

Simulation Experiment of Routing Strategy for Evacuees and Disaster Responders

SeHoon Lee, Jang Won Bae, Junseok Lee, Jeong Hee Hong, and Il-Chul Moon
Department of Industrial and Systems Engineering

KAIST

shlee0814@kaist.ac.kr, reputed82@kaist.ac.kr, agil923@kaist.ac.kr, jhhong@smslab.kaist.ac.kr, and
icmoon@kaist.ac.kr

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Abstract

Under urban crisis situations, one of the most important response tasks is routing the vehicles. Such crisis initiates a massive evacuation from the disaster scene to the outside; at the same time, crisis responders have to enter the scene. Whereas we need routes for responders, current disaster response plans frequently dictate to turn bidirectional roads into one-ways to ensure quick evacuation. This routing conflict should be resolved prior to actual crises, and we approached this problem with simulation based experiments. We modeled and simulated the urban traffic network, the responder agents and the evacuation agents. Our major decision factor is how to choose road lane utilization to facilitate the evacuation as well as the response. We evaluated the efficiency of the route planning with responder arrivals and evacuation durations. The results may provide some insights to disaster managers or authorities under crisis.

1. INTRODUCTION

In densely populated urban area, disasters can occur without warning, cause the large number of human loss, and damage to city infrastructures. When facing a large-scale disaster, massive population initiates to evacuate from the disaster location to outside; at the same time, crisis responders enter the city for rescue. In the evacuation aspect, faster evacuation can save more people from additional strike of disaster or secondary damage from the disaster. For example, there is a research that describes the gridlock in the traffic network lead to massive loss of life by hurricane [12]. For more efficient evacuation and rescue plan, urban planners are challenged to control the traffic. Evacuation traffic management is a critical part of evacuation plan and traffic control function includes enforcing and prohibiting the traffic [14]. Enforcing the traffic is allowing more traffic demand to the road capacity, and prohibiting the traffic is allowing less traffic demand to the road capacity. There are many researches considering traffic demand and road capacity during evacuations [15] [16].

However, making a plan of traffic control in a disaster situation is quite complex due to the dynamics of evacuation,

such as the large number of people and their interactions, and external factors including destroyed road network [17]. Current disaster response plans frequently dictates to turn bidirectional roads into one-ways to ensure fast evacuation. For example, Florida has one-way evacuation plan [18]. Moreover, finding balanced routing plan between evacuation and rescue activity is a critical and hard problem in the dynamics of evacuation. Unfortunately, few researchers have considered the inconsistency between the evacuation and the rescue plans.

In order to provide a more improved analysis for both evacuation and rescue plan, we approached this problem with simulation based experiments. Particularly, we utilized an agent-based model (ABM). Because of the property of ABM, it is generally applied to gain the insights into dynamic changes induced by individuals. Especially, ABM is one of the most frequently applied methods to simulate the population movements [13]. We also apply a geographic information system (GIS) data [19] for reflecting reality to our model.

This paper introduces the details of our models, simulations and virtual experiments. The simulated area is GangNam, a district in Seoul. GangNam area is approximately 62 square kilometers, which is about 13% of Seoul, and there is a large number of population, and crucial buildings, such as the headquarters of companies and public organizations. We modeled and simulated evacuation agents, rescue agents, emergency manager agent and the traffic environment. Our major decision factor is how to assign lane ratios of roads for evacuation and rescue in the specific area, and we evaluate the efficiency of the route planning with duration of rescue and evacuation activity.

2. PREVIOUS RESEARCH

2.1. Evacuation Model

The goal of effective evacuation is to lead the people rapidly and safely to the city shelter of outside of the city, avoiding further damage from the disaster. There are a number of evacuation models in literature. The Network Emergency Evacuation (NETVAC) model was developed by Sheffi et al [1]. It was a macro traffic simulation model for estimating the network clearance time in evacuation of a nuclear power plant area. They assumed that a driver

approaching an intersection makes a route selection to take a faster routing. The driver's route selection was based on the prior knowledge and myopic behavior. Although this model can handle various evacuation management strategies applying network topology and intersections control, it cannot capture the behavior of individual vehicles.

