufficient participants and children can pass through the bottleneck nearly freely. The trajectories are smoother compared to the other four runs. From video recording, we can observe lanes sometimes in the corresponding runs during the experiment. However, from the trajectories it is not as obvious as that in [8], where there are about 250 participants in the experiment. It does not mean that the lane can be observed from the trajectory if we have more participants, because more participants may lead to serious congestion around the bottleneck and the situation will be similar to b < 0.8m.

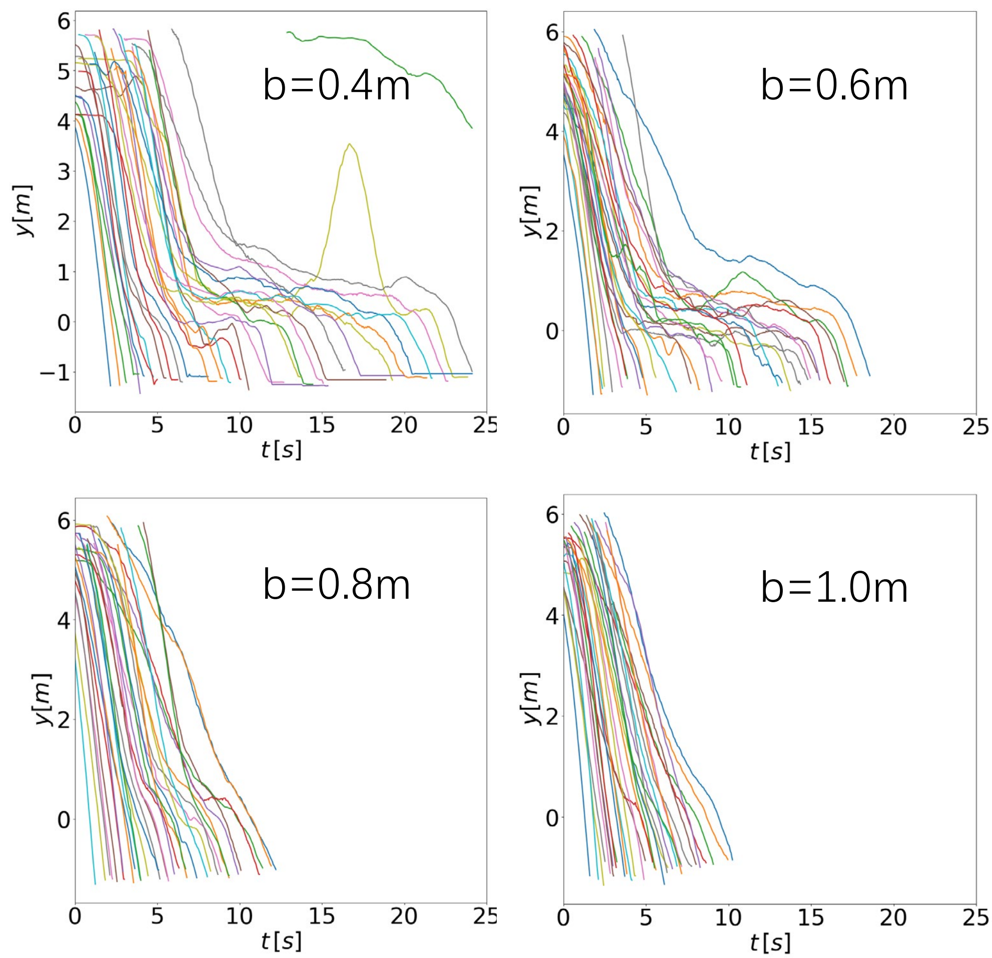

Fig. 3: Time space diagrams for four different scenarios. Here we focus on the movement towards the bottleneck (y direction).

