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Research Article

Dynamic Guidance Strategy for Pedestrian Travel in Large-Scale Activity under Harsh Environment

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Large-scale activities such as the Winter Olympics are usually held in areas with low temperature or other harsh environments, which greatly affects the spectating experience of pedestrians. In order to improve the travel efficiency and reduce the safety risk of pedestrians, an adaptive information-distribution strategy of VMS (variable message sign) for road networks is proposed to guide the pedestrians. In the proposed strategy, the dynamic feedback mechanism between the VMS information distribution and the state of crowded pedestrians is established, and the dynamic optimization model of the VMS information release layout is formulated. To evaluate the effectiveness of the strategy, a multiagent-based simulation method is proposed. Through numerical simulation, it is found that the guidance strategy can improve the movement efficiency by adjusting releasing duration of VMS information or improving the information obedience rate of pedestrians. In this paper, a large-scale competition area in the Xiaohaituo Mountain in Beijing was taken as an example to simulate the scenarios of ingress and egress with and without the strategy. The results show that the average walking time and the road congestion can be significantly reduced in the road network with the strategy, and the proportion of pedestrians with shorter travel time can be increased. Therefore, the research can provide theoretical foundation and data support for managers to guide passenger flows and improve the spectating experience.

1. Introduction

Some large-scale activities, for example, the Winter Olympics, are usually accompanied by harsh environments such as low temperature, windy, rugged, or snowy mountain roads, and so on. The environments have a great impact on the pedestrians traveling. At the same time, the passenger flow of large-scale activities has the characteristics of strong short-term aggregation and uneven spatiotemporal distribution. Especially during the peak hours of ingress and egress, congestion is more likely to occur in the road network. If the pedestrians stay in the environment for a long time, it will seriously affect their spectating experience and even cause safety incidents such as frostbite and trampling. Some research studies show that the guidance information issued by the VMSs (variable message signs) can effectively alleviate congestion problems under various traffic conditions [1–3], thereby improving the traffic capacity of the road network. Therefore, the use of VMSs to provide pedestrians with guidance information, such as passenger flow state in the road network, emergencies, travel guidance, and so on, has become an effective means for managers to control passenger flow. This can effectively improve the travel efficiency and reduce the impact of harsh environments [4, 5].

The location layout and information release of the VMSs affect the evacuation capacity of the road network, and the effect varies with different scenarios. At present, many scholars have carried out some research studies on the problem, and the works are mostly focused on the crowded scenes. Based on the queuing model, Jeihani et al. [6] studied the effect of VMS information in a crowded traffic flow environment and compared the route choice behavior of drivers under different traffic conditions. The research shows that the driver can effectively change the route according to the VMS information prompt. For the setting of VMSs in the road network, the optimal layout of VMS locations can be achieved by rational optimization model. Ji and Qin [7] proposed a two-level planning model for VMS locations in crowded scenarios. With the model, the smallest risk decision and the largest induced benefit can be achieved. The research shows that the random demand of travelers and the risk preference of decision makers have a significant impact on the locations of VMSs. Guo et al. [8] established a VMS location optimization model for a complex transport network with the object of maximizing the actual induction utility. With the model, overall induction efficiency of the network in a crowded environment can be improved. Of course, the individual characteristics of pedestrians will also affect the inducing effect of VMS information. Wu and Liang [9] found that drivers with different personalities have different compliance rates for the VMS information. In order to improve the efficiency of VMS information guidance, they established a VMS location deployment model based on information service satisfaction.

In addition to the locations, the information content and the information release duration of the VMSs also have a greater impact on travelers' decision making. Lam et al. [10] proposed an allocation model of VMSs in road network considering travel time by analyzing the current state of traffic congestion in Hong Kong. With the model, the VMSs releasing the relevant travel time can be deployed at the optimal locations to assist travelers selecting travel routes. The research shows that the information release of VMSs in crowded roads makes the evacuation effect more significant. Subsequently, inspired by Lam, Li et al. [11] discussed the impact of VMSs displaying queue length information on travelers' routes selection in the scenario of repeated congestion in the road network. By improving the stochastic network equilibrium model, they determined the deployment locations and information release time of VMSs. Zhou et al. [12] developed a data mining method to explore the effectiveness of information types of VMSs on congestion alleviation. Through the analysis of road network in Beijing with the method, they found that the guidance information provided by VMSs is more effective than the notification information for alleviating traffic congestion.

Compared with information services for travelers in general scenarios, VMS information guidance strategies in special scenarios such as severe weather and emergencies are of great significance for travelers' safety and efficient evacuation. In terms of severe weather, Zhao et al. [13] studied the impact of VMS information content on travelers' decision making under foggy condition. Research shows that travelers prefer guidance information such as delay time and route guidance information in foggy condition. In terms of emergencies, Huynh et al. [14] proposed a location optimization method for the VMSs in the emergency road network based on a heuristic algorithm. The method can effectively guide the passengers to other alternate routes and achieve the evacuation of passengers. Chili and Huynh [15] improved the tabu search algorithm to determine the best locations and number of VMSs in the road network under traffic accidents and discussed the interaction between the number and locations of the VMSs and the road network structure. With the method, the locations of VMSs in the local road network in Texas were calculated to verify the effectiveness. Xuan and Kanafani [16] discussed the impact of setting up VMSs on the accident-prone roads on the route choice of travelers. Research shows that the accident information released by VMSs has a significant effect on path diversion. Yin et al. [17] established a two-level planning model to study the content and locations of VMS information release under the condition of public transport interruption. They proposed a "one station, one plan" information release strategy. With the strategy, the Beijing public transport was taken as an example to explore the effectiveness.

As can be seen, at present, there are more works focused on the travel problems in general conditions other than severe environments, and the information release layout of VMSs in road network is usually fixed. The strategy of VMS information release is difficult to adapt to the dynamic changes of the passenger flow in road network under harsh environments. So, the travel guidance is difficult to achieve the best. Therefore, for the pedestrians traveling in the large-scale activity area in harsh environments, an adaptive information release strategy of VMSs is proposed in the paper. With the strategy, the crowded pedestrians can be effectively guided, so as to realize the effective guidance of passenger flow.

The content of the paper is organized as follows. Section 2 describes the releasing strategy of VMS information. The strategy mainly consists of three parts: (1) interactive feedback between information and passenger flow; (2) releasing layout optimization of VMS information; and (3) releasing rules of VMS information. In Section 3, the method of scenario simulation for the strategy based on multiple agents is proposed. With the method, the impact of key parameters of the strategy on traveling is analyzed with the numerical calculation in Section 4. Section 5 discusses the application of the strategy in a real case. Conclusions are given in Section 6.

2. Releasing Strategy of VMS Information

2.1. Interactive Feedback with Passenger Flow State. The release of VMS information and the state of passenger flow can form a benign interactive feedback, and the feedback can provide support for realizing the guidance and travel guarantee for pedestrians in harsh environment. The information about passenger flow congestion level can be released dynamically by VMSs in the large-scale activities. On the one hand, the pedestrians can make better travel decisions according to the information so that the road congestion can be reduced and the travel efficiency can be improved. On the other hand, the information content in the VMSs and the road sections chosen to release the information can be dynamically adjusted according to the current

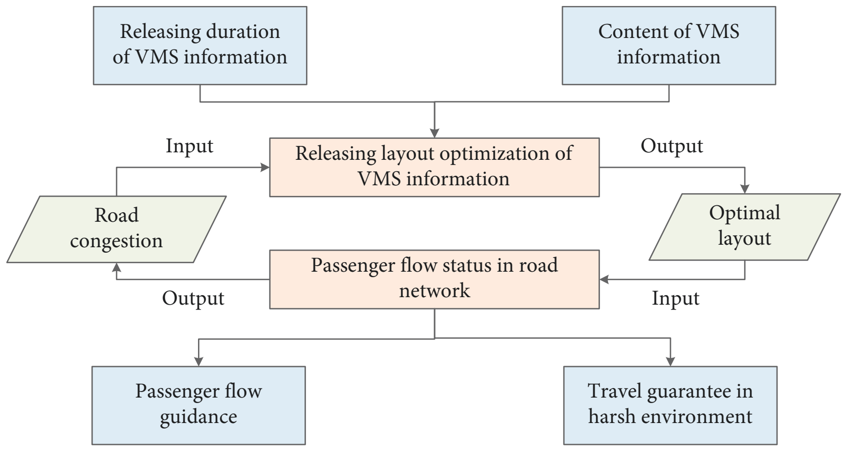

Figure 1: Feedback between information release and passenger flow state.