In evacuation, behavior of individual has critical effect on the evacuation result. To capture the behavior of individual and their interactions, agent-based model is a powerful modeling technique describing the individual's behavior and interaction. Many researchers have applied the agent-based model in evacuation study. Kagaya et al. developed multi-agent simulation to reproduce the traffic behavior and interactions during earthquake impact [2]. The agents were categorized into seven groups based on the survey. Action rule of agent depended on its group. Chen et al. designed agent-based model for analysis of hurricane evacuation. This study attempted to estimate the clearance time needed for evacuation and the number of stranded people, if evacuation route becomes impassable. They applied population data and real road network data. They assumed the agents adjust their route dynamically based on real time traffic conditions. Chen and Zhan developed agent-based model to investigate the effectiveness of evacuation strategies [3]. The agents in different zones were organized to evacuate in different sequence. They also suggested three types of road network structure including grid structure, ring structure, and real road structure. They compared the evacuation time between different strategies. Rossetti and Ni developed agent-based model for evacuation in commercial shopping districts [4]. They used GIS data involving road network and parking lots. They estimated the traffic bottlenecks from the simulation experiments. Chen et al. developed a predictive model of emergency behavior using cell phone and GIS data, with agent-based systems [5]. Cell phone data was used for estimating the agent's evacuation movement. The simulation was continuously updated with real time cell phone data. Madireddy et al. developed agent-based model for analysis of evacuation traffic management [6]. They tested the evacuation strategy called throttling, which involved closing the road segment when the traffic congestion level exceeds the threshold. Zia et al. developed agent-based evacuation model [7]. The generated agents were categorized into 2 types. One type of agent only moves to nearest destination, and another type of agent calculates the optimal with available information. The environment was modeled as cellular-automate based on real map. Unfortunately, all of studies focus on not both evacuation and rescue operations but evacuation only.

2.2. Rescue Model

The goal of effective rescue model is to save as many as possible casualties in the disaster area. Casualties who

have got damaged from the disaster need rescue operations to be transported to specified hospitals. Thus, some researchers have studied to provide effective managements of rescue services. The first rescue model was developed by Christie and Levary [8]. The objective of the model was to make an effective plan of transportation of the seriously injured to hospitals after human-caused disaster in a crowded city. They developed queuing simulation model and compared the transportation time in three different scenarios. They took the distributions of travel time from the disaster site to hospital as an input variable. However, their model didn't consider the behaviors of individual or the dynamics of emergency.

ABM is also applied for several rescue models. Takahashi et al. applied multi-agent approach to a rescue model [9]. This paper estimated the efficient rescue operation with different communicating types between rescue agents. There were residential agents in the area and they had damage level of body and stamina. The rescue agent was composed of three types, fire brigades, ambulances, and polices. The role of fire brigades was firefighting. Ambulance can bring the residential agents to refuge, and police can repair collapsed roads. They also applied real GIS map for environment model. Chu et al. built a decision supporting system (DSS) to provide a useful means for building ambulance decision making [10]. They applied interactive learning and machine learning technique to teach the ambulance agent. They also used GIS data for environment modeling. Furuya and Sadohara developed rescue activity model in earthquake to investigate factors significantly affecting rescue efforts [11]. It described the evacuation and rescue activities but there was no separate rescue agent. After the evacuation agent move to rescue spot, then it will take part in rescue. The initial positions of the agent were determined manually. They used GIS data for environment model.

3. METHOD

This section describes the overall structure of the model, details of each model with formal description, and virtual experiment design of our simulations.

3.1. Overall structure of the model

Figure 1 shows the hierarchical structure of our model. In the hierarchical structure, the bottom level models are atomic model in DEVS formalism and higher level models are coupled model in DEVS formalism. The simulation model consists of the multi agents model and the multi environments model. The multi agents model is composed of three kinds of agent model; evacuation agent model, ambulance agent model, and emergency manager agent model. Each of the agents is modeled for a different agent

