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Research Article

Improvement Strategy at Pedestrian Bottleneck in Subway Stations

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The bottleneck normally refers to a narrowed region that decreases the flow, which is the key limiting factor in the pedestrian flow in the subway station. Due to the confined space, pedestrians are frequently forced to gather together at bottlenecks, which could not only limit the pedestrians' efficiency and comfort but also cause serious crowd catastrophes such as stampedes. Optimization techniques for crowd congestion in subway stations should be investigated. This study proposed and demonstrated a set of optimization methods using conduction field experiments. The effects of passing time, traffic efficiency, speed, and density were explored using different design models. Results showed that optimization methods such as the design with a 45° funnel, broken guardrail, concaves, and column on the left had significant optimal effects. The optimization methods used in this study would help to implement bottlenecks in subway stations and provide design suggestions to subway designers.

1. Introduction

Subways are playing the lead role in public transportation. According to the Ministry of Transport of the People's Republic of China, in 2021, the passenger capacity of the subway in central cities accounted for 38.7% of the total passenger capacity of public transport, 4.7% higher than that of 2020. Especially, the passenger capacity of the subway in Beijing accounted for 57.4% of the total passenger capacity of public transport [1]. Due to the high loading of pedestrian flow, congestion often occurs in infrastructural bottlenecks to reduce the traffic efficiency and pedestrian comfort in subway stations, even causing serious stampede accidents, threatening the lives of pedestrians, for example, elevator accident of Beijing Subway Line 4 on July 5, 2011 [2].

On the condition of the people-centered social context, the safety and feelings of pedestrians in subway station gains attention [3, 4]. Thus, how to make the pedestrian safely and quickly walk through the bottleneck becomes a new task for the management of subway operation, particularly for those subway stations with the regularly large pedestrian flow during rush hour. This study investigated the optimization of pedestrian flow organization and the facility design in urban rail transit.

Studies have characterized pedestrian behaviors through the use of advanced data collection technologies [5, 6]. Except pedestrian behaviors with different individual characteristics were studied [7, 8], the environmental conditions also were discussed, such as different facilities [9–11]. These studies showed that different types of environments in different pedestrian behaviors.

With the rise of infrastructure construction, pedestrian behaviors at bottlenecks have been highlighted. Scholars first studied pedestrian characteristics at bottlenecks, such as speed, density, and so on. Through using a pedestrian behavior model, the mechanisms of panic and jamming at bottlenecks were investigated and some sensible methods to forestall risky crowd pressures from occurring were advised [12]. Seyfried et al. studied the flow characteristics of unidirectional pedestrian streams through bottlenecks, including individual velocities, local densities, time gaps, and so on [13]. Li and Han Proposed a Cellular Automata model to analyze pedestrian behavior through the bottleneck in evacuation. They found both highly conservative and very aggressive behaviors could slow down the speed of evacuations [14]. Handel and Borrmann examined pedestrian service bottlenecks from the view of traditional analytic queuing theory and computational simulation [15]. Luo et al. conducted a series of simulation experiments to explore the pedestrian arching mechanism at bottleneck in subway transit hub [16]. Deng et al. studied the flow of luggage-carrying pedestrians through a bottleneck in both normal and emergency situations [17].

Meanwhile, Scholars have extensively studied the impact of bottleneck length and width on pedestrian flow. For example, Hoogendoorn and Daamen identified the zipper effect at a bottleneck. They found that with the increasing width of the bottleneck to less than 3m, the capacity of the bottleneck was increased in a stepwise fashion [18]. Kretz et al. found the different distribution of time gaps between narrow (one person at a time) and wide bottlenecks (two persons at a time) by analyzing pedestrian experiment data [19]. Wei et al.' research showed that the flow rate increases linearly with the bottleneck width, and pedestrians' behavior has a significant effect on the time headways and their distribution [20]. Through well-controlled laboratory experiments with up to 350 test persons, Liao et al. found a linear dependency is found between the flow and bottleneck width (up to 5 m) [21]. Garcimartín et al. analyzed the pedestrians' flow through narrow doors with different competitiveness [22]. Tang proposed that the probability of an arching and the bottleneck width is an exponential function relationship, so when the stampede occurs in the middle of the bottleneck, the probability of arching will increase exponentially [23]. Wang et al. investigated the influence of door sizes and exit locations on pedestrian crowd flow at bottleneck [24]. Li et al. performed an experiment to compare the movement characteristics of high and low-motivated pedestrians passing through bottlenecks with different widths [25]. Through a modified model, Wang et al. found that the "pass-way" after the bottleneck length has a negative impact on the evacuation performance only in the scenarios that the bottleneck length is not more than 2.0 meters [26].

With an in-depth understanding of pedestrian characteristics at the bottleneck, scholars began to find some improvement strategies at the bottleneck. Helbing and Molnar discussed two instances at the bottleneck, using two doors and using a roundabout, for improving standard elements of pedestrian facilities [27]. They further found that expanding a funnel-shaped space in the bottleneck construction could improve the pedestrian flow [28]. Bolay recommended that a funnel-shaped development could enhance pedestrian passage efficiency at bottlenecks [29]. Sun et al. found funnel shape effectively could improve the traffic efficiency at bottleneck in subway, especially under large volumes [30]. Through numerical models, Parisi and Patterson found an increase in the bottleneck length increases the evacuation time by more than 20%, for any exit position [31]. Luo et al. analyzed efficiency, smoothness, and security to evaluate three optimization measures at bottlenecks in the subway, straight funnel shape, surface funnel shape, and column obstacle [32]. Shi et al. examined the effect of size and location of obstacles near an exit as well as the location of exit on the outflow of individuals, which includes normal walking and slow running conditions [33]. Tavana and Aghabayk studied how funnel-shaped bottlenecks with different angles affect the microscopic and macroscopic properties of pedestrian egress flow [34].

