Research on evacuation simulation of underground commercial street based on reciprocal velocity obstacle model

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ABSTRACT
The current study evaluates the influence of different exit quantity and location on evacuation efficiency of underground commercial street, and analyzes the difference of evacuation efficiency. The author selected the same underground commercial street design, with different locations layout of various exports. The improved RVO is used to generate the regional evacuation path tree according to the evacuation hierarchy of underground commercial street. A node monitoring mechanism is introduced to calculate and store the evacuation path of personnel nodes to prevent “penetration” and simulation stagnation. This paper analyzes the influence of the number and location of evacuation exits on evacuation efficiency by comparing the evacuation time of personnel, and puts forward relevant design principles. The experimental results show that under the same condition of layout and the total width of the outlet, simply increasing the number of outlets cannot effectively improve the fire evacuation efficiency of the underground commercial street. With the same number of exits, symmetrical distribution of both sides with the exit location is more conducive in improving the evacuation efficiency. This paper is expected to provide suggestions for the design of the number and location of the underground commercial street exit.

KEYWORDS
Underground commercial street; exit; RVO; evacuation efficiency

1. Preface
The underground commercial street usually has the characteristics of complex layout and diverse functions. Reasonable arrangement of evacuation exits location and width can help the personnel immediately find the escape exit and quickly evacuate to the safety area on the ground in case of fire, which is of great significance for ensuring the safety of life and property.

Previous studies have established models for safe evacuation in the underground commercial street. For example, Zeng et al. analyzed the critical risk conditions and evacuation characteristics of underground commercial street fire and put forward the safety evacuation model of underground commercial street personnel. They determine the calculation method of personnel safe evacuation time, identifying the critical personnel density for the safe evacuation (Sheng, Xiaoqian, and Yanfang 2008). Chen et al. established a two-dimensional random cellular automaton model for the safe evacuation of personnel in a large-scale shopping mall in the computer simulation study of the safe evacuation of personnel. They consider many factors for this design, including the distance from the exit, local attraction, detour, repulsive force of walls and obstacles (yu, Ping, and Xiaoying 2010). Chu et al. present a novel platform, SAFEgress (Social Agent For Egress), in which building occupants are modeled as agents who decide their evacuation actions on the basis of their knowledge of the building and their interactions with the social groups and the neighboring crowd (Chu et al. 2014). Chu’s algorithm is of great benefit for writing the current paper. However, the focus of this paper is to study the building space scene, discretize the scene, divide it into evacuation levels according to the difficulty of evacuation, and then calculate the shortest evacuation path in real-time. Pan et al. developed a new continuous geometry evacuation model based on analyzing and comparing existing models. The model considered exit attraction and was used to deal with the problem of exit selection in a multiple exits plan. The way finding algorithm was introduced to circumambulate the obstacle in the plan. The behaviors during evacuation such as overtaking, waiting and rounding were well presented in the simulation with the algorithm of geometric (Zhong, Changbo, and Buying 2006). Pelechano and Malkawi et al. studied the challenges in modeling high-rise building evacuation with cellular automata approaches. They focused on explaining the importance of incorporating human psychological and physiological factors into the models (Pelechano and Malkawi 2007). Hong et al. investigate a dynamic route planning problem in a restricted-space evacuation. It can reduce the delay in the model, improve the evacuation efficiency (Yi et al. 2018). Their research object is Restricted-Space (the underground pipeline,
tunnel, and mine laneway). It is different from the underground commercial street, these spaces have low personnel density and poor environmental condition, which are prone to disasters. When the disaster occurs, the exit is easy to collapse and block, and the evacuation is difficult. Therefore, they focus on dynamic path planning based on the multisource to multi-destination model. An underground commercial street is a crowded place with high space quality. When there is a fire incident, most people can evacuate orderly. Therefore, the concept of evacuation level is introduced to plan the evacuation path. In addition, Kirchner et al. proposed a new cellular automaton model by considering the friction between people (Kirchner and Schadschneider 2002). Although this model can well reflect the interaction between people during the escape, the buildings with high density and complex functions are difficult to simulate, and the simulation speed is slow.