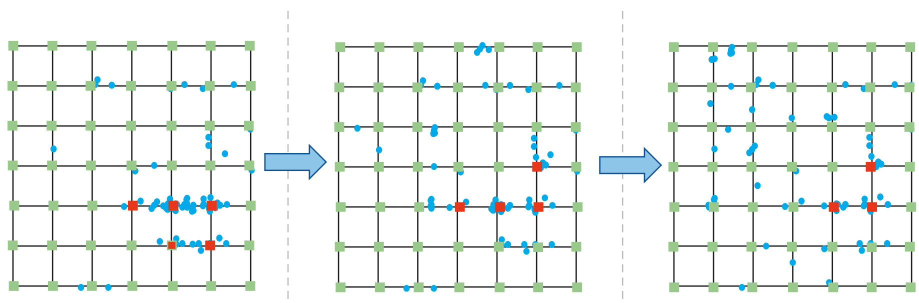

Figure 2: The evacuation process of crowded passengers under the release of VMS information in road network.

passenger flow state and emergency conditions, so that the optimal information guidance effect with the minimum release cost can be achieved. The interactive feedback mechanism is shown in Figure 1.

In particular, in order to reduce the waste of resources, not all VMSs in the road sections release information at the same time and continuously. Instead, VMSs on certain road sections are dynamically selected to release the information according to the passenger flow state or emergencies. Figure 2 shows the evacuation process of crowded passengers under the release of VMS information in road network. In Figure 2, the grids represent the road network, the blue dots represent the pedestrians in the road network, and the squares represent the VMSs. The green squares represent the VMSs without information releasing, while the red squares represent the VMSs with information releasing. In the dynamic feedback between the VMS system and the passenger flow state, the dynamic update of information releasing locations of VMSs is realized.

2.2. Optimization of Releasing Layout

2.2.1. Model. In this paper, the layout formed by the locations of VMSs that release information during a certain period of time in road network is called the releasing layout of VMS information during the period. Different passenger flow states correspond to the different optimal releasing layouts of VMS information. Therefore, the releasing locations of the VMS information in the network are regarded as variables, and a multiobjective dynamic optimization model for the layout is formulated in the paper.

In the model, the first objective considers the travel impedance of the network and the releasing cost of VMSs in the network within a certain period of time. After the information is released, the smaller the average travel impedance of the roads in the network and the fewer the road sections that release information in a certain period of time, the better the objective. If the starting time of information releasing is t0, the objective can be expressed by

$$\min Z_1 = \int_{t_0}^{t_0+\Delta T} \sum_{(i,j)\in E} \left[\frac{C'_{ij}\;(t)}{L_{ij}} + aS_{ij}(t) \right] dt, \text{s.t}\, S_{ij}(t) = 0, 1, \tag{1}$$

where $C'_{ij}\;(t)$ is the travel impedance of road section (i, j) at time t, which can be expressed by the generalized travel cost of the road section; L_{ij} is the travel length in the road section (i, j); ΔT is the calculation time after the information is released; $S_{ij}(t)$ is 1 if there is information released in road section (i, j); otherwise, it is 0; a is the cost of the information release for single VMS per unit time, which can be expressed by time cost; and E is the collection of road sections.

Firstly, considering the factor of passenger congestion, the generalized travel cost function of passenger flow in a road section (i, j) at time t is established, as shown in the following equation:

$$C_{ij}(t) = \overline{t_{0,ij}}\left[1 + \alpha_c\left(\frac{g_{ij}(t)}{c_{ij}}\right)^{\beta_c}\right], (i, j) \in E, \quad (2)$$

where $\overline{t_{0,ij}}$ is the average time cost of pedestrians walking freely in road section (i, j); $g_{ij}(t)$ is the total passenger volume on road section (i, j) at time t after the information is released; c_{ij} is the capacity of road section (i, j); and α_c, β_c are the delay coefficients caused by the crowded passengers on the road section.

Then, as pedestrians will be affected by the harsh environment such as low temperature, wind, and snow, the cold index is used to measure the impact of the harsh environment on the pedestrians [18]. So, the generalized travel cost function for the pedestrians can be expressed as follows:

$$C'_{ij}(t) = C_{ij}(t)(1 + \widetilde{Q}), (i, j) \in E, \quad (3)$$

where

$$Q = (37 - T_e)\left(9.0 + 10.9V_w^{1/2} - V_w\right),$$
$$\widetilde{Q} = \frac{Q}{Q_{\max}}, \quad (4)$$

where Q and $\widetilde{Q}$ are, respectively, the cold index and the normalization of the cold index in the calculation period, which represents the degree of impact caused by the factors such as temperature and wind speed. $\widetilde{Q}$ is between 0 and 1, and the closer the value is to 1, the greater the impact is. $Q_{\max}$ is the largest cold index value in the area. T_e is the temperature, °C. V_w is the wind speed.

The endurance of pedestrians in low temperature will be reduced. The high congestion of network will increase the travel time of pedestrians in the harsh environment, which will seriously affect the comfort of pedestrians. Therefore, we should pay attention to not only the generalized cost of all the road sections but also the highly congested road sections. In this paper, the second objective in the model is built to minimize the cumulative duration of high congestion in the road sections. If the releasing time of VMS information is started at t0, the objective can be expressed by (5). Within a certain period of time, the smaller the cumulative duration of the road congestion and the smaller the amplitude above the threshold, the better the objective.

$$\min Z_2 = \int_{t_0}^{t_0+\Delta T} \sum_{(i,j)\in E}\left(1 + \frac{g_{ij}(t)}{c_{ij}}\right)\delta_{ij}(t)\mathrm{d}t, \quad (5)$$

where

$$\delta_{ij}(t) = \begin{cases} 1, & \exists\dfrac{g_{ij}(t)}{c_{ij}} > c_0, \\ 0, & \text{else}, \end{cases} \quad (6)$$

where c_0 is the congestion threshold of the road section.

2.2.2. Algorithm. Genetic algorithm is widely used in optimization problems [19, 20]. The algorithm has strong robustness for complex systems and is easy to implement parallel design. Therefore, the solving algorithm of the model is designed based on genetic algorithm.

(1) Chromosome Coding. According to the characteristics of network optimization, the integer encoding method is adopted. The encoded chromosome is shown in (7), and $S_{i_1,j_1}, S_{i_2,j_2}, \ldots, S_{i_{|E|},j_{|E|}}$ represent whether the VMSs in the road sections release information. If the VMS in road section (i, j) releases information in the calculation time, $S_{i,j} = 1$; otherwise, $S_{i,j} = 0$. An individual is expressed by a chromosome, which represents a releasing layout of VMS information.

$$\left\{\overbrace{\left(\underbrace{i_1, j_1}_{\text{Road section}}, \underbrace{S_{i_1,j_1}}_{0-1}\right)}^{\text{Allete}}, \left(i_2, j_2, S_{i_2,j_2}\right), \left(i_3, j_3, S_{i_3,j_3}\right), \ldots, \left(i_{|E|}, j_{|E|}, S_{i_{|E|},j_{|E|}}\right)\right\}. \quad (7)$$

(2) Genetic Operations. In terms of crossover operation, the single-point crossover method is adopted to generate offspring individuals, as shown in (8). The positions of crossover points in chromosomes are randomly selected.

$$\begin{aligned}
&\text{Parent 1: } \left\{\underbrace{\left(i_1, j_1, S_{i_1,j_1}\right), \left(i_2, j_2, S_{i_2,j_2}\right)}_{\downarrow}, \left(i_3, j_3, S_{i_3,j_3}\right), \ldots, \left(i_{|E|}, j_{|E|}, S_{i_{|E|},j_{|E|}}\right)\right\},\\
&\text{Parent 2: } \left\{\overbrace{\left(i_1, j_1, S'_{i_1,j_1}\right), \left(i_2, j_2, S'_{i_2,j_2}\right)}^{\uparrow}, \left(i_3, j_3, S'_{i_3,j_3}\right), \ldots, \left(i_{|E|}, j_{|E|}, S'_{i_{|E|},j_{|E|}}\right)\right\}\\
&\qquad\qquad\Downarrow\\
&\text{Offspring 1: } \left\{\left(i_1, j_1, S'_{i_1,j_1}\right), \left(i_2, j_2, S'_{i_2,j_2}\right), \left(i_3, j_3, S_{i_3,j_3}\right), \ldots, \left(i_{|E|}, j_{|E|}, S_{i_{|E|},j_{|E|}}\right)\right\},\\
&\text{Offspring 2: } \left\{\left(i_1, j_1, S_{i_1,j_1}\right), \left(i_2, j_2, S_{i_2,j_2}\right), \left(i_3, j_3, S'_{i_3,j_3}\right), \ldots, \left(i_{|E|}, j_{|E|}, S'_{i_{|E|},j_{|E|}}\right)\right\}.
\end{aligned} \tag{8}$$

Similarly, an allele of a parent individual is randomly selected to perform mutation operation, as shown in the following equation:

$$\begin{aligned}
&\text{Parent: } \left\{\left(i_1, j_1, S_{i_1,j_1}\right), \underbrace{\left(i_2, j_2, S_{i_2,j_2}\right)}_{\downarrow}, \left(i_3, j_3, S_{i_3,j_3}\right), \ldots, \left(i_{|E|}, j_{|E|}, S_{i_{|E|},j_{|E|}}\right)\right\},\\
&\text{Offspring: } \left\{\left(i_1, j_1, S_{i_1,j_1}\right), \overbrace{\left(i_2, j_2, S'_{i_2,j_2}\right)}^{\downarrow}, \left(i_3, j_3, S_{i_3,j_3}\right), \ldots, \left(i_{|E|}, j_{|E|}, S_{i_{|E|},j_{|E|}}\right)\right\}.
\end{aligned} \tag{9}$$

After the crossover and mutation operations are completed, individuals with higher fitness are selected as the parent individuals in the next iteration. The calculation of fitness value is shown in the following equation:

$$f(Z) = \frac{1}{Z} = \frac{1}{Z_1 + Z_2}. \tag{10}$$

In order to prevent the algorithm from falling into local optimization due to "premature convergence," the algorithm ensures that the generated offspring population has a certain diversity in each iteration. If the diversity of the offspring population is poor (the number of individuals of a certain type accounts for a large proportion), it is necessary to continue the crossover and mutation operations among the parents until the offspring population with high diversity is generated.