Although the above studies on pedestrian flow provided suggestions to improve pedestrian performance at bottlenecks, a comprehensive and in-depth study on this topic still needs to be carried out. The purpose of this article is to propose an improvement strategy and improve pedestrian performance at bottlenecks. This study used a series of pedestrian experiments to explore the feasibility and effect of optimization methods at bottlenecks, which could improve efficiency, safety, and comfort at the pedestrian bottleneck in subway stations. The research results can provide an important theoretical and practical basis for subway managers. Types of optimization methods were the funnel shape, the extended guardrail, the shape, and the column obstacle. The paper was organized as follows. Section 2 described the controlled pedestrian experiment. Section 3 listed the different pedestrian flow characteristics of the optimization methods at bottlenecks. Section 4 concluded this study and proposed recommendations for future research.

2. Methodology

Due to the enclosure space and the complex environment in subway stations, collecting video data becomes a very difficult task. Additionally, the pedestrian flow and settings at subway bottlenecks cannot be effectively controlled. Hence, the controlled pedestrian experiment, which has clear research targets, is suitable for analyzing optimization methods in all kinds of scene settings. Pedestrian experiments have been widely used in previous pedestrian studies [13, 18–20, 27, 33]. There are some disadvantages of the controlled pedestrian experiment. For example, experimental settings in such experiments are not exactly the same as the real station, which may have an impact on pedestrian movement [32]. However, its advantages prevail. For example, settings in such experiments are controllable, and they are very purpose-oriented, and researchers can change settings more flexibly according to their needs [30]. Therefore, the controlled pedestrian experiments were chosen to be the research method to analyze four optimal designs at bottlenecks in the subway. By handling the experiment video, the pedestrian movement parameters and the rule of the walk were extracted.

2.1. Settings of Experimental Scenes

2.1.1. Fundamentals. The controlled pedestrian experiments were conducted between two teaching buildings in the Beijing University of Technology with ample space and broad vision. The ground was flat, without any slopes or bumps. The ambient environment was in favorable conditions, the illumination there was very stable, no shadows affecting the sight, and the weather was fine. No pedestrian flow resistance existed before the pedestrian flow passed through the bottleneck of the experimental corridor. To analyze the change of positions and speed of pedestrians, a pixel camera with a resolution of $1920 * 1080$ was set up vertically 20 meters above the ground.

2.1.2. Geometrical Layout. Figure 1 displays the coordinates and the experimental site. The width of the corridor was set to be 5 m, which was close to the width of a typical corridor in Beijing subway stations and this setting also helped to observe pedestrian characteristics at the bottlenecks. The width of the bottleneck, the length of the corridor, and the length of the bottleneck were 1 m, 6 m, and 4 m respectively. The region between two lines of corridors (including the bottleneck area) was defined as the trial region. At the wider end of the trial region. There was a defined preparation region with an area of $10\,m^2$ ($2\,m \ * 5\,m$). Pedestrians' walking direction was along the positive direction of the X-axis. Artificial walls were bounded to corridors on two sides of the trial region to prevent pedestrian from looking out of corridors, in turn avoiding the change of the effective width of the bottleneck. The highest participant was 181 cm, which is low than the height of the corridor (200 cm).

2.1.3. Experiment Scenarios. In previous studies, Helbing put forward that a funnel-shaped construction is capable of improving the efficiency of pedestrian flow at bottlenecks [28]. In conventional construction, pedestrians in front of the bottleneck were divided into two directions, causing pedestrian conflicts. The funnel-shaped structure guides the pedestrian flow to avoid pedestrian conflicts, consequently improving efficiency. However, in Helbing's study, the optimal funnel angle was not put out. In Beijing subway stations, an extension of the guardrail before taking escalators is used to remind pedestrians of the bottleneck ahead, as shown in Figure 2. In this way, it makes pedestrians more adaptive to the bottleneck environment by reminding them in advance. Bolay studied a fluid-dynamic traffic model to propose an optimal form called convex, which is an evolutionary optimization [29]. Further, Helbing recommended placing columns asymmetrically in the front of the exit to prevent the fatal buildup pressures by improving the efficiency of pedestrian outflows [12].

Thus, this study presented four optimal designs as shown in Figure 3, which include a design with funnel-shaped, a design with extended guardrails, a design with concave or convex, and a design with column obstacles. The funnel-shaped design was set to be 30°, 45°, and 60°, as shown in Figure 3 to test their optimization. The extended guardrail design included two settings, one was with a continuous guardrail, another one was with a broken guardrail. The obstacle columns were placed in the middle, on the right, or on the left.

According to the TCQSM (Transit Capacity and Quality of Service Manual), the standard capacity for one direction passageway is 5000 person/h/m [35]. In the experimental setting, the mass pedestrian flow rate was 5000 person/h/m (more than 4200 person/h/m. 4200 person/h/m is the cumulative 85% percentage of the rush hour volume at the Guomao subway station, a typical transfer station), which can be used to simulate congestion at the bottleneck. Participants were asked to queue in line in order to control the flow volume. The flow volume is 5000 person/h/m, consequently, there were 7 experiment participants on a row randomly. When given the signal to start the experiment, experimental participants started to walk. Table 1 lists the total 11 scenario configurations.

2.1.4. Experiment Participants and Training. In order to minimize the familiarity, 50 healthy undergraduate students from different classes in departments were the experimental subjects, concluding with 27 males, and 23 females. Their heights range between 160 cm and 181 cm, and the average height was 169 cm. Their ages range from 18 to 25 years old, and the average age was 22 years old. All experimental subjects were required to wear red or blue hats to make it easier for the camera to detect and track.

Before conducting these experiments, the experimental organizer provided an instruction on the rules and purposes of the experiments to the participants. Some important rules are highlighted:

(1) To prevent the participants from obtaining learning behaviors during the trials, in each experimental trial, the participants were randomly queued in front of the yellow start line.

