# Influence of bottleneck on single-file pedestrian flow: Findings from two experiments*

Cheng-Jie Jin(金诚杰)[1,2,†], Rui Jiang(姜锐)[3], and Da-Wei Li(李大韦)[1,2]

[1] *Jiangsu Key Laboratory of Urban ITS, Southeast University of China, Nanjing* 210096, *China*

[2] *Jiangsu Province Collaborative Innovation Center of Modern Urban Traffic Technologies, Nanjing* 210096, *China*

[3] *Key Laboratory of Transport Industry of Big Data Application Technologies for Comprehensive Transport, Ministry of Transport, Beijing Jiaotong University, Beijing* 100044, *China*

(Received 2 March 2020; revised manuscript received 13 April 2020; accepted manuscript online 28 April 2020)

In order to investigate the influence of bottleneck on single-file pedestrian flow, we conduct two different bottleneck experiments. The first one is on ring road, while the second one is on straight route. For the first one, the global density is always set to be 1.5 ped/m. The corresponding critical flow rate for the bottleneck activation is about 0.57 ped/s. The data of the detectors set at different locations, including the velocities and time-headways, show that the amplitude of the oscillation of the stop-and-go waves gradually increases during the upstream propagation. Besides, when the measured flow rates are the same, the different situations in the single-file experiments with and without bottleneck are compared and discussed. For the second one, lower flow rates are used and the bottleneck is always activated. In all the runs, the system can reach one stable state, and the time needed is nearly the same. Inside the stable area, the statistics of pedestrians' velocities keeps nearly constant in both time and space. Outside this area, when the waiting time is not long ($X = 10$ s), the phenomenon observed is similar to that found on ring road, *e.g.*, the statistics of pedestrians' velocities also gradually increases during the upstream propagation. This phenomenon is similar to that found in vehicular traffic flow, which shows the universality of different traffic flows. But when the waiting time becomes longer ($X = 20$ s), this situation will be broken since the actions of many pedestrians become much slower. All these results can facilitate understanding more about the influence of bottleneck on single-file pedestrian flow.

**Keywords:** pedestrian flow, single-file flow, experiment, bottleneck, stop-and-go

**PACS:** 89.40.–a, 45.70.Vn **DOI:** 10.1088/1674-1056/ab8da3

## 1. Introduction

The study of pedestrian flow has a long history.[1–7] Among the many phenomena of pedestrian dynamics, the bottleneck effect is very important. Bottlenecks usually have significant influence on pedestrian flow, often leading to high densities and low velocities and then inevitable congestion. In order to enhance the efficiency of pedestrian movements, the mechanism of bottlenecks needs studying and discussing.

For the study of bottlenecks, both empirical data and controlled experiments are useful, and in this paper we concentrate on the latter case. In recent days, many bottleneck experiments have been done and different findings have been obtained. For example, Helbing *et al.*[8] found that the so-called "obstacles" can stabilize flow patterns and make them more fluid. The zigzag-shaped geometries and columns can also reduce the pressure in panicking crowds. Hoogendoorn and Daamen[9] discussed the microscopic pedestrian behaviors in different bottlenecks. For the narrow bottleneck case two layers are formed, while for the wide bottleneck case four or five layers are formed. The zipper effect causes the capacity of the bottleneck to increase in a stepwise fashion with the width of the bottleneck increasing. Seyfried *et al.*[10] studied the effects of the bottlenecks of different widths. They found that maximal flow values measured at bottlenecks can significantly exceed the maxima of empirical fundamental diagrams. From the experimental results, Liao *et al.*[11] reconfirmed that the specific flow is constant as bottleneck width changes. Moreover, they found the ratio of pedestrian number to bottleneck width can be considered as the criterion to judge the steady states. The critical value is about 1.15 persons/m. Nicolas *et al.*[12] investigated the pedestrian flows through a narrow doorway. They found that the flow rate grew monotonically with the local density increasing up to the situation of "close-packing". According to the experimental results, Dong *et al.*[13] studied the self-organized phenomena of counterflow through a wide bottleneck in a channel, and they found the view field plays a vital role in reproducing these phenomena.

Although the above results are very helpful, we find that most of these studies did not focus on the single-file flow, and the following relationship between preceding pedestrians was seldom mentioned. Actually, in recent days many single-file experiments have been conducted, and lots of findings have been revealed. For example, Seyfried *et al.*[14] did an experiment in Germany, while Chattaraj *et al.*[15] used the same con-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 71801036, 71971056, 71621001, and 11302022) and the Fundamental Research Funds for the Central Universities, China.

†Corresponding author. E-mail: yitaikongtiao@gmail.com

 

figuration and conducted another experiment in India. By the intercultural comparison, they found that the speed of Indians is less dependent on density than that of Germans. The estimated minimum personal space for the Germans is more than that of Indians, which indicates that the jam density for India is higher. In the Yanagisawa *et al.*'s stusy,[16] they found that if the rhythm is slower than normal-walking pace in the low-density regime, the flow can be increased, and the flow-density diagram is convex downward in the high-density regime. Cao *et al.*[17] studied the influence of different age compositions on the pedestrian flow in the single-file experiment. They found that the fundamental diagrams of the three groups are obviously different from each other, and cannot be unified into one diagram. Ma *et al.*[18] and Zeng *et al.*[19] studied the stepping behaviors of pedestrians under different conditions. However, we also found that in none of these experiments other control is used. The situation where there exists bottleneck is not considered. In other words, the influence of bottleneck on single-file flow has not been studied before.

