Agent-Based Modelling and Simulation of Urban Evacuation: Relative Effectiveness of Simultaneous and Staged Evacuation Strategies

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Agent-based modelling and simulation of urban evacuation: relative effectiveness of simultaneous and staged evacuation strategies

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This study investigates the effectiveness of simultaneous and staged evacuation strategies using agent-based simulation. In the simultaneous strategy, all residents are informed to evacuate simultaneously, whereas in the staged evacuation strategy, residents in different zones are organized to evacuate in an order based on different sequences of the zones within the affected area. This study uses an agent-based technique to model traffic flows at the level of individual vehicles and investigates the collective behaviours of evacuating vehicles. We conducted simulations using a microscopic simulation system called Paramics on three types of road network structures under different population densities. The three types of road network structures include a grid road structure, a ring road structure, and a real road structure from the City of San Marcos, Texas. Default rules in Paramics were used for trip generation, destination choice, and route choice. Simulation results indicate that (1) there is no evacuation strategy that can be considered as the best strategy across different road network structures, and the performance of the strategies depends on both road network structure and population density; (2) if the population density in the affected area is high and the underlying road network structure is a grid structure, then a staged evacuation strategy that alternates non-adjacent zones in the affected area is effective in reducing the overall evacuation time.

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Introduction

The primary objective of this study is to investigate the effectiveness of 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 affected area is divided into different zones, and residents in different zones are organized to evacuate in a sequence. In both strategies, evacuation effectiveness is measured by the total time needed to evacuate the same number of vehicles in an affected area once 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 network, a ring road network, and a real road network from the City of San Marcos, Texas. We used a grid and a ring network because they are typically found in existing urban road network structures (Knox, 1994). A residential area of the City of San Marcos was selected to investigate the relative effectiveness of the two evacuation strategies in a hypothetical evacuation situation on a real road network.

The general approach to model emergency evacuation is to delineate the area impacted by a potential hazard, and then estimate the time needed to evacuate all people in the area through simulation. It is well known that the behaviour of individual vehicles plays a crucial role in an emergency evacuation. Unfortunately, existing evacuation modelling systems are based on network flow models that simply cannot capture the behaviour of individual vehicles. Agent-based modelling, sometimes called individual-oriented, or distributed artificial intelligence-based, is a powerful modelling technique for simulating individual interactions and capturing group behaviour resulting from individual interactions in a dynamic system. Traffic flow resulting from the interactions of individual vehicles during an evacuation can only be understood when the behaviour of individual vehicles is taken into consideration in the modelling process.

Agent-based modelling decomposes a complex system into a number of constituent units called agents. Each agent is assumed to follow a set of rules to interact with other agents and its environment. The power of agent-based modelling lies in its ability to capture the collective behaviour of all agents in a complex system. This collective behaviour is

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often called emergent behaviour which is often difficult to capture using other methods such as quantitative methods of macro-simulation (Bonabeau *et al*, 1999; Bonabeau, 2002a). In modelling an emergency evacuation, individual vehicles are treated as autonomous decision-making agents, and each vehicle interacts with other vehicles on the road and the driving environment. With the aid of agent-based simulation techniques, the collective behaviour resulting from the actions and interactions of individual vehicles during an evacuation can be captured naturally. The outcome of the collective behaviour can be measured as the total time needed for all vehicles to get out of the affected area.

This study was prompted by the staged evacuation strategy used in the evacuation of residents from the Los Alamos area affected by the wildfire in 2002. Staged evacuation appeared to be a good practice in that evacuation. In coastal South Carolina, it was suggested that a staged evacuation would help relieve traffic congestion during an evacuation and speed up a hurricane evacuation (Farrell, 2005). In addition, it has been documented that a staged evacuation plan was used during the evacuation of New Orleans in response to Hurricane Katrina in 2005 (Wolshon *et al*, 2006). However, it stills remains unknown as to: (1) whether a staged evacuation strategy is more effective than the simultaneous evacuation strategy, and (2) which staged evacuation strategy is most effective for a given road network structure. Therefore, this study aims to answer the two questions across the three sets of road networks and provide insights for further study in this regard. We report an agent-based modelling and simulation study of the simultaneous and staged evacuation strategies in this paper. In the rest of this paper, the next section briefly reviews some related work, the third section describes the design and implementation of the simulation. The penultimate section discusses the findings, and the final section addresses issues related to future research.

