

# **Agent-Based Simulation of Evacuation Strategies under Different Road Network Structures**

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## **Abstract**

This study aims to investigate the effectiveness of simultaneous and staged evacuation strategies in different road network structures using agent-based simulation. In the simultaneous strategy, all residents in the affected area are informed to evacuate simultaneously; whereas, in the staged evacuation strategy, residents in different zones of the affected area are organized to evacuate in a sequence. The effectiveness is measured by the total time needed to evacuate the population in the affected area. With the aid of agent-based modeling, this study was able to model traffic flow at the level of individual vehicles and to present the collective behaviors resulting from the interactions of individual vehicles during an evacuation in a natural way. We conducted simulations on three types of road network structures: a grid road structure, a ring road network, and a real road structure from the city of San Marcos, Texas. We used the default rules in a simulation software package called Paramics for trip generation, destination choice, and route choice in the simulations. For each road network structure, we recorded the evacuation time for each strategy under different numbers of departing vehicles from a block. Preliminary results indicate that: (1) When the traffic is in a free flow mode and there is no congestion on the road, the simultaneous evacuation strategy is the fastest; (2) under a congestion situation, some

staged evacuation strategies are more effective than the simultaneous evacuation strategy on the grid road network; there is no obvious advantage of the staged evacuation strategies over the simultaneous evacuation strategy on the ring road network and the real road network in this study; (3) under the same evacuation strategy, it takes less time to evacuate the similar amount of vehicles on the grid road network than on the ring road network.

## **1. Introduction**

This study aims to investigate the effectiveness of the simultaneous and staged evacuation strategies under different road network structures using agent-based simulation. In the simultaneous strategy, all residents in the affected area are informed to evacuate simultaneously, whereas in the staged evacuation strategy, the study divides the affected area into different zones, and residents in different zones of the affected area are organized to evacuate in a sequence. In both strategies, evacuation effectiveness is measured by the total time needed to evacuate all vehicles in an affected area since the first notification of evacuation is given. The study examines the performance of the evacuation strategies on three types of road network structures: a grid road structure, a ring road network, and a real road structure from the city of San Marcos, Texas. For a given evacuation strategy, the study also attempts to find out what type of road network structure would be more advantageous in an emergency evacuation.

The general approach to model emergency evacuation is to delineate the area impacted by a known hazard, and then estimate the time needed to evacuate all people in the area through simulation. However, existing methods are based on network flow models that are unable to capture the behavior of individual vehicles which play a crucial role in emergency evacuation.

Agent-based modeling, sometimes called individual-oriented, or distributed artificial intelligence-based, is an increasingly powerful modeling technique for simulating individual interactions in a dynamic system and is distinctive in its ability to simulate the situation where the future is unpredictable (Lampert 2002). Contrary to macrosimulation, microsimulation is able to track the fine detail of an individual in an emergency situation. In agent-based modeling, individual vehicles are treated as autonomous decision-making agents and each agent makes decision and acts based on the interactions with other agents and the information collected from the environment. The basic characteristic of an agent is that it is an intelligent decision maker that generates events or movements that can affect itself and other agents (Deadman 1999). An agent can adapt its actions to the actions of other agents as well. With the aid of agent-based microsimulation, the emergence or group/collective behavior as a result of the actions and interactions of the individual vehicles during the process of an evacuation can be captured naturally. The outcome of the collective behavior can be further measured as the total time needed for all vehicles to get out of the affected area.

Given the limited road network capacity in an area, the staged evacuation strategy may take less time than the simultaneous evacuation strategy if traffic congestion happens. It is not practical or too costly to carry out the experiment and find out the answer in real life. However, with the aid of agent-based modeling technique, the results from this study will help shed light on the development of an effective evacuation strategy under different road network structures, as well as on the design of the most advantageous road network layout in transportation planning, from the perspective of emergency evacuation.

The rest of this paper is organized as follows. Section 2 briefly reviews some related work. Section 3 describes the design and implementation of the experiment. Section 4 discusses

the findings of the study, and Section 5 addresses issues related to future research.

## 2. Literature review

Few microsimulation studies of emergency evacuation have been documented in the literature before 1990s. Some earlier examples of microsimulation regarding emergency evacuation are given by Peat *et al.* (1973), Sugiman and Misumi (1987), and Stern and Sinuany-Stern (1989). The lack of microsimulation studies was largely due to the fact that modeling traffic flows at the individual vehicle level is a computationally challenging task, and there were inadequate computer technology and advanced software engineering to easily simulate the complexity of traffic flow involving a large number of vehicles. The traditional approaches thus have chosen to estimate evacuation time from an affected area using static analysis tools at the macro or meso level (Moeller *et al.* 1981; Sheffi *et al.* 1982; Hobeika and Jamie 1985; Pidd *et al.* 1996; Farahmand 1997; Cova and church 1997; ORNL 1998; Urbanik II 2000).