Therefore, in order to remedy the deficiencies, we conduct two bottleneck experiments based on single-file pedestrian flow. The first one is conducted on a ring road, while the second one is on a straight route. An unmanned aerial vehicle (UAV) is used to film the two experiments, and many useful data can be obtained from the UAV video. In both experiments the fixed global density (1.5 ped/m) is adopted, and similar results are found in different tests: the amplitude of the oscillation of the stop-and-go waves gradually increases during the upstream propagation. These results can faciliatate learning more about the influence of bottleneck on single-file pedestrian flow.

The rest of this paper is organized as follows. The setup and the results of the first experiment are introduced in Section 2, while those of the second experiment are discussed in Section 3. The conclusions are drawn in Section 4.

## 2. First bottleneck experiment on ring road

### 2.1. Experimental setups

We did the first bottleneck experiment in the Jiulonghu Campus of Southeast University of China on December 3, 2017. The experiment was conducted on a large square, and we used plastic stools and bars to form the boundaries as shown in Fig. 1. For this narrow ring road, the radii of the inner boundary and the outer boundary were 7.8 m and 8.2 m. Thus the averaged radius for all the pedestrians was 8 m. In order to measure the velocity of each pedestrian, we used a UAV to film the whole experiment. It hovered over the center of the two circles, and the height was about 25 m. The weather was good, and there was nearly no wind during the experiment. Thus the UAV could be stable and the accuracy of data could be ensured. The video is 25 frames per second, and the resolution is $2704 \times 1520$. The microscopic data obtained from the video can be manually extracted by the software named Tracker (http://physlets.org/tracker/).

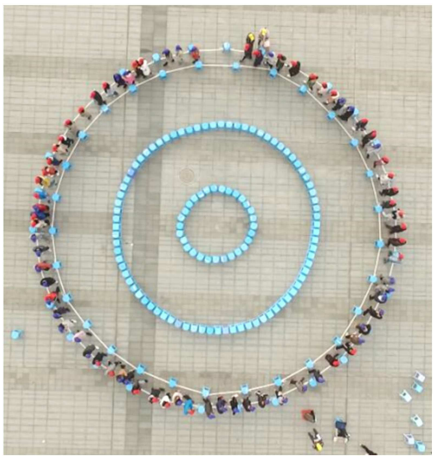

**Fig. 1.** The basic configuration of the first experiment: one snapshot of Run $(6,3)$.

In this experiment, we always used 75 pedestrians (the corresponding linear density is 1.5 ped/m) in all the runs. The reason was that we found that in some empirical data, the averaged linear density for queuing was about 1.8 ped/m. Thus here we chose a density value which is a little smaller than that. At the bottleneck location, we asked one student to control the flow. The parameters were $(X, Y)$, which meant that within $X$ seconds, no more than $Y$ pedestrians could pass through this bottleneck. If the flow was larger than $Y/X$ ped/s, they had to wait as shown in Fig. 1. The details of all the runs in this experiment are shown in Table 1.

**Table 1.** Details of each run in the first experiment.

| Run number | Number of pedestrians | Duration (m:ss) |
|---|---|---|
| (4, 2) | 75 | 4:47 |
| (5, 2) | 75 | 4:31 |
| (5, 3) | 75 | 3:50 |
| (6, 2) | 75 | 3:23 |
| (6, 3) | 75 | 3:40 |
| (7, 4) | 75 | 3:39 |

Note that on the same day, we also used these participants to perform some bi-directional experiments. Thus we asked them to wear the caps in different colors. But in all these bottleneck experiments, both red ones and blue ones were identical. Besides, the other plastic stools with smaller radii were also used for the uni-directional and bi-directional experiments.[20] The discussion on these bi-directional experiments was beyound the scope of this paper.

### 2.2. Experimental results

In this subsection we discuss the results of the first bottleneck experiment. Generally speaking, all the runs can be categorized into two types.

(i) The bottleneck is activated, including Run (6, 2), Run (5, 2), Run (4, 2), and Run (6, 3).

(ii) The bottleneck is NOT activated, including Run (5, 3) and Run (7, 4).

For the type-(i) runs, the queuing of pedestrians can be observed, and the queues do not dissipate until the end. On the contrary, for type-(ii) runs, queues never emerge. The critical situation is found in Run (7, 4) and Run (6, 3), so we can make the conclusion that the critical flow for the bottleneck at $\rho = 1.5$ ped/s is about 0.5 ped/s∼0.57 ped/s.

