Emergency safety evacuation decision based on dynamic Gaussian Bayesian network

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Abstract. Emergency incidents in public areas with high pedestrian density may lead to chaos and congestion, which threaten the safety of pedestrians. Therefore, management departments need to make rapid and accurate evacuation decisions. The evacuation decision-making model proposed in this paper consists of three parts: pedestrian distribution prediction model, pedestrian flow calculation model and path situation and feedback correction model. Considering the dynamic, random and uncertain characteristics of pedestrian distribution on the road network, this paper uses dynamic Gaussian Bayesian network to predict pedestrian distribution. Several classical pedestrian flow velocity calculation formulas are introduced as pedestrian flow calculation model, including the Furin model, Tangming model and Liu Dongdong model. Path length, evacuation time and pedestrian density are used as three factors to evaluate the route situation. Two feedback correction methods are proposed to guide pedestrians flow reasonably. They are route planning method and diversion rate method. Taking Wuhan Guanggu Metro Station as an example, the simulation results in GENIE show that the evacuation decision model in this paper can effectively evacuate pedestrians and reduce risk.

1. Introduction

Emergency evacuation refers to the evacuation of people to safe areas as soon as possible in the event of floods, strong winds and other disasters in outdoor environments and terrorist attacks, fires, earthquakes, etc. in indoor environments [1]. In this process, corresponding management evacuation decisions in the department play a crucial role. Wrong decisions can lead to crowding and even stampede events. It is extremely important for management to make correct and efficient evacuation decisions.

In recent years, more and more scholars have studied emergency evacuation decisions in different practical scenarios, and proposed many representative methods, mainly based on simulation methods and mathematical analysis methods. The simulation method is generally applied to simulate the flow of pedestrians and the traffic congestion in the evacuated road network during the emergency evacuation process. It can be used to predict the evacuation time and evaluate the evacuation plan [2]. The evacuation decision research will involve the pedestrians. For modeling of flows, models are generally divided into macro-class models and micro-class models. The macro-class model starts from group behavior and usually uses the physical characteristics of gas or flowing liquid to treat the flowing population as a continuum of flow [3]. Micro-class models, such as the cellular automaton model [4] and the social power model [5], treat a single pedestrian as a single particle that can be acted upon.

The method of mathematical analysis is mainly based on network flow optimization. The large-scale evacuation of indoor small-scale evacuation and outdoor open environment is transformed into the problem of evacuation network optimization [6]. Georgiadou et al. [7] consider the movement of evacuated pedestrians as a discrete Markov process, and the solution in this paper can provide the spatio-temporal distribution of the evacuees. However, the effectiveness of these mathematical analysis
methods is limited due to the lack of sufficient detailed data and rigorous assumptions. These studies are summarized as optimization methods for evacuation plans. They focus on the best exit routes or crowded links, but lack an understanding of the global and real-time link status of evacuated road networks under certain guidance or control measures.

In the research of this paper, the complexity and variability of evacuation decision-making measures and the randomness of pedestrian flow are realized. The dynamic Gaussian Bayesian network and the pedestrian flow velocity calculation model are innovatively integrated, and real-time feedback is adopted. The control mechanism is used for real-time pedestrian emergency evacuation decision, and the experimental verification of this paper is effective.

2. Establishment of emergency evacuation decision model

The emergency evacuation decision model proposed in this paper is mainly composed of three aspects: the Pedestrian Distribution Forecasting Model based on DGBN, combined with the Flow Computing Model and the Path Situation Computing Model to form an emergency evacuation decision model to provide scientific emergency evacuation for subway station managers.

The population distribution prediction model uses the dynamic Gaussian Bayesian network as a carrier to predict the distribution of human flow on the evacuation network. The human flow calculation model and the path situation calculation model feedback the dynamic Gaussian Bayesian network to make the prediction more accurate. The evacuation decision model is shown in Figure 1.