Most literature has focused on the evacuation speed and evacuation model in the process of escape, but seldom mentioned the layout form, location and width of the safety exit. Under the condition when the safety exit meets the distance and stipulated width of the code, the reasonable layout can reduce the evacuation time and improve the evacuation efficiency. At present, more mature crowd evacuation algorithms include Reciprocal Velocity Obstacles (RVO) model (Snape et al. 2010; van den Berg, Guy, and Lin et al. 2011; van den Berg et al. 2011), Social Force Model (Helbing and Vicssek 1999; Helbing et al. 2000; Helbing, Buzna, and Johansson et al. 2005), Mesh Model (Zheng and Siiuming 2001) and A* Algorithm (Hart, Nilsson, and Raphael 1968), etc. The theoretical basis of the Social Force Model is Newton’s second law in mechanics, which can calculate the force between two individuals and solve the speed for each individual. However, it requires an extensive calculation and is inefficient under the environment of real-time operation to study the speed of each individual. Especially for complex evacuation scenarios, such as underground commercial street, this model is ineffective. Compared to the Social Force Model, the RVO model is more efficient (Snape, van den Berg, and Guy et al. 2010; van den Berg, Guy, and Lin et al. 2011; van den Berg and Abbeel et al. 2011), which introduces velocity obstacle (VO), transforms the complex individual evacuation problems into low-dimensional linear programming problems, and add dynamic obstacles. However, it mainly focuses on solving the problem of individual avoidance, it is lacks of the effective dynamic path planning method, and cannot simulate the complex scenes efficiently (Yangyu, Wei, and Guodong 2013). Especially for the large and complex underground commercial street, the movement of individual in the whole evacuation space is lack of systematic guidance, which cannot effectively simulate the evacuation process. In the Mesh Model (Zheng and Siiuming 2001), the individual’s movement depends on the grid and a large amount of memory space, thus it is not flexible and not the true optimal global path, which cannot reflect the anisotropy between individuals and the continuity of two-dimensional space. However, the search efficiency of the heuristic A* Algorithm (Hart, Nilsson, and Raphael 1968) significantly depends on the quality of the evaluation function, and the search efficiency is unstable due to excessive changes in the environment. Especially for the underground commercial street, the evacuation speed is always updated, and the evacuation efficiency is changed with time. It is impossible to simulate the whole complicated and changeable evacuation process by a single evaluation function. In terms of real-time simulation of large crowds, the RVO model has become an interesting research subject because of its performance advantages (Yangyu, Wei, and Guodong 2013). RVO algorithm is optimized on the basis of the VO algorithm. In 1998, Fiorini P et al. first proposed the velocity obstacle algorithm, also known as VO algorithm (Fiorini and Shiller 1998). Since then, the algorithm has been widely used in the field of robot navigation. Van der Berg J applied the algorithm to crowd simulation in 2008 (van den Berg, Lin, and Manocha 2008), and improved the algorithm to solve the jitter problem, and then proposed the Relative Velocity Obstacle (RVO) method.

In this paper, the concept of evacuation level was introduced, and the evacuation path tree was generated to overcome the shortcomings of RVO model, based on retaining its high performance and individual collision avoidance advantages. Firstly, the underground commercial street scene was discretized, according to the degree of evacuation difficulty. Which was divided into several evacuation levels, and the shortest path from the person node to the exit in the scene, i.e. scene shortest path (SSP) was obtained by using Shortest Path Faster Algorithm (SPFA) (Fanding, 1994). In the process of real-time simulation, the optimal evacuation path of personnel nodes was dynamically updated according to SSP, and the actual path without “penetration” and collision of personnel nodes was calculated in real-time according to the current crowd distribution based on the RVO model (Yangyu, Wei, and Guodong 2013).