(3) Solving Process. Figure 3 shows the overall execution process of the algorithm. It is considered that the algorithm reaches convergence if there is no better solution after successive iterations. In the algorithm, the fitness of each individual needs to be calculated based on the objective function under the corresponding releasing layout of VMS information.

2.3. Releasing Rules. In this paper, the time interval between the end of the last information release and the start of the next information release is called the releasing interval Δt_b of VMS information. After one-time releasing of VMS information, it is necessary to decide whether to re-optimize the releasing layout according to the current passenger flow state in road network under the adaptive releasing strategy of VMS information. If the passenger flow continues to be highly congested, Δt_b can be 0, that is, after one-time information release, a new layout optimization is started immediately. Therefore, the releasing time and the releasing locations of VMS information are all in adaptive state. The adaptive releasing rules of VMS information are shown in Figure 4, and the process is as follows.

Step 1. System initialization: if the road congestion is small, the VMSs in road network are closed. At this time, the pedestrians travel in the road network without VMS information guidance.

Step 2. When the road congestion exceeds the threshold, the releasing layout optimization of VMS information is started. The VMSs release information according to the optimal layout, and the pedestrians continue to travel under the guidance of information.

Step 3. If the releasing duration reaches Δt_c, check whether there are pedestrians in the road network and turn to Step 4.

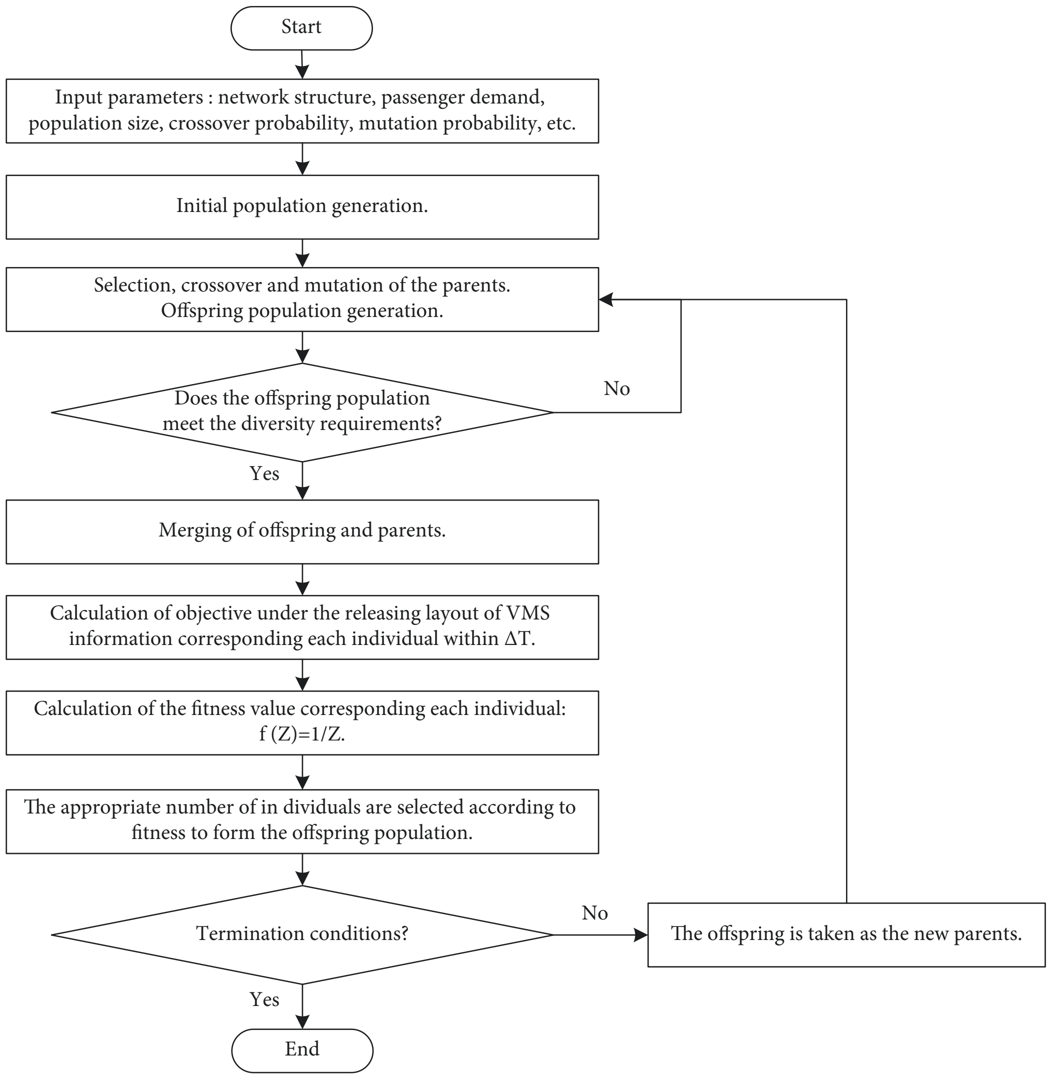

Figure 3: The overall execution process of the algorithm.

Step 4. If there are no pedestrians traveling in the road network, the VMS system will be closed, and the information release will be stopped. Otherwise, go to Step 2.

3. Scenario Simulation with Multiple Agents

3.1. Model Discretization. In this paper, a scenario simulation method for the VMS information release strategy based on multiple agents [21, 22] is proposed. With the method, the effectiveness of the strategy could be verified. In the simulation progress, the time needs to be discretized. So, the discrete form of equations (1), (3), (5), and (6) can be expressed as follows:

$$\text{s.t}\, S_{ij} = 0, 1,$$

$$\min Z_2' = \sum_{s=s_1}^{s_n} \sum_{(i,j)\in E} \left[\left(1 + \frac{g_{ij}^s}{c_{ij}} \right) \delta_{ij}^s \Delta t \right], \min Z_1' = \sum_{s=s_1}^{s_n} \sum_{(i,j)\in E} \left(\frac{C_{ij}^s}{L_{ij}} \Delta t \right) + \sum_{(i,j)\in E} a S_{ij} \Delta T, \tag{11}$$

