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REPRESENTING CROWDS WITH A MULTI-AGENT MODEL
－Development of the SimTread™ pedestrian simulation system －

Takeshi KIMURA[*1], Tomonori SANO[*2], Kazuto HAYASHIDA[*3], Naohiro TAKEICHI[*4], Yoshikazu MINEGISHI[*5], Yoshiyuki YOSHIDA[*6], and Hitoshi WATANABE[*7]

SimTread has been developed as a pedestrian simulation system following a straightforward, highly user-definable pedestrian and spatial model. Unlike network and mesh models, this pedestrian model is a multi-agent system, where an individual pedestrian is modeled as an agent, and the spatial model is based on actual coordinates; this enables the direct representation of plans by the SimTread model.
The crowd characteristics represented by this system have been evaluated through test cases by measuring the flow rate, a primary indicator of crowd evaluation.

The major results are as follows:

1. In a simple plan that is equivalent to network models, SimTread demonstrated reasonable crowd behavior simulation; this performance, along with the added benefits of operability, is highly desirable.
2. In cases where a bottleneck accumulated enough pedestrians to block nearby exits, SimTread accurately portrayed the resulting crowd propagation, which allowed qualitative analysis of the crowd.

Keywords: pedestrian, simulation, multi-agent, crowd, flow rate

1. Introduction

In recent years, computer simulation techniques have been used to predict and evaluate complex situations in a variety of fields, such as architectural construction and architectural environments. Along with these techniques, performance standards from the Building Standards codes of Japan have made it possible to create plans with methods other than those specified by the rules and regulations, especially in the field of fire safety design. New pedestrian and crowd simulation methods are attracting attention; for example, the Tokyo Fire Department is now requiring studies such as verification using potential simulation[1)]. In other countries, the current use of simulation is much more prevalent than in Japan. In the United States and England, the development of pedestrian simulation is progressing, and in Taiwan, simulation has also been extensively applied in the field of fire safety design and evaluation. In addition to its use in evacuation planning, simulation has also proven to be an effective means of examining the daily flow line plan or scale plan of facilities used by large numbers of people.

For example, crowd flow can be visually represented using animation or by other methods. These methods allow for an easily-understood safety evaluation by the construction client or architect. However, even though it is commonly known that hallway corners have an effect on crowd flow, a simulation system that could evaluate this type of situation is not in use.

The analysis of a floor plan and location can contribute to both a safe and high-quality design, but in a way that may be difficult for the general public—including construction clients—to understand. In addition, even in a typical pedestrian simulation, problems with analysis reproducibility have made it difficult to verify the validity of crowd flow analysis results. Therefore, when conducting a simulation, it has been crucial for the developers to clearly indicate the model mechanism and verify its validity.

Both designers and other simulation users seek an analysis model that is easy to understand. The multi-agent model proposed here is thought to aid understanding because it separates the spatial and pedestrian models and represents them accurately, without abstracting the effects of the spatial geometry. In addition, it also handles the difficult-to-capture behavior of individual pedestrians in a crowd[2)].

* 1 A&A Co., Ltd.
*2 Assoc. Prof., Faculty of Human Sciences, Waseda Univ., Dr. Eng.
*3 Visiting Assoc. Prof., Faculty of Science and Eng., Waseda Univ., Dr. Eng.
*4 Takenaka Corporation, Dr. Env.
*5 Takenaka Corporation
*6 Takenaka Corporation, Dr. Eng.
*7 Prof., Faculty of Science and Eng., Waseda Univ., Dr. Eng.

Unlike a network model, an actual coordinate system multi-agent model can simulate crowd overflow from an exit, including qualitative changes in flow. The purpose of the authors of this paper is to use the research[3) – 9)] they have conducted with the SimTread pedestrian simulation software to both clarify its mechanism and validate its reproducible flow rate change results (a known indicator of crowd simulation reproducibility) as compared to analysis by the network model.

2. Existing Research

Various systems of simulating evacuation behavior from a model have been researched and developed[10) – 18)]. As previously noted, to assist the construction client and designer, it is desirable to reproduce the space—faithful to the design proposal—using an actual spatial coordinate system. However, most of the previous research has adopted a spatial model using a network or mesh representation, for ease of development or shortened processing time[10), 13), 14), 16)]. Use of a network leads to spatial abstraction problems and requires that potential bottlenecks be planned ahead of time. Mesh models, on the other hand, have difficulties with representing smooth pedestrian movement because the movement depends on the size of the mesh.