(2) To make sure the pedestrian flow entering the bottleneck is a regular pedestrian flow, the subjects were instructed to the way they do in actual subway stations.

(3) To ensure that the results of these experiments were close to reality, each setting was tested 3 times.

2.2. Validity Analysis of Pedestrian Experiment. The validity of pedestrian experiments has been a controversial topic [30, 32]. Thus, this study evaluated the availability of the experimental scene in the controlled pedestrian experiment. The pedestrian flow in the experiments was compared with the pedestrian flow in actual subway stations. Both subjective (questionnaires) and objective (comparing the walking speed and acceleration of experimental pedestrians to those of actual pedestrians in real subway stations).

Subjective questionnaires were distributed to experimental pedestrians after conducting the experiments. As shown in Figure 4, when it comes to the environment, 13.92%, 36.71%, and 34.18% of the human subjects considered the experimental environment to be very similar, similar, and generally similar to the actual subway environment, respectively. when it comes to the scene, 3.8%, 39.42%, and 92% of the participants thought that pedestrians in the scene and the actual subway scene were very similar, similar, and generally similar, respectively. Regards to the walking speed, more than 92% of the participants thought

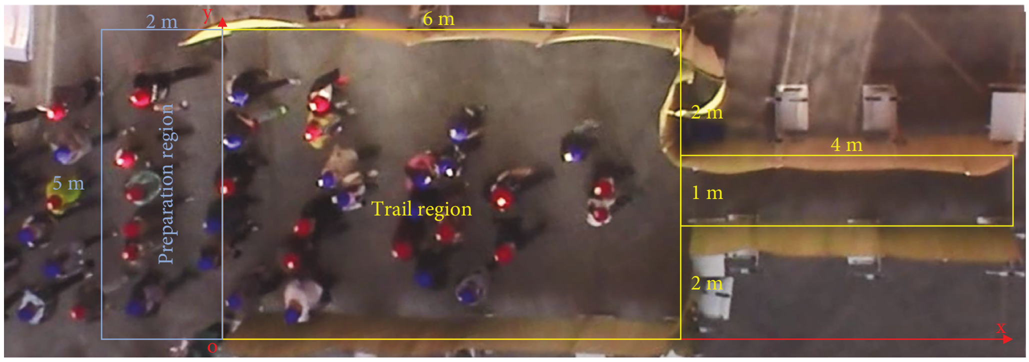

Figure 1: Settings of experimental scene.

Figure 2: The guardrail in front of the escalator in Beijing subway station.

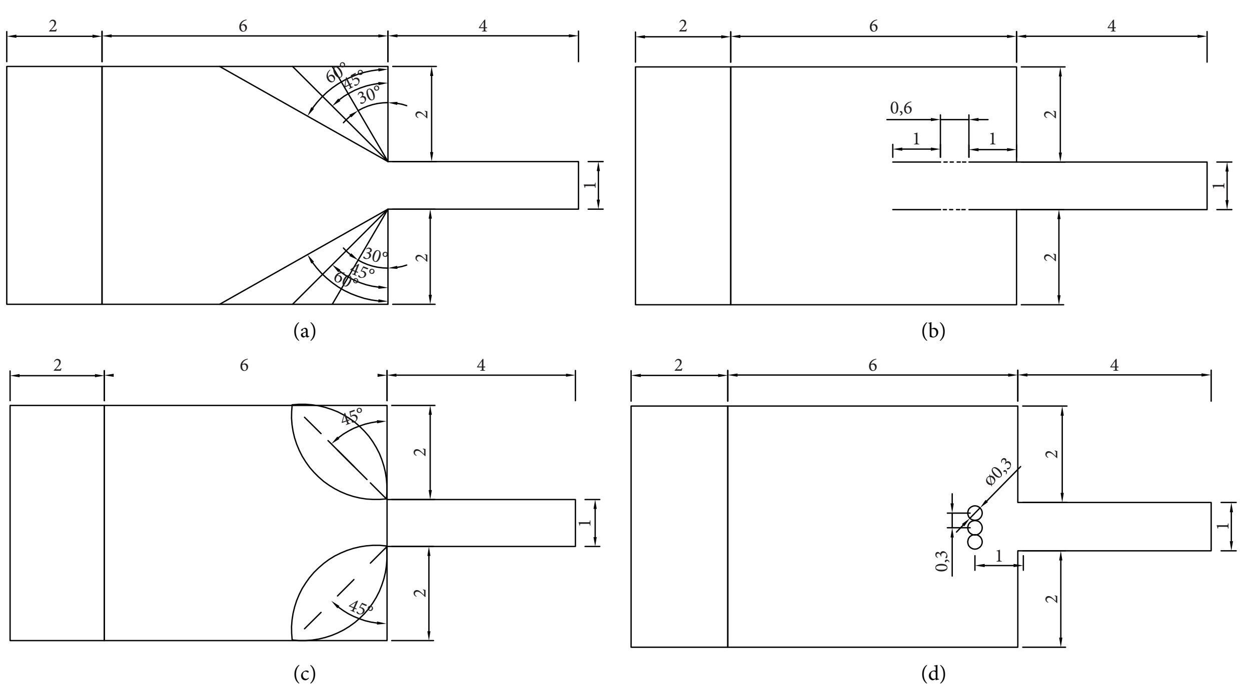

Figure 3: Setting of optimization methods [30, 32]. (a). A design with funnel-shaped (b). A design with extended guardrails (c). A design with concave or convex (d). a design with column obstacles.

Table 1: Experiments scenario configurations.