where

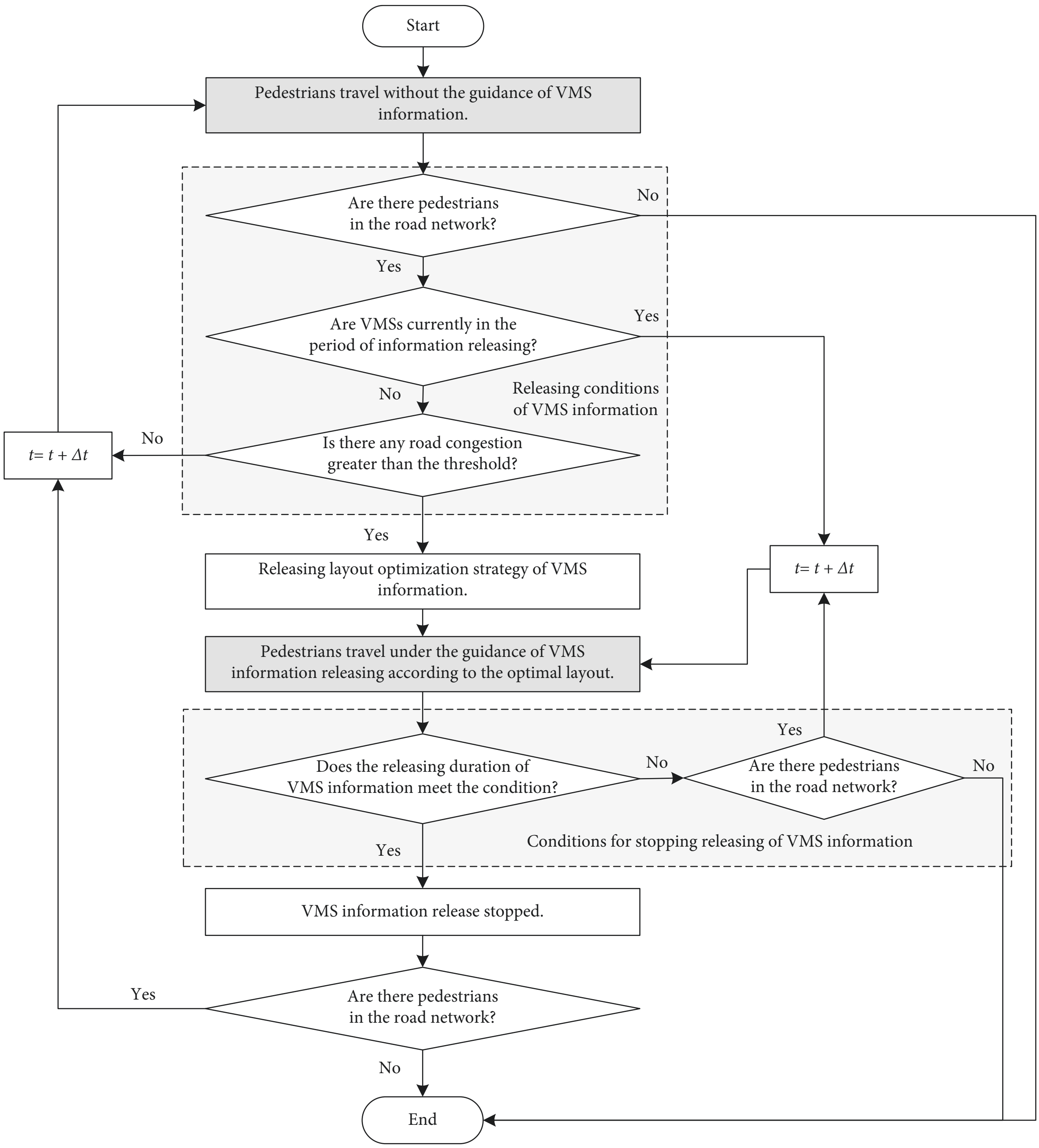

Figure 4: The adaptive releasing rules of VMS information.

$$\delta_{ij}^{s} = \begin{cases} 1, & \exists \dfrac{g_{ij}^{s}}{c_{ij}} > c_0, \\ 0, & \text{else}, \end{cases} \tag{12}$$

$$C_{ij}^{s} = \overline{t_{0,ij}}\left[1 + \alpha_c \left(\frac{g_{ij}^{s}}{c_{ij}}\right)^{\beta_c}\right](1 + \widetilde{Q}), \quad (i, j) \in E,$$

where g_{ij}^{s} is the passenger volume on road section (i, j) of the sth analysis step after the releasing of VMS information; C_{ij}^{s} is the travel impedance on road section (i, j) of the sth analysis step, which can be expressed by the generalized travel cost of the analysis step; δ_{ij}^{s} is a 0-1 variable, and the variable is set to 1 when the congestion degree of road section (i, j) in the sth analysis step is greater than the critical value; otherwise, it is set to 0; and Δt is the duration of an analysis step in simulation, satisfying $\sum_{s=s_1}^{s_n} \Delta t = \Delta T$.

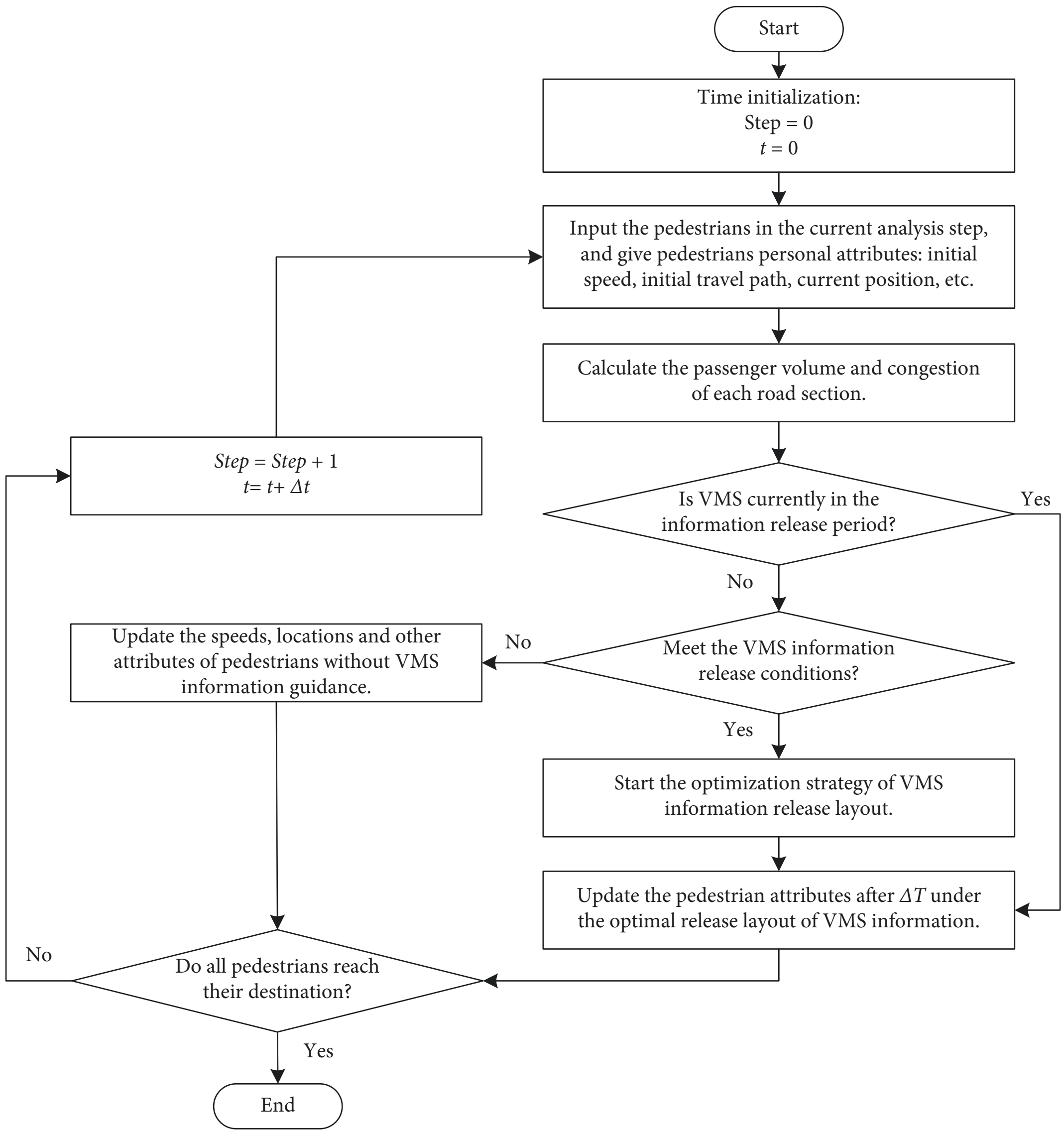

Figure 5: The overall simulation process of pedestrian travel for the scenario with VMS information release strategy.

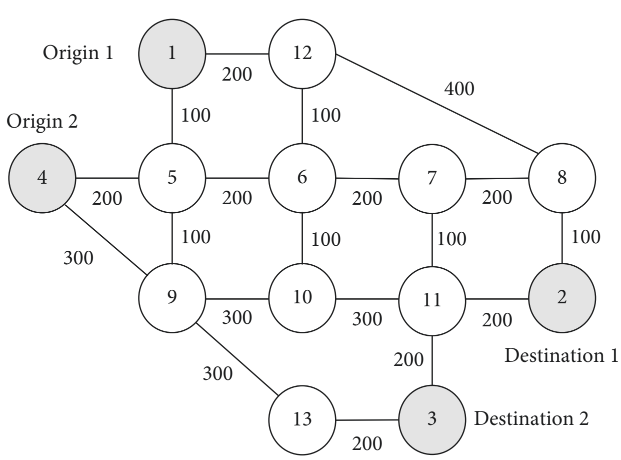

Figure 6: The road network structure for calculation.