Firstly, we compare the situations where there exists one bottleneck but there is no control. We take Run (6, 2) for example. It is easy to understand that the averaged flow rate in Run (6, 2) is about 0.33 ped/s, and it keeps nearly constant during the experiment. In our previous paper,[21] we have discussed the results of single-file experiments without bottleneck. Seven different global densities are adopted, including 1, 1.5, 2, 2.5, 3, 3.5, and 4 ped/m. We find that when the fixed global density is 1.5 ped/m (in this paper, we call it Run B for short), the averaged flow rates are much higher than that of Run (6, 2). On the contrary, the results when the fixed global density is 2.5 ped/m (we call it Run D for short) are very close to those of Run (6, 2). This contrast could be clearly seen in Fig. 2 (On the ring road, we choose eight equidistant locations. At each location, we count the number of pedestrians who passed through the cross section during 15 seconds. And then, we calculate the averaged values of the eight results and show the time series in Fig. 2).

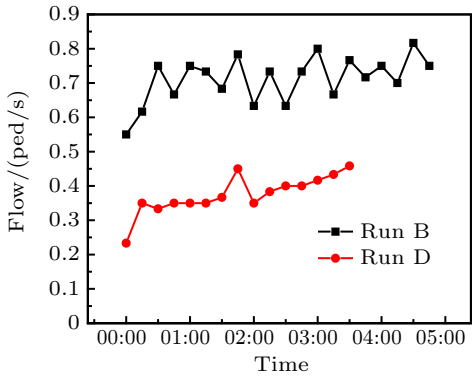


**Fig. 2.** Averaged flow rates in single-file experiments without bottleneck, including Run B with $\rho = 1.5$ ped/m and Run D with $\rho = 2.5$ ped/m.

However, the upstream situations of Run (6, 2) and Run D are quite different. As marked by the yellow lines in Fig. 3(a), when the system becomes stable in Run (6, 2), only about 3/4 circle is occupied by the queue (In Figs. 3(a) and 3(b), we can see some participants sitting on the stools which form the boundaries of the inner ring road. They are having a rest, and preparing for the other following experiments. Their behaviors have no relationship with the bottleneck experiments). Thus the actual density upstream the bottleneck in Run (6, 2) is about 1.9 ped/m. This value equals the measured value found in the empirical pedestrian queues. On the contrary, in Run D the distribution of all the pedestrians is nearly homogeneous as shown in Fig. 3(b), and large space never emerges. The reason is that in the bottleneck experiments, all the pedestrians do not have enough enthusiasm to move fast. If they cannot move forward, they just stop, and never push the preceding ones. Therefore, the maximum queuing density (about 1.9 ped/m) can be always maintained, even if the controlled flow rate is smaller. As a result, here we do not have a fixed flow-density relationship.

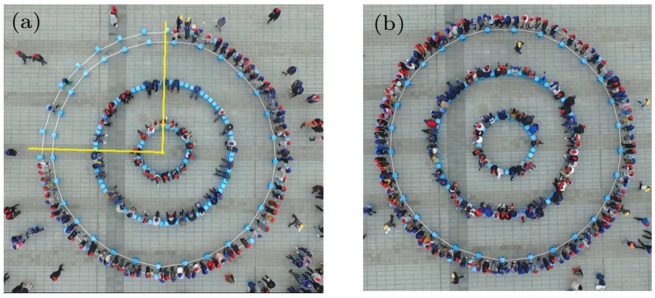


**Fig. 3.** Situation with averaged flow rate of 0.33 ped/s for (a) Run (6,2), and (b) Run D when $\rho = 2.5$ ped/m.

This difference can also be found in the pedestrians' trajectories. For the first experiment, we choose 16 pedestrians in each run, and try to make all the initial distances between them nearly equal (about 22.5°). We use polar coordinates to measure the positions of all the chosen pedestrians. The origin is located in the center of the circle. We collect the position data in intervals of 0.5 s, and then, we show the corresponding angles at all the time instants in Fig. 4. Thus all the values are always between 0°–360°.

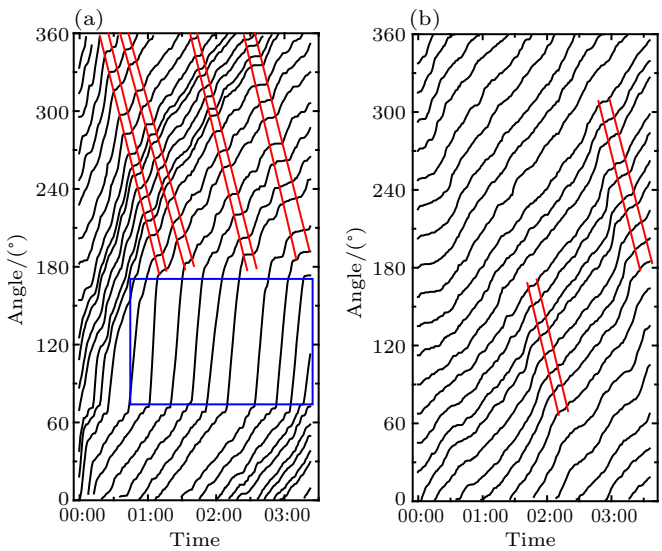


**Fig. 4.** Angular trajectories of 16 typical pedestrians in runs when the flow rate is 0.33 ped/s of (a) Run (6, 2) and (b) Run D when $\rho = 2.5$ ped/m.