Another novel outcome of this paper is establishing the guidelines for urban planning and architectural designing. The author extracted a typical plan of underground commercial street, selected a complete fire compartment as the evacuation scene, and used a superior model to simulate the evacuation. In contrast to previous building simulation, most of the models selected in previous studies do not consider the typical aspects of building design, the model scale is rarely defined according to one fire compartment, and the evacuation scene is
relatively simple. The simulation results have a very clear and significant guidelines for the layout of domestic underground commercial streets.

This paper studied the influence of different exit points and locations on evacuation efficiency of the underground commercial street and analyzed the difference of evacuation efficiency. The evacuation exits with the same width but different amounts and positions in a fire compartment were adopted, and the influence of the number and position of evacuation exits on evacuation ability was analyzed by comparing evacuation time of personnel. This paper aimed to provide a basis for the set of the mouth for the underground commercial street in the future.

2. Research method

In order to make this study representative, the model of the underground commercial street used in this paper is based on the investigation and analysis of underground street engineering in many cities of China. It is based on the classification and arrangement, according to the requirements of national architectural design standard and fire prevention code of architectural design. Optimized extraction of the underground commercial street typical plane. The typical plan adopts the layout mode of the shops on both sides of the single-channel, which are most common in the domestic underground commercial streets. The export design not only meets the requirements of the current fire prevention code but also considers the economic rationality. Therefore, it has certain consistency, thus effectively reflecting the performance of fire evacuation in underground commercial street. The evacuation exits were arranged in one fire compartment, and different exit numbers and positions were set up under the condition of a certain total width, to simulate the evacuation ability of underground commercial streets.

2.1. Basic assumptions

(1) It is assumed that the trapped personnel are always rational and can choose the shortest evacuation path to the nearest exit without falling or crushing, and the movement direction for the current time step can be carried out according to the optimal choice of the next time step.

(2) At exits, such as doors and stairs, evacuation speed is a function of personnel density. In the early stage of evacuation, personnel density at the exit is low, evacuation speed is fast, no clogging phenomenon occurs, and evacuation can be carried out smoothly. However, after a certain stage of evacuation, the density of personnel at the exit gradually increases, and the evacuation speed gradually decreases, and congestion begins to appear.

(3) The ignition point is located in the center of the fire compartment.

(4) External influences, such as evacuation instructions are not considered for the time being.

2.2. Area, number of people and evacuation width

According to the national “Code for Fire Protection Design of Building” GB50016-2014 (Code for Fire Protection Design of Building) (hereinafter referred to as the “code") article 5.5.21, Table 5.5.21–1 and Table 5.5.21–2, the number of evacuees and evacuation width were determined.

“Code” regulation: when automatic fire alarm system and fire extinguishing system are installed, and the interior is decorated in accordance with the current national standard “code for fire prevention in design of interior decoration of buildings” (GB50222-2017) (Code for Fire Protection in Design of Interior Decoration of Buildings) relevant provisions, the maximum allowable building area for each fire compartment in the business hall can be increased to 2000 m². According to the investigation and statistics of the underground street project in China, the underground commercial street in this model adopted the most common single-channel and double-sided store layout. The underground commercial street model is 93 m long and 18 m wide. The total construction area of the model is 1990 m², including the area of the entrance and exit. The internal dimensions are shown in Table 1.

According to the requirements of the Table 5.5.21–2 in the “code,” for the store located on the first floor underground have the personnel density of 0.6/m², and the evacuation numbers should be calculated at each layer of business hall construction area multiplying with 0.6. According to the above parameters, the maximum capacity of people in the fire compartment of this model is 1990 × 0.60 = 1194.

The model is designed for the ground floor, and the difference between the model and the ground height is \(\Delta H \leq 10\text{m}\). According to the requirements of the “code” Table 5.5.21–1, the minimum evacuation width of the safe exit and evacuation staircase is 0.75 m/100 people, and the net width of the exit to the outside can be obtained as 1194 ÷ 100 ÷ 0.75 = 8.9m, which is actually taken as 9.0 m.