The use of actual coordinates enables smoother pedestrian movement and allows a detailed evaluation of door and corridor dimensions (dimensions which are too small can cause critical evacuation bottlenecks). In addition, this model is a behavioral model based on accumulated research into the behavioral characteristics of pedestrians. However, this method cannot directly model the spatial structure and walking behavior. There are complicated situations, such as those with a complex networked structure[12)], those where one spatial area needs to be segmented[15), 17)] or examples when certain pedestrian characteristics must be placed in a different physical model. To resolve these potential problems with the use of a model, it is necessary to create an easy-to-understand model, more in line with the realistic behavior of pedestrians.

3. SimTread Overview[9)]

The SimTread target system has been developed as a multi-agent model with behavior rules for each defined agent. The overall crowd behavior is the result of individual agent operation.

3.1 Model Structure

The objects that comprise a SimTread model are listed here.

Pedestrian: Includes spatial position, direction, and maximum walking speed

Barrier: Obstacle (walls, furniture, or areas where pedestrians cannot pass through or enter)

Destination: Locations (areas) that pedestrians move towards

Each pedestrian, barrier, and destination is specified as a calculation condition. Figure 1 shows a simple example of this system, created over a CAD platform.

- Door selection

When leaving a room, studies show that a pedestrian does not leave from the door along the shortest path, but selects the door that is the closest to his or her position.

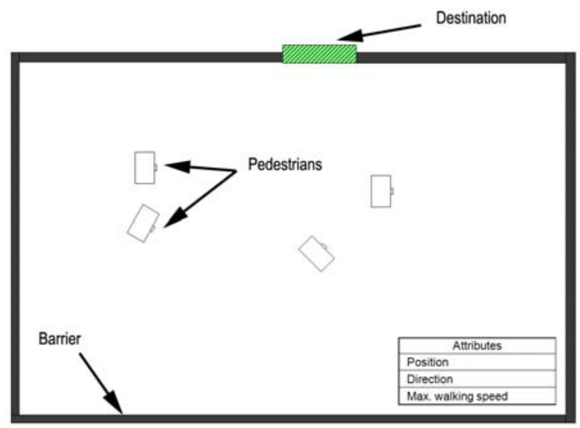


Figure 1 Pedestrians, Barrier, and Destination

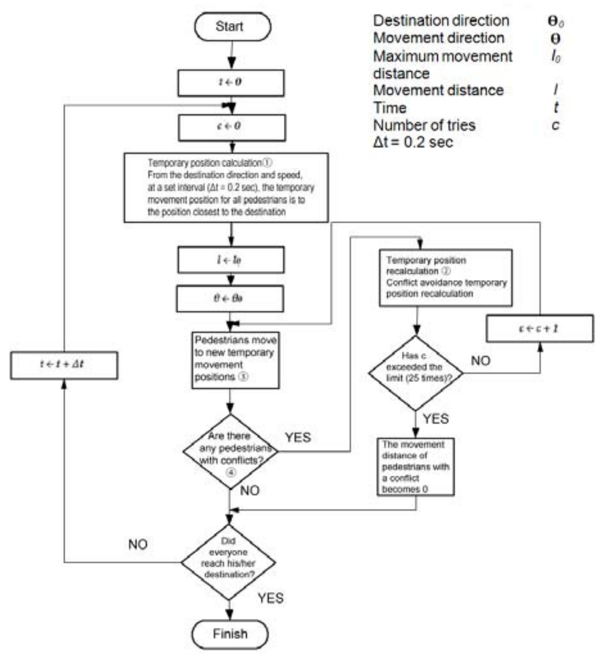


Figure 2 Simulation Calculation Flow Chart

Because this model is normally a "shortest path" model, to simulate the selection of the nearest door, we grouped the destinations (in this case, the doors). When pedestrians move towards a destination that has been grouped, the nearest one in the group is selected.

For example, if all the doors in a room are grouped, pedestrians leaving the room will exit from the room by moving to the nearest door.