In the past decade, because of the advancement of computer technology, there has been a surge of traffic flow studies using microscopic simulations. Using a behavioral-based micro traffic simulation model, Sinuany-stern and Stern (1993) examined the sensitivity of network clearance time to several traffic factors and route choice mechanisms in a radiological emergency situation. Interaction with pedestrians, intersection traversing time, and car ownership were the major traffic factors, whereas shortest path and myopic behavior were the route choice considerations in their study. They found evacuation time comes closer to reality when interaction with pedestrians and a uniform distribution of intersection traversing time are assumed. Another noticeable emergency evacuation research at the micro scale was done by Pidd

*et al.* (1996). By linking a geographical information system (ARC/INFO) with a specially written object-oriented micro-simulator, Pidd *et al.* presented a prototype spatial decision support system (SDSS) for use by emergency planners in developing contingency plans for evacuation from disaster areas. The vehicle was designed to find the way to the destination via available roads without immediate congestion. However, this study did not entail the interactions between individuals and the effect of the collective characteristics of the drivers on evacuation.

Due to its advantage in capturing individual and collective human behaviors in a dynamic complex system, agent-based microsimulation modeling has received significant attention in recent years (Bonabeau 2002a, 2002b; Anderson 1999; Ebeling and Schweitzer 2001; Gilbert and Banks 2002). In an agent-based simulation, an agent is an autonomous decision-making entity. A model of the agents and a model of their environment are two basic components of agent-based modeling (Deadman 1999). A set of rules is used to govern the behavior of the agents. As a result of the actions and interactions of the agents, the emergence, or the group behavior can often be obtained through the outcome of the simulation. Agent-based simulation can help a researcher to study how a change of behavior rules can affect the behavior of a group of agents, or how different environmental settings can influence the group behavior.

Because it is relatively easy to specify the environment information in traffic, such as road category, traffic lights, and traffic signs, and to formalize the behavior rules in driving, such as the rule regarding accelerating, decelerating, and lane changing, there has been an increasing interest in modeling traffic by employing agent-based modeling (Blue and Adler 1998; Dia 2002; Cetin *et al.* 2002; Wahle *et al.* 2001; Claramunt and Bin Jiang 2001). Based on agent-based microsimulation techniques, Church and Sexton (2002) investigated how evacuation time can be affected under different evacuation scenarios, such as opening an alternative exit, invoking traffic

control, changing the number of vehicles leaving a household etc. Cova and Johnson (2002) applied agent-based microsimulation to test neighborhood evacuation plans in an urban-wildland interface. With the aid of agent-based technique, Cova and Johnson were able to assess the spatial effects of a proposed second access road on household evacuation time in a very detailed way. Batty et al. (2002) described an agent-based model to simulate the changing of the route of an annual Carnival event over two days each year. They examined how behavior emerged from the accumulated interactions between small-scale agents and demonstrated how congestion and problems over safety could be resolved through introducing traffic controls. The studies mentioned above suggested that the environment and outer factors play important roles in influencing individual behaviors so as to the collective behaviors and eventually affect the effectiveness of the evacuation plan. What's more insightful is that those works revealed the great benefits of employing agent-based microsimulation technology in emergency study. However, according to the author's knowledge, no work has assessed the effectiveness of the simultaneous evacuation strategy and the staged evacuation strategies at a microscopic level.

On the other hand, it is also important to investigate the effectiveness of different road network structures under emergency situations. A study by Hobeika and Kim (1998) suggested that evacuation performance is largely dependent on the network structure and the number of vehicles produced in an emergency planning zone. However, a lot of studies regarding road network performance were conducted under normal circumstances (Ball *et al.* 1995; Lam and Xu 1999; Chen *et al.* 1999; Quiroga 2000; Sanso and Milot 1999; Russon and Vitetta 2002). Few of them took into account traffic demand under emergency situations and addressed the effect of the interactions between individuals' driving behaviors in an emergency situation. Although the work by Russon and Vitetta (2002) incorporated driver behavior to analyze urban transportation

performance under emergency conditions, they used a static equilibrium model to address the highly dynamic features in traffic flow and the imposed artificial rules to govern a driver's behavior. With the aid of agent-based microsimulation, the assessment of the performance of different road network structures is much closer to reality.