According to the above analysis, the typical plan of the underground commercial street was obtained, as shown in Figure 1.

| Table 1. The internal dimensions (m). |
|--------------------------------------|
| Total length | Total width | Passage width | Shop Width | Shop Length | Shop Door width |
| 93          | 16          | 6             | 8.4        | 6            | 4             |
the distance from the evacuation exit, the flow direction of evacuation in the underground street, was determined, and then the evacuation levels of shops, passageways, exits, stairway lobby, stairway and other spaces to 1, 2, 3, 4 and 5 were set (Figure 2), respectively. Meanwhile, the evacuation levels also indicate the degree of evacuation difficulty in each area of the commercial street. Then, the evacuation path tree (Figure 3) was generated through the evacuation levels. In the evacuation path tree, each node represents space, and the data structure of the node is composed of two coordinates for the lower left and upper right of the space and a pointer to the parent node.

(2) Anti-penetration collision detection
To prevent the “penetration” phenomenon between people and the walls, and between people in the scene, collision detection was carried out when the position coordinates of people were determined. First, the collision detection was conducted between the personnel model and the scene. When “penetration” occurred, the coordinate was re-selected, and the detection process was cyclic until the appropriate coordinate was selected. The person was then added to the scenario as a node to prevent “penetration” between the later added person and the previously added person model.

The penetration effect is shown in Figure 4. The collision of nodes collide depends on whether the line segment intersects each surface of the node bounding box. It can be judged by calculating the extension of the line segment from the center of the staff node in all directions intersects with the bounding box of other objects, that is, whether the distance between the center of the ball and the bounding box of other objects is higher than the ball radius r. In Figure 5, the light box is the node bounding box, the red line is a line segment drawn from the center of the node, and the green part is the intersection point of the line segment with the bounding box of the adjacent nodes. The equation for calculating the distance “d1” between the center of the ball and each surface of the bounding box of other models are as follows:

$$d_1 = \frac{|Ax + By + Cz + D|}{\sqrt{A^2 + B^2 + C^2}}$$

2.3. Evacuation speed of personnel

According to the investigation, the research personnel of the underground commercial street is composed of an unspecified majority and a fixed number of personnel. The specific types can be divided into three types, including normal people (85%), elderly people (11%) and children (4%) (Wenli, Hong, and Xiaodong 1999). According to their characteristics, the maximum speeds $V_{max}$ for different types are shown in Table 2, where $V_{max}$ is a fixed value (Gang 2013). During the whole movement process, the movement speed $V_{new}$ should be calculated to ensure that the node reaches the exit as soon as possible and does not collide with other nodes.

2.4. Simulation algorithm

Based on the RVO model, the following improvements were made in the pre-processing and running stages of the program.

2.4.1. Algorithm modification in the pre-processing stage

(1) Generation of the regional evacuation path tree, according to the underground commercial street model.

According to the location of the evacuation exit, the commercial street model was first divided into different evacuation levels into various regions, and then the evacuation path tree was generated. According to

| Types                      | Percentage | $V_{max}$ |
|----------------------------|------------|-----------|
| Normal                     | 0.85       | 1 m/s     |
| Elderly including people with mobility problems | 0.11       | 0.59 m/s  |
| Children                   | 0.04       | 0.66 m/s  |

Figure 2. Schematic diagram of hierarchical division for the space evacuation.
x, y, and z are the coordinates of the center of the ball, and A, B, C, and D are constants.

d_1 \geq r \text{ means that the node does not intersect the surface; } d_1 \geq r \text{ represents the intersection of the node and the surface; } d_1 \geq \min(r) \text{ indicates that the straight line intersects the plane, and the straight line penetrates the spherical surface, and there is a penetration phenomenon; } d_1 \geq \min(r), \text{ means that the line does not intersect the plane and no penetration exists. }

(3) Calculation and storage of the evacuation path for each person

When the RVO model is used for crowd evacuation simulation, the crowd will often stop moving, and the simulation process cannot continue when the angle between the obstacle and the forward direction of the crowd is 90°, and the obstacle is large in the direction of about 90°. The evacuation scene in the current paper is for the underground commercial street, and the model is relatively complex, thus it is easy to reveal the above phenomenon by directly using the RVO. In order to solve this problem, the evacuation path of each staff node was calculated and stored in the pre-processing stage for the real-time query at run-time.