Related work

Few microsimulation studies of emergency evacuation have been documented in the literature before 1990. Peat, Marwick, Mitchell and Company (1973), Sugiman and Misumi (1988), and Stern and Sinuany-Stern (1989) provided some earlier examples of microsimulation regarding emergency evacuation. The lack of microsimulation studies was largely due to the fact that modelling 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. Thus, previous modelling systems have chosen to estimate evacuation time from an affected area using static analysis tools at the macro or meso level (Sheffi *et al*, 1982; Hobeika and Jamei, 1985; 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 (see, eg, Nagel and Herrmann, 1993; Nagel and Paczuski, 1995; Nagel, 1996; Nagel *et al*, 2003). Using a behavioural-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 behaviour 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 geographic information system (ARC/INFO) with a specially written object-oriented micro-simulator, Pidd *et al* (1996) developed a prototype spatial decision support system (SDSS) that can be used by emergency planners to evaluate contingency plans for evacuation from disaster areas. The system enables a vehicle to find the way to a destination via available roads without congestion. However, this system does not take the interactions between individual vehicles into consideration and cannot account for the effect of the collective behaviours of all evacuating vehicles.

Owing to its advantage in capturing individual and collective behaviours in a dynamic complex system, agent-based modelling and simulation have received significant attention in recent years (Anderson, 1999; Ebeling and Schweitzer, 2001; Bonabeau, 2002a,b; Gilbert and Bankes, 2002). The two basic components of agent-based modelling are a model of the agents and a model of their environment (Deadman, 1999). In the agent-based model, a set of rules is used to govern the behaviour of agents. In this context, individual agents make decisions based on interactions with other agents and localized knowledge (Teodorovic, 2003). The emergence, or group behaviour, is then obtained through the outcomes generated from simulations of agent behaviour. Thus, agent-based simulation modelling assists researchers who investigate how individual behaviours might affect collective behaviours of a group of agents, and how different environmental settings might influence the collective behaviour of a large group in a complex and dynamic system.

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 behaviour rules in driving, such as the rules regarding accelerating, decelerating, and lane changing, there has been an increasing interest in modelling traffic by employing agent-based modelling (Blue and Adler, 1998; Dia and Purchase, 1999; Claramunt and Jiang, 2001; Wahle *et al*, 2001; Cetin *et al*, 2002). Based on agent-based simulation techniques, Church and Sexton (1998) 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 simulation to test neighbourhood evacuation plans in an urban–wildland interface. With the aid of agent-based techniques, 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. Chen *et al* (2006) investigated the hurricane evacuation procedures for the Florida Keys using agent-based simulation. In another very different study, Batty *et al* (2002) described an agent-based simulation of a carnival. They examined how group behaviour would emerge from the accumulated interactions between small-scale agents, and demonstrated how traffic controls can be deployed to help ease congestion and improve safety during a carnival. The studies mentioned above suggested that the environment factors influence both individual and collective behaviours and eventually affect the effectiveness of an evacuation plan. In addition, these studies also demonstrated the great benefits of agent-based modelling and simulation in studying emergency evacuation. However, no reported work has assessed the effectiveness of simultaneous evacuation strategy and staged evacuation strategies at a microscopic level. This study attempts to fill that void.

From the operational aspect, three major microsimulation software systems are used in transportation modelling. Among them, CORSIM was developed by the US Federal Highway Administration in 1970s and has been used over the past 30 years. Paramics, developed by Quadstone Limited in Britain, is suitable for simulating traffic at the individual level on local arterial as well as regional freeway networks. VISSIM, developed by Planung Transport Verkehr (PTV) in Germany, is one of the latest microsimulation software capable of simulating traffic for multi-modal transportation. According to an evaluation done by Choa *et al* (2002), both Paramics and VISSIM provide better matched simulation results with field observed conditions. Boxill and Yu (2000) also suggested that Paramics is the leading model for simulation of a large number of vehicles. Based on these studies, we selected Paramics as the simulation environment.