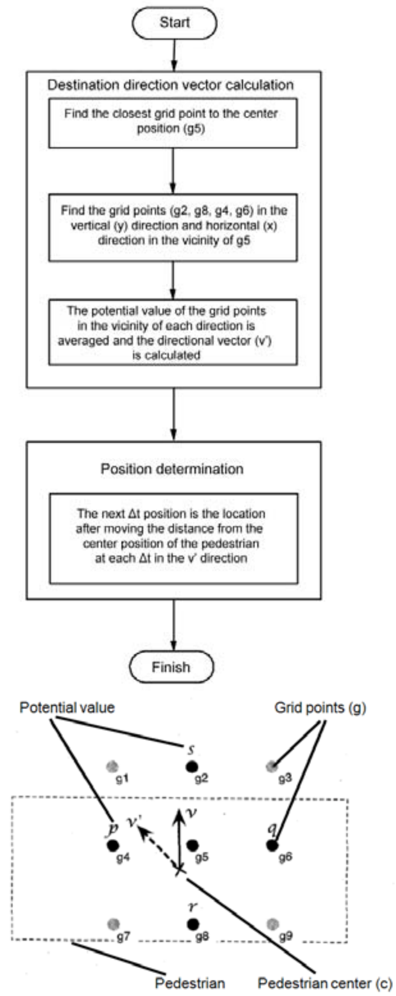


Figure 3 Temporary Movement Re-calculation Flow Chart

3.2 Simulation Procedure

- Calculation of each Δt

At a set interval (Δt = 0.2 sec), the potential next position of a pedestrian is continuously calculated by accounting for the “temporary position ①”, “conflict avoidance (temporary position recalculation ②)” and “movement to temporary position (temporary position determination ③)”. This calculation procedure is repeated (Figure 2) until all the agents arrive at the last destination.

- Distance grid point

To calculate the direction of the destination with the shortest path, distance grid points are arranged at regular intervals (in this paper, we used 100 mm [Note 1)]). The distance of the shortest path to the destination is recorded at this grid point.

- Temporary position

The calculation of the Figure 2 ① temporary movement position, as indicated in Figure 3, first finds the closest grid point to the center position of the pedestrian, and then determines the direction of the destination [Note 2)] by calculating the potential gradient from all possible values (distance to the destination) of the grid points in the vicinity.

Based on the direction of movement and the movement distance according to the given walking speed, the movement position is determined.

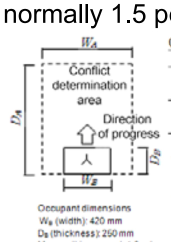
- Conflict avoidance

A conflict is considered to be a condition where any pedestrians who have moved to their temporary positions are in an area with other pedestrians or obstacles. In Figure 2 ④, a conflict occurs if there are other pedestrians or obstacles (see “1st Attempt” in Figure 5) within the conflict determination area (Figure 4) that is defined for each pedestrian. The temporary movement position is recalculated for pedestrians with a conflict.

- Conflict determination area

The conflict determination area, as shown in Figure 4, changes in two stages according to agent speed. In this model, crowd flow characteristics, such as flow rate or density, contribute greatly to setting the dimensions of the conflict area.

For this study, the conflict determination area was adjusted by trial and error [Note 3)] to represent the walking ability described in Reference 19 and the evacuation safety verification method[20]. Specifically, the conflict determination area, in conjunction with the maximum walking speed of 1.0 m/s (maximum movement distance of 200 mm per Δt),was adjusted (Figure 4) so that the flow rate at a simple opening (Figure 6) was normally 1.5 people/ms.



Conflict determination area dimensions

Status		W_A [mm]	D_A [mm]
Avoiding a person	Normal*1	(70 x 2) + W_B*2	810 + D_B
	Speed Reduction*1	W_B*2	150 + D_B
Avoiding a wall	Normal*1	(10 x 2) + W_B*2	600 + D_B
	Speed Reduction*1	W_B*2	75 + D_B

*1 Normal: walking speed is the maximum value
Speed reduction: walking speed is less than 0.75 m/s

*2 70 mm and 10 mm each, on both sides of person width W_B, is added to the dimension

Figure 4 Conflict Determination Area [Note 4)]

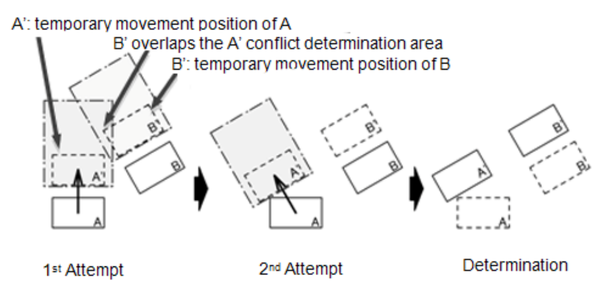
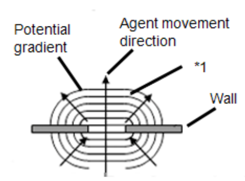