### 3. Simulation Procedures

#### 1) Preparation of road network

The simulations were performed in Paramics — a software designed for microscopic traffic simulation (Quadstone 2002). To investigate the effectiveness of the simultaneous evacuation strategy and the staged evacuation strategy, we prepared three sets of road networks. The first two sets are simulated road networks, one Manhattan network and the other ring road network (Fig. 1a, 1b). The third set of road network is based on the real road network in a residential area in the city of San Marcos, Texas (Fig. 2).

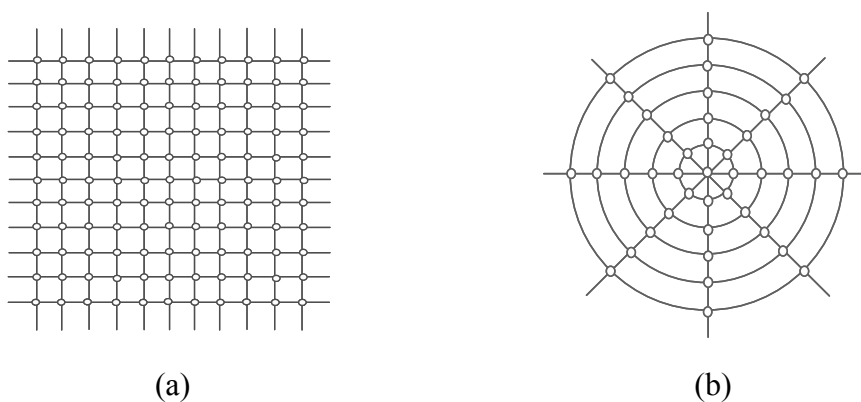


Figure 1. (a) grid road network containing 121 nodes; (b) ring road network

Roads in the simulated networks were set as urban roads with the same speed limit. Each road segment has two lanes, one in each direction. The road segments between two nodes along those straight lines are of the same length in both networks. All rings have the same center in the ring network. For each grid in the grid road network, one exit/entrance at one side was provided for the vehicles to leave or enter the block. In the ring road network, the exits/entrances were also set along the road segments based on a similar distance interval as those in the grid road network. Priority turns were set for each intersection in such a way that straight traffic has higher priority than right-turn traffic and right-turn traffic has higher priority than left-turn traffic. No traffic lights were used. Based on the 1-meter digital orthophoto Quadrangles (DOQs), we built the third set of road network. The driveway of each household was also digitized. The speed limit and traffic settings were set according to those in the study area.

## 2) Trip generation and destination choice

Once the road network and the settings are ready, the study defined a hypothetical affected area. The study used an ellipse as an affected area and superimposed the ellipse over the road networks (e.g. Fig. 2). In order to compare the performance of the grid and ring road networks, we delimited similar affected areas in both road networks. Furthermore, a destination was selected for vehicles departing from each block inside the affected area. The destination is defined as the place that is outside the affected area and costs the vehicle the least amount of time to arrive under a free-flow traffic situation. Therefore, vehicles from the same origin block have the same destination.

After the origins and destinations are determined, the number of trips between the origins and destinations was specified. In order to test how the change of traffic flow would affect the



Figure 2. The figure shows the real road network in a residential area in San Marcos, Texas. The ellipse is the hypothetical affected area.

performance of each evacuation strategy, the study assigned four different population density and hence departing vehicles in each block. For the grid road networks, the four levels are 20 vehicles per block, 40 vehicles per block, 50 vehicles per block, and 80 vehicles per block. For the ring road network, the average number of vehicles per area unit is equivalent to that in the grid road network in each of the four levels of population density. Therefore, the further the block from the center of the rings, the greater number of vehicles that will depart from that block; if two blocks are at the same distance from the center, then the numbers of departing vehicles are the same. Those specifications of the number of vehicles are to assure the total numbers of vehicles that need evacuation are the same for the same area on both road networks in order to compare the performance of the road network structures.

There are 485 households in the affected area in the real road network. The study first specified two levels of population density: an average of one vehicle per household and an average of two vehicles per household. However, the study area is located at the suburb of a small town with low population density. What if a potential affected area is highly populous and traffic would be very congested? Will the staged evacuation strategies help reduce the evacuation time? Therefore, we added another two more levels of population density, an average of four vehicles per household and an average of eight vehicles per household.