Simulation procedures

Preparation of road network

We performed the simulations in Paramics V4.0 (Quadstone, 2002). We prepared three sets of road networks for testing the effectiveness of simultaneous and staged evacuation strategies. The first two data sets are general road networks: one grid road network and one ring road network (Figure 1(a) and (b)). In terms of general road networks, we refer them to the typical road network structures found in existing urban systems. Properties of general road networks can be constructed using homogeneous settings such as same link length and width, same properties of lanes, and uniform characteristics of intersections. These general road networks are called simulated road networks. The main advantage of using general road networks is that it allows us to gain a better understanding about the relative effectiveness of the two evacuation

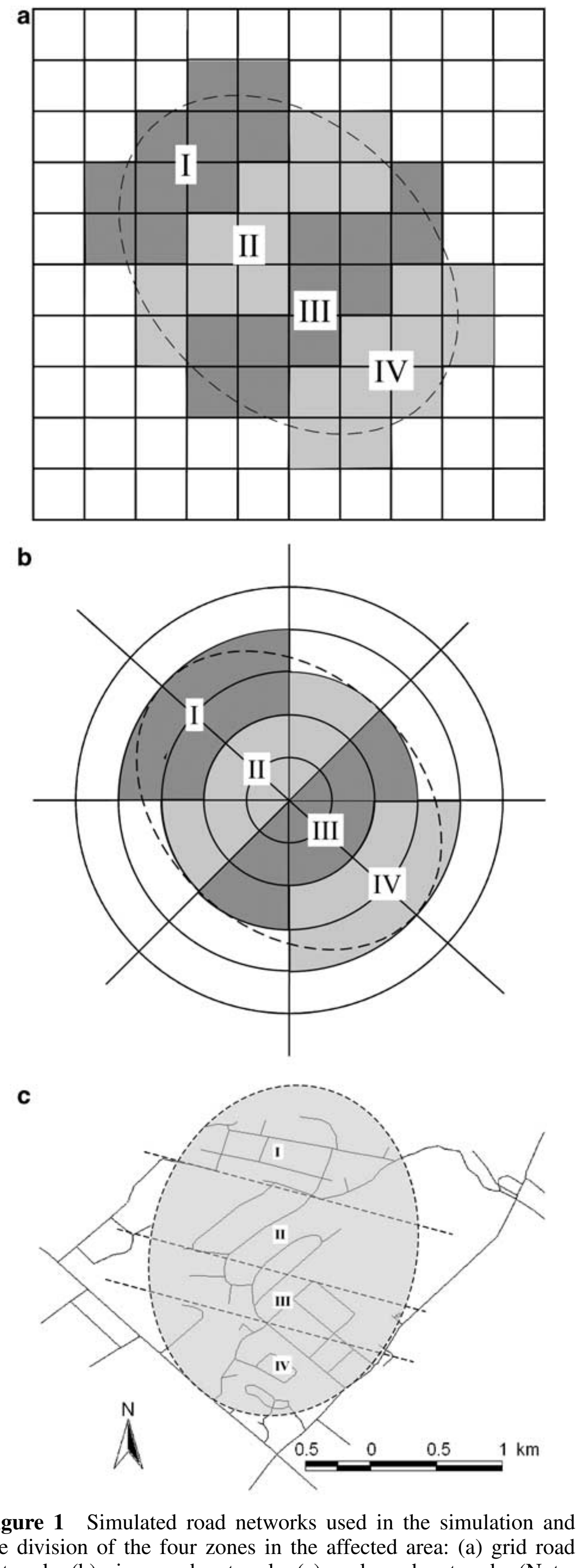

Figure 1 Simulated road networks used in the simulation and the division of the four zones in the affected area: (a) grid road network, (b) ring road network, (c) real road network. (Note: ellipse—hypothetical affected area, solid lines—road networks, dashed lines in (c)—zone divisions).

strategies on typical network structures. The third set of road network is a real road network in a residential area in the City of San Marcos, Texas (Figure 1(c)). The reason for using a real road network is to use the simulation results from the real road network to argument the results from the simulated road networks.

In Paramics, a road network is comprised of nodes and links. Nodes represent intersections. Links represent road segments. Links are classified into several categories that are distinguished by different link parameters such as speed limit, link width, number of lanes, type, and cost. In our study, 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 centre in the ring network. For traffic arriving at an intersection at the same time, right of way for all vehicles was set for each intersection in such a way that traffic going straightforward has the right of way over traffic turning right, and traffic turning right has the right of way over traffic making left turns. No traffic lights were used in the simulation. Based on the 1-m Digital Orthophoto Quadrangles (DOQs), we constructed the digital version of the real road network in San Marcos for the simulation. We also digitized the driveway of each household. We set the speed limits and traffic settings according to those in the study area.