As marked by the orange lines in Fig. 4(a), the stop-and-go waves are typical in the bottleneck experiment. Both the time duration and the propagation distance of the stop-and-go waves are quite large. Especially, the effect of the bottleneck can be found in the downstream locations: as marked by the blue rectangle, all the pedestrians can move very fast in this open area (the 1/4 circle in Fig. 3), since the slopes of all the curves are very high. On the contrary, in Fig. 4(b), the stop-and-go phenomenon is not clear. The oscillation of the pedestrians' velocities is not large as shown by the orange lines, when the pedestrians slow down for a short while, they do not completely stop.

Next, in order to check the propagation of induced stop-and-go waves, we set 5 detectors on the ring road, which are marked by 5 yellow circles in Fig. 5. The length of each detector is 1 m, and we can record many data when the pedestrians pass through the detector, including the velocities and time-headways. The yellow line indicates the position of the bottleneck, which is in the middle of Detectors 1 and 5. All the distances between nearby detectors are 10 m.


**Fig. 5.** Positions of 5 detectors in Run (5, 2).

Here we mainly concentrate on the runs when the bottleneck is activated. The statistics of pedestrians' velocities in Run (5, 2) and Run (6, 2) are shown in Fig. 6. Since the queue propagates to detector 1 in neither of the runs, we only present the results of other 4 detectors. It is found that the averaged velocity (AV) and the standard deviation of velocity (SDV) have the similar tendencies. With the stop-and-go waves propagating upstream (5→4→3→2), they gradually increase, showimg the growth of the wave amplitude. Besides, it is clear that the growth of Run (6, 2) is much faster than that of Run (5, 2). And then, the statistics of pedestrians' time-headways is presented in Fig. 7. The 4 averaged time-headways (ATs) are nearly the same, which means that the averaged flow rates do not essentially change at different locations. But the standard deviation of time-headway (SDT) gradually grows, which implies that the averaged time for stopping also increases. Here the growth of Run (6, 2) is also faster, which implies stronger effect of bottleneck on the system.

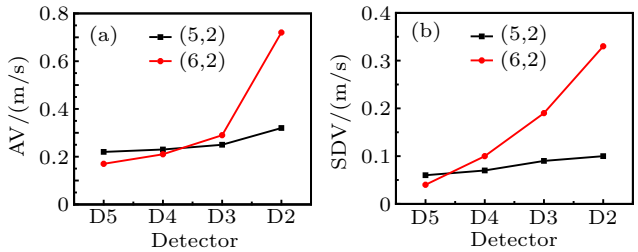


**Fig. 6.** The statistics of velocities in runs of the first experiment, when bottleneck is activated for (a) averaged velocities (AV) and (b) standard deviations of velocities (SDV).

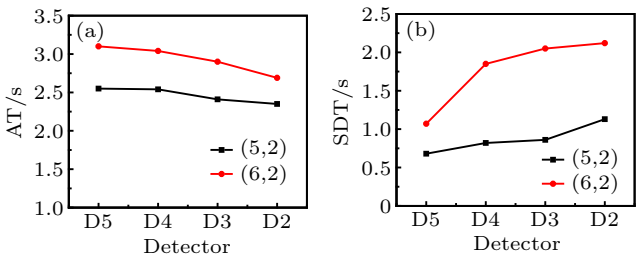


**Fig. 7.** Statistics of time-headways in runs of the first experiment, when bottleneck is activated for (a) averaged time (AT) headways, and (b) standard deviations of time (SDT) headways.

## 3. Second bottleneck experiment on straight route

### 3.1. Experiment setups

The second bottleneck experiment was conducted also in the Jiulonghu campus of Southeast University of China on December 15, 2018. Like the scenario in first experiment, we also conducted the uni- and bi-directional flow experiments on the same day (the ring road surrounded by plastic stools could be seen in the center of Fig. 8). Their results showed no relationship with the bottleneck experiments, which are beyound the scope of this paper. We also used a UAV to file the experiment, and the parameters were just the same. But the basic setup of the second experiment was quite different from that used one year ago: we asked the pedestrians to move on the straight route as shown in Fig. 8(a). This time we used A4 papers to indicate all the scales, and the distance between nearby A4 papers was always 1 m. The total length of this route was 112 m as shown in Fig. 8(b). Thus the positions and linear velocities of pedestrians could be easily measured by the scales on the ground (Note that sometimes the pedestrians' positions were not exactly on the straight line as shown in Fig. 7(b). But we only considered the results projected on the route.). At the same time, some other microscopic results, *e.g.*, the time-headways were still manually extracted by Tracker.