Optimization methods	Scenario	Settings	Volume (p/h/m)
None (blank control group)	1-1	—	5000
Funnel shape	2-1	30°	5000
	2-2	45°	5000
	2-3	60°	5000
Extended guardrail	3-1	Continuous	5000
	3-2	Broken	5000
Shape	4-1	Concave	5000
	4-2	Convex	5000
Column obstacle	5-1	Column in the middle	5000
	5-2	Column on the right	5000
	5-3	Column on the left	5000

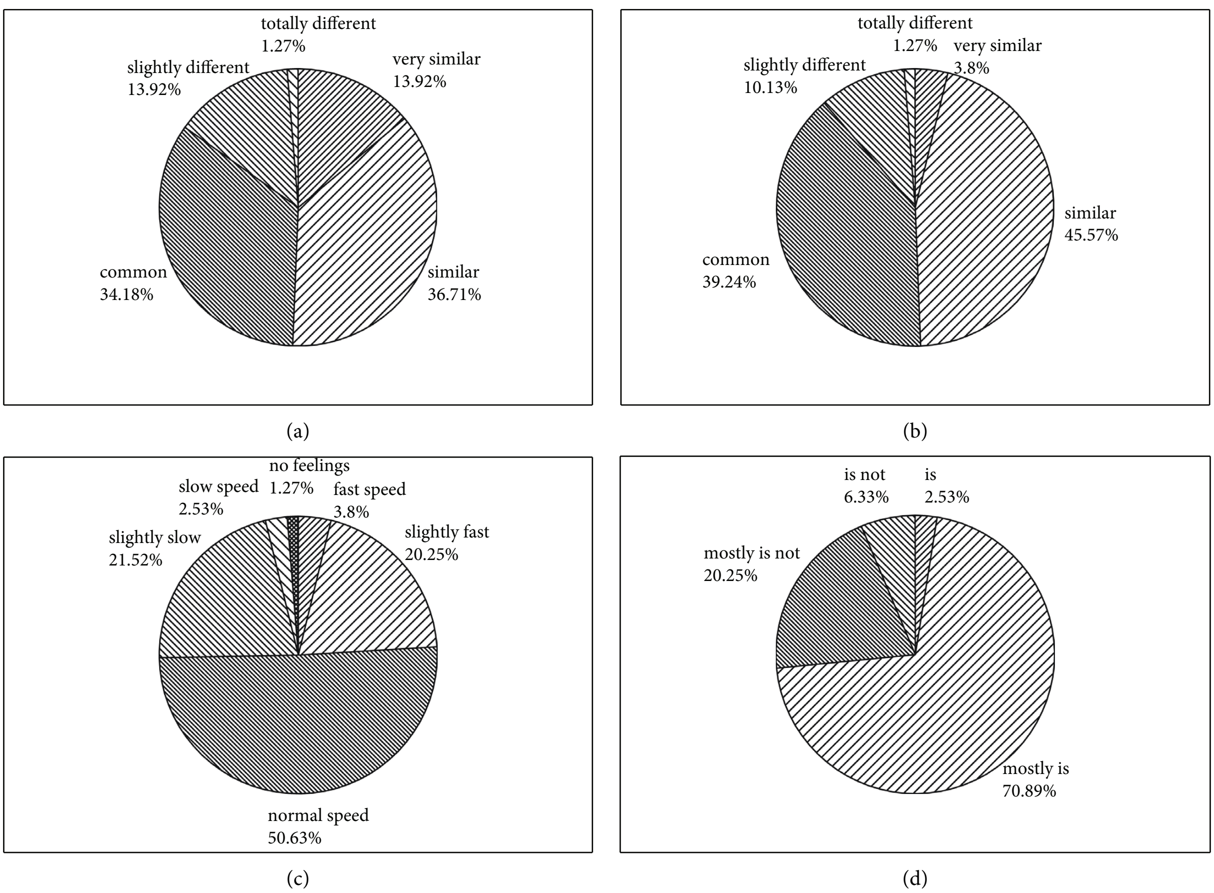

Figure 4: Result analysis of subjective questionnaire. (a). Do you think the experiment environment is similar to the subway (b). Do you think experiment scene is similar to the subway (c). What do you think your walking speed compared with usual (d). Do you see the experiment flow in subway frequently.

that their walking speed in the experiments was the same when they walk in the subway or only slightly different. In concern of pedestrian flow, 73.42% of participants believed that the pedestrian flow in the experiments was often seen in the actual subway environment. In general, the experimental settings were validated by the subjective perceptions of the participants in the experiments.

In addition, pedestrian flow in experimental and real-life environments was compared to each other. The one-way ANOVA was conducted to analyze speed and acceleration of pedestrian flow in the subway and experiment. In significance test results, F speed $(2, 4902) = 1.9023$, $p = 0.15$, F acceleration $(2, 4902) = 0.1169$, $p = 0.88$. In statistical language, $p < 0.05$ represents a significant difference and

$p > 0.05$ represents no significant difference. Thus, the significance test revealed that there was no significant effect on the speed and the acceleration in the two scenarios. This finding demonstrated that the experiments could imitate the actual environment in the subway station. Thus, the experiments were also validated by the objective analysis.

3. Results and Analysis

Pedestrians are most concerned with efficiency, safety, and comfort. According to previous research results, passing time, traffic efficiency, and speed are important parameters to describe the efficiency of the subway [16, 31]; Speed and density are important parameters to describe safety and comfort [36]. Thus, passing time, traffic efficiency, speed, and density are selected to represent the level of efficiency, safety, and comfort.

3.1. Total Passing Time and Individual Passing Time. The total passing time is defined as the total time starting from the first pedestrian entering the trial region to the departure of the last pedestrian from the trial region. It is an overall indicator of pedestrian traffic. The total passing time T is calculated according to.

$$T = t_{nd} - t_{1e}, \tag{1}$$

where t_{1e} represents the time when the first pedestrian entered the trial region, and t_{nd} represents the time when the last pedestrian n departed from the trial region.

The individual passing time represents the total passing time of an individual pedestrian. In this study, it refers to the time starting from a pedestrian entering the trial region to the departure of this individual pedestrian from the trial region. The individual passing time t_i was calculated according to Eq. (2).

$$t_i = t_{id} - t_{ie}, \tag{2}$$

where t_{ie} represents the time when pedestrian i entered the trial region, and t_{id} represents the time when the pedestrian i departed from the trial region.