Fig. 3 shows the time-space diagrams for four different scenarios. We focus on the movement towards the exit and thus y direction is considered. It is obvious that both the total evacuation time and the number of children under stop state decrease with the increasing bottleneck width. For the first few children, they leave the experiment scenario with relatively free speed without stop. For the other children, they firstly accelerate and then decelerate when congestions occur around the bottleneck. At the same time, there are children under both stop and movement state. Several intersections for the curves from stopping and moving children mean that the children pass through the bottleneck without obeying the "first come first out" principle under competitive conditions. The aggressive child always pushes away others to leave firstly and the children closely behind can then follow his path easily. For example, in Fig. 4 left, the child in the circle stopped at the corner and cannot leave for a long time because the one with black coat and his followers pushed her. Besides, poor balance and hard to be controlled can be two obvious properties of children compared to adults. They are more likely to fall even without push and pull from others. Once a child falls down, several children behind will fall down also. In this case, even if you ask them stop, nearly nobody cares about the command (See Fig. 4 right). In other word, for the safety of children movement, the best way is to take methods that can avoid or decrease falling down especially under emergency.

Fig. 4: Two snapshots from the experiment. Left: the child in the circle was pushed and cannot leave the bottleneck for a long time even if she arrives there earlier. Right: children are hard to be controlled. When there are children fall down, others behind don't stop move forward even if the organizers ask them stop during the experiment.

3.2. Evacuation Time

In this section, we focus the evacuation speed and time of the 32 children in the experiment. Fig. 5 shows the evolution of speed for each child along the movement direction from two runs with bottleneck width of 0.4 m and 1.0 m. It can be seen that the influence of the bottleneck on the speed can extend to 2 m away under the experiment condition. Of course, this range may change for different number of evacuee and different distance to waiting area. The children accelerate from zero to the maximal speed in the area from the waiting area to $y = 2$ m. The bottleneck width shows less influence on the movement of the children in the area. Then they decrease to a lower speed from $y = 2$ m to the bottleneck. The minimum speed is around zero for the scenario with $b = 0.4$ m, whereas it is about 0.5 m/s for the run with $b = 1.0$ m. Not only the maximal speed but also the minimal speed varies in a wide range for different children based on their location in the crowd. The maximal speed for the first few children can be over 3 m/s and reach 4 m/s, whereas it is lower than 1 m/s for the ones at the end. In any case, it is obvious that the minimal speed appears at the bottleneck $y = 0$ m, which means the bottleneck do have influence on pedestrian movement even it is very weak for wide bottleneck. Besides, the periodic oscillation of the speed around a certain value for each individual is due to the alternation of the two legs. The frequency of the oscillation agrees well with that of two legs. That is also the reason why less oscillation is observed for high speed.

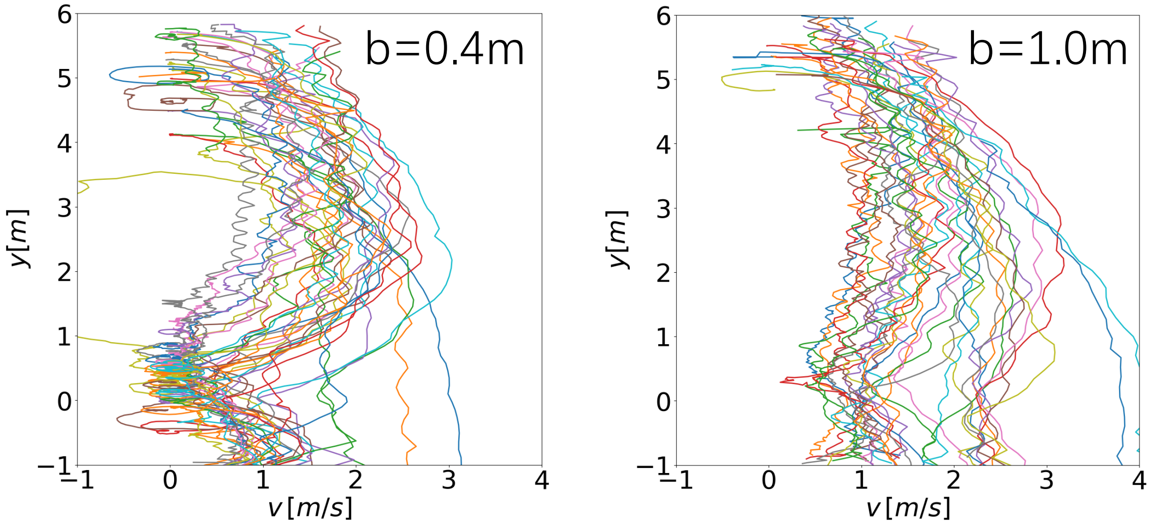

Fig. 5: The evolution of speed over space in different runs.