2.1. Distribution Forecasting Model Based on DGBN

2.1.1. Dynamic Gaussian Bayesian Network. A Bayesian network is known as a Gaussian Bayesian network if and only if the joint probability density (JPD) associated with its variables $X$ is a multivariate normal distribution $N(\mu, \Sigma)$. The JPD function is specified in the form

$$f(x_1, x_2, \ldots, x_n) = (2\pi)^{-n/2} \exp\left\{-1/2 (X - \mu)^T \Sigma^{-1} (X - \mu)\right\}$$

(1)

Under the Bayesian network framework, JPD function can be decomposed into the product of conditional probability densities (CPDs), that is

$$f(x_1, x_2, \ldots, x_n) = \prod_{i=1}^{n} f_i(x_i | x_1, \ldots, x_{i-1}) = \prod_{i=1}^{n} f_i(x_i | \pi(x_i))$$

(2)

The CPD function is given by
\begin{equation}
\begin{split}
f_i(x_i|\pi(x_i)) & \sim N\left[ \mu_i + \sum_j \beta_{ij} (x_j - \mu_j), \nu_i \right] \\
\end{split}
\end{equation}

Equation (3) can be written in the following form:

\begin{equation}
\begin{split}
f_i(x_i|\pi(x_i)) & \sim N\left[ b_i + \sum_j \beta_{ij} x_j, \nu_i \right] \\
\end{split}
\end{equation}

where is \( x_j \in \prod(x_i) \) the parent node of \( x_i \).

2.1.2. \textit{DGBN network extraction}. The dynamic Gaussian Bayesian network is a human flow prediction model based on a specific place plan, a dynamic location Bayesian network and a Gaussian distribution. The method is based on the plan of a certain area, abstracts the plane area map into a "point map" with the evacuation point and the branch point as the nodes, and the evacuation route as the arc, and then based on the Bayesian network. The graph is converted to a directed acyclic graph of the Bayesian network. The arc in the Bayesian network represents the dependencies between the nodes. If there is an arc connection between the two nodes, there is a causal relationship between them, and vice versa.

Due to changes in time, the position and number of pedestrians in the Bayesian network model are changing, that is, the sample data changes. In order to more accurately observe the change of pedestrian status, the Bayesian network must be expanded to a dynamic Bayesian network in which time-affected data is observed, that is, the variable is not only affected by the surrounding environment and the state of the person in the current state, but also by the relevant factors at the previous moment. Considering the complexity of data collection and processing, the Markov property of dynamic Bayesian networks is introduced, that is, the current state is only affected by the state of the relevant factors at the previous moment and its own.

2.2. \textit{Flow Computing Model}

When an emergency occurs, it is especially important that the personnel in the subway station can quickly evacuate to a designated safe place in a shorter period of time, and the evacuation time and the walking speed of the personnel, the flow density, the structure of the building, and the personal characteristics of the personnel, Environmental factors are closely related. People's popular walking speed is closely related to different channel types, such as channel structure. Generally, pedestrians walk faster in the horizontal channel than stairs, because the variables involved in the stairs are much more complicated and much more. For example, the size and height of stair steps, whether there are handrails and armrests, etc. environmental factors mainly refer to weather conditions, smoke, gas, road lighting and crowding; personal characteristics mainly refer to the age and gender of pedestrians. Physical and mental conditions and physical strength. A large number of domestic and foreign scholars have obtained a series of experiments and observations that the walking speed of the human flow is closely related to the flow density of the person in the position. Generally speaking, when the flow density is low, the walking speed of the personnel is relatively fast. When the flow density is large, the walking speed of pedestrians is relatively slow or even stagnant.

At present, many scholars around the world have done a lot of research on the evacuation behavior and speed of pedestrians in different evacuation channel types and evacuation environments, but because of the randomness of pedestrian evacuation behavior under the influence of various factors and Uncertainty, there will always be some differences between the results of different scholars. In order to facilitate our research, according to the relationship between pedestrian density and unit flow rate, the following models were selected for the influence of population density of different types of evacuation channels on pedestrian walking speed: Fruin model \cite{8}, Tang Ming model, Liu Dongdong model.

The Fruin model shows that when the population is in a one-way flow state on a straight channel and the flow density is 0.2 person/m2 ≤ D ≤ 4.0 person/m2, the formula for the forward speed is shown in equation (5):
\[ V_L = 1.427 - 0.3549D \]  \hspace{1cm} (5)

Where \( D \) is the density of people in units of person/m².