Table 1 The evacuation sequence of the 25 strategies

Strategy	*Zone*			
	I	*II*	*III*	*IV*
1	1	1	1	1
2	1	2	3	4
3	1	2	4	3
4	1	3	2	4
5	1	3	4	2
6	1	4	2	3
7	1	4	3	2
8	2	1	3	4
9	2	1	4	3
10	2	3	1	4
11	2	3	4	1
12	2	4	1	3
13	2	4	3	1
14	3	1	2	4
15	3	1	4	2
16	3	2	1	4
17	3	2	4	1
18	3	4	1	2
19	3	4	2	1
20	4	1	2	3
21	4	1	3	2
22	4	2	1	3
23	4	2	3	1
24	4	3	1	2
25	4	3	2	1

Note: The numbers under the zones represent the evacuation sequence of the corresponding zone. For example, 1111 represents simultaneous evacuation; 1243 means to evacuate zone *I* first, zone *II* second, zone *IV* third, and zone *III* last.

Evacuation zones and sequences

Once the networks are prepared, the next step is to delineate the hypothetical affected area and divide the area into a number of zones from which the evacuation traffic will originate. We used an ellipse to delineate the boundary of the affected area and superimposed the ellipse over the networks. Figure 1(c) illustrates the delineation of the affected area using the San Marcos network. We used only four zones to partition the affected area related to each network in this study (Figure 1). It is hard to have identical division of the different zones for different networks. However, we tried to keep the size of the four zones in both the grid and ring road networks similar. The decision to divide the area into four zones was arbitrary. It is certainly possible to divide the affected area into less or more than four zones. We chose four zones for the simulations reported in this paper and will use different numbers of zones in future research.

We are now ready to discuss the evacuation sequences based on the four zones in the affected area. In the simultaneous evacuation strategy, it is assumed that all people in different zones are informed at the same time and all vehicles enter the queue of evacuating vehicles at the same time. The simultaneous evacuation strategy is named Strategy 1 in the experiment. For the staged evacuation strategy, there are many different evacuation sequences based on different groupings and orderings 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 these sequences, vehicles in any given zone are assumed to enter the queue of evacuating vehicles in that zone at the same time, but vehicles from different zones are assumed to leave at a different time based on a given time interval between the departure time between different zones. Combining with the simultaneous strategy, there are a total of 25 evacuation strategies (Table 1). For example, Strategy 8 corresponds to sequence *II-I-III-IV*, meaning vehicles in Zone *II* are the first group to enter the queue of evacuating vehicles, then vehicles from Zone *I* after a predetermined time interval, then Zone *III*, and finally Zone *IV*. Other sequences can be understood similarly.

After the evacuation sequences are determined, time interval between immediate evacuating zones need to be defined. There is no empirical evidence that can be used to guide the choice of the time interval for informing people to evacuate from different zones. Therefore, based on the size of the simulated road networks, this study used 1-min 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.

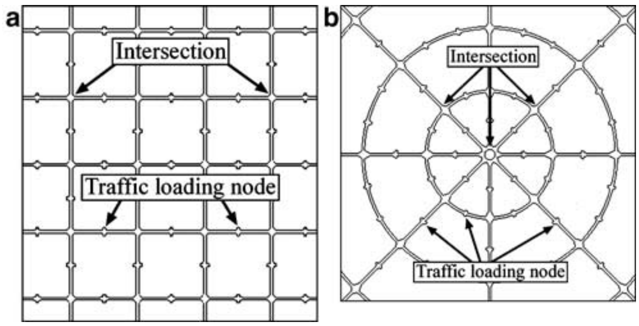

Figure 2 Examples of traffic loading positions: (a) grid road network, (b) ring road network.

For example, if we set 5 or 10 min as the interval, then the total evacuation time will be more than 15 or 30 min for the sequenced strategies. Then, we cannot see any benefits of informing the affected population sequentially if evacuation time is less than 15 or 30 min under the simultaneous evacuation strategy even though traffic may be highly congested. Nevertheless, when performing simulations on the real road network, we first tested the effects of using different time intervals with several staged strategies. Then, we set a 1-min time interval for organizing people to evacuate from different zones for the first two levels of population density (an average of one vehicle per household and an average of two vehicles per household), and a 4-min time interval for an average of eight departing vehicles per household. The total evacuation time for each run of the simulation is recorded as the difference between the arrival time of the last vehicle to reach its destination and the departure time of the first evacuating vehicle.