As shown in Figure 5, the total passing time and the average individual passing time was different under various measures, but both trends were consistent. The four scenarios, funnel of 45° (30.8 s), broken guardrail (30.7 s), concave (30.7 s), and column on the left (30.5), had a minimum of the total passing time. Thus, these four scenarios were recommended at the entrance of the bottleneck. Compared with the blank control group (30.7 s), the guardrail and convex scenarios spent more total passing time, 33.3s and 33.5s respectively. Therefore, the guardrail and convex scenarios were not recommended at the entrance of the bottleneck. The means of the individual passing the time in all measures were lower than the blank control group (16.1 s), especially the broken guardrail (13.2 s) and the concave (13.8 s), 17.87% and 13.95% lower than the blank control group, respectively.

Table 2 shows the statistical summarization of the individual passing time different circumstances, and the rate of mean change compared with the blank control group (1–1). The total passing time and the average individual passing time were different by using different designs, but both trends were synchronous. By using four designs, which were the funnel of 45° (30.8 s), the broken guardrail (30.7 s), the concave (30.7 s), and the column on the left (30.5), the total passing time achieved its minimum. Thus, these four designs were recommended at the entrance of the bottleneck. Compared with the blank control group (30.7 s), the guardrail and convex scenarios spent more total passing time, 33.3s and 33.5s respectively. Therefore, the guardrail and convex scenarios were not recommended at the entrance of bottlenecks. The average of the individual passing the time in all designs was lower than the blank control group (16.1 s), especially the broken guardrail (13.2 s) and the concave (13.8 s), 17.87% and 13.95% lower than the blank control group, respectively.

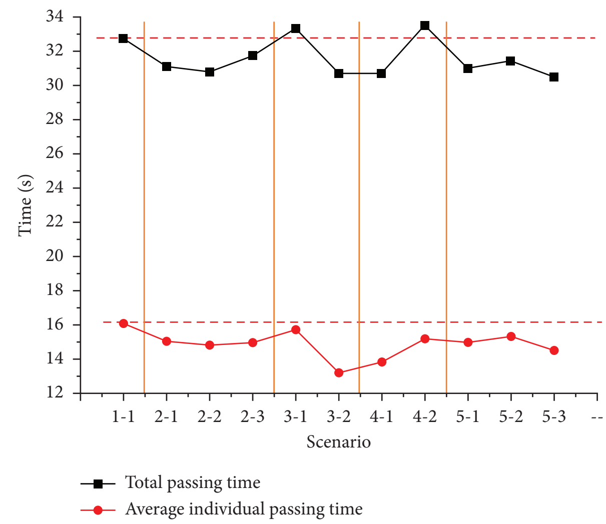

Figure 5: Passing time under different measures.

The mean, medium, and min of individual passing time under different measures all decreased while the max and the standard deviation of individual passing time increased. The broken guardrail had extreme value, changing 17.86%, 11.49%, 5.11%, 22.22%, and 3.52% of the individual passing time of the blank control group, respectively. Standard deviation reflects the degree of dispersion of a data set. The standard deviations of the funnel of 45°, the funnel of 60°, the guardrail, the broken guardrail, and the concave were larger than standard of the blank control group, implying that the distribution of individual passing time is discrete under these optimization methods. To sum up, the measures had an impact on the passing time. The optimal effects of the broken guardrail and the column on the left were the most obvious.

3.2. Traffic Efficiency at Exit. The traffic efficiency of pedestrian flow is defined as the number of people within a unit width during a time interval, which can reflect the condition of space utilization. Analysis of pedestrian flow at the exit of the bottleneck could evaluate the pedestrians' passing

Table 2: Experiments scenario configurations.

Angle of funnel (°)	Mean (s)	Medium (s)	Max (s)	Min (s)	Std.	Rate of mean change
None (1-1)	16.071	14.800	23.500	6.300	5.277	
Funnel of 30° (2-1)	15.040	16.000	25.800	5.800	5.865	-6.42%
Funnel of 45° (2-2)	14.807	15.200	23.500	5.800	5.151	-7.87%
Funnel of 60° (2–3)	14.947	15.800	24.900	5.600	5.149	-6.99%
Guardrail (3-1)	15.693	15.200	23.700	5.000	5.711	-2.35%
Broken guardrail (3-2)	13.200	13.100	22.300	4.900	5.091	-17.86%
Concave (4-1)	13.829	13.500	22.800	5.300	5.188	-13.95%
Convex (4–2)	15.209	15.500	25.200	5.500	6.085	-5.36%
Column in the middle (5-1)	14.953	15.300	23.800	5.600	5.313	-6.96%
Column on the right (5-2)	15.304	14.900	24.600	5.700	5.325	-4.77%
Column on the left (5-3)	14.511	14.900	23.200	5.700	5.386	-9.71%