The relationship between the unit pass rate (flow rate) \( f_L \) and the flow density \( D \) for the effective width section of the channel is given by equation (6):

\[ f_L = 1.427D - 0.3549D^2 \]  \hspace{1cm} (6)

2.3. Path Situation Computing Model and Feedback Correction Model

Evacuation time, evacuation time, individual risk perception, individual psychology and many other factors will affect individual behavioral decisions in the evacuation process, and the impact of these factors will also change over time. According to the experience-driven mindset, people tend to choose the nearest evacuation route during emergency evacuation, but since this usually works with the shortest path, since the shortest path is static, the path of minimum moving time is dynamically changing. The shortest path is easier to calculate. If pedestrians don't have time to think too much about their choices, they usually choose the nearest route. However, whether it is the shortest evacuation distance or the shortest evacuation time, it is easy to cause "the faster is slower" because the information they receive is incomplete. Therefore, the phenomenon in essence is that pedestrians lack a comprehensive understanding of the current road congestion and the time required for evacuation so that they cannot make the optimal decision to evacuate the route. Therefore, many evacuees will make the same evacuation path based on the incomplete information they perceive, and choose the same evacuation path. However, whether it is the shortest evacuation distance or the shortest evacuation time, it is easy to cause "the faster is slower" because the information they receive is incomplete. Therefore, the phenomenon in essence is that pedestrians lack a comprehensive understanding of the current road congestion and the time required for evacuation so that they cannot make the optimal decision to evacuate the route. Therefore, many evacuees will make the same evacuation path based on the incomplete information they perceive, and choose the same evacuation path. Therefore, the three factors of evacuation route length (L), evacuation process time (T) and flow density (D) are selected as the crucial factors of path situation.

The evacuation route length factor is intended to record the total length of the entire evacuation route from the start node to the end node, the value of which can be expressed in equation (7).

\[ L_n = \sum_{i=1}^{k} w_i \times a_i \times bool_i, n = 1, 2..., m \]  \hspace{1cm} (7)

Where \( L_n \) representing the length of the nth evacuation route. \( w_i \) and \( a_i \) respectively representing the impedance and length of the ith link. \( w_i \) is defined by considering the link complexity of the path. When the layout of the path link is more complicated, the value should be higher; When the link \( a_i \) is included in the nth evacuation route, \( bool_i \) is defined as 1, otherwise zero.

The evacuation process time factor is intended to record the total duration of the pedestrian evacuation from the starting node to the end node, which is a combination of walking time and waiting time on the relevant path between the node and the node, which can be solved by equation (8).

\[ T_n = \sum_{i=1}^{k} \left\{ \left( \frac{a_i}{1.427 - 0.3549D_i} \right) \times bool_i \right\}, n = 1, 2..., m \]  \hspace{1cm} (8)

Where \( T_n \) represents the time of the nth evacuation route; \( a_i \) and \( D_i \) represent the link length and density of the ith road respectively.

The flow density coefficient is designed to record the congestion on the evacuation route from the start point to the end point. The value can be obtained by equation (9).

\[ D_n = \sum_{i=1}^{k} \left\{ \frac{num_i}{S_i} \right\} \times bool_i, n = 1, 2..., m \]  \hspace{1cm} (9)

Where \( D_n \) represents the pedestrian density of the nth evacuation route. \( num_i \) represents the pedestrian density of the ith evacuation link, the value of which can be obtained during the simulation.

The macro-dispatched staff of the subway station is based on the current flow of people on each road.
and the prediction of the flow of people at the next moment. Combined with the unit time pass rate of the road environment impact, the premise of the largest and fastest safe evacuation, from the previous node Provisioning appropriate person traffic to the current road or dispersing part of the traffic to the corresponding other links. This is a negative feedback control system. The path decision of the evacuated person flow is affected by the distribution of the flow of people at the last moment, that is, the dynamic Gaussian Bayesian network. The prediction model is predicted and calculated by the Fruin model, the Tang Ming model, and the Liu Dongdong model. The main flow distribution corrections follow the following model: The shunt rate correction model. After the flow of people coming from the previous line reaches a node, according to the actual situation of different roads, it flows into a different path according to a certain proportion. We call this ratio the shunt rate $\beta_{ij}$. The function of shunt rate correction model is given by equation (10) and equation (11).

\[
Situation_n(t) = \sum_{j=1}^{m} (L_n(t))^{\alpha} \times (T_n(t))^{\beta} \times (D_n(t))^{\gamma}
\]  
\[
\beta_{ij}(t) = \frac{\text{Situation}_i(t)}{\text{Situation}_1(t) + \text{Situation}_2(t) + \ldots + \text{Situation}_m(t)}
\]

$Situation_n(t)$ represents the target value considering the factors such as evacuation length and evacuation time; $L_n(t)$, $T_n(t)$ and $D_n(t)$ represent the evacuation length, evacuation time and the density of the evacuation route; $\alpha$, $\beta$ and $\gamma$ respectively represent the evacuation length, evacuation time and the density of the above factors, and we assume the above three factors have the same contribution in this study, and their values are all 1.0 in equation (10).