Figure 5 Conflict Avoidance

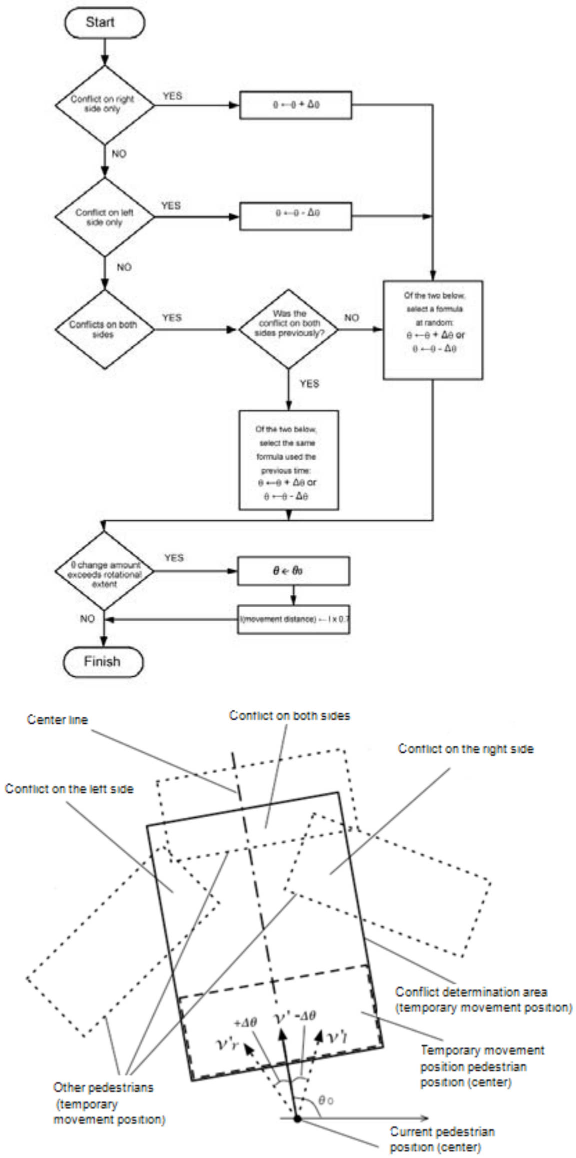


*1 For people to quickly distance themselves from the exit without changing the flow from the exit, the potential is arc-shaped (however, to maintain the walking direction when passing through the exit, the majority of pedestrians proceed normally, in the forward direction).

Figure 6 Open Model Parameter Considerations

- Recalculation of the temporary position Note 5)

The temporary movement position ② recalculation (conflict avoidance) shown in Figure 2, as indicated in Figure 7, involves calculating the agent rotational direction change ($\Delta\theta$ = 12°) in increments within a 90° range limit until the conflict is avoided. If this rotation still does not place the agent in a suitable position, then the distance movement value is reduced by a fixed (30%) ratio (speed reduction). This is repeated and directional rotation is attempted once again.



When the right side of the conflict determination area (right side from the center line) contains overlapping pedestrians, a conflict on the right side is determined to exist. Similarly, conflicts for the left side or for both sides are determined.

Destination Direction		θ_0	
Movement Direction	v'	θ	
Left avoidance direction	$v'r$	$\theta + \Delta\theta$	(avoids right side conflicts)
Right avoidance direction	$v'l$	$\theta - \Delta\theta$	(avoids left side conflicts)
Avoidance angle	$\Delta\theta = 12°$		Rotational extent $\theta_0 \pm 90°$
Movement Distance	l		

Figure 7 Temporary Movement Re-calculation (Conflict Avoidance Calculation)

If all attempts fail (the limit for the number of tries has been reached without moving to a suitable position), the movement distance becomes 0 and that agent does not move at all during Δt.

An example of conflict avoidance is shown in Figure 5, with pedestrian B showing no conflict at B' after Δt, and pedestrian A's position A' after attempting movement.

In the first attempt, B' is within the conflict determination area of A'. For the second attempt, the position of A' rotates the set amount to change its movement direction. Since B' is no longer within the A' conflict determination area, the position of A' is determined on the second attempt.