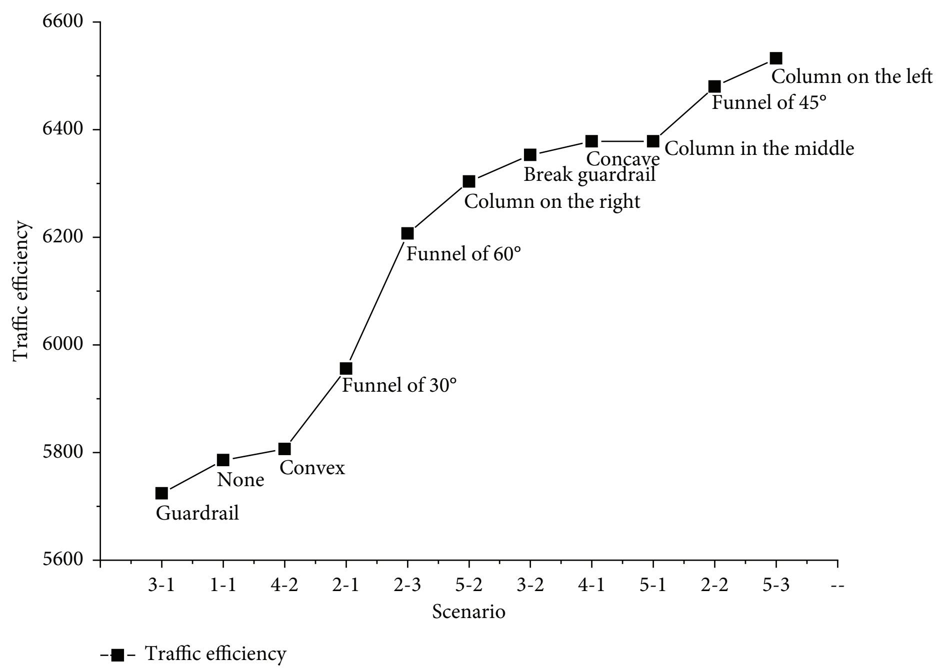

Figure 6: Traffic efficiency under different measures.

situation while they were passing the bottleneck region. The efficiency can be calculated by using (3):

$$E = \frac{3600}{T} * \frac{n}{w} = \frac{3600}{t_{n\,d} - t_{1e}} * \frac{n}{w}, \quad (3)$$

where E represents the traffic efficiency of the pedestrian flow at exit (p/h/m), T represents the passing time of the whole pedestrian flow across the exit (s), n represents the total number of experimental pedestrians, w represents the width of the exit (m), $t_{nd}\mathrm{t}_{\mathrm{nd}}$ represents the time when pedestrian n departed from the trial region (s), and t_{1e} represents the time when the first pedestrian departed from the trial region (s).

In Figure 6, designs with column on the left, the funnel of 45°, the columns in the middle, the concave, and the broken guardrail are very effective designs. The traffic efficiency increased by 12.90%, 12.00%, 10.24%, 10.24%, and 9.80%, respectively, compared with the blank control group. If the traffic efficiency increased 10% at a bottleneck in the subway, it would significantly reduce congestion during rush hours. The design of guardrail made the traffic efficiency decrease by 1.06%. Therefore, it is suggested that subway stations should abolish the existing guardrail at the entrance of bottlenecks and turn to other designs to improve efficiency.

3.3. Speed. Speed is defined as the walking distance during a unit of time (m/s), which is one of the main parameters describing pedestrian flow [37, 38]. The time mean speed, which better described the microcosmic characteristic than space mean speed did, was calculated according to (4):

$$v_i(t) = \frac{w_i(t)}{T_0}, \quad (4)$$

where $v_i(t)$ refers to the time mean speed of pedestrian i within the duration of t (m/s), $w_i(t)$ refers to the walking