3.2. Rules of Agents

3.2.1. Pedestrian Speed. In the simulation, the pedestrians are regarded as multiple agents. Pedestrian speed changes adaptively with the changes of congestion degree in the remaining road section in front of the pedestrian's location, and the calculation method is given in (13). The pedestrian speed is a dynamic variable. When the congestion of the remaining section in front of the pedestrian is large, the speed becomes slower. In particular, when a pedestrian's speed is 0, the capacity of the remaining road section in front of the pedestrian reaches its maximum. As the congestion dissipates, the pedestrian speed gradually increases until it returns to the speed under free flow.

$$v^p(t) = v^p_{0,ij}\left[1 - \alpha_v\left(\frac{g^p_{ij}(t)}{c^p_{ij}}\right)^{\beta_v}\right], v^p(t) \geq 0, \qquad (13)$$

where $v^p(t)$ is the walking speed of pedestrian p at time t; $v^p_{0,ij}$ is the walking speed of pedestrian p in a free state; $g^p_{ij}(t)$ is the passenger volume of the remaining section in front of the pedestrian's location in road section (i, j) at time t; and c^p_{ij} is the capacity of the remaining section in front of the pedestrian's location in road section (i, j).

Similarly, considering the impact of harsh environment, the pedestrian speed can be calculated by

$$v'^p(t) = v^p(t)(1+\widetilde{Q}), v^p(t) \geq 0. \tag{14}$$

3.2.2. Initial Path Selection for Pedestrians. Since pedestrians already know their destinations before entering the large-scale activity area, it is assumed that the pedestrians have already completed the initial path planning when they initially enter the road network. Because pedestrians only travel along the effective paths and the longer the travel time, the lower the path selection probability, the effective path between the starting place and the destination should meet the following condition:

$$C^r_{od} \leq (1+H)C_{od,\min}, \tag{15}$$

where C^r_{od} is the generalized travel cost of the effective path r between the starting place and the destination; $C_{od,\min}$ is the generalized travel cost of the shortest path between the starting place and the destination; and H is the maximum detour coefficient of path r.

According to the random utility theory [23, 24], the probability of choosing the initial path depends on the utility of the path. The utility can be measured by the generalized travel cost of the path. Compared with the absolute utility, pedestrians are more concerned about the relative utility between the effective paths. Therefore, the selection probability of the initial path can be calculated by

$$p^r_{od} = \frac{\exp\left(-\theta C^r_{od}/\overline{C_{od}}\right)}{\sum_{q\in R}\exp\left(-\theta C^q_{od}/\overline{C_{od}}\right)}, \tag{16}$$

where $\overline{C_{od}}$ is the average value of the generalized travel cost of the effective paths.

3.2.3. Path Selection under Information Release. Under the current guidance of VMS information, if the pedestrians on the road section with information release are not in the last section of the path and are affected by the congestion, they will re-plan the travel path according to the information obedience rate. Within the same time period, pedestrians on the same road section where the information is released can re-plan their travel paths at most once. Also, for the same pedestrian, the time of re-planning the path during the entire travel process is limited by the maximum value.

The overall simulation process of pedestrian travel for the scenario with VMS information release strategy is shown in Figure 5.

4. Numerical Simulation

4.1. Questionnaire. In order to obtain the characteristic parameters of human behavior in harsh environments, we conducted a questionnaire survey on 840 people. Data collection includes issues such as route selection, maximum outdoor endurance time, the information obedience rate of pedestrians, etc. The collection of these parameters is to prepare for passenger flow simulation.

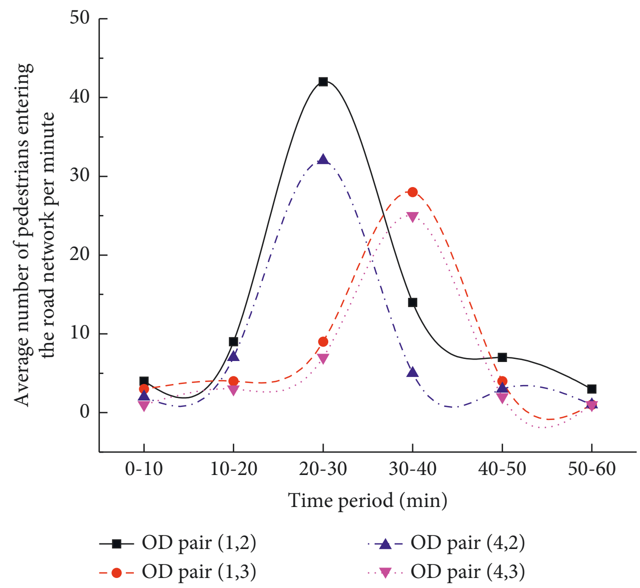

Figure 7: The ingress rules of passenger flow between different OD pairs.

4.2. Scenario and Parameters. In this paper, numerical simulation is used to analyze the influence of the changes of different parameters on travel guidance under the VMS information release strategy. Assume that the road network structure in a large-scale activity area for the calculation is a Nguyen–Dupuis network [25], as shown in Figure 6. The network has two starting points (entrances to the large-scale activity area) and two destinations (places for activity). The nodes in the network represent intersections, the line segments represent road sections, and the numbers on the line segments represent the length of the road sections in meters. The congestion level of the sections can be released dynamically in VMSs in the network. For the calculation, the ingress rules of passenger flow between different OD pairs are shown in Figure 7. After the pedestrians enter the road network from the two entrances, they will go to the destinations under the guidance of VMS information.

Actually, in addition to the releasing strategy, the guidance effect of pedestrians is related to some important parameters, especially the parameters that can be adjusted or guided by managers, such as releasing duration of VMS information, information obedience rate of pedestrians, and passenger volume between OD pairs. In the simulation, the scenario with the parameter values in Table 1 is taken as the scenario for comparison, and the impact of the parameters on the releasing strategy is simulated and analyzed by changing their values. Other parameters in the simulation are shown in Table 2.

Table 1: Values of the key parameters of the scenario used for comparison.

Parameter	Meaning	Value
Δt_c	Releasing duration of VMS information, min	5
Po	Information obedience rate of pedestrians	0.7
RI	Increasing rates of passenger volume between OD pairs	0

Table 2: Other simulation parameters.

Parameter	Meaning	Value
c_0	Congestion threshold of road sections when staring the releasing layout optimization of VMS information	0.7
a	Information release cost of a single VMS per unit time, s/(min pcs)	10
H	Maximum detour coefficient of the effective paths	1.5
n_r	Maximum times of re-planning the path during the entire travel process	3
$\overline{v}^p$	Initial average speed of pedestrians, m/min	79
$v^p_{\max}$	Initial maximum speed of pedestrians, m/min	1.2 $\overline{v}^p$
$v^p_{\min}$	Initial minimum speed of pedestrians, m/min	0.8 $\overline{v}^p$
α_v, β_v	Speed function parameters of pedestrians	0.640, 1.668
α_c, β_c	Generalized travel cost function parameters	1.119, 2.011
Δt	Simulation step, min	1

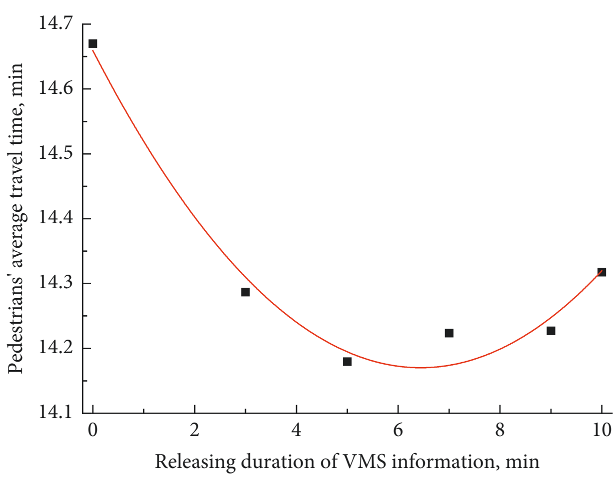

Figure 8: The impact of the releasing duration of VMS information on the pedestrians' average travel time.

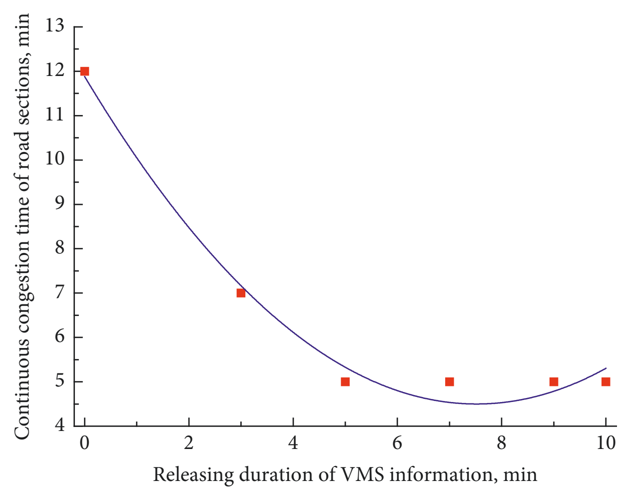

Figure 9: The impact of the releasing duration of VMS information on the continuous congestion time of road sections.