Trip generation

We conducted simulations for each set of road network under four different levels of population density for all 25 evacuation strategies. 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. The loading point was set at the middle position of every link and then loaded the traffic onto the grid network. So, there are four loading points for each block (Figure 2(a)). While loading the traffic to the ring network, we tried to place the loading points evenly on the road network. For links within the most inner ring, we placed the loading points in the middle position of a link. Then we used the distance between a node and a loading point on a link in the most inner ring as the benchmark distance to locate the loading points on other links (Figure 2(b)). On the real road network, vehicles were loaded to the network from the driveways of individual households.

Based on random seed numbers, Paramics uses a random number generator to determine the numbers of vehicles departing from all origins within a zone. Therefore, the number of departing vehicles and hence the total number of trips under different evacuation strategies are not necessarily the same for the same level of population density. In order to compensate for this problem, we conducted simulations with different random seed numbers for each evacuation strategy in order to keep the number of total departing vehicles under different evacuation strategies for the same level of population density as close as possible.

Route and destination choice

For the simulation, we set all locations outside the affected area as one area—the safe area. The destination of an evacuating vehicle can be any location in the safe area. The exact location of the destination of each evacuating vehicle depends on the exact evacuating route used by the vehicle. This study assumes that all drivers have a good knowledge of the area and follow the fastest (least time) route to evacuate to their destinations. We used dynamic routing procedures available within Paramics to determine the fastest evacuating route for each vehicle. Dynamic routing assumes that drivers adjust their routes dynamically based on real time traffic conditions while *en route*. This assumption means that vehicles from the same origin may take different evacuating paths to get to their respective destinations because vehicles at the same origin may have to enter the queue of evacuating vehicles at a different time and thus face different traffic conditions while they are on the road.

Population density in the affected area

After the origins and destinations were determined, we specified the number of trips between the origins and destinations. In order to test how the change of traffic flow would affect the performance of each evacuation strategy, the study assigned different levels of population density and hence different numbers of departing vehicles from each block. For the grid road network and ring road network, we set four levels of population density—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 farther the block from the centre of the rings, the greater number of vehicles that will depart from that block. If two blocks are at the same distance from the centre, then the number of departing vehicles is the same in the two blocks. Those specifications of the number of vehicles would assure that the total number of evacuating vehicles is the same for the same area on both general road networks.

There are a total of 485 households in the affected area in the San Marcos 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. The coverage of area is about 5.6 km^2. That is less than one household per 100 m^2. What would happen if a potential affected area has a

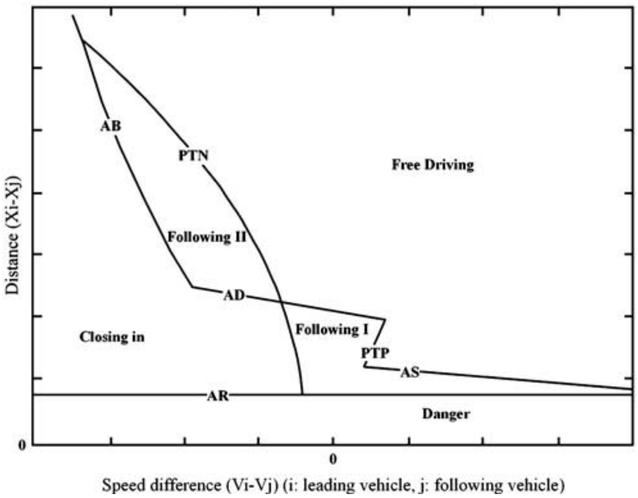

Figure 3 Fritzsche car-following diagram (After Fritzsche, 1994).

much higher population density and traffic is very congested? Will the staged evacuation strategy help reduce the evacuation time? In order to answer these questions, we added an additional level of population density for the simulation, an average of eight evacuating vehicles per household.

Car following behaviour

In Paramics, individual drivers are modelled as driver-vehicle-units. The dynamics of vehicular movement is implemented through car-following and lane-changing models. The car-following model in Paramics is a modified version of the psycho-physical model developed by Fritzsche (Fritzsche, 1994; Olstam and Tapani, 2004). In the model, the car-following process is categorized by five different modes: the danger mode, the closing in mode, the free driving mode, the following I mode, and the following II mode (Figure 3) (Fritzsche, 1994). Actions in each of the five modes are determined by speed thresholds and distance thresholds between two trailing vehicles, including perception thresholds of speed difference (PTN/PTP), desired distance (AD), risky distance (AR), safe distance (AS), and braking distance (AB). A positive perception threshold of speed difference (PTP) and a negative perception threshold of speed difference (PTN) are defined to distinguish two situations. When the speed of the following vehicle is faster than the speed of the vehicle immediately ahead of this vehicle (called leading vehicle hereafter), PTN is used. Whereas when the speed of the following vehicle is slower than that of the leading vehicle, PTP is introduced.