After recalculating all agents' temporary movement positions, all the agents move to new positions and are recalculated to check for conflicts again.

The calculation of the temporary movement position is limited to 25 times for each Δt.

It is important to note that because the temporary movement calculation of the agents is not performed until all conflicts have been resolved (instead of considering the position of each agent in turn), the calculation results do not depend upon the order in which the agents are calculated.

3.3 Simulation Results

Simulation results can be output in one or both of the following formats.

- Video (.mov file): Animates pedestrian movement on a plane. Creates a graph (Figure 8) at a set point showing, for each Δt, the change over time of the number of people passing through (flow rate).
- Data log (.txt file): Lists the position, direction, and distance traveled of each agent for every Δt. The data make it possible to perform quantitative analyses of crowd flow as described in the following sections.

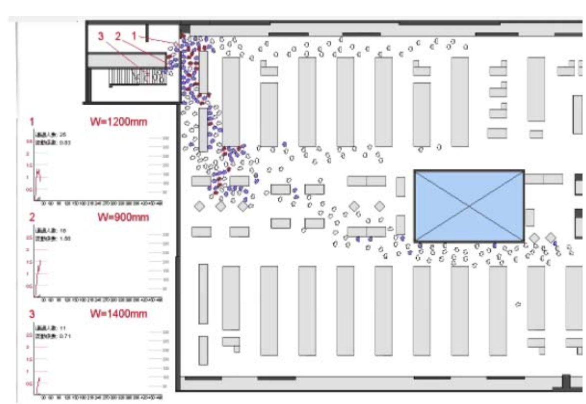


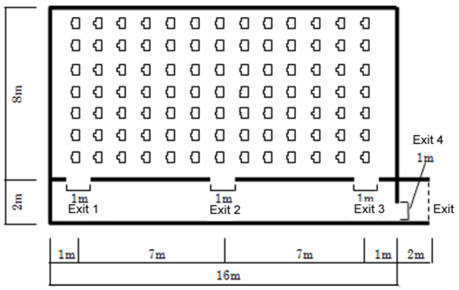
Figure 8 Video Output Example

4. Reproducing the flow rate dynamic change through a doorway

In this section, to verify the validity of our model, we will analyze the flow rate change for a doorway in a virtual room. It is believed that the number of people that flow through a doorway changes over time due to the influence of pedestrians gathering near the door, as well as the presence of pedestrians outside the door.

4.1 Case Study

We'll assume a floor plan that consists of a room and corridor as indicated in Figure 9.



Number of people in the room: 91
Since the population density on the room at this time is 0.7 people/m2 (according to reference 1), this is the equivalent of a classroom.
Case 1: The only exit from the classroom is Exit 2
Case 2: It is possible to exit the classrooms from Exits 1 - 3

Figure 9 Room/Corridor Diagram

Should a fire occur in the room, the room's occupants must quickly move away from the fire and smoke, exiting nearest their current position and evacuating via the corridor and the stairway connected to it. For the sake of simplicity, only the exit from the corridor, and not the actual stairway, is considered for this analysis. The effects of the flames and smoke are not considered; there are no exits from the room that cannot be used.
For comparison purposes, two cases are calculated. Case 1 has only one room exit (Exit 2), and Case 2 has three room exits (Exits 1 – 3).

4.2 Calculation Results and Discussion

Case 1

Figure 10 illustrates a typical evacuation over time. You can see that about 6 seconds after the start of the evacuation, all the room occupants gather before Exit 2 and then gradually flow into the corridor. Note that no pedestrians linger or stop near Exit 4, which is the exit from the corridor. Figure 11 shows the flow rate change over time at Exits 2 and 4.

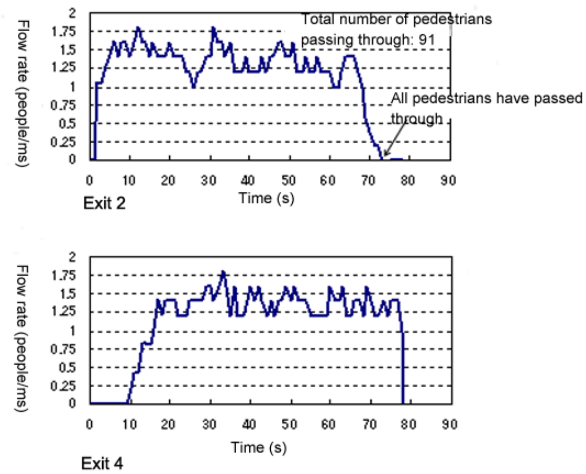


Figure 11 Case 1 Flow Rate Over Time

Examining the flow rate after the occupants have started gathering around Exit 2, we can see that despite small variations and a slight decreasing trend, the flow rate remains roughly constant. The flow rate for Exit 4 shows that the outflow of evacuees begins about 10 seconds after they reach the doorway and, with some slight variations, remains practically constant.