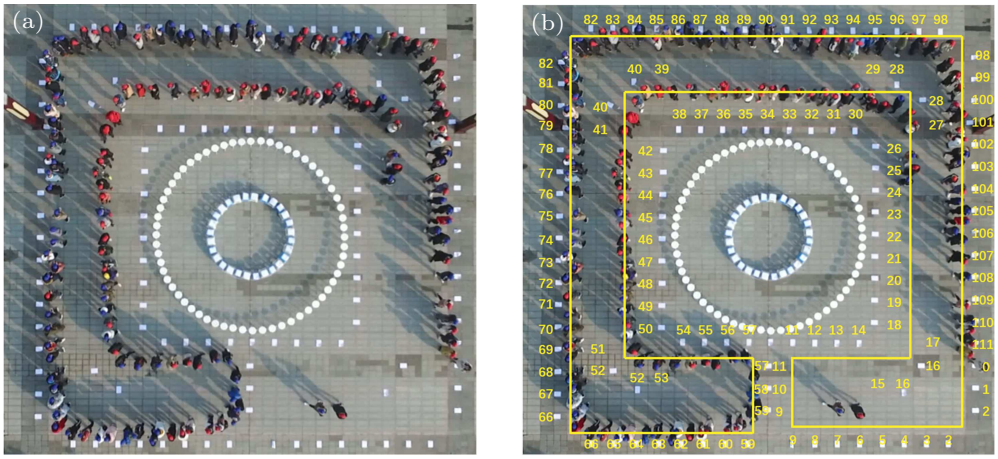


**Fig. 8.** Basic configuration of the second experiment: (a) snapshot of Run (20, 2) and (b) corresponding route and scales on the ground.

**Table 2.** Details of each run in the second experiment.

| Run number | Number of pedestrians | Duration (m:ss) |
|---|---|---|
| (10, 1) | 135 | 7:33 |
| (20, 2) | 154 | 8:33 |
| (10, 2) | 147 | 8:38 |
| (20, 4) | 143 | 4:55[a] |
| (10, 3) | 138 | 8:04 |
| (20, 6) | 136 | 7:31 |

[a]Due to a small technical problem of UAV, we quickly ended Run (20, 4). But the data of this run are still available.

The bottleneck was located at the starting point ($L = 0$ m), which could also be considered as the finishing point ($L = 112$ m). We asked one student to control the flow rate, and the method was just the same as that of the first experiment. This time we set much lower flow rates, in order to make the bottleneck always active, and the parameters are shown in Table 2. Although the pedestrian numbers in each run are not the same, these differences have no influence on the queuing phenomenon nor the statistical results.

### 3.2. Experimental results

In this subsection we discuss the results of the second experiment. Firstly, we show the trajectories of some typical pedestrians in Fig. 9. In each run, we choose one from ten pedestrians. For example, in Run (10, 2) there are 147 pedestrians, so we select 14 ones to show their trajectories, including No. 10, 20, 30, ..., 140. The No. 1 pedestrian is the one who is close to the bottleneck at the beginning.