### 2.4.2. Algorithm improvement in the running stage

(1) Calculation of direction vector for the staff node

The direction vector of the node was calculated by the target vector and the current position vector of the personnel node.

\[
\vec{C} = \overrightarrow{OA} - \overrightarrow{OB}
\]  

(2)
\( \vec{OA} \) is the target vector of the personnel node, and represents the evacuation direction and evacuation speed of the personnel node; \( \vec{OB} \) is the current vector of the staff node, and represents the current forward direction and speed of the staff node. The \( \vec{C} \) is the evacuation vector of the next step for the personnel node, and represents the direction and speed of the next step for the personnel node.

For individuals A and B, speed obstacle \( VO_{AB} \) refers to the velocity space of A relative to B, and there will be a collision at a certain time less than \( \tau \) time (Yangyu, Wei, and Guodong 2013).

It is formally defined as follows:

\[
D(p, r) = \{ q | q = r \}
\]

\[
D(p, r) \text{ represents the open interval with the center } p \text{ as the radius } r, \text{ and:}
\]

\[
VO_{AB} = \left\{ v \mid \exists t \in [0, \tau] : t \cdot v \in D(p_B - p_A + r_A + r_B) \right\}
\]

\( VO_{AB} \) and \( VO_{BA} \) are symmetric with respect to the origin. Suppose \( v_A \) and \( v_B \) are the current speeds of individual A and the individual B, respectively. The explanation of velocity obstacle is \( v_A - v_B \) to \( VO_{AB} \), that if the individual A and the individual B continue to move at the current speed, they will collide with a certain time. Conversely, if \( v_A - v_B \) is \( VO_{BA} \), then they will not collide in \( \tau \) time.

(2) Update of evacuation target points for personnel nodes

To update the evacuation target point of the personnel node, the distance between the personnel node and the current evacuation target point was calculated. When the distance is less than a certain value \( r \), the personnel is considered to reach the current evacuation target point, and then the evacuation path of the current personnel node should be updated. The value \( r \) should be appropriate. When \( r \) is too large, the personnel will be considered to reach the target at a place far away from the evacuation target, and it will be easily blocked by obstacles when moving to the next evacuation target. When the \( r \) value is too small, some nodes will move to the next evacuation node along with the crowd due to the crowd pushing. The \( r \) value in this paper was determined based on the channel width of the evacuation space, to ensure that the node can be detected when the personnel node moves into the circle with the target point as the center. The distance between the personnel node and the current evacuation target point \( d_2 \) is:

\[
d_2 = \left( \sum_{i=1}^{n} |x_i - y_i| \right)^{1/2}
\]

where \( d_2 \) is the Euclidean distance between the personnel node and the current evacuation target point, and \( r_i \) is the action radius of the evacuation target point. When \( d_2 < r_i \), it is considered that the personnel has reached the current evacuation target point, and then the evacuation path of the current personnel node is updated. When \( d_2 \) is greater than or equal to \( r_i \), it is considered that the personnel has not reached the current evacuation target point, and the evacuation path is not updated.

(3) Node monitoring

To prevent the human node from stagnation due to obstacle limitation, a node monitoring mechanism was introduced in the program running stage. During the simulation, the evacuation of personnel nodes within a certain number of frames is saved. For nodes whose displacement is less than a certain value, the evacuation path is recalculated by monitoring their current coordinates, and the evacuation path is forced to be updated.

\[
d_j = \sum_{i=1}^{n} w_i
\]

where \( d_j \) is the sum of the displacements of the most recent \( n \) frame nodes; if \( d_j \) is less or equal to the set value, it means that the node is stagnation; if it is greater than the set value, it means that the node is not stagnation. The set value in this paper was \( 10^{-3} \).