### 3) Route choice

This study assumes all drivers have good knowledge of the area and will follow the shortest path to get out of the affected area. The shortest path here is the route that costs the least amount of time in normal traffic conditions. Therefore, for the vehicles originating from the same place and going to the same destination, they will follow the same route. For the time being, the study does not assume that drivers will adjust the shortest path if traffic jam exists. However, this issue will be taken into account in future studies.

### 4) Evacuation sequences

The study first divided the affected area into four zones. It is hard to have identical division of zones under the grid and ring road networks. However, we tried to keep the size of four zones in both road networks similar. Fig. 3 shows how the affected area is divided into four zones in the ring road network. We divided the affected area of the real road network with regard to the geographic extent of the area and the road configurations.

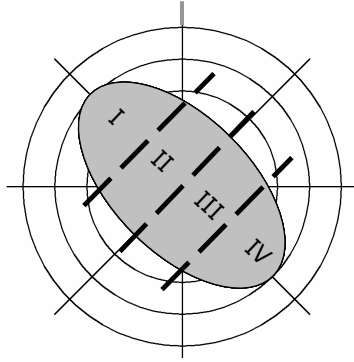


Figure 3. The affected area is depicted like an ellipse, which is divided into four zones: *I*, *II*, *III*, and *IV*.

In the simultaneous evacuation strategy, all people in different zones are informed at the same time and leave within a certain time period. The simultaneous evacuation strategy is named strategy 1 in the experiment. For the staged evacuation strategy, there are sequences based on the combinations of the four zones. For example, we can organize people to leave one zone at a time or organize people from two zones to leave at one time. In this study, we only tested the effectiveness of the sequenced strategies in which people are organized to leave one zone at a time. So, there are a total of 24 sequences for four zones. In those sequences, vehicles in different zone leave their origins one after another after a given time interval. The staged evacuation strategies are named strategies 2 to 25. There is no empirical experience on the time interval for informing people in different zones. For the simulated road networks, this study used one-minute intervals. This is not ideal, but because the simulated study area is not very big and it does not take a very long time to clear the network, it is not practical to set a big time interval. For example, if we set 5 minutes or 10 minutes as the interval, then the total evacuation time will be more than 15 minutes or 30 minutes for the sequenced strategies. Then, we cannot see any benefits of informing the affected population sequentially if evacuation time is less than 15

minutes or 30 minutes under the simultaneous evacuation strategy even though traffic may be highly congested. Nevertheless, when carrying out simulations on the real road network, we first tested the effects of using different time intervals with several sequenced strategies. Then, we set one-minute informing intervals for the first two levels of population density (an average of one vehicle per household and an average of two vehicles per household), three-minute intervals for the average of four vehicles departing from a household, and four-minute intervals for the average of eight vehicles departing from a household.

#### 5) Driving rules

This study assumes that drivers accelerate when they can, slow down if they must, or sometimes do not accelerate at all (LANL 1997). Based on the speed limit and the distance between itself and the vehicle right ahead of it, a vehicle makes its decisions on acceleration and deceleration. The distance between two immediately following vehicles, which is also called a gap, is based on the safe distance associated with the speed of two vehicles. Because both the simulated road and the real roads only have two lanes, one in each direction, only one type of lane changing happens in our study. That is when the vehicle makes its turn at the intersections. At intersections, the vehicle is automatically placed in a queue and change the lane based on the priority of the turns and the oncoming traffic. Those rules were implemented within the microsimulation environment.

Usually, there are two types of driving: conservative driving, aggressive driving (Fuks and Boccara 1997). For the conservative driving, a maximum speed limit will be assigned to each vehicle with regard to the vehicle type and the road type. For the aggressive driving, a minimum speed limit will be assigned to each vehicle. That is, as long as the vehicle is running

below the theoretically highest speed limit, there is no maximum speed limit for vehicles as long as they can run as fast as they can. It is too ideal to assume that all drivers follow the conservative driving or aggressive driving. Instead, the study assumes a normal distribution of the aggressiveness of the driving behavior, which means that most of the drivers have an average aggressiveness and some of the drivers show very high or very low aggressiveness.

There were 100 simulations for one set of road network at four levels of population density for all 25 evacuation strategies. However, due to a random number generator is used to determine the numbers of vehicles leaving from origins in Paramics, the numbers of total trips under different evacuation strategies are not necessary equal to each other for each level of population density. Thus, we carried out simulations with different random number seed for each evacuation strategy in order to keep the number of total departing vehicles close to each other under different evacuation strategies at the same level of population density. The arrival time for the last evacuating vehicle to reach its destination was recorded and used to evaluate the effectiveness of the strategies.