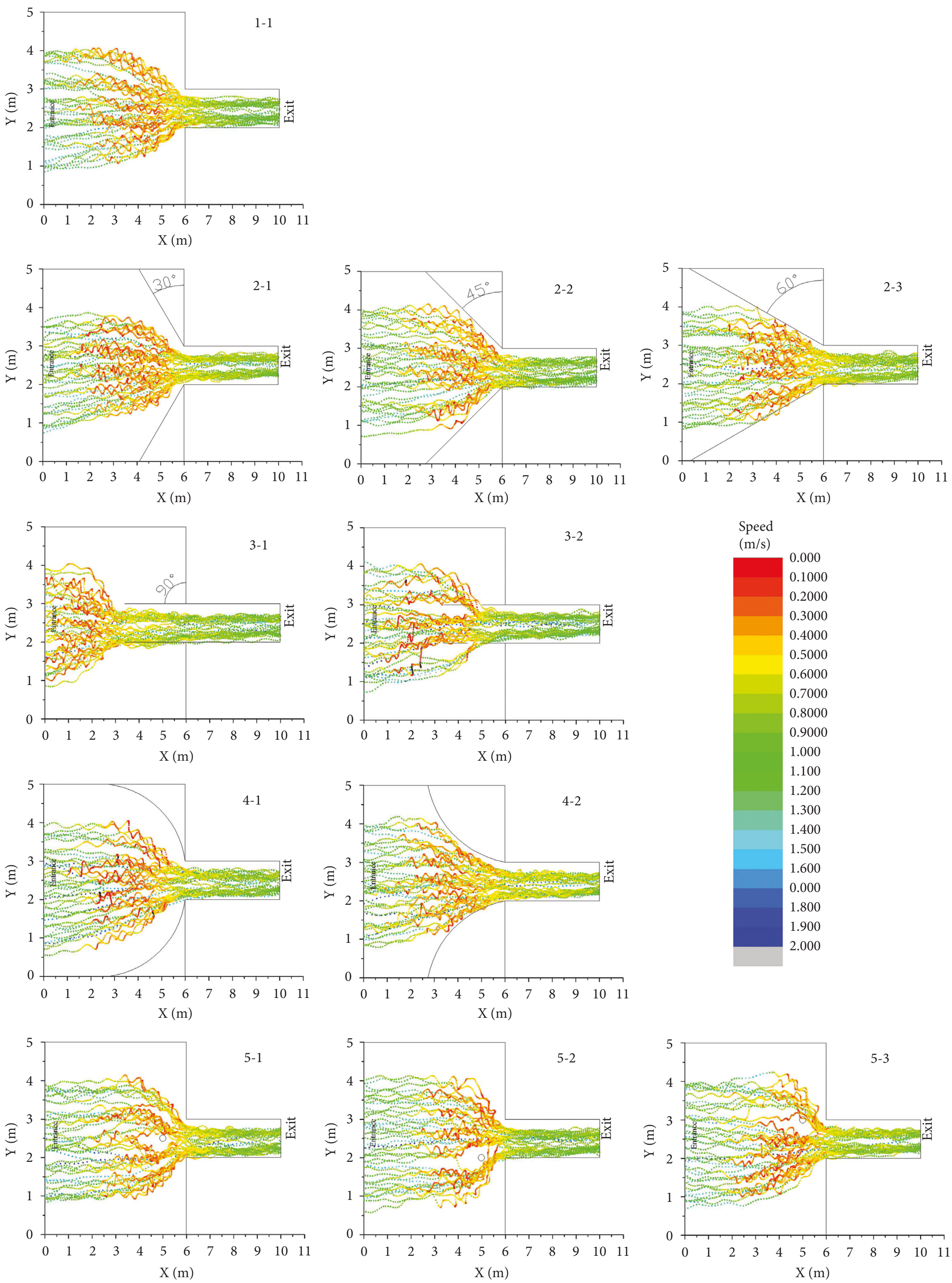

Figure 7: Map of pedestrian track and speed under different measures.

Table 3: Descriptive statistics of speed under different measures.

Angle of funnel (°)	Mean (s)	Medium (s)	Max (s)	Min (s)	Std.	Rate of mean change
None (1-1)	0.596	0.452	1.677	0.086	0.353	
Funnel of 30° (2-1)	0.606	0.422	1.948	0.011	0.361	1.68%
Funnel of 45° (2–2)	0.619	0.498	1.890	0.000	0.359	3.86%
Funnel of 60° (2-3)	0.603	0.490	1.906	0.008	0.346	1.17%
Guardrail (3-1)	0.594	0.521	2.671	0.021	0.359	-0.34%
Broken guardrail (3–2)	0.777	0.761	2.292	0.030	0.396	30.37%
Concave (4-1)	0.744	0.725	2.008	0.023	0.375	24.83%
Convex (4-2)	0.684	0.622	2.666	0.015	0.358	14.77%
Column in the middle (5-1)	0.693	0.656	2.030	0.045	0.345	16.28%
Column on the right (5-2)	0.691	0.671	1.907	0.000	0.359	15.94%
Column on the left (5-3)	0.718	0.719	1.942	0.026	0.370	20.47%

distance of pedestrian i within the duration of t (m), and T_0 was the time interval (0.1 s in this study).

The instantaneous velocity was reprocessed to be trajectory diagram, in which colors are used to indicate the walking speed of pedestrians. From red to dark blue, the speed increases progressively. As shown in Figure 7, the distribution of pedestrian speed varies by using different designs at the bottleneck. For the funnel-shaped design, the amount of high-speed dots (represented by green or blue dots) in the 45° funnel and the 60° funnel was more than that of the 30° funnel. For the extended guardrail design, the amount of the low-speed dots (represented by red dots) in the guardrail was more than the broken guardrail. For the design with concave or convex, the amount of the low-speed dots (red) in the concave was more than in the convex, but at the bottleneck corridor, the amount of the high-speed dots (green) in the concave situation is more than in the convex situation. For the obstacle column design, the amount of the low-speed (red) in the middle column situation or the left column situation was more than in the right column situation.

By using quantitative analysis, Table 3 gathers statistics of pedestrians' walking speed and the rate of mean change compared with the blank control group (1–1). The mean, medium, and maximum of speeds all changed to some extent after applying optimal designs, comparing with the blank control groups. The mean of speed increased by applying different measures, except in the guardrail situation. The maximum speed also increased by using different designs. The minimum of speed decreased by applying all different measures. The standard deviation of all optimization designs increased expect the funnel of 60° and column in the middle, compared with the blank control groups. The results showed that the optimization methods, especially the broken guardrail, had a significant impact on improving pedestrians' walking speed.

3.4. Density. Density refers to the ratio of the number of pedestrians to the area of the experimental site, expressed as the number of people per square meter (per/m^2) [39]. The cumulative density of the observed areas is derived from dividing the number of pedestrians by the areas within the total time. In this paper, cumulative density is calculated according to equation 5

$$D_{xy} = \frac{N_{xy}}{S_{xy}} = \frac{\int_{t_0}^{t} N_t \mathrm{d}t}{\int\int_{x_1 y} \mathrm{d}x\mathrm{d}y}, \quad (5)$$

where D_{xy} represents the cumulated density of x^*y area, N_{xy} represents the number of the pedestrians in the x^*y area within the whole time, S_{xy} represents the area of the x^*y, t_0 represents the start time, t represents the end time, N_t represents the number of the pedestrians in the.area at a random time point t, and are the coordinates.

Figure 8 presents the cumulative density diagram, in which x and y are the coordinates, color shows the magnitude of the cumulative density. From dark blue to red, the cumulative density increases progressively. And the cumulative density bigger than 100 $p/(0.5\,\mathrm{m}^*0.2\,\mathrm{m})$, is regarded as cumulative high density. In the blank control group, the high cumulative density occurred on both sides of the entrance of the bottleneck, while the distribution of the high cumulative density area changed after applying the optimization methods. For the funnel shape, the 30° funnel had widespread high cumulative density, even spread to the bottleneck corridor. The area range of high cumulative density in the 45° funnel was very small. The area range of high cumulative density in the 60° funnel was still concentrated on both sides of the entrance of the bottleneck but was smaller than the blank control group. For the extended guardrail, the area range of high cumulative density was very small, about 0.2 m^2, especially in the broken guardrail. For the concave and convex design, the area range of high cumulative density in concave was very small, about 0.1 m^2. Meantime, the area range of high cumulative density in convex was comparatively large, about 0.2 m^2. For the obstacle column, the area range of high cumulative density still existed, but not so concentrated, but with a uniform distribution. The area range of high cumulative density in column on the right situation was close to 0, and maybe it was related to the low walking speed and the low traffic efficiency by using this design.