2.4.3. Analysis and comparison of RVO model and improved RVO model

Under the same experimental conditions, the RVO model was compared with the improved RVO model. A different number of evacuation in the fire scene has distinct degree of crowding, which has a significant impact on the choice of individual evacuation path and evacuation speed. Three groups of data were selected in the experiment, including 100 people in the first group (not crowded), 500 people in the second group (relatively crowded), and 1000 people in the third group (very crowded). The evacuation process and evacuation efficiency of the two models are compared through experiments.

Table 3 shows the evacuation time of the two models under different evacuation numbers. It can be seen that the evacuation time of the three RVO models is longer than that of the improved RVO model. With the increase in evacuation number, the difference in evacuation time is gradually increasing. It shows that the improved RVO model can guide the evacuation to the exit more effectively in the complex scene of the underground commercial street. From the perspective of the evacuation process, Figures 6 and 7 show the evacuation scene in the 40th second of the third group of experiments. It can be seen that the three exits in the RVO model were
very congested, and only 24.0% of the people were evacuated successfully. In the improved RVO model, there is already an entrance and exit where fewer people gather, and 37.4% of the people were successfully evacuated at the same time.

In addition, the RVO model has a stagnant state, as shown in Figure 8. The experimental results show that the improved RVO model is superior to the RVO model in terms of evacuation process and evacuation time.

2.5. Evacuation simulation of different exit layouts

First, three schemes of relatively ideal uniform and symmetrical layout of exits were simulated, and two exits, three exits and four exits were set, marked as F1, F3 and F7 with the width of 4.5 m, 3.0 m and 2.75 m for single evacuation exit, respectively (Figure 9). Through simulation, the impact of the entrance and exit number on the evacuation ability of the underground street was analyzed. Then, considering the actual engineering use and fire prevention protection in practical engineering, the smaller the number of evacuation exits, the wider the width of a single evacuation exit, when the total width of the exit is the same.

Due to the high fire risk in an underground commercial street, the "Code for Fire Protection Design of Commercial Buildings (GB 50016–2014)" has high requirements for the evacuation of the underground commercial street. Exits with a width of 9 m should be set at every 2000 m² (one fire compartment). The underground commercial street is usually located under the road, and the exit needs to be exposed from the sidewalk. The width of the exit is significantly affected by the width of the sidewalk. The larger the exit width, the larger will be the occupied sidewalk width. The width of each exit of F1 reaches to 4.5 m, which is difficult to implement in practical engineering, because the width of the sidewalk is usually less than 4 m. There are too many exits in F7. Especially when constructing underground commercial street under the existing road in the city, it is difficult to arrange the exit. On the one hand, the width of the existing sidewalk is limited, whereas the exit should not block the entrance of the existing building. Based on the above two aspects, F7 is not common. F3 is widely used in practical projects because of its moderate width and suitable quantity. Therefore, three

![Figure 6. RVO model T = 40s.](image)

![Figure 7. Improved RVO model T = 40s.](image)

![Figure 8. Stagnant state.](image)
3. Results and analysis

3.1. Analysis of the influence of the evacuation exit number on personnel evacuation

Compared with F1, F3 and F7, the relationship between evacuation time (T) and evacuation number (N) is shown in Figure 11. F1 is the shortest, F3 is in the medium, and F7 is the longest. The simulation results showed that in the first 15 seconds, no personnel was successfully evacuated; and within 16 ~ 20 seconds, people close to the evacuation exit begin to evacuate successfully. Twenty-five seconds ago, the evacuation efficiency was low, and personnel gathered at the evacuation exit can cause congestion and blockage, which reduce the evacuation efficiency. Evacuation efficiency was higher in 26~70 seconds; after 70 seconds, the evacuation efficiency was reduced, and the roundabout escape route of some people affects the overall evacuation efficiency.