In the danger mode, the distance between the following vehicle and the leading vehicle is below the risky distance. The following vehicle decelerates as much as possible to avoid a collision.

In the closing in mode, the following vehicle travels at a faster speed than the leading vehicle and the actual speed difference is larger than PTN. The gap between the two vehicles is less than the desired distance but greater than the risky distance. Under this circumstance, the following vehicle decelerates until it slows down to the speed of the leading vehicle.

There are two situations in the free driving mode: the following vehicle drives faster than the leading vehicle, but the gap between the two vehicles is larger than the desired distance, or the following vehicle is slower than the leading vehicle and the gap is larger than the risky distance. In both situations, the following vehicle accelerates to achieve its desired speed until it reaches another regime of thresholds.

In the following I mode, when the actual speed difference is between PTN and PTP and the gap is greater than the risky distance and less than the desired distance, or when the actual speed difference is larger than PTP and the gap is greater than the risky distance and less than the safety distance, the following vehicle makes no conscious actions on deceleration or acceleration.

In the following II mode, the speed of the following vehicle is faster than the leading vehicle and the actual speed difference is larger than PTN. However, the gap is larger than the desired distance or braking distance. Therefore, the following vehicle does not need to make any action and can drive freely.

We used default parameters relevant to the thresholds in Paramics in the simulations. During the simulations, two time steps per second were set to define the number of discrete simulation intervals per second. At the end of each time step, the system updates the position, velocity, and rate of acceleration/deceleration of each vehicle. Statistics for traffic flows can be then obtained from the simulation results at the end of the simulation.

Rules governing drivers' behaviour

This study assumes that drivers accelerate when they can, slow down if they must, or sometimes do not accelerate at all (Los Alamos National Laboratory, 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, or gap, between two immediate adjacent vehicles in the same lane heading in the same direction, is based on the safe distance associated with the speed of two vehicles. Because there are only two lanes, one in each direction, in both the simulated roads and the real roads, only one type of lane changing—turns at intersections—takes place in the simulations. At each intersection, a vehicle is automatically placed in a queue and allowed to make a lane change based on the priority of the turns and the oncoming traffic.

Usually, there are two types of driving: conservative driving and aggressive driving (Fuks and Boccara, 1998). For conservative driving, a maximum speed limit is assigned to each vehicle with regard to the type of vehicle and the type of roads. For aggressive driving, a minimum speed limit is assigned to each vehicle, that is, a vehicle can drive as fast as conditions permit. It is not realistic to assume that all drivers would follow either conservative driving or aggressive driving. Instead, this study assumes that drivers' aggressiveness follows a normal distribution, which means that most of the drivers have an average aggressiveness in driving and only a small percentage of the drivers would be either very aggressive or conservative in driving. Under this assumption, the exact degree of aggressiveness for each driver was achieved by setting a normal distribution of aggressiveness and awareness values in Paramics.

Results

Performance of the evacuation strategies on the grid road network

Figure 4 shows the simulation results related to the grid road network under different levels of population density. The first line graph from the bottom represents the performance of the strategies when the population density is 20 vehicles per block, the second line for 40 vehicles per block, the third line for 50 vehicles per block, and the fourth line for 80 vehicles per block. We can see that when the population density is low with 20 vehicles leaving each block, the simultaneous evacuation strategy has the least evacuation time and therefore is the most effective strategy. When the population density increases to 40 vehicles per block, the advantage of the simultaneous evacuation strategy becomes less obvious (Figure 4) because the evacuation times of Sequences 15 (*II-IV-I-III*), 16 (*III-II-I-IV*), and 21 (*II-IV-III-I*) are very close to that of the simultaneous strategy. When population density increases to 50 and 80 vehicles per block, the simultaneous evacuation strategy is clearly no longer the best choice because it takes less time for several staged evacuation strategies to evacuate people from the affected area. The results indicate that Sequences 15 (*II-IV-I-III*) and 22 (*III-II-IV-I*) are the best performing strategies when population density is high. Sequence 22 (*III-II-IV-I*) is the best performing strategy for both 50 and 80 vehicles per block (Figure 4).