4.3. Analysis of Key Parameters

4.3.1. Information Releasing Duration. Figures 8 and 9 show the impact of the releasing duration of VMS information on the pedestrians' average travel time and the continuous congestion time of road sections, respectively. As can be seen, when the duration is set to 6–8 minutes, the average travel time and the continuous congestion time reach the minimum. At this time, the information guidance effect can be the best. This is because the evacuation of the passenger flow takes a certain amount of time, and when the releasing duration is too short, it is difficult to give full play to the role of information guidance. On the other hand, when the releasing duration is too long, the timeliness of the current information will be lost, and the guidance effect will be poor. Therefore, managers should select an appropriate releasing duration according to the dynamic demand of pedestrians and timely adjust the information content.

4.3.2. Information Obedience Rate. Pedestrians have different obedience rates to the VMS information, which ultimately leads to different passenger flow states in the road network. Figures 10 and 11 show the pedestrians' average travel time and the maximum congestion of road sections under different information obedience rates, respectively. As can be seen, there is an inverse relationship between the information obedience rate and the average travel time. That is, the lower the information obedience rate Po, the worse the information guidance effect with longer average travel time. The results show that network congestion can be effectively reduced and the personal travel time can be saved by increasing information obedience rate Po. So, managers can improve the guidance effect by increasing pedestrians' obedience rate by means of manual guidance and broadcasting.

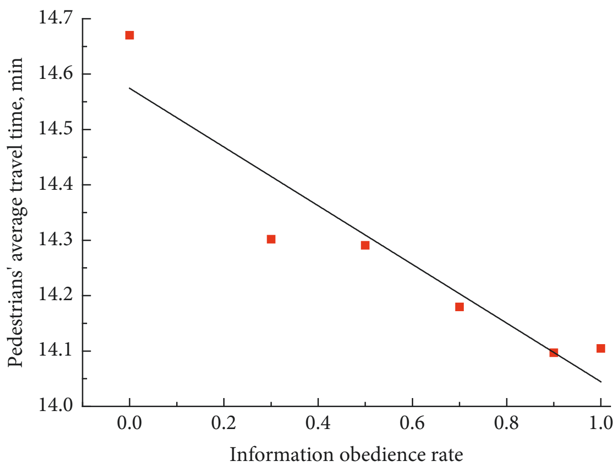

FIGURE 10: The pedestrians' average travel time under different information obedience rates.

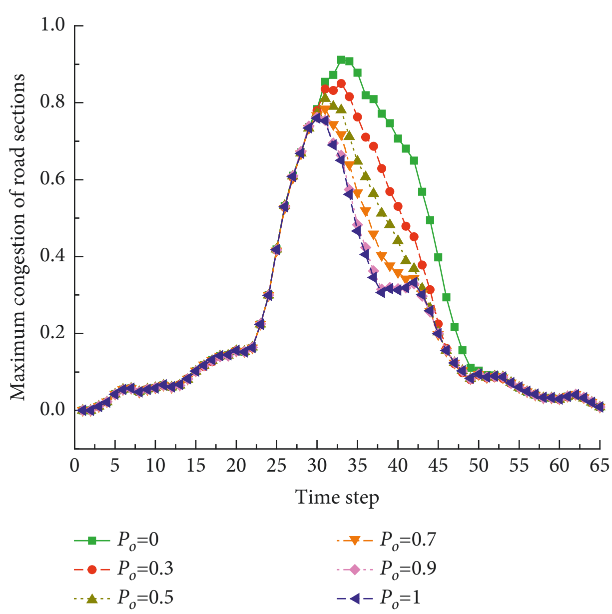

FIGURE 11: The maximum congestion of road sections under different information obedience rates.

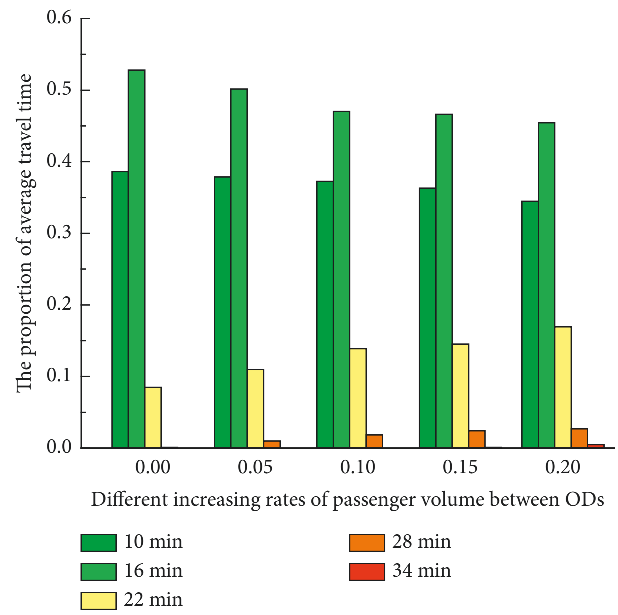

FIGURE 12: The proportion distribution of average travel time under different increasing rates of passenger volume between OD pairs.

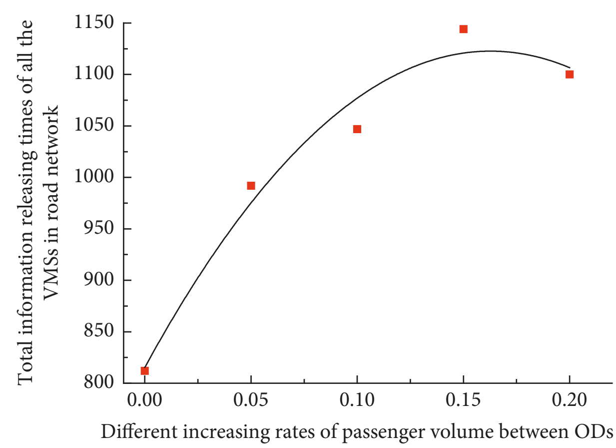

FIGURE 13: The total information releasing times of all the VMSs in road network under different increasing rates of passenger volume between OD pairs.

4.3.3. Passenger Volume between OD Pairs. The proportion distribution of average travel time and the total releasing times of all the VMSs under different increasing rates of passenger volume between OD pairs are shown in Figures 12 and 13, respectively. It can be seen that with the increase of passenger volume between OD pairs, the proportion of long travel time gradually increases, and the network gradually presents a more congested state. When the OD passenger volume increases by 15%, the average releasing time of VMS information reaches the maximum. The results indicate that the VMS information has limited control over passenger flow. When the passenger volume exceeds the threshold, too much VMS information intervention not only is ineffective but also increases the cost of information release. Therefore, managers should control the passenger flow in the road network in advance to reduce the guidance cost.

5. A Large-Scale Case Study

5.1. Parameters. A large-scale competition area is located in a mountain in Beijing, with the highest altitude of 2198 meters. It is cold and windy in winter, and the road is often accompanied by snow and ice. In the competition area, the functional areas where spectators are allowed to travel can be divided into three types: walking area, service area, and boarding or alighting area. Among them, the walking area is the area where spectators watch the outdoor games by walking or walk to other destinations. Therefore, the walking area is taken as an example to study the effectiveness of the

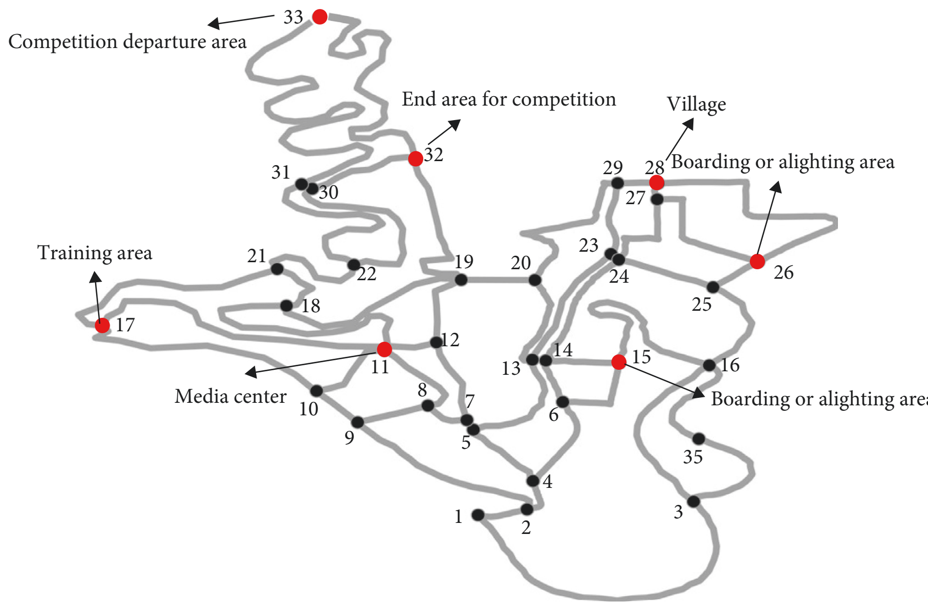

Figure 14: The road network around the Sleigh Center.