3. Simulation of emergency evacuation decision model

After the emergency security incident, the individual's evacuation decision forms an evacuation flow. The station management personnel use the human flow as the base to make macro-control of the evacuation path of the crowd after fully collecting the evacuation route link information, so as to ensure that the evacuation group makes full use of each effective path. In this paper, the emergency safety incident occurred at the F port of Wuhan Guanggu Square subway station as an example to simulate the evacuation control process to verify the effectiveness of the emergency evacuation decision model.

3.1. Evacuation network and dynamic Bayesian network establishment

According to the plan view of the Optics Valley Square station shown in Figure 2 (a), the evacuation network map is constructed as shown in Figure 2 (b) (assuming other terrorists such as terrorist
attacks or explosions at the exit F, 1, 2, and 3 is an escalator, a, b, and c are single-channel gates, and B, C, E, and F are exit nodes, and f, e, c, and b are outlet nodes corresponding to the exit, called intermediate nodes, intermediate nodes, and End nodes are considered to be critical nodes. The evacuation network is converted into a Bayesian network, and the network structure diagram is given by Figure 2 (c). There are 8 evacuation path connections in the hall of Optics Valley Square, namely f1, f2, f3, e1, e2, c1, c2, b1. Table 1 shows the path impedance values and lengths of these 8 path connections (including physical length and evacuation).

| Road link | Road impedance | Road length (m) | Road width (m) | evacuation length |
|-----------|----------------|----------------|----------------|------------------|
| f1        | 0.8            | 15             | 8              | 24               |
| f2        | 1.3            | 42             | 3.5            | 54.6             |
| f3        | 1.0            | 20             | 3              | 20               |
| e1        | 1.0            | 24             | 4              | 24               |
| e2        | 1.3            | 42             | 2.5            | 54.6             |
| c1        | 1.0            | 30             | 6              | 32               |
| c2        | 1.0            | 20             | 4              | 20               |
| b1        | 1.0            | 15             | 5              | 15               |

3.3. Simulation results
After ten simulations of ten time series, each time interval is 20s, compared with pedestrian free evacuation, the above proposed evacuation decision model has a certain effect, which can significantly reduce the possibility of crowding and stamping events.

Under the self-extraction, the changes in the number of pedestrians and pedestrian density in each path are given by Figure 3(a) and Figure 3(b), respectively. It can be seen that without an effective evacuation strategy, pedestrians will blindly choose an evacuation path for evacuation. At this time, due to lack of understanding of the congestion status on the path, it is very likely that some road sections will have serious congestion, path c2 and path. The pedestrian density on f3 reached 6 people per square meter at the highest level, and this flow density is extremely crowded and dangerous.
When the station management department can adopt the diversion rate evacuation scheme, that is, each corresponding diversion point arranges the corresponding staff to strictly follow the calculation of the diversion rate calculated by the optimization model for pedestrian guidance. In this case, the simulation is performed, and the average number of pedestrians and pedestrian density are obtained. The variation maps are shown in Figure 3(c) and Figure 3(d), respectively.

Under the emergency evacuation model, the maximum human flow density on the c2 and f3 paths is reduced to about 4 people per square meter, and there is basically no stamping event, which is a safe level, indicating the effectiveness of the emergency evacuation model proposed in this paper.

4. Conclusion
Considering the complexity of pedestrian distribution on the road network and the real-time characteristics of road conditions, this paper proposes an emergency evacuation strategy model with real-time feedback. The evacuation decision-making model consists of three parts: pedestrian distribution prediction model, pedestrian flow calculation model and path situation and feedback correction model. The dynamic Gaussian Bayesian network is introduced in the prediction model mainly because of its capacity in dealing with continuous random variables and complex reasoning. Three classical pedestrian flow velocity calculation formulas are introduced as pedestrian flow calculation model. The route planning method and diversion rate method can be dynamically fed back to the prediction model by adjusting the shunt rate. The simulation results in GENIE show that the evacuation decision model is efficient and effective. However, the actual factors considered in the modeling process are not comprehensive enough, such as the impact of stairs. Establishing an emergency evacuation decision-making model considering more practical factors will be one of the next research directions of the author.

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