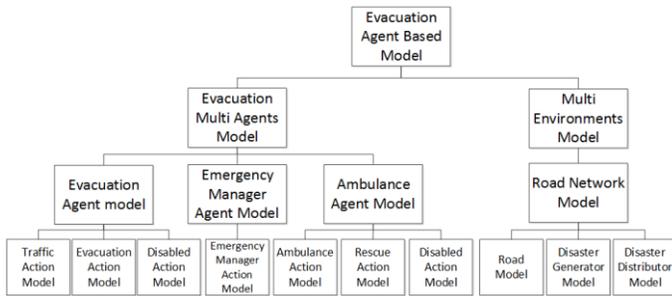


Figure 1. Hierarchical structure of the evacuation agent based model

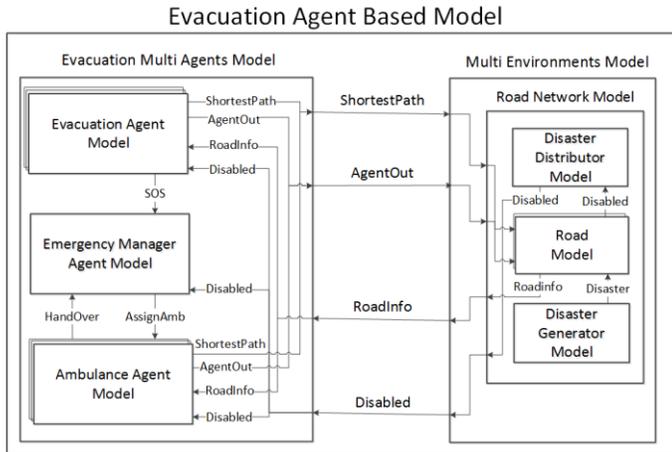


Figure 2. Coupling relations of the interaction events in the evacuation agent based model

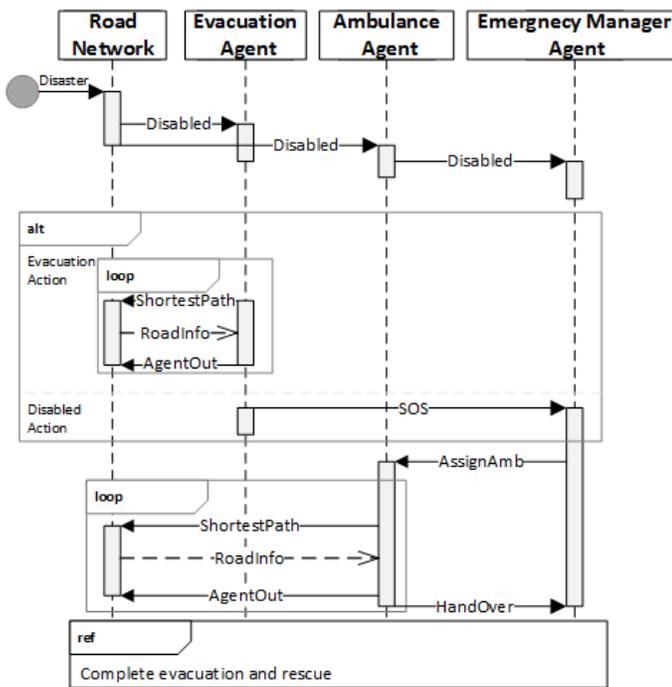


Figure 3. Event flows between component models in the evacuation agent based model

models (traffic action model, evacuation model, disabled action model), and selects one of the action models under the agent status. Similarly, an ambulance model contains three action models (ambulance action model, rescue model, disabled action model), and selects one of the action models under the certain condition. The emergency manager agent model has one action model, emergency manager action model. The multi environments model contains a road network model. The road network model is composed of multiple road models, a disaster generator, and a disaster distributor model.

Figure 2 shows coupling relations of interaction events in the evacuation agent based model. The coupled model describes interactions between the multi agents model and multi environments model. The agents interact with environments by exchanging messages, such as *ShortestPath*, *AgentOut*, *RoadInfo*, and *Disabled* message. First, *ShortestPath* message is sent from multi agents model to multi environments model. The agent model requests a shortest path by sending this message, when it needs to move. Second, *AgentOut* message is sent from multi agent model to multi environments model. When an agent arrives at the end of a road, the agent notifies that it is leaving from the road to road model. Third, *RoadInfo* is sent form multi environments model to multi agents model. When the road network finds shortest path of an agent, it delivers the first road information to the agent, such as velocity and direction of the road. Finally, the *Disabled* message is sent from multi environments model to multi agents model. When disaster occurs, the evacuation agents or ambulance agents decide whether they are damaged or not by the information of message.