Table 3: The pedestrian feelings under different cold indexes.

$\tilde{Q}$	Level	Description
0~0.43	1	Slightly cold, most people feel uncomfortable.
0.44~0.57	2	Cold, most people feel very uncomfortable.
0.58~0.71	3	Very cold and need enough clothes to keep body temperature.
0.72~0.86	4	Extremely cold, high risk of frostbite.
0.86~1.00	5	Unbearable cold, higher risk of frostbite.

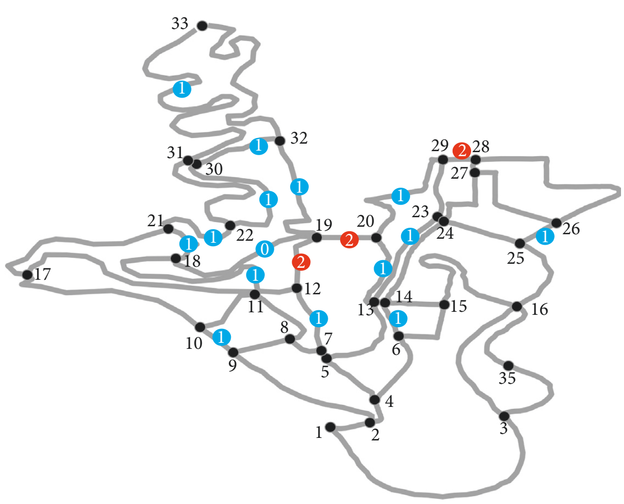

Figure 15: VMS information release times of each road section for the scenario of ingress.

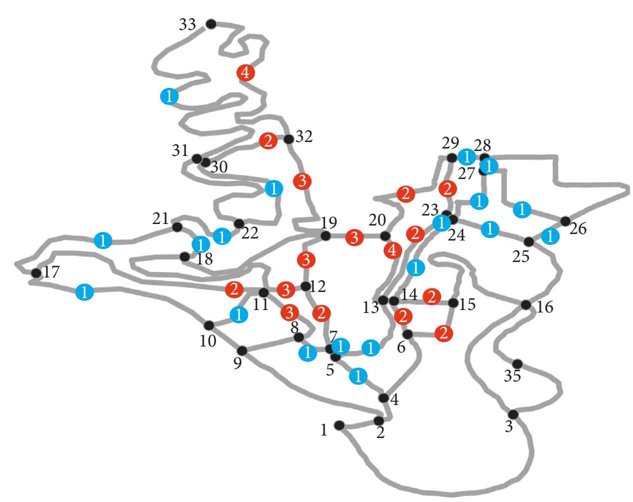

Figure 16: VMS information release times of each road section for the scenario of egress.

strategy. In the walking area, there are many pedestrian trips from the "boarding or alighting area" to the Sleigh Center, and the road network around the Sleigh Center is shown in Figure 14. During the peak time for ingress and egress, the passenger volume is large, which can cause agglomeration of passenger flow and congestion of the road network. So, the travel of pedestrians needs to be guided by information release. In order to study the applicability of the VMS information release strategy, simulation was performed for the case.

According to the data from the meteorological department, the average winter temperature in the large-scale activity area from 2015 to 2019 was about −10.5 degrees, and the wind speed was around level 6, which was 10.8–13.8 m/s.

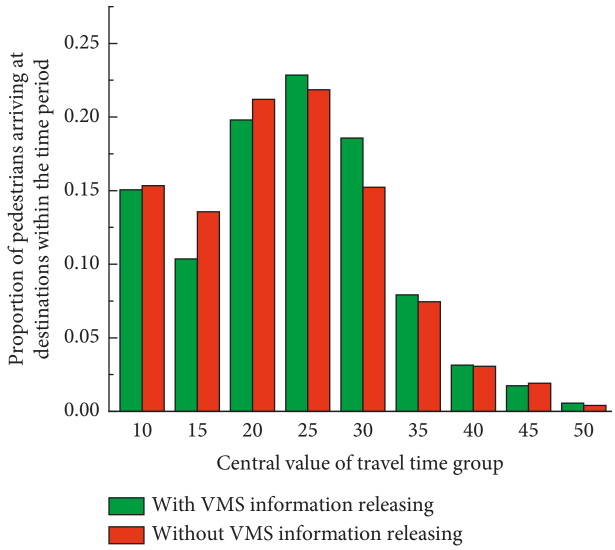

FIGURE 17: Travel time distribution of pedestrians for the scenario of ingress.

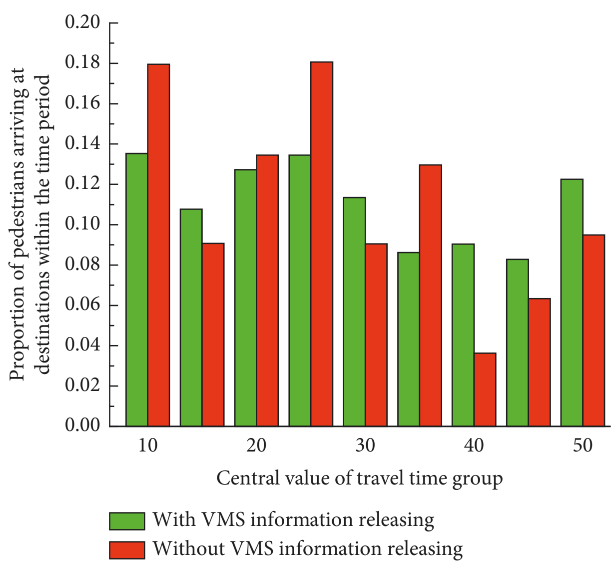

FIGURE 18: Travel time distribution of pedestrians for the scenario of egress.

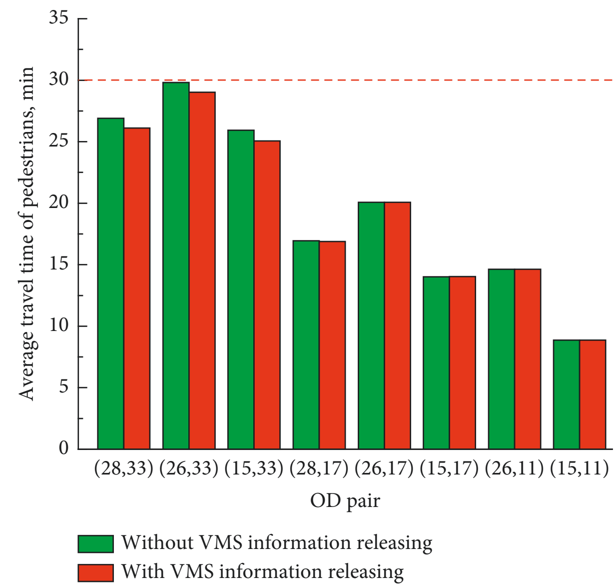

FIGURE 19: Distribution of travel time between each OD pair for the scenario of ingress.

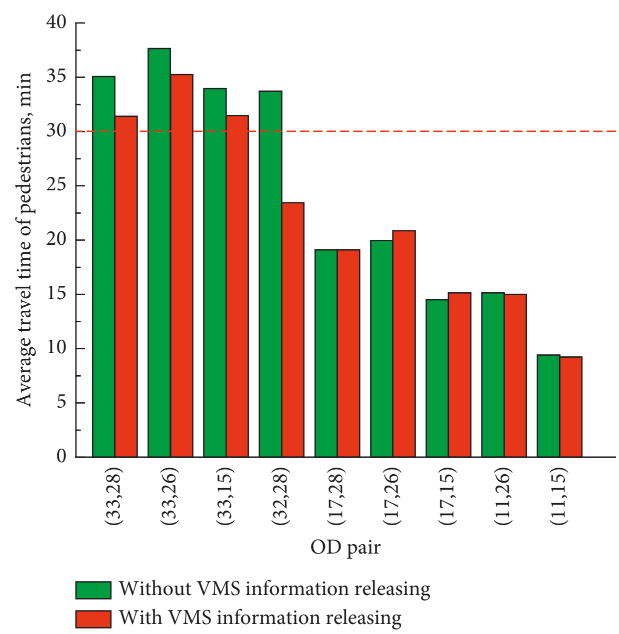

FIGURE 20: Distribution of travel time between each OD pair for the scenario of egress.