Even if the speed of each children shows apparent difference over space and time, from Fig. 6 we can see that the total evacuation time decrease linearly with the bottleneck width and then keeps a constant even in the competitive situations. For the given number of evacuees, increase of the width of bottleneck does not always have influence on the total evacuation time, for example the two scenarios with b = 1.0 m and 1.1 m. Especially, the evacuation time for b = 0.7 m is the longest one over all the experiment. That is because several children fall down outside the bottleneck and affect the movement of others behind.

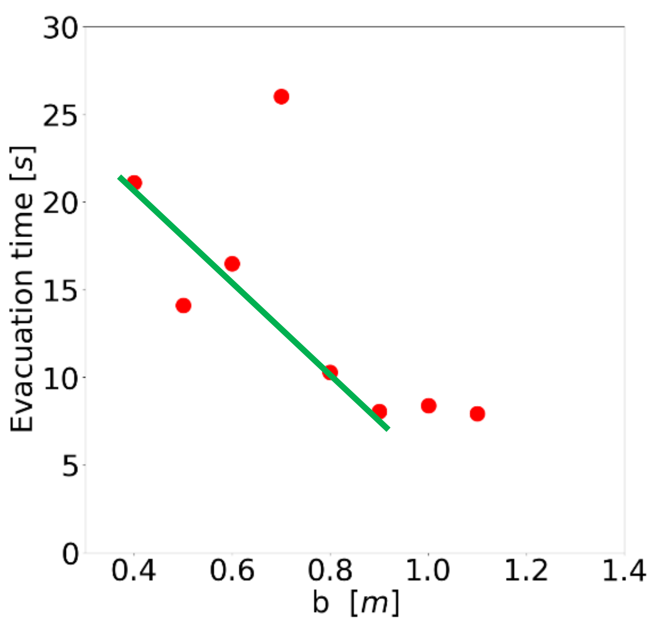

Fig. 6: The relation between the total evacuation time and bottleneck width.

4. Conclusion

In this work, we mainly focus on evacuation characteristics of young children through a bottleneck experimentally. Totally 32 kids with the age of 3-5 years old in a kindergarten participated in 16 runs experiment by changing the width of bottleneck from 0.4 m to 1.1 m at 0.1m intervals. The trajectories of each child are extracted from video recordings by using the software Petrack. The trajectories are relatively smooth when the bottleneck width is larger than 0.8 m, whereas serious oscillations are obvious in narrow bottleneck scenarios. The process of lane formation is not observed in all widths of bottleneck under competitive conditions, which is different from previous studies in normal movement without pushing. From time-space diagram, stop-and-go state is observed. It is found that the first arrive first out principle does not work anymore. The aggressive children will push or pull others to leave earlier. Unlike adults, it is more likely to fall down for preschool children and they are much harder to be controlled during movement. Even in the situation that some children fall down and block the path, the children behind continue moving forward without following the new instructions from outside. The evacuation speed varies over the whole space and shows great dependency on the location in the crowd. The highest individual speed reaches over 3 m/s for the children in front of the crowd. The total evacuation time displays a linear relation with the bottleneck width b for $b < 0.9$ m and then keeps a constant for $b > 0.9$ m. For the given number of evacuees, increasing bottleneck width does not always decrease the evacuation time. However, falling down of children increases the total evacuation time incredibly.

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References

[1] U. NATIONS. (2017). World Population Prospects 2017. Available: https://esa.un.org/unpd/wpp/Download/Standard/Population/

[2] V. Kholshevnikov, D. Samoshin, and A. Parfenenko, "Pre-school and school children building evacuation," in *Proceedings of the Fourth International Symposium on Human Behaviour in Fire*, 2009, pp. 243-254.

[3] I. Zuriguel et al., "Clogging transition of many-particle systems flowing through bottlenecks," *Sci Rep*, vol. 4, p. 7324, Dec 4 2014.

[4] T. Rupprecht, W. Klingsch, and A. Seyfried, "Influence of Geometry Parameters on Pedestrian Flow through Bottleneck," pp. 71-80, 2011.