Figure 3 describes the event flows between component models in the evacuation agent based model. When disaster occurs, *Disabled* message is distributed from road network model to evacuation agent and ambulance agent models. If an ambulance agent is disabled, then it sends a *Disabled* message to emergency manager agent. When an evacuation agent receives the *Disabled* message, it chooses the evacuation action or disabled action. In the evacuation action, it finds the nearest evacuation point and begins to evacuate. In disabled action, it requests for rescue and waits. When emergency manager agent receives *SOS* message, it finds the nearest and available ambulance and assigns the disabled agent to the ambulance. After finishing the transfer, the ambulance sends a *HandOver* message to the emergency manager. Simulation is end if all the evacuation and rescue activity is completed.

3.2. Evacuation Agent Model

Evacuation agent model represents an individual vehicle. Before the simulation starts, the agents are positioned on the roads based on the real world traffic data.

Table 1. Summary of geospatial data for GangNam region

Category	Descriptive Statistics on Gangnam region
Scope of latitude coordinate	37.4754 ~ 37.5306
Scope of longitude coordinate	126.0782 ~ 126.9862
Size of the region	62km ²
Number of roads	12,730
Number of junctions	8,990

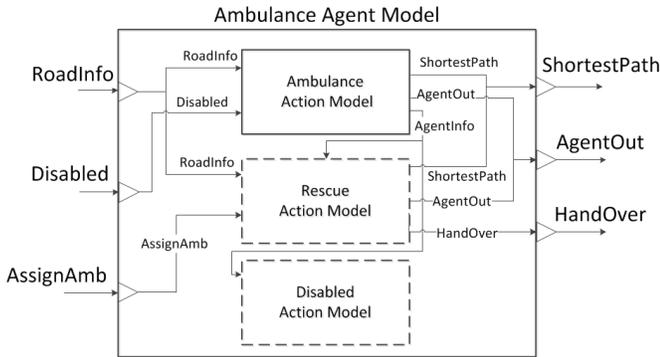


Figure 4. Model diagrams of ambulance agent mode

Using the speed at roads from the real data, we calculate the required number of agent on each road by reverse operation of road velocity. In section 3.6, the description of applying real data will be explained in detail. When the simulation starts, it selects the traffic action model, which describes agent actions in daily life. After perceiving the disaster, the agent decides whether it begins to evacuate or sends request for rescue. If it selects disabled action, the action model is changed to disabled action model. The disabled agent requests for rescue by sending a *SOS* message to emergency manager agent and waits until being rescued by an ambulance agent. If it is out of the range of the disaster, then the action model is changed to evacuation action model. In figure 5, the evacuation action model is described as a DEVS diagram. In the evacuation state, the agent selects the nearest evacuation point by Manhattan distance. When the agents find the nearest evacuation point, they plan to a route by sending *ShortestPath* message. It moves along the route until arrive the evacuation point.

3.3. Ambulance Agent Model

Ambulance agent model takes rescue operations in disaster situations by transporting disabled agents to the hospital. The level of damage was not considered, so the ambulance agent transports all the disabled agents in same manner. Figure 4 represents a coupled model diagram of ambulance agent model. When the simulation starts, it selects an ambulance action model. The ambulance operation in daily life is out of our objectives, so it stays in

the initial position before disaster. When disaster is occurs, it receives the *Disabled* message. If it is damaged from the disaster, then its action model is changed to disabled action model. Otherwise, its action model is changed to rescue action model, which is described as a DEVS diagram in figure 5. An ambulance agent waits until it is assigned to a disabled agent. When it perceives *AssignAmb* message, it plans to rescue to disabled agent by sending *ShortestPath* message. After transporting the disabled agent to hospital, it notifies the finish by sending *HandOver* message and waits the next assignment.

3.4. Emergency Manager Agent Model

Emergency manager agent model controls disaster responses by assigning an ambulance to a disabled agent. It contains emergency manager action model and it is described as a DEVS diagram in figure 5. Initially, it has the information of ambulances. When a disaster occurred, it receives the *SOS* message from a disabled agent and assigns the nearest ambulance to a disabled agent by sending *AssignAmb* message. When it sends the *AssignAmb* message, the information of the ambulance is changed from idle to busy. When it receives a *HandOver* message, the information of the ambulance is changed from busy to idle.