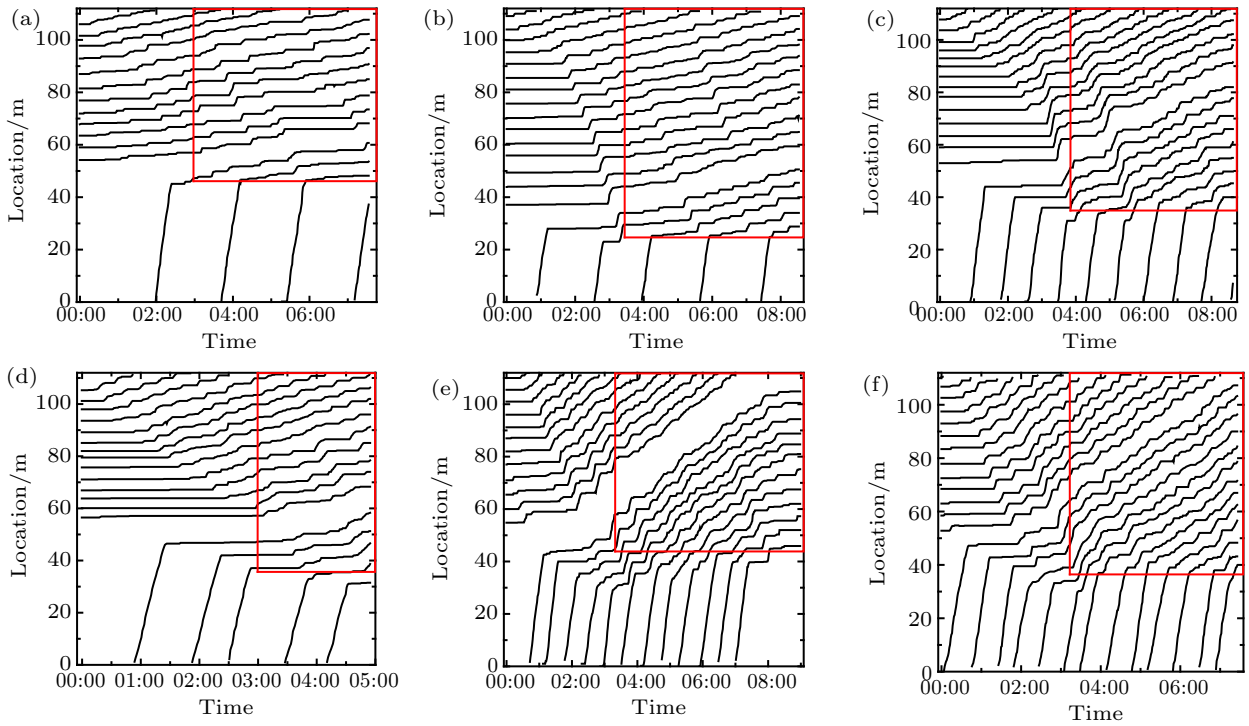


**Fig. 9.** Trajectories of some typical pedestrians in the second experiment for (a) Run (10, 1), (b) Run (20, 2), (c) Run (10, 2), (d) Run (20, 4), (e) Run (10, 3), and (f) Run (20, 6).

Here all the diagrams exhibit similar features, which can be divided into two areas. Area 1 is marked by the red rectangle, in which all the trajectories are similar. For such a situation, the system is relatively stable, which is the main object that we need to further study. The other area belongs to Area 2, which includes the pedestrian movements between the bottleneck and the tail of the queue, and the transient state when the system is not stable (In the first experiment, the system also needs some time to reach the stable state. But the duration is much shorter, since the road is not long). Here we can find that the time for reaching a stable state (the starting instant for the red rectangle) is similar in all the runs: it is about 3:30 to 4:00.

In order to confirm the stability of queuing system, we collect some data in different time intervals and make some comparisons. Run (10, 2) is taken for example. We collect all the pedestrians' velocities at time $T = 360$ s, 370 s, 380 s, ..., 480 s, and show the statistics in Fig. 10. It is clear that the averaged values and standard deviations have similar tendencies: they keep nearly constant. Thus in the following calculations, we arrange all the data in a red rectangle.

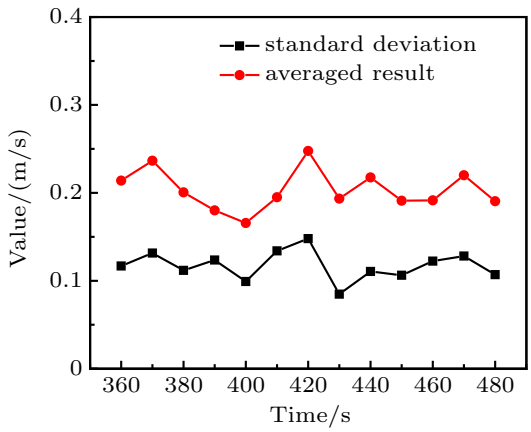


**Fig. 10.** Statistics of all pedestrians' velocities at different time instants in Run (10, 2).

Then we also compare the statistics of pedestrians' velocities and time-headways. Similarly, we choose 5 different locations: $L = 107$ m, 97 m, 87 m, 77 m, and 67 m, and named locations 5, 4, 3, 2, 1. After checking the experimental video, we find that the corners have some influence on the pedestrians' movement. For example, they do not exactly follow the straight route when they turn (see Fig. 8(b)). This causes the measurement of pedestrians' data in these areas not to be very accurate. Therefore, in all the following statistics we do not consider the data in the corners (*e.g.*, at $L = 57$ m and the other upstream locations).

In Figs. 11 and 12, all the data are within the time period marked by the red rectangle in Fig. 8. We only show the results of Run (10, 1), Run (10, 2) and Run (10, 3), since we find the relationship between the results and the locations of detectors is unclear in the other 3 runs when $X = 20$ s. In the runs when $X = 10$ s, both the AV and SDV values gradually increase when the locations become far from the bottleneck. Although the growing amplitudes are different in different runs, the tendencies in Fig. 11 are similar to those in Fig. 6. And in Fig. 12, the AT values also keep nearly unchanged, while the SDT values also gradually increase. Here the growing amplitude of Run (10, 1) is larger, which means that the effect of bottleneck in Run (10, 1) is much stronger. These situations are also similar to those found in Fig. 7.

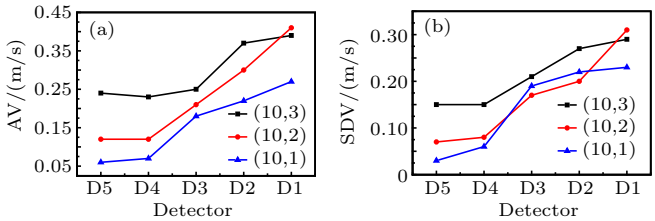


**Fig. 11.** Statistics of velocities in 3 runs of the second experiment, when $X = 10$ s showing (a) averaged velocities, (b) standard deviations of velocities.

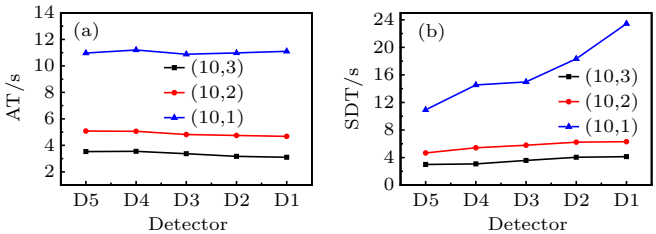


**Fig. 12.** Statistics of time-headways in 3 runs of the second experiment, when $X = 10$ s, showing (a) averaged time-headways and (b) standard deviations of time-headways.