#### **4. Results**

##### 1) Performance of the evacuation strategies on the Manhattan road network

Fig. 4 shows the simulation results related to the grid road networks. The first line from the bottom represents the performance of the strategies when 20 vehicles are assumed to leave a block, the second line for 40 vehicles, the third line for 50 vehicles, and the fourth line for 80 vehicles departing each block. We can see that when the roads are not congested with 20 vehicles leaving each block, the simultaneous evacuation strategy works best. When the

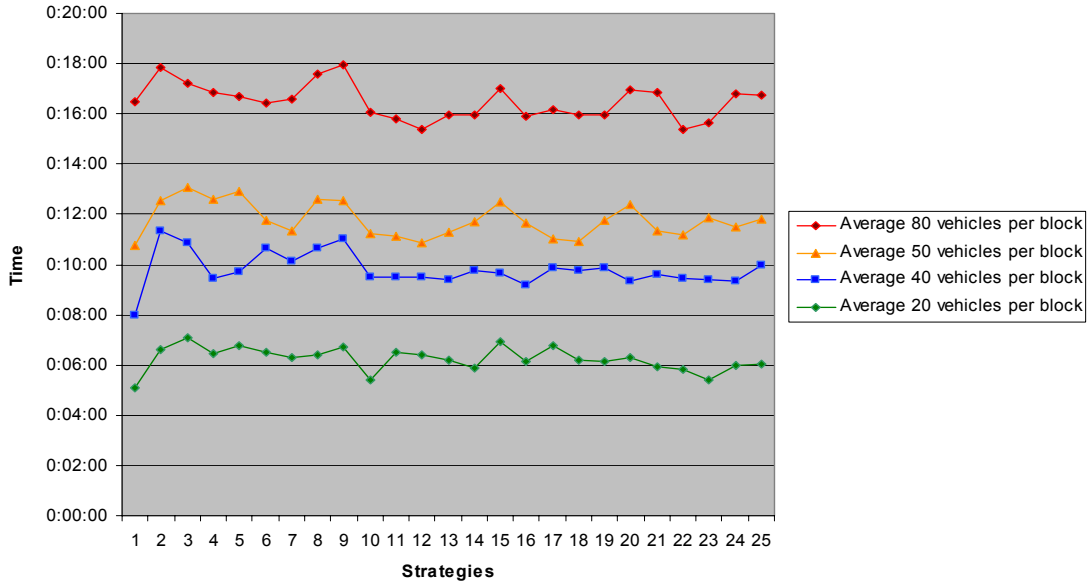


Figure 4. Performance of different strategies on the Manhattan network

population density is doubled, the simultaneous evacuation strategy still holds its place and stands out from other strategies. However, when population density increased to 50 vehicles per block, the simultaneous evacuation strategy loses its advantage with the evacuation time being close to that of the staged evacuation strategies. When the population density is further increased to 80 vehicles per block, the simultaneous evacuation strategy is no longer the best choice. Obviously, several staged evacuation strategies take less time to evacuate the population than the simultaneous evacuation strategy. The finding demonstrates that when population density is high and roads are congested, the staged evacuation strategy does have an advantage. The results indicate that sequences 12 (*III I IV II*) and 22 (*III II IV I*) work better than other sequences (Fig. 5). The order of *III II IV I* suggests that evacuating the people in the two zones (*II* and *III*) at the central part of the affected area one right after another can help release the traffic congestion. This is reasonable because the main traffic is concentrated in the central area. The advantage of this order is more obvious when the traffic volume in the central part of the area is significantly

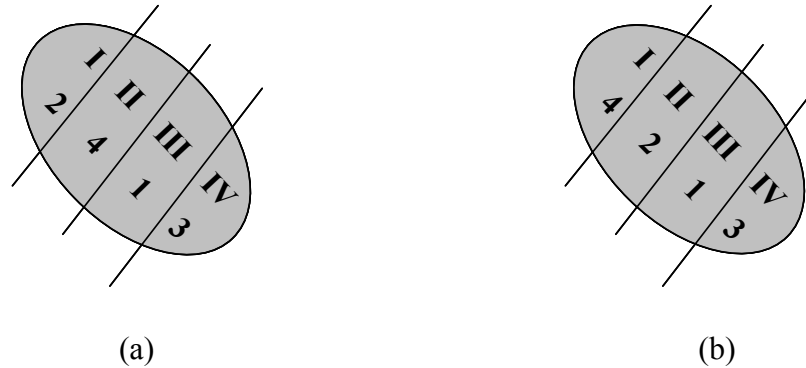


Figure 5. Two best sequences *III I IV II* and *III II IV I*. (note: Arabic numbers indicate the order of evacuation of a zone.)