3.5. Road Network Model

Road network model is the environment model, which finds the shortest path in the current traffic applying A* algorithm, generates the disaster, distributes the result of disaster, and updates the dynamic of road network. There are three atomic models under road network model: road model, disaster generator model, and disaster distributor model. First, a road model is the essential component in network structure and end points of the road is regarded as junctions. Road is generated by the GIS data. From the real GIS data, parameters of the road, such as road end point, maximum velocity, lane, length, and layer of the road, are set. In the simulation, the road model has a critical role in movement of agent on evacuation and rescue. The road model updates the velocity, when it receives the *ShortestPath* or *AgentOut* message. The agent sends *ShortestPath* message when it comes to a road and *AgentOut* message when it moves out from the road. To calculate the velocity by changing of the number of agents on a road, we defined density of the road. The road density is defined as the number of agents (No.Agent) over road area (area = lane × length). Based on the concept of the road density, we assume that the velocity decreases as the number of agents on the road increases. If there is no agent on the road, the velocity is same as the maximum velocity. We also added a coefficient 'c' to relax the assumption of

road status. Road density function and velocity function are as follow:

$$(\text{Road Density}) = \frac{(\text{No. Agent})}{(\text{Road Area})} \quad (1)$$

$$(\text{Road Velocity}) = \frac{(\text{Maximum Velocity})}{c \times (\text{Road Density}) + 1} \quad (2)$$

Second, a disaster generator describes time and area. Third, a disaster distributor model delivers the disaster information to the agent models and the other environment models.

3.6. Virtual Experiment

To evaluate the efficiency of evacuation routing plan, we performed simulation-based experiments. As an experiment scenario, we developed local disaster situation of GangNam region in Seoul. As the core region of Seoul, GangNam has the large number of population and buildings. Besides, Seoul could be the possible target of attack of North Korea. Considering these conditions, we designed the scenario in which agents will evacuate to the outside of the region. Before the simulation starts, the evacuation agents are located on the roads in GangNam region, based on the real traffic data. When disaster occurs, the environment models in disaster area are destroyed and traffic control is performed in the predefined area. In addition, evacuation

agents start to evacuate from the damaged road network and disabled agents request rescues, and emergency agents allocate the ambulances to disabled agents. Then, the ambulance agents start to rescue. The simulation would be end when all of evacuation and rescue activity is finished or at simulation end time. Based on our scenario, we applied real data to the model and designed the virtual experiment. In next subsections, we explain the applied real data and virtual experiment design.

3.6.1. Description of applied real data

Two datasets are used to provide a simulation scenario for our model. The first dataset is traffic data that is utilized to allocate the initial positions of evacuation agents. The second data is GIS data, which contains the geospatial data, to generate the road network model.

Initial position of the agents is the important factor to the simulation result. Hence, to reflect reality to our model, we calibrated the initial position through real traffic data. The traffic data contains average velocity of roads, which is provided by National Transport Information Center. We generated agent distributions by reverse operation of equation (2). From the reverse operation, we get below equation.