Because this example models walking properties based on the width of the doorways and the flow rate, it can be considered to be similar to a network model. Both Exits 2 and 4 have the same opening width, so we can assume the same flow rate for both doors. The occupants only gather *before* going through Exit 2; therefore, the time difference between the outflow of Exits 2 and 4 can be explained by the time it takes to walk between the two doorways. These simulation results are, therefore, comparable to those of a network model.

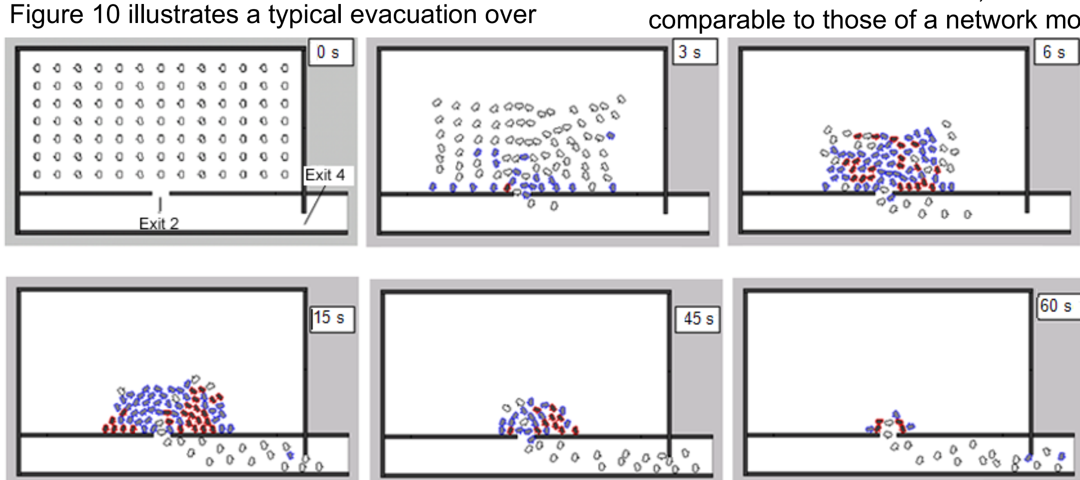


Figure 10 Case 1 Time Variations

Case 2

Figure 12 illustrates a different type of evacuation example. The occupants are almost evenly distributed throughout the room and there are three exits located in the center and at each end of the room. About half of the occupants will aim for Exit 2, in the center, while one quarter each of the remaining occupants will move towards either Exits 1 or 3.

Similar to Case 1, after some time has passed from the start of evacuation, people begin to gather around each door. However, the congestion resolves first at Exit 1, then 2, and finally 3. Even though the width of each doorway is the same, 1.0 m, and there are fewer people moving through Exit 3 than through Exit 2, it takes the longest to resolve the crowding at Exit 3. This is because there is also crowding at Exit 4, the exit from the corridor, impeding the smooth flow of people from Exit 3 located nearby.

Figure 13 shows the flow rate change over time for each doorway. Up until approximately 8 seconds after the start of the evacuation, the flow rate of all three exits (1 – 3), shows an increasing trend approaching 1.5 people/ms. When the evacuation begins, there are fewer people right next to the exits, so the speed of the outflow from the doorway is greater than the speed of people congregating near the doorway. The actual flow rate at the exit is equal to the speed of crowding of evacuees at the exit.

At Exit 1, the flow rate is generally around 1.5 people/ms, 8 – 13 seconds after the start of evacuation, with a slight decrease after that time. When there are enough occupants crowded in front of an exit, the flow rate rises to its highest possible value. As crowding increases further, people must enter the doorway from a standstill, reducing the number of occupants who can go through the opening and therefore, the flow rate.