more than that in the other two zones. This finding was justified with another experiment in which traffic volume originating from the two central zones significantly exceeds that in the other two zones. The order of *III I IV II* indicates that evacuating people in zone *I* and *II* or *III* and *IV* one immediately after another is not good if the traffic volume is high. This result is expected since vehicles from two adjacent zones (*I* and *II*, *III* and *IV*) would share same destinations and roads, therefore, increasing the chance of traffic jams.

## 2) Performance of the evacuation strategies on the ring road network

The performance of different evacuation strategies on the ring road network is somewhat different from that related to the grid road network. As can be seen from Fig. 6, no significant difference in the total evacuation time between the simultaneous evacuation strategy and the staged evacuation strategies is observed when population density increases with the increase of the traffic flow. The relatively better staged evacuation strategies are sequences 7 (*I IV III II*), 10

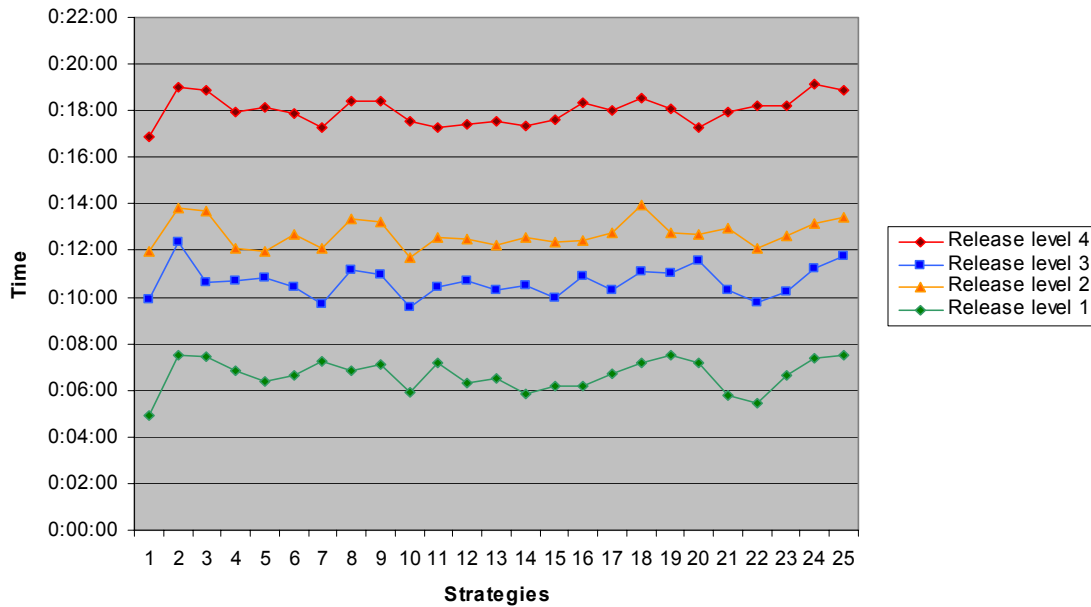


Figure 6. Performance of the evacuation strategies on the ring road network

(III I III IV), and 22 (III II IV I). Sequence 7 suggests that evacuating people in the two end zones of the affected area is more effective. This is due to that large traffic is concentrated in those two zones and the major outlets of the evacuation are the radial straight roads, which are limited in each direction. The presence of both sequences 7 (I IV III II) and 22 (III II IV I) indicates that either evacuating people at the end zones or zones at the central part earlier than other zones would help reduce evacuation time. This is largely due to the fact that the vehicles from zones I and II or zones III and IV would have to follow same roads (those straight roads) to get out of the affected area (Fig. 3). Sequences 7 (I IV III II) and 22 (III II IV I) distribute the traffic flow to the same direction in different time period; therefore help reduce the total travel time. However, based on the results of the simulations, we cannot conclude that those staged evacuation strategies are more effective than the simultaneous evacuation strategy on the ring road network no matter the traffic volume is low or high, suggesting that any of the 24 staged evacuation strategies is not better than the simultaneous strategy.