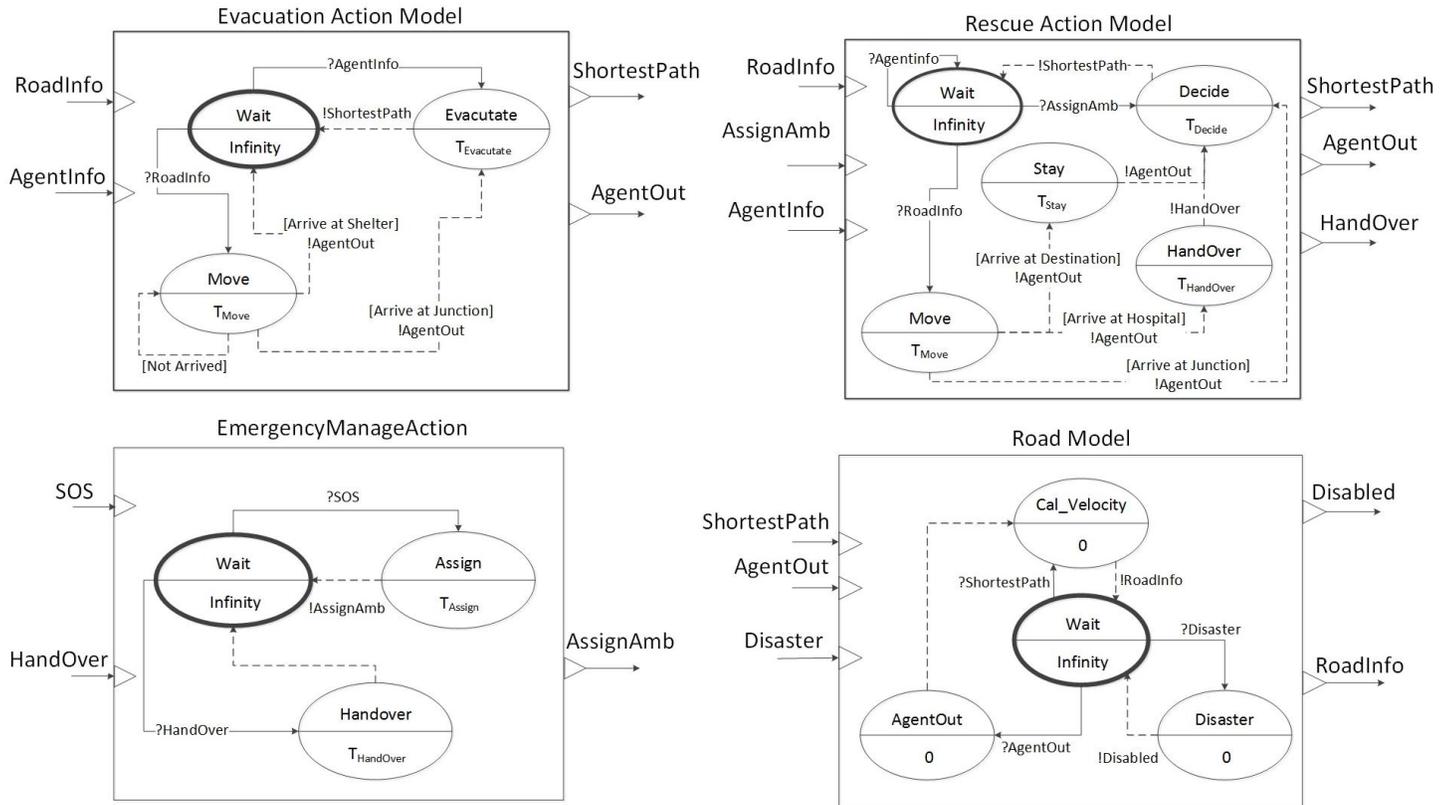


Figure 5. State diagrams of atomic models: evacuation action model of evacuation agent (Top-Left), rescue action model of ambulance agent (Top-Right), emergency manage action model of emergency manager agent (Bottom-Left), and road model of environment (Bottom-Right)

Table 2. List of input variables, output variables, and parameters of the evacuation agent-based model

Type	Name	Implications
Input	Lane ratio	Lanes for evacuation : lanes for rescue (Lanes for evacuation / Total lanes of Road)
Output	Average of evacuation time	Average evacuation time of successfully evacuated agents
	Average of rescue time	Average rescue time of successfully rescued agents
	Average number of rescued agents	Average number of successfully rescued agents
Parameter	Re-routing probability	Probability of re-routing, when agent encounters the traffic congestion (default = 0.5)
	Width of traffic control area	Width of traffic control area, where the traffic controls are in operation (default = 250 m)
	Number of ambulance agent	Number of ambulance agents in the simulation (default = 24)
	Initial position of ambulance agent	Initial position of ambulance. Tertiary hospitals and fire stations (default = 2 tertiary hospitals and 7 fire stations)
	Total number of evacuation agent	Number of evacuation agent in the simulation (default = 3000)
	Evacuation point	Destination of evacuation. Based on the scenario, points at the outside of the region is selected (default = 23 points)
	Coefficient of road velocity	Coefficient of road velocity to relax the assumption of road density (default = 0.001)
	Number of disaster	Number of local disaster (default = 8)
	Location of disaster	Source of disaster (default = randomly selected in region of interests)
	Radius of disaster	Distance from the source, when disaster occurred (default = 365 meters)
	Simulation end time	End time of simulation (default = 3000 time tick)