3.5. Discussion. Previous research has shown that the funnel shape design could enhance pedestrian passage efficiency at bottlenecks [28, 30, 32, 34], which is consistent with the research conclusion of this paper. This paper further found that the walking efficiency firstly increased progressively as

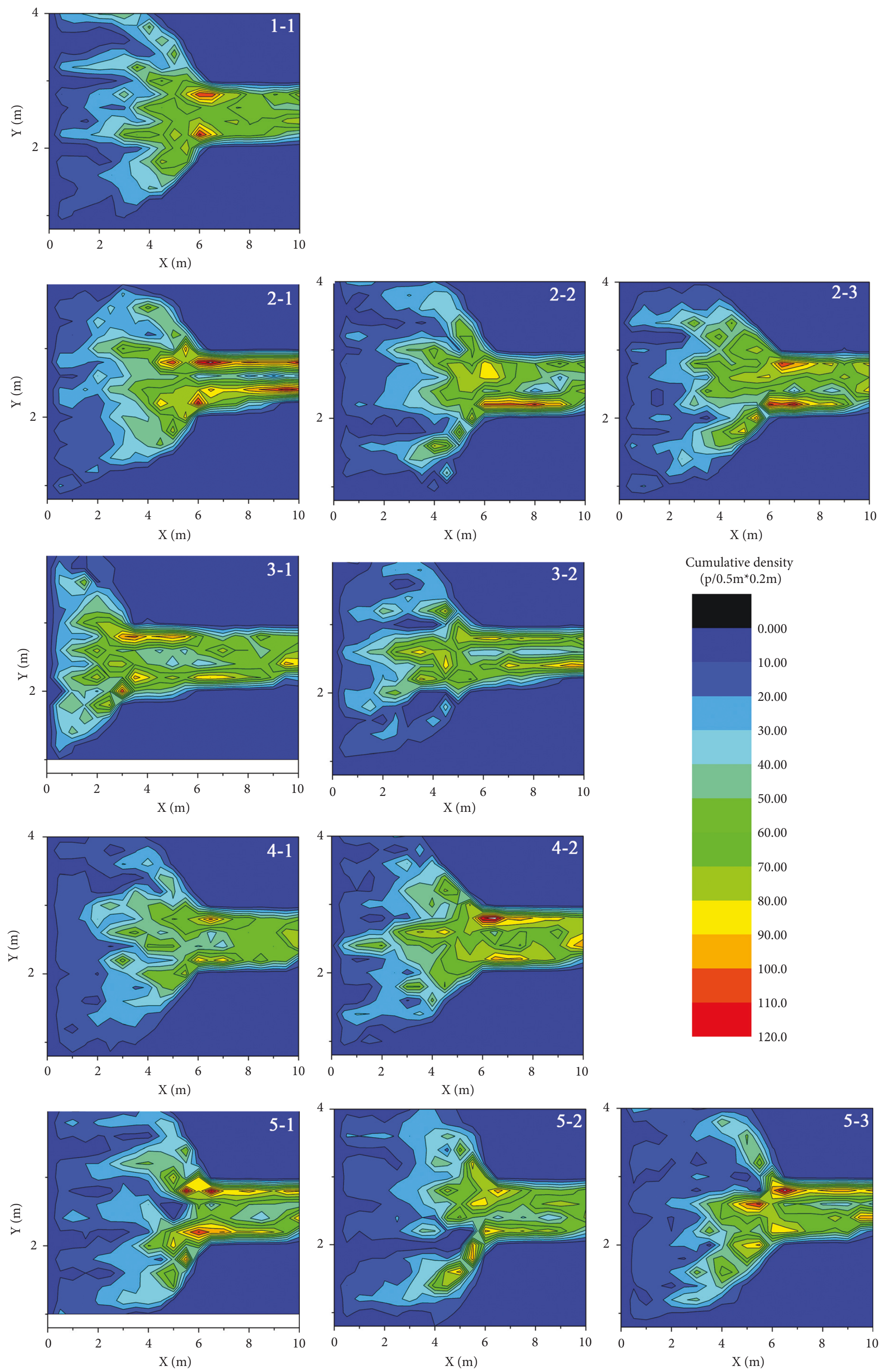

Figure 8: Cumulative density diagram under different measures.

the increase of angle, after reaching a critical point, it started to decrease. The best funnel angle was between 30° and 60°. Moreover, some scholars found setting an obstacle near an exit is effectively improving pedestrian evacuation and has a different performance at middle and corner exits [32, 33]. In this study, one new finding is setting obstacles on the left achieved a higher pedestrian walking efficiency than setting other settings did. Besides, there are two other important and new findings: The convex shape was less efficient in optimization than the concave shape; The extended guardrail was not an effective measure to reduce pedestrian congestion. The subway management can set different improvement strategies according to the actual situation at different bottlenecks.

4. Conclusions

This study conducted pedestrian experiments to investigate various optimization methods at the bottlenecks to solve pedestrian congestion and potential risk problems in the Beijing subway. The experimental results showed that when applying the funnel shape design, the walking efficiency firstly increased progressively as the increase of the angle, and after reaching a critical point, it started to decrease. The best funnel angle was between 30° and 60°. Moreover, the effects of the guardrail and the broken guardrail were significantly different. The broken guardrail had positive effects, and the guardrail had adverse effects, that is to say, the extended guardrail was not an effective measure to reduce pedestrian congestion. Besides, the shape of the surface had an effect on pedestrian walking efficiency. The convex shape was less efficient in optimization than the concave shape. Lastly, the location of obstacle had an impact on the pedestrian walking efficiency. Setting obstacle on the left achieved a higher pedestrian walking efficiency than setting other settings did.

Research results can provide management and design recommendations for subway managers. It should be pointed out that this study only considers one flow volume, which is not enough. In fact, there are varies pedestrian volume in the subway. Future studies will consider more pedestrian volume and a more complex bottleneck. Advanced simulations will be applied to the study of the overall performance model of bottlenecks.

Data Availability

The data used to support the findings of this study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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