Table 4 shows the time taken to evacuate 0, 25%, 50%, 95% and 100% of individuals under different numbers of evacuations. At the beginning of the fire, the evacuation time for the first individual of the three schemes was almost the same; the evacuation efficiency ranks as F1 < F7 < F3 (Figure 12). In F1, due to the small number of evacuation exits, the phenomenon that a large number of people will create crowd and blocking of the evacuation exit in the early stage of the fire is very serious. With the increase of the evacuation exits, the flow of people is dispersed, and the number of people gathered at the evacuation exits decreases. In the middle stage of the fire, 50% of the people were evacuated, and F3 had the highest evacuation efficiency. F1 is improved rapidly, followed by efficiency. The evacuation efficiency of F7 decreases rapidly to the lowest. It indicates that in the middle stage of fire, with the decrease in width of a single evacuation exit, the evacuation ability of a single evacuation exit will decreases, which affects the evacuation efficiency in the middle stage of fire. At the end of the fire, 95% of the evacuation time was spent, the evacuation efficiency follows the sequence of F7 < F3 < F1.
Table 4. Comparison of evacuation efficiency under different numbers of evacuation ports.

|                  | Minimum evacuation time (s) | 25% evacuation time (s) | 50% evacuation time (s) | 95% evacuation time (s) | Maximum evacuation time (s) |
|------------------|-----------------------------|-------------------------|-------------------------|-------------------------|-----------------------------|
| F1 two exits     | 19.48                       | 38.28                   | 48.72                   | 70.48                   | 77.68                       |
| F3 three exits   | 19.72                       | 35.60                   | 47.08                   | 73.96                   | 85.12                       |
| F7 four exits    | 19.36                       | 35.24                   | 48.80                   | 75.96                   | 86.12                       |

Figure 12. 35 s exit evacuation scenario. (a) F1-two exits, (b) F3-three exits, (c) F7-four exits.

Through observation, it was found that F7 has a low efficiency of evacuation in the later stage of the fire. Some evacuation exits are crowded with people, while some have not been evacuated for a long time. The evacuation time of the whole model follows the sequence of F1 < F3 < F7. It shows that in the case of the same total width of evacuation exits, it can simply increase the number of evacuation exits, but did not improve the overall evacuation ability. In addition, under the same layout and equal total width of evacuation exits, it is more favorable for evacuation in the initial stage of fire, with more evacuation exits, whereas, with less exits, it is more likely to cause congestion and blockage. At the end of the fire, with the increasing number of evacuation exits, the phenomenon of low utilization rate for evacuation exits is more likely, and delaying the overall evacuation time. On the contrary, the smaller the number of evacuation ports, the higher will be the utilization rate, and the more conducive to personnel evacuation.

3.2. Analysis of the influence of evacuation exit location on personnel evacuation

For underground streets with the same layout, the locations of evacuation exits are different, and with various individual choices of evacuation paths. Therefore, optimizing the relative position of evacuation exit and the underground street can effectively improve the evacuation efficiency. Three exit schemes were selected to compare the evacuation efficiency of four different exit positions in the same fire protection zone, named as F3-1, F3-2, F3-3 and F3-4, respectively (Figure 10). The changes in the number of individuals with time who have been evacuated are shown in Figure 13 and Table 4.

The simulation results in Figure 13 demonstrated that evacuation situations of F3-1 and F3-4 are similar, with the highest evacuation efficiency, followed by F3-2 and F3-3. The simulation results of F3-1 and F3-4 revealed that at constant transverse position whether the three evacuation exits are arranged on both sides or the same side, it
Figure 13. Relationship between evacuation time and the number of evacuees at different evacuation exit locations.

has little influence on the overall evacuation efficiency, which is related to the characteristics of the small section width of the underground commercial street. Compared with F3-2, the evacuation efficiency of F3-1 is comparable in the range of 40 seconds in the initial stage of fire. After 40 seconds, the evacuation efficiency of F3-2 decreases obviously until the end of the entire evacuation process. The exits of F3-2 are located at both ends of the fire compartment, and there is no evacuation exit in the middle of the zone, which leads to the increase of evacuation distance for people in the middle of the fire compartment, thus reducing the overall evacuation efficiency. Compared with F3-3, F3-3 combines the two evacuation ports of F3-2 to form a pair of evacuation ports, similar to a two-port plan. As the number of F3-3 mouth decreases, the evacuation efficiency decreases in the initial stage of fire, and there are congestion and queuing phenomenon. Eighty seconds after the end of the fire, there is a phenomenon that the utilization rate of some evacuation exits is not high.