The finding demonstrates that when population density is high, it is more effective to use a staged evacuation strategy. The order of *II-IV-I-III* suggests that evacuating people in Zones *I* and *II* or *III* and *IV* one immediately after another is not a good practice when the underlying population density is high and vehicles from two adjacent zones (*I* and *II*, or *III* and *IV*) would compete for the same roads in an evacuation. Sequence 22 (*III-II-IV-I*) indicates that evacuating people in the two zones (*II* and *III*) in the central part of the affected area ahead of the other two zones can help ease traffic congestion and hence reduce evacuation time. The finding is reasonable because heavier traffic is expected in the central portion of the affected area. This result is also confirmed by the performance of Sequence 15 (*II-IV-I-III*), in which the population in Zone *II* is evacuated first. The advantage of this strategy is even more obvious when the traffic volume in the central part of the area is significantly heavier than that in the other two zones.

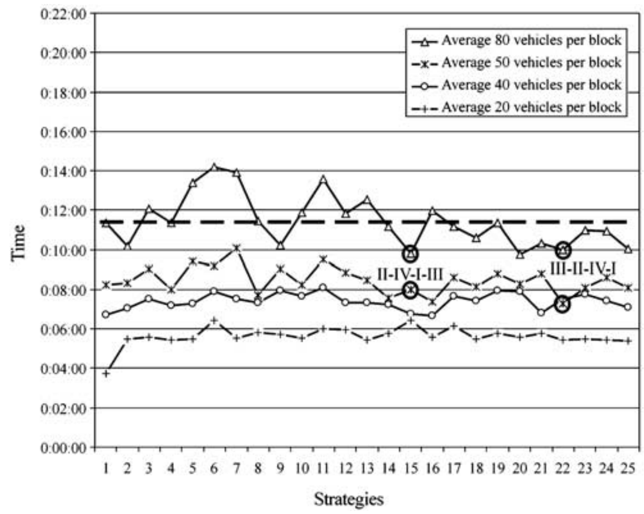

Figure 4 Performance of the evacuation strategies on the grid road network.

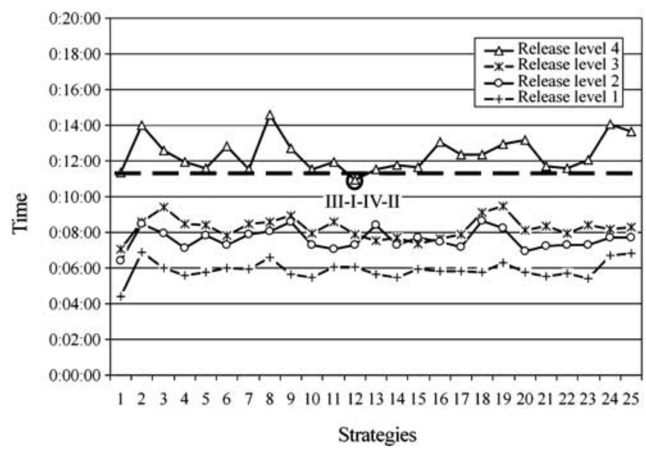

Figure 5 Performance of the evacuation strategies on the ring road network.

Performance of the evacuation strategies on the ring road network

For simulations related to the ring road network, four different levels of population density equivalent to those in the grid road network are used. The four levels of population density are measured in terms of number of vehicles per unit area and they are called four release levels. 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 Figure 5, no significant difference in the total evacuation time between the simultaneous evacuation strategy and the staged evacuation strategies is observed when population density increases. At Release Level 4, Sequence 12 (*III-I-IV-II*) is relatively a little bit better, which suggests separating traffic from Zones *III* and *II* in the central part of the affected area if the population density is high. This result