According to equation (4), the normalized cold impact factor $\widetilde{Q}$ is about 0.68. Also, according to the literature [26], the pedestrian feelings under different cold indexes are shown in Table 3. In order to obtain the characteristic parameters of pedestrian behavior in this environment, a questionnaire survey on about 240 people was conducted. According to the investigation, when the road congestion is about 0.43, 0.71, and 1, the compliance rate of pedestrians to VMS information is about 0.3946, 0.6906, and 0.861 respectively. Other parameter values in the case are the same as those in Table 2.

5.2. Information Releasing of VMSs. The congestion level of the sections in road network can be released dynamically in the VMSs, and the releasing layout is different under different passenger flow states. According to the releasing strategy proposed in the paper, the average releasing time of each road section for the scenarios of ingress and egress is calculated, respectively, as shown in Figures 15 and 16. The number of each road section is the average releasing times, and the times of unmarked road sections is 0. As can be seen, compared with the scenario of ingress, the releasing of VMS information in the scenario of egress is more frequent, which is due to the greater agglomeration characteristics of the passenger flow.

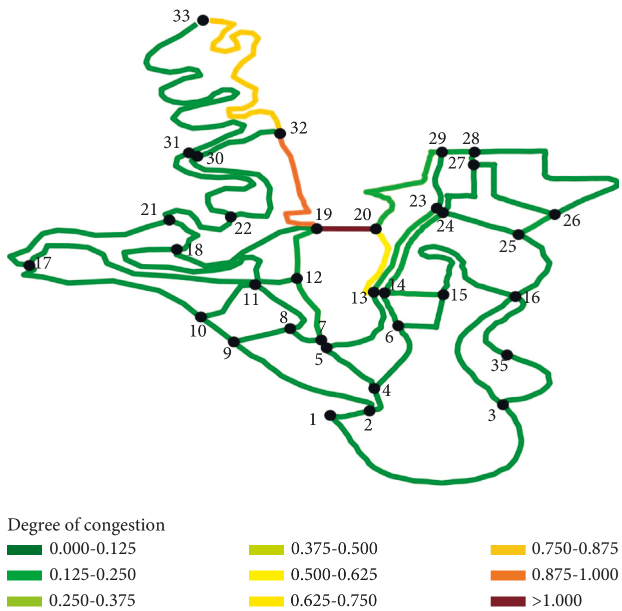

Figure 21: The maximum congestion of the road network for the scenario of ingress without VMS information releasing.

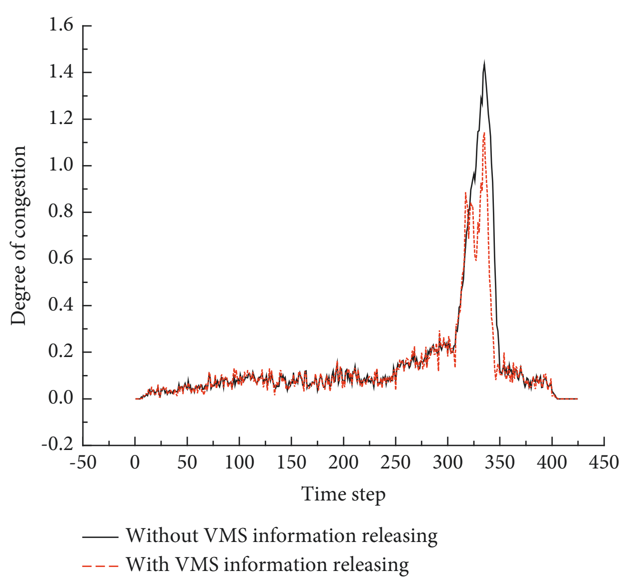

Figure 22: The change of congestion degree of the road section (20, 19) during traveling for the scenario of ingress.

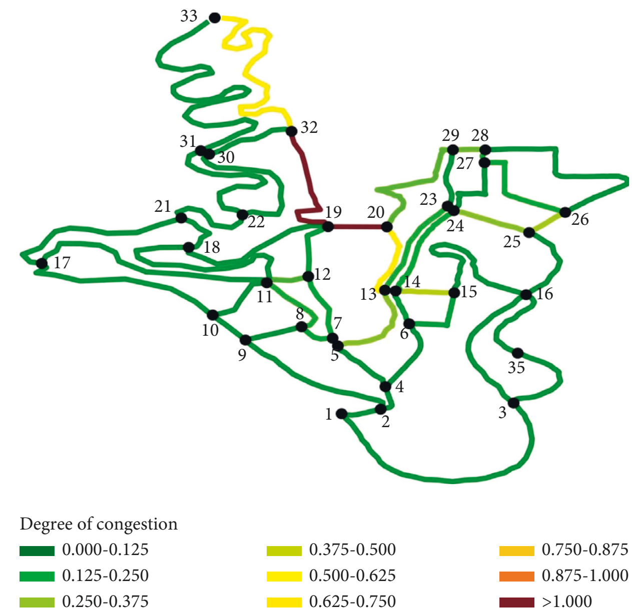

Figure 23: The maximum congestion of the road network for the scenario of egress without VMS information releasing.

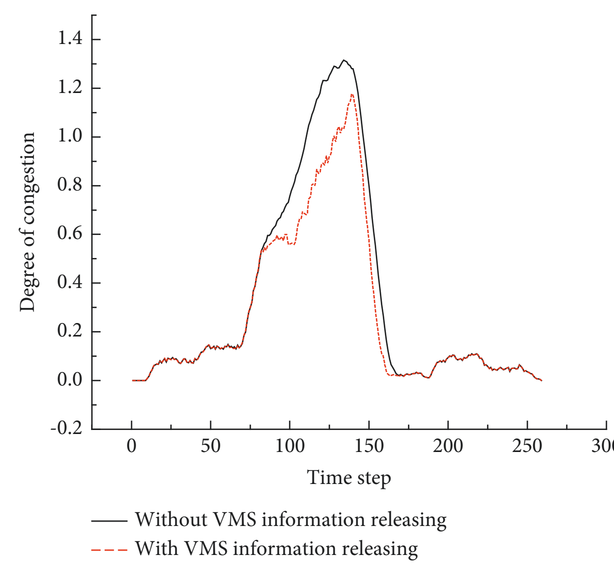

Figure 24: The change of congestion degree of the road section (20, 19) during traveling for the scenario of egress.

5.3. Results and Discussion

5.3.1. Travel Time of Pedestrians. Figures 17 and 18 show the comparison of travel time distribution of pedestrians for the scenarios of ingress and egress, respectively. As can be seen, in the both scenarios, the proportion of pedestrians' short-term travel can increase with the VMS information releasing: the proportion of pedestrians with travel time less than 20 minutes increased by about 3.75% for the scenario of ingress, and the proportion of pedestrians with travel time less than 25 minutes increased by about 7.36% for the scenario of egress. In addition, under the guidance of VMS information, the average walking time of pedestrians decreased by about 2.6% and 7.0% for the scenarios of ingress and egress, respectively. Therefore, the results show that the travel efficiency of pedestrians in harsh environment can be effectively increased with the VMS releasing strategy.

Figures 19 and 20 show the distribution of travel time between each OD pair for the scenarios of ingress and egress, respectively. As can be seen, the travel time between each OD pair is less than 30 minutes for the scenario of ingress, while the travel time between the OD pairs (33, 26), (33, 28), and (33, 15) is more than 30 minutes for the scenario of egress. According to the investigation, the maximum tolerable outdoor travel time in this environment is no more than 30 min. The longer the travel time, the greater the risk of pedestrian frostbite. Therefore, temporary heating places should be set in the paths between the three OD pairs, and the corresponding location information of the places should be released.

5.3.2. Congestion of Roads. The maximum congestion of the road network for the scenario of ingress without VMS information releasing is shown in Figure 21. It can be seen that the road section with the maximum congestion is (20,19). In order to verify the mitigation effect of information guidance on road congestion, the change of congestion degree of the road section in the scenario is obtained, as shown in Figure 22. The results show that the maximum congestion of the road section can be reduced by about 20.45% with the VMS information releasing for the scenario.

Similarly, the maximum congestion of the road network for the scenario of egress without VMS information releasing is shown in Figure 23. As can be seen, the road section with the maximum congestion is (32,19), and the change of congestion degree of the road section in the scenario is shown in Figure 24. The results show that he maximum congestion of the road section can be reduced by about 10.51% with the VMS information releasing for the scenario.

6. Conclusions

In view of the large-scale agglomeration of passenger flow and the low comfort of travel in some large-scale activities with harsh environment, an adaptive release strategy of VMS information in the road network is proposed. In this strategy, the dynamic feedback and optimization mechanism are considered the key. Through numerical calculation and case analysis, it is found that the strategy plays a significant role in reducing road network congestion and improving travel efficiency. Therefore, the strategy can be popularized and applied to the traffic management for large-scale snow or winter competitions, scenic spots, and other activities theoretically. In the future, we will further verify the applicability and accuracy of the strategy after the influence of COVID-19 which is restricting the holding of large-scale gathering activities [27].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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