Table 5 shows the time taken for individuals to complete evacuation at different positions of evacuation exits: 0, 25%, 50%, 95% and 100%. At the beginning of the fire, the evacuation time of the first individual in the four schemes is almost the same. Subsequently, in the initial stage of the fire, 25% of the evacuation time is spent, with the highest evacuation efficiency in F3-4, the lowest in F3-3, and the medium in F3-2 and F3-1. In the middle stage of fire, evacuation time for half of the staff is 50%, and evacuation efficiency of F3-1 and F3-4 is significantly improved. F3-2 falls in the fastest evacuation category. F3-3 evacuation efficiency remains the lowest and continues to decline (Figure 14). At the end of the fire, 95% of the evacuation time is spent, with the highest evacuation efficiency in F3-1, followed by F3-4, lower F3-2 and the lowest F3-3.

From the perspective of the entire evacuation process, the evacuation efficiency of F3-1 and F3-4 is relatively high. Both schemes have the characteristics of uniform distribution of evacuation exits, strong accessibility of evacuation exits, short evacuation distance of personnel, and high evacuation efficiency.

The results indicate that uniform distribution of evacuation exits is more conducive to improve evacuation efficiency in the case of the same number of exits. The evacuation exits of F3-1 are distributed on both sides, therefore, they are more even than the unilateral distribution of F3-4, and the evacuation efficiency is slightly higher. However, the evacuation exits of F3-2 and F3-3 are concentrated at both ends of the underground street, which is not conducive to the evacuation of people in the middle. Due to the combination of evacuation exits in F3-3, the number of evacuation exits decreases, and a large number of people are gathered at the exits in the early stage of the fire, causing congestion; and at the end of the fire, the utilization rate of evacuation exit is not high. Therefore, the combination of F3-3 evacuation ports is not conducive to fire evacuation.

4. Conclusion

The improved RVO model retains the advantages of RVO model with high performance and individual collision avoidance. It introduces the concept of evacuation level, discretizes the underground commercial street scene, and divides it into several evacuation levels according to the degree of evacuation difficulty. The node monitoring mechanism is introduced to calculate the shortest path of personnel node scene in real-time according to the crowd distribution, which can effectively overcome the “pene-tration” and stagnation phenomenon of the original model. The results show that the improved RVO model can more objectively and accurately simulate the evacuation scene of the underground commercial street.

In this paper, the improved RVO model was used to analyze the evacuation efficiency under different exits and positions in the same fire protection zone of the underground commercial street. The experimental results showed that, firstly, under the same layout and total width of the outlet, only increasing the number of outlets cannot effectively improve the fire evacuation efficiency of the underground commercial street. Secondly, with the same number of exits, symmetrical distribution on both sides of the exit location is more conducive in improving evacuation efficiency.

In the future, the actual project will be selected, and the improved RVO model will be used for simulation. The

| Minimum evacuation time (s) | 25 % evacuation time (s) | 50% evacuation time (s) | 95% evacuation time (s) | Maximum evacuation time (s) |
|-----------------------------|--------------------------|-------------------------|-------------------------|-----------------------------|
| F3-1                        | 19.24                    | 36.36                   | 47.84                   | 72.16                       | 84.00                       |
| F3-2                        | 19.40                    | 35.56                   | 49.32                   | 81.52                       | 94.24                       |
| F3-3                        | 19.88                    | 38.76                   | 49.96                   | 85.92                       | 95.76                       |
| F3-4                        | 19.32                    | 35.40                   | 46.64                   | 73.52                       | 85.20                       |
corresponding improvement measures will be forwarded to design the number and location of the evacuation exists in the underground commercial street outlet. This study will provide the basis and guidance for the optimization of the underground commercial street outlet.

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