Table 3. Virtual experiment design of scenario of interests

Experiment Variable Name	Experiment Design	Implications
Lane Ratio	1:1(0.50), 1:2(0.33), 1:3(0.25), 2:1(0.67), 3:1(0.75) (5 cases)	Lanes for evacuation : lanes for rescue (Lanes for evacuation / Total lanes of road)
Total Number of Experiment Cells	5 experiment cells	Each cell is replicated for 10 times

$$(\text{No. agent}) = \frac{(\text{current velocity})}{(\text{maximum velocity})} \times \frac{(\text{road area})}{c} \quad (3)$$

In equation (3), current velocity is obtained from the traffic data and other parameters are defined by GIS data. The number of agents is calculated from real data, but total number of agents is often defined in a model parameter. Hence, the sum of agents from real data is not always same as the total number of the agents. To prevent this situation, we represent agent distributions from the number of agents from real data, which is defined by dividing the number of agents by the total number of agents. With the agent distributions, we determined the number of the agents in the road before simulation starts. Moreover, we also reset the coefficient in equation (2) with respect to varying the located number of agents on the road. Figure 6 (a) illustrates the initial position of the agents. The evacuation agent is illustrated as yellow star and ambulance agent is illustrated as red cross in the map.

In our simulation, all evacuation agents and rescue agents move through the road network of the region. The structure of the road network is significant to the outputs of simulation, evacuation and rescue time. Thus, we developed the road network based on geospatial data of GangNam

region to make the simulation results more realistic. GIS data of the region is obtained from OSM (OpenStreetMap). GIS data from OSM include information of roads and buildings about coordinates, type, and identification. Applying GIS data, we develop roads and junctions. The length, width, and velocity of the road were also defined based on the real data. The summary of geospatial data is described in Table 1. We covered 12,730 roads and 8,900 junctions in GangNam region.

3.6.2. Virtual Experiment Design

We built the agent-based model in disaster situation to describe the evacuation and rescue. Simulating models, we estimate the efficiency of routing plan. Table 2 enumerates the utilized datasets, simulation parameters and the generated output for analysis. The output is the average time of evacuation and rescue, and the average number of rescued agents. The width of the traffic control area is where the traffic control is applied. The length of the traffic control area is the distance between hospital and the location of disaster. The width of the traffic control area is our experiment variable. The traffic control area is defined as rectangle with the length and width of traffic control area.

Because the conflict between evacuation and rescue is occurred in specific area, which is nearby the disaster point and hospital, we defined the traffic control area between disaster point and hospital with rectangle shape and changed lane in traffic control area depending on the lane ratio. Evacuation and ambulance agents make a re-routing, when they encounter the traffic jam. The number of ambulance agents is 24 as a default value, which could affect the conflict of the road and the rescue time. Table 3 shows the virtual experiment design to setup the scenario of interests and estimates the efficiency of routing plan. For a routing plan, we tested 5 cases, varying the ratio of lane for evacuation and rescue. As more lanes are allocated to evacuation, the evacuation time will decrease and rescue time will increase. Considering these variables of experiment with different parameters, we simulated and analyzed 5 experiment cases. We replicated the simulation of our model for 10 times for statistical analyses.

4. RESULTS

Based on our virtual experiment design, we performed simulation experiments. We analyzed the results with performance analysis. Figure 6 is the screenshots of the virtual experiment. It would help to understand the dynamic changes of the simulation.

Figure 7 (a), (b), and (c) illustrate the results of the average evacuation time, average rescue time, and average number of rescued agents with different lane ratio, respectively. The results show that the lane ratio with 0.5 outperformed on all performance indices. It means that the routing plan is more efficient when the lane is equally allocated for evacuation and rescue.

5. CONCLUSION

We studied the efficiency of routing plan under crisis situation with simulation experiments. Our model is calibrated with real traffic data and GIS data. The analysis results estimate that evacuation and rescue activity developed well in the road network with equally allocated lane. We expect that the result of our experiment can be an example to provide some insights to disaster manager or authorities under crisis.