During the same 8 – 13 second time period from the start, the flow rate of Exit 2 is around 1.5 people/ms. From 13 – 21 seconds, the flow rate decreases to 1.0 people /ms. This is because, 13 seconds after the start of evacuation, the flow of people from Exit 1 reach Exit 2 and prevent people from leaving Exit 2 smoothly. After 21 seconds, the flow rate shows a temporary recovery back near 1.5 people/ms,

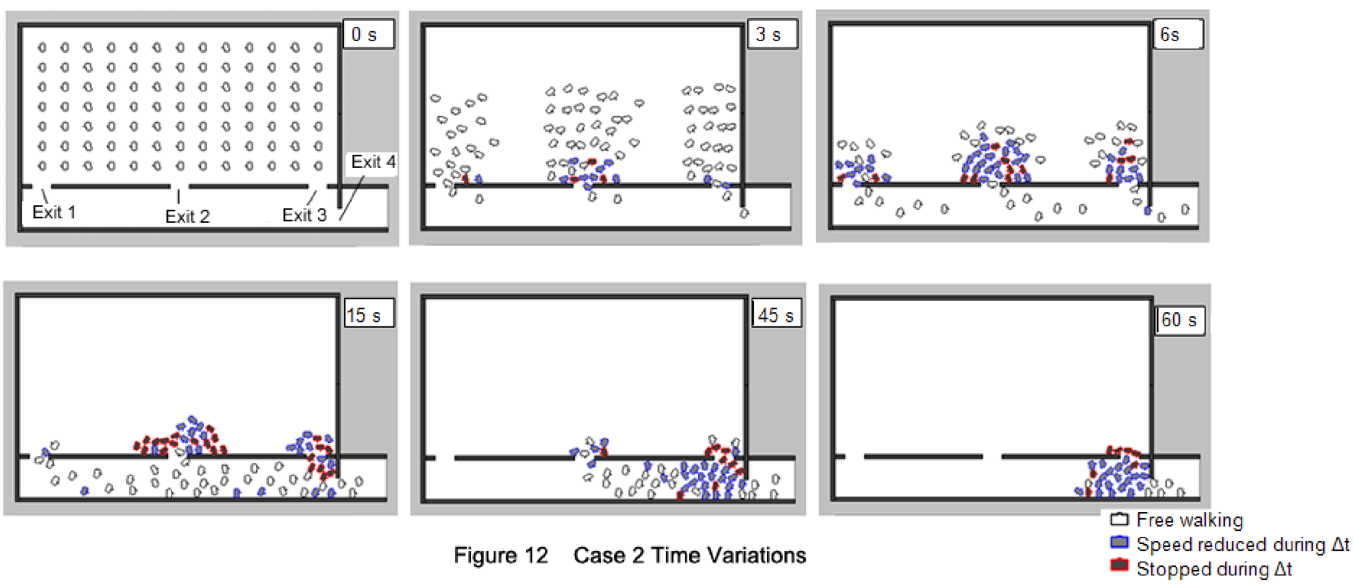


Figure 12 Case 2 Time Variations

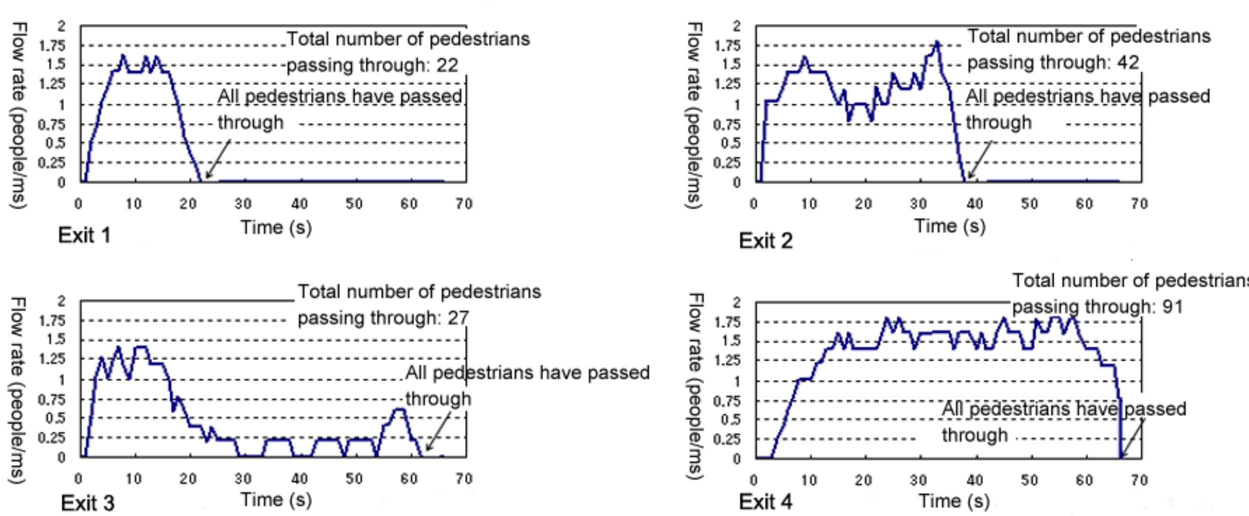


Figure 13 Case 2 Flow Rate Over Time

because fewer people from Exit 1 are blocking the flow of people from Exit 2.

For Exit 3, 13 seconds from the start, the flow rate decreases to an average of 0.15 people/ms, and practically no evacuees can get out. The corridor exit (Exit 4) has become a bottleneck, preventing people from leaving the corridor smoothly. This, in turn, impedes the flow from Exit 3. The flow of evacuees from Exit 3 ends 62 seconds after the start of evacuation, and the final evacuation of all people from the corridor occurs at 67 seconds, indicating that the final flow of people from Exit 3 could not occur until almost all of the people crowding around Exit 4 had left the corridor.

The flow rate for Exit 4 soars 15 seconds past the evacuation start. The flow becomes roughly constant after that. This area became a bottleneck at this time, and during the crowding, the flow of people remained steady.

These studies confirm that the SimTread system can predict the time sequential change in the flow rate and the congestion at doorways. This shows that SimTread can reproduce crowd flow and behavior by taking into account the effect of crowding at exits on the flow rate, which cannot be done with a network model.

5. Summary

The characteristics of the SimTread pedestrian simulation system used for this research are:

- Multi-agent model system with pedestrian agents
- Accurate calculation of the pedestrian conflict avoidance process
- Spatial model based on real coordinates

The following properties have been confirmed for a SimTread study of the change in flow rate over time when simulating typical crowd flow from a room to a corridor exit:

① A sufficient number of occupants leaving a room produces a steady flow rate. People crowding the exit, or a low number of occupants in the room, reduce the flow rate through the doorway. The flow rate changes according to the crowding situation at the doorway.