Since we can obtain more accurate data of pedestrians' positions and velocities in the second experiment, it is possible to study the relationship between the pedestrians' velocities and the distance from the bottleneck. For each run, the start time and the end time are marked by the red rectangle in Fig. 9, and the time interval for data collection is 10 s. Here we study the velocities in each 5 m area as shown on the $X$ axis of Figs. 13 and 14. The data in the corners are also excluded, *e.g.*, those of 12 m–17 m and 27 m–32 m. The comparison of results between Figs. 13 and 14 show that the tendencies are similar to those in Fig. 11. When $X = 10$ s, both the averaged velocities and the standard deviations gradually increase with the distance from the bottleneck increasing. Their relationships are nearly linear as shown by the dotted lines in Figs. 13 and 14. In other words, during the upstream propagation, the amplitude of oscillation of pedestrian flow gradually grows. No matter whether the track is straight route or circular road, the growth can always be found. This phenomenon is similar to that observed in vehicular traffic flow. In the single-file flow, it is impossible for the pedestrians to move laterally. Thus the mechanism of pedestrian movement may be similar to that of

vehicles. This also shows the universality of different traffic flows.

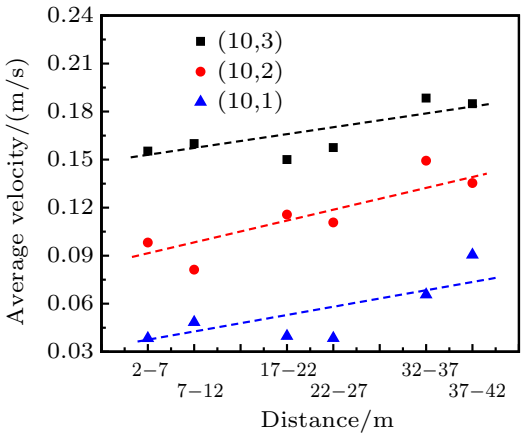


**Fig. 13.** Relationships between averaged velocity and corresponding 5-m area in the second experiment.

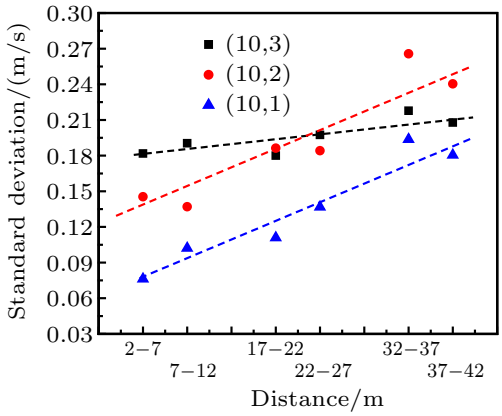


**Fig. 14.** Relationships between standard deviation of velocity and corresponding 5-m area in the second experiment.

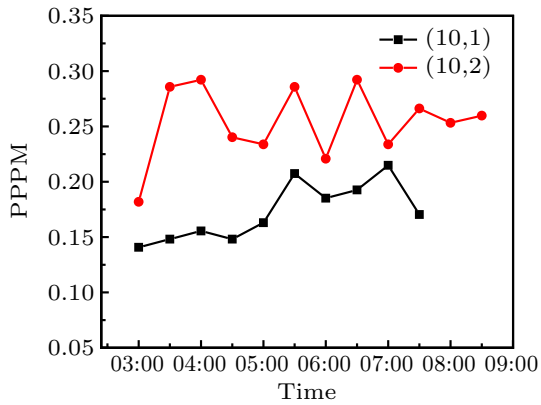


**Fig. 15.** PPPM *versus* time in Run (10, 1) and Run (20, 2) for comparison.

Finally, in order to investigate the reason why different situations occur in the runs when $X = 20$ s , we collect the data of pedestrians who play with mobile phones. As discussed in our previous paper,[22] this phenomenon is frequently observed in the real life, and these data can be considered as an important factor which can show the pedestrian dynamics in different situations. It is easy to understand that the bottleneck experiment is a little boring for the participants. Thus sometimes they try to do something to kill the time, especially when they queue and wait. Here we present the proportions of pedestrians who play with mobile phones (PPPM) in the second experiment as indicated in Fig. 15, and the interval for collecting data is 30 s. It can be found that for the same flow rate (0.1 ped/s), the PPPM values when $X = 20$ s are much larger than when $X = 10$ s. In other words, longer waiting time makes more pedestrians do some irrelevant things, which may lead to longer reaction time. This effect may break the propagation of disturbances.

## 4. Conclusions

In this paper we study the effect of bottleneck on single-file pedestrian flow in a large-scale experiment. Two different types of experiments are conducted and compared.