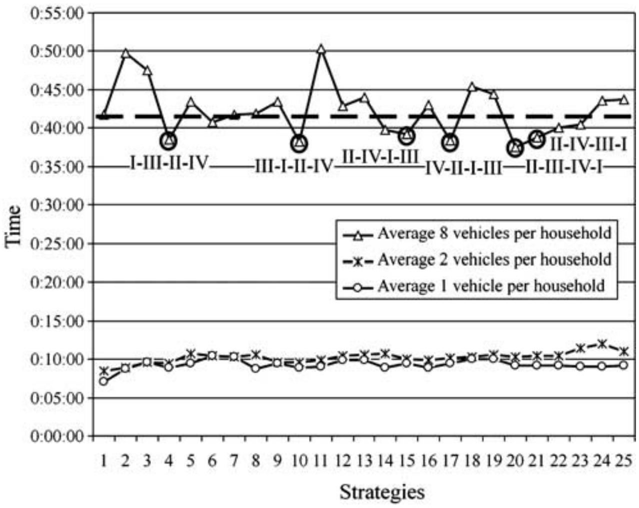

Figure 6 Performance of the evacuation strategies on the real road network.

makes sense because traffic from Zones *II* and *III* compete for the same roads in the evacuation process, but there is not much conflict between traffic from Zones *I* and *IV*, Zones *III* and *I*, and Zones *IV* and *II*. Nevertheless, based on the difference between the evacuation times of the simulations, we cannot conclude that staged evacuation strategy corresponding to Sequence 12 is more effective than the simultaneous evacuation strategy on the ring road network.

Performance of the evacuation strategies on the real road network

Results from simulations related to the real road network also suggest that there is no clear advantage to use the staged evacuation strategy over the simultaneous strategy when the average number of vehicles leaving a household is low—one to two vehicles per household (Figure 6). No traffic jam was observed in the simulations when the average number of vehicles leaving a household is one to two. However, when population density increases to eight vehicles per household, ten staged evacuation strategies had less evacuation time than the simultaneous evacuation strategy. Among them, Sequences 4 (*I-III-II-IV*), 10 (*III-I-II-IV*), 15 (*II-IV-I-III*), 17 (*IV-II-I-III*), 20 (*II-III-IV-I*), and 21 (*II-IV-III-I*), have an obvious advantage over the simultaneous strategy. In these sequences, one can observe that, in most cases, vehicles from two adjacent zones, Zones *I* and *II*, or Zones *III* and *IV*, are not organized to evacuate sequentially. From Figure 1(c), we can see that the most vehicles from Zone *I* and *II* would compete for the same roads to get out the affected area. The same applies to vehicles from Zones *III* and *IV*. Therefore, if traffic from adjacent evacuation zones follows same evacuation routes, the evacuation sequences that separate traffic from adjacent zones could help ease traffic on the way out and thus reduce the overall evacuation time.

Conclusions

This study explored the relative effectiveness of the simultaneous evacuation strategy and the twenty-four sequences as possible candidates for a staged evacuation strategy. It demonstrated the feasibility of using agent-based modelling techniques to examine evacuation performance in different evacuation situations. The agent-based model provided capabilities to address detailed individual driving characteristics in an evacuation. In this study, only total evacuation time was investigated. However, other relevant evaluation indicators such as link speed, delay on a link, number of evacuating vehicles at any time periods, can be extracted from the simulation results to analyse the evacuation process in more detail when necessary. These benefits cannot be achieved using traditional macro-based modeling techniques.

Overall, the simulation results indicate that: (1) there is no evacuation strategy that can be considered as the best strategy across different road network structures, and the performance of the strategies depends on both road network structure and population density; (2) when the traffic is in a free-flow mode and there is no congestion on the road, the simultaneous evacuation strategy is the fastest way to get people out of an area affected by a hazard; (3) if the population density in the affected area is high and the underlying road network structure is a grid structure, then a staged evacuation strategy that alternates non-adjacent zones in the affected area is effective in reducing the overall evacuation time. This observation also applies to the situation related to the San Marcos road network. There is no clear advantage to use the staged evacuation strategy when the underlying transportation is a ring road network even if the population density is high.

We are fully aware that it is necessary to conduct a complete set of simulations using large-scale networks to test the effectiveness of the evacuation strategies in larger geographical areas. Results about these simulations are reported elsewhere (Chen, 2006; Chen *et al*, 2006). In addition, many variables were not considered in the simulations, and a number of issues are subject to further investigation. Future studies along this line of research will need to investigate the effects of additional types of road network structures on evacuation effectiveness, examine the sensitivity of the evacuation strategies to the size and shape of the affected area, identify a method for dividing an evacuation area into different evacuation zones, test the effects of additional evacuating zone groupings, and discuss the impacts of aggressiveness of drivers during an evacuation.

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