② If there are pedestrians outside an exit, blocking people who are trying to exit, the flow rate from the doorway is reduced. In addition, crowding at another exit can prevent proper flow of occupants from a nearby exit. The flow of occupants from the blocked exit cannot continue until the first crowding situation has been resolved.

③ Similar simulations without any flow rate reductions (no crowding) display crowd flow analyses that are equivalent to those predicted by network models.

Property ① is difficult to reproduce with a network model. Although there is some room for discussion as to the degree, it can be said that SimTread can accurately predict and reproduce actual crowd flow phenomena. In addition, although Property ② could potentially be replicated with a network model, it would not be able to take the floor plan into account. Regarding Property ③, naturally, a floor plan which does not create a crowding situation will also not restrict the flow rate, and it has been confirmed that similar results can be obtained from both a multi-agent model and a network model.

As mentioned, it is clear that the SimTread multi-agent model pedestrian simulation system, which is based on the use of an actual model, is both useful and effective in reproducing crowd flow.

Future research topics include defining a parameter set based on the results of a variety of current pedestrian studies, optimizing the dimensions of the conflict determination area, and simulating actual walking properties of pedestrians.

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Notes

Note 1) Grid spacing, based on the Δt and walking speed, was set considering computing speed and memory usage so as to ensure sufficient accuracy in the study design.

Note 2) The advantage of this method, as opposed to the simple method which aims towards a single grid point with a low potential value, is that movement direction is not limited to the grid point direction.

Note 3) In this system, the values of the various parameters can be changed and it is possible to set more realistic values, but the settings indicated here were determined to match both verification methods and conditions for a network model comparison.

Note 4) This figure is a correction of Figure 3 in Reference 3.

Note 5) The limit to the number of times the rotation extent, a certain angle, a certain ratio, and the temporary movement position can be recalculated is determined correctly while changing the parameters, repeating the simulation experiment and verifying the behavior of an individual human model.

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