In the first experiment, circular road is used, and the global density is set to be 1.5 ped/m. For the bottleneck activation, the critical flow rate is about 0.57 ped/s. The data from the five detectors set at different locations, including the pedestrians' velocities and time-headways, show that the amplitude of the oscillation of the stop-and-go waves gradually increases during the upstream propagation. Besides, when the flow rate is the same (*e.g.*, 0.33 ped/s), the different situations in the experiments with and without bottleneck are compared. We find that in the bottleneck experiment, the density upstream of the bottleneck is lower, and never exceeds a maximum value (about 1.9 ped/m). But the stop-and-go phenomenon is much more significant than the situation without bottleneck.

In the second experiment, straight road is used. The lower flow rate is used, thus the bottleneck is always activated. In all the runs, the system can reach a stable state, and the time needed is similar: it is always about 3:30 to 4:00. Inside the stable area, the statistics of pedestrians' velocities keeps nearly constant in time and space. Outside this area, when the waiting time is not long ($X = 10$ s), some similar phenomena are observed, such as the statistics of pedestrians' velocities also gradually increase during the upstream propagation. It means that the different geometry of road does not essentially change the feature of pedestrian movement. Besides, we check the data of pedestrians' velocities in each 5-m area, and we find that both the averaged value and the standard deviation gradually increase with the distance from the bottleneck increasing. This phenomenon is similar to that observed in vehicular traffic flow, which shows the universality of different traffic flows. But when the waiting time becomes longer ($X = 20$ s), these laws will be broken since the actions of many pedestrians become slower. All these results can conduce to learning more about the effect of bottleneck on pedestrian flow.

Although we have obtained some findings from these experiments, there remain lots of work to be done. Due to the limitation of time and funds, there are only 6 runs in each experiment. The data of only 12 runs may be not enough. It is possible to conduct more runs in future experiments, and more densities need considering. Besides, in order to improve the quality of the bottleneck experiment, some technical problems need solving. For example, in the second experiment, the corners of the straight road may have some influences on the pedestrian movement as discussed in Section 4. These influences cannot be easily eliminated in the statistical data. However, if there exists no corner on the route, the length of the experimental road may be too short, and the collected data may be not enough. A possible way is to conduct the experiment of straight road on an even larger square, and two or three UAVs are used for filming the pedestrians' movement at the same time. But whether it is a good idea still needs checking in the future studies.

## Acknowledgement

We are very grateful to Yi-Xiao Zou, Fei Xie, Chen-Yu Zhang, Shao-Yang Qin, Hong-Feng Liang, Rui-Wen Li, Tian-Shu Wang, Ling-Hui Li, Hui-Jie Song, Qi-Qi Zhou and Shi-Han Wang for their help to extract the data from the experimental video.

## References

[1] Papadimitriou E, Yannis G and Golias J 2009 *Transportation Research Part F* **12** 242
[2] Ma W and Yarlagadda P K D V 2015 *Journal of Urban Planning and Development* **141** 04014030
[3] Haghani M and Sarvi M 2018 *Transportation Research Part B* **107** 253
[4] Zarita Z and Lim E A 2012 *Chin. Phys. Lett.* **29** 078901
[5] Li X and Dong L Y 2012 *Chin. Phys. Lett.* **29** 098902
[6] Wang L, *et al*. 2016 *Chin. Phys. B* **25** 118901
[7] Dong H R, *et al*. 2017 *Chin. Phys. B* **26** 098902
[8] Helbing D, Buzna L, Johansson A and Werner T 2005 *Transportation Science* **39** 1
[9] Hoogendoorn S P and Daamen W 2005 *Transportation Science* **39** 147
[10] Seyfried A, *et al.* 2009 *Traffic and Granular Flow* '07, June, 2007, Paris, France, pp. 189–199
[11] Liao, *et al*. 2016 *Physica A* **461** 248
[12] Nicolas A, Bouzat S and Kuperman M N 2017 *Transportation Research Part B* **99** 30
[13] Dong L Y, Lan D K and Li X 2016 *Chin. Phys. B* **25** 098901
[14] Seyfried A, Steffen B, Klingsch W and Boltes M 2005 *Journal of Statistical Mechanics* P10002
[15] Chattaraj U, Seyfried A and Chakroborty P 2009 *Advances in Complex Systems* **12** 393
[16] Yanagisawa D, Tomoeda A and Nishinari K 2012 *Phys. Rev. E* **85** 016111
[17] Cao S, *et al*. 2016 *Phys. Rev. E* **94** 012312
[18] Ma Y, Sun Y Y, Lee E W M and Yuen R K K 2018 *Phys. Rev. E* **98** 062311
[19] Zeng G, Cao S, Liu C and Song W 2018 *Physica A* **500** 237
[20] Jin C J, Jiang R, Wong S C, Xie S, Li D, Guo N and Wang W 2019 *Transportation Research Part C* **109** 137
[21] Jin C J, Jiang R, Li R and Li D 2019 *Physica A* **531** 121718
[22] Jin C J, Jiang R, Wei W, Li D and Guo N 2018 *Physica A* **506** 237