### 3) Performance of the evacuation strategies on the real road network

Under the four levels of population density, we cannot see the advantages of the staged evacuation strategies over the simultaneous strategy on the real road network (Fig. 7). The outcome is somewhat similar to that related to the ring road networks. By examining the road network structure of the real road network, we can find that there are limited exits to the unaffected area, which is similar to the situation on the ring road network. Nevertheless, the evacuation time under several staged evacuation strategies gets closer to that under the simultaneous evacuation strategy when the average number of vehicles leaving from each household reaches eight. The best performing staged evacuation strategies are sequence 9 (*III IV III*) and sequence 21 (*II IV III I*).

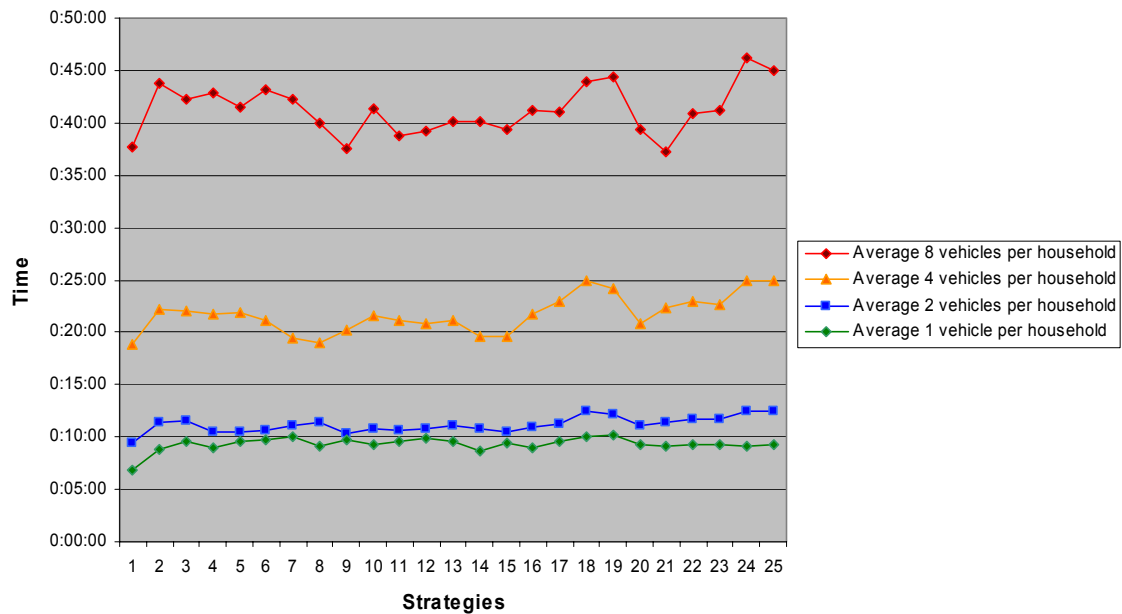


Figure 7. Performance of the evacuation strategies on the real road network

#### 4) Relative advantages of the road network structures under different evacuation strategies

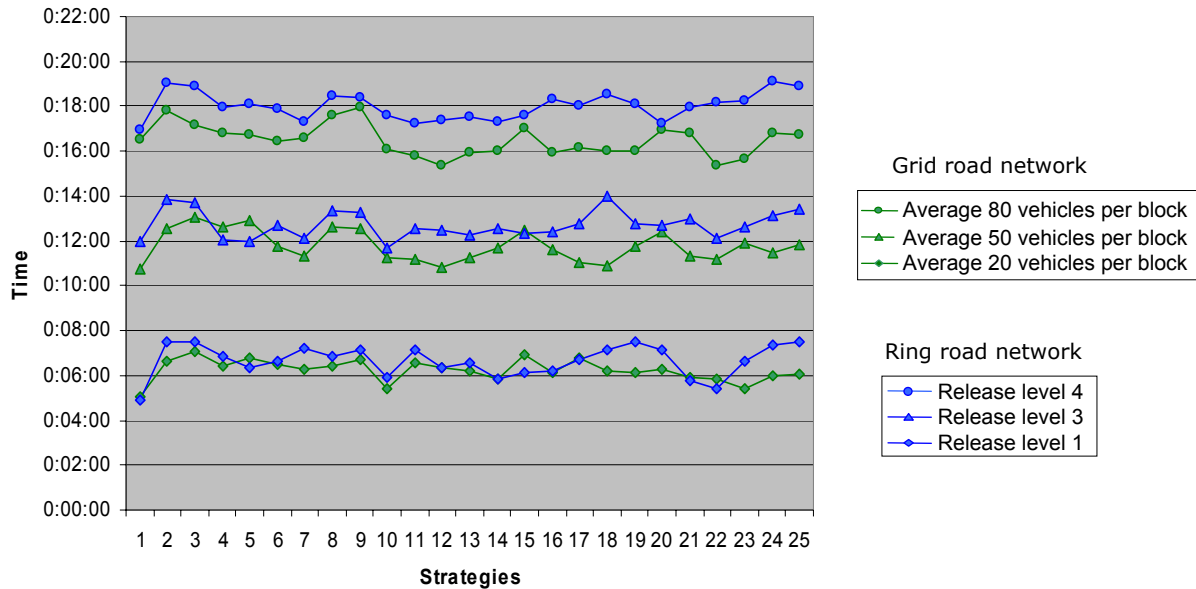


Figure 8. Performance of the grid network and the ring road network under different evacuation strategies

Based on results shown in Fig. 8, it takes more time to evacuate the same number of vehicles on the ring road network than on the grid road network. When the traffic volume is low, the difference in the total evacuation time is small between the two road structures. However, while the roads are more congested, it takes more time to evacuate on the ring road network in most cases. This is not hard to understand if the number of vehicles per exit is concerned. The exit here refers the roads that connect the affected area and the unaffected area. Only through those exits can the vehicles escape from the affected area. Apparently, there are more exits on the grid road network than on the ring road network. The comparison suggests that ring road network is not as advantageous as the grid road network for an area if evacuation is necessary under emergency situations.

## 5. Conclusions

This study explored the effectiveness of the simultaneous evacuation strategy and twenty-four staged evacuation strategies through agent-based simulation using two simulated networks and road networks in a small residential area in San Marcos. The findings reveal that the performance of the staged evacuation strategies is highly related to road network structure and population density in the area of interest.

When the traffic is in a free-flow mode and there is no congestion on the road, the simultaneous evacuation strategy is the fastest. When the roads are very congested, evacuating people in different zones in certain sequences do help reduce the total evacuation time, especially when the road network has a Manhattan structure. Although the staged evacuation strategies cannot help reduce the total evacuation time significantly on the ring road network and the real road network used in the experiment, adopting the staged strategies can bring some benefits if the total evacuation time is closer to that related to the simultaneous strategy. The staged evacuation strategy can help reduce the exposure to the hazard given