[5] A. Garcimartin, D. R. Parisi, J. M. Pastor, C. Martin-Gomez, and I. Zuriguel, "Flow of pedestrians through narrow doors with different competitiveness," (in English), *Journal of Statistical Mechanics-Theory and Experiment,* Apr 2016.

[6] W. Liao, A. Seyfried, J. Zhang, M. Boltes, X. Zheng, and Y. Zhao, "Experimental Study on Pedestrian Flow through Wide Bottleneck," *Transportation Research Procedia*, vol. 2, pp. 26-33, 2014.

[7] T. Kretz, A. Grünebohm, and M. Schreckenberg, "Experimental study of pedestrian flow through a bottleneck," *Journal of Statistical Mechanics: Theory and Experiment,* vol. 2006, no. 10, pp. P10014-P10014, 2006.

[8] J. Liddle, A. Seyfried, W. Klingsch, T. Rupprecht, A. Schadschneider, and A. Winkens, "An experimental study of pedestrian congestions: influence of bottleneck width and length," *arXiv preprint arXiv:0911.4350,* 2009.

[9] A. Seyfried and A. Schadschneider, "Empirical Results for Pedestrian Dynamics at Bottlenecks," (in English), *Parallel Processing and Applied Mathematics, Part Ii,* vol. 6068, pp. 575-+, 2010.

[10] A. Seyfried, B. Steffen, A. Winkens, T. Rupprecht, M. Boltes, and W. Klingsch, "Empirical Data for Pedestrian Flow Through Bottlenecks," (in English), *Traffic and Granular Flow '07,* pp. 189-+, 2009.

[11] L. Sun, W. Luo, L. Yao, S. Qiu, and J. Rong, "A comparative study of funnel shape bottlenecks in subway stations," *Transportation Research Part A: Policy and Practice,* vol. 98, pp. 14-27, 2017.

[12] A. Seyfried, O. Passon, B. Steffen, and M. Boltes, "new sights into pedestrian flow through bottlenecks," *Transportation Science,* vol. 43, August 2009.

[13] T. Masuda, K. Nishinari, and A. Schadschneider, "Critical bottleneck size for jamless particle flows in two dimensions," *Phys Rev Lett,* vol. 112, no. 13, p. 138701, Apr 4 2014.

[14] D. Duives, W. Daamen, and S. Hoogendoorn, "Anticipation Behavior Upstream of a Bottleneck," *Transportation Research Procedia,* vol. 2, pp. 43-50, 2014.
[15] W. Daamen and S. Hoogendoorn, "Capacity of doors during evacuation conditions," *Procedia Engineering,* vol. 3, pp. 53-66, 2010.
[16] D. Helbing, I. Farkas, and T. Vicsek, "Simulating dynamical features of escape panic," *Nature,* vol. 407, no. 6803, p. 487, 2000.
[17] H. Oh and J. Park, "Main factor causing "faster-is-slower" phenomenon during evacuation: rodent experiment and simulation," *Sci Rep,* vol. 7, no. 1, p. 13724, Oct 20 2017.
[18] J. M. Pastor et al., "Experimental proof of faster-is-slower in systems of frictional particles flowing through constrictions," *Phys Rev E Stat Nonlin Soft Matter Phys,* vol. 92, no. 6, p. 062817, Dec 2015.
[19] X.-d. Liu, W.-g. Song, and W. Lv, "Empirical Data for Pedestrian Counterflow through Bottlenecks in the Channel," *Transportation Research Procedia,* vol. 2, pp. 34-42, 2014.
[20] A. R. Larusdottir and A. S. Dederichs, "Evacuation of Children: Movement on Stairs and on Horizontal Plane," *Fire Technology,* vol. 48, no. 1, pp. 43-53, 2010.
[21] A. R. Larusdottir and A. S. Dederichs, "Evacuation Dynamics of Children – Walking Speeds, Flows Through Doors in Daycare Centers," pp. 139-147, 2011.
[22] A. Cuesta and S. M. V. Gwynne, "The collection and compilation of school evacuation data for model use," (in English), *Safety Science,* vol. 84, pp. 24-36, Apr 2016.