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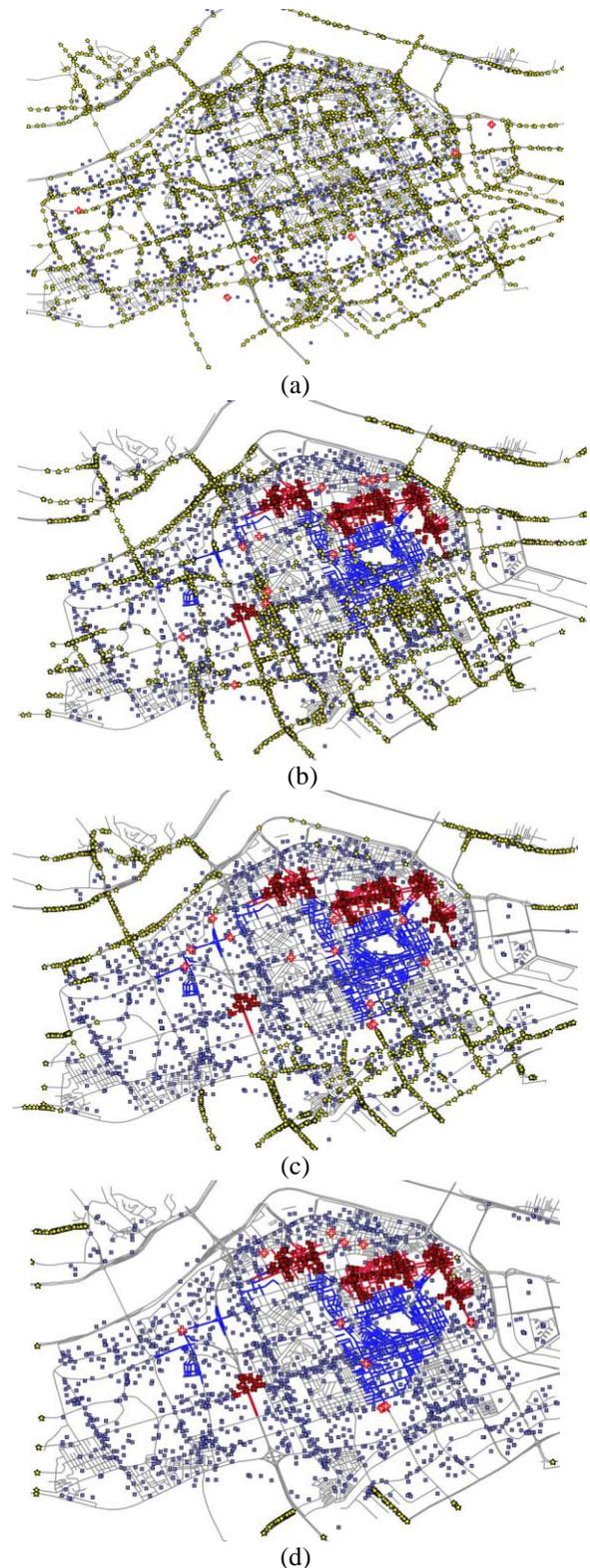


Figure 6. Simulation screen shots: (a) initial position of agent, (b) simulation screen shot at 300 ticks, (c) simulation screen shot at 1000 ticks, and (d) simulation screen shot at 3000 ticks. (red: destroyed roads, blue: traffic control roads)

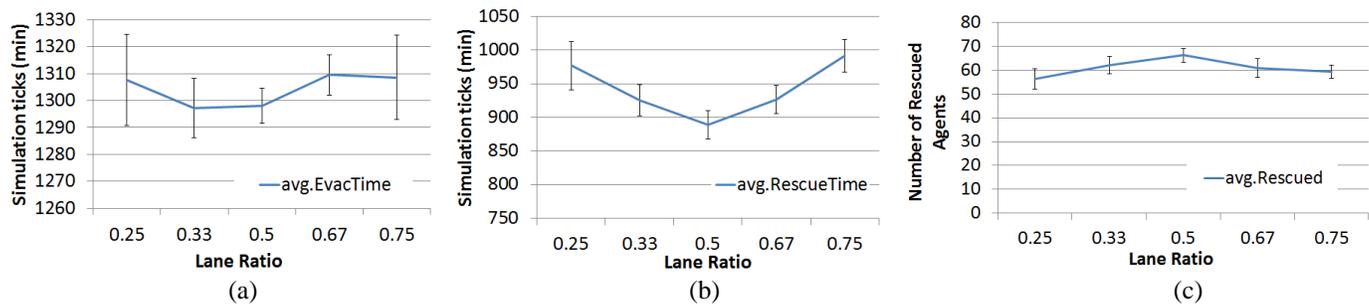


Figure 7. Results of virtual experiments: average of evacuation time (a), average of rescue time (b), and average of the number of rescued agents (c) for overall scenarios.

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