the fact that less travel time on the road for most households (Cova and Johnson 2002). Because people in different zones are informed after a certain time interval in the staged evacuation strategies, those people notified at a later time can spend less time on the road, which therefore helps to reduce their exposure to a hazard. The staged evacuation strategy can help alleviate traffic jam and decrease the probability of traffic accidents as well. Traffic jam and accidents should be avoided by all means in emergency evacuation. Given that fewer vehicles are on the road under the staged evacuation strategy than those under the simultaneous evacuation strategy, the staged evacuation strategy is preferable if the total evacuation time comes closer.

On the other hand, the results of the study suggested that performance of the staged evacuation strategies is directly related to road network structure and the number of exits on the network. The grid road network works more efficiently than the ring road network under an emergency evacuation because there are more exits on the grid road network.

Many variables were not considered in the simulation, and a number of issues are subjected to future research.

First, the definition of the affected area, such as the size and shape, will definitely have some impacts on the performance of the evacuation. So, more experiments with different definitions of the affected area are needed in order to examine the sensitivity of the evacuation strategies to the size and shape of the affected area.

Second, for the evacuation sequences, the study only examined the effectiveness of the staged evacuation strategies in which people in one zone are notified at one time. More sequences are can be used and examined. For example, we can inform people in two zones at one time or people in three zones at one time. Our simulation shows the benefits of informing people in two nonadjacent zones sequentially if they do not use the same roads to get out. This finding sheds light on the fact that informing people in two nonadjacent zones at the same time might work better. However, further experiments are necessary to confirm this finding.

Third, in the simulation, it was assumed that most drivers follow the speed limit. However, we can anticipate that drivers may drive more aggressively under emergency circumstances. So, we can increase the aggressiveness of the drivers and examine how that change would affect the outcome of the simulation.

Another point that should be considered is the choice of the shortest path. In this study, if the drivers are from the same place, then they are supposed to follow exactly the same shortest

path to get out of the affected area. Given that some drivers are familiar with the local road and they will automatically adjust the shortest path if a traffic jam occurs, a dynamic shortest path routing should be employed in future studies.

Last, but not the least, the study only tested the effectiveness of the evacuation strategies in a small residential area. We hope to carry out the experiment on some other real road networks and find out the effectiveness of the strategies on those roads.

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