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A GIS-based Micro-simulation Queue Model for Vehicle Evacuation

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Abstract

In urban areas, people's life may be threatened by disasters such as earthquakes. To reduce the life risks, efficient responses including evacuation are of critical importance. However, a drill evacuation appears impossible; simulation is thus used to examine the effectiveness of an evacuation plan. Considering the capacity of the routes, a *GIS-SimQueue* vehicle evacuation model is integrated with a Geographic Information System. Simulation results indicate that the model can reproduce vehicle evacuation features, which are in agreement with empirical ones.

Keywords: Evacuation model, Simulation, GIS.

1. Background

In facing a major event, such as the World Expo or the Olympic Games, a densely populated city may need to establish a crisis response strategy to manage the vehicular traffic and crowd movement under disastrous situations, such as earthquake, nuclear plant accident, floods, tsunami, wildfire, tornadoes or leakage of toxic gases. We understand that absolute prevention of disasters and controlling their spread maybe impossible. Thus evacuation of people from the hazardous region(s) is *per se* a way to reduce the life risks of disasters. Inefficient evacuation may cause life lost, e.g., in 1984, thousands were killed in a poisonous gas leak at a Union Carbide Corporation pesticide plant in Bhopal, India. While in contrast, the Mississauga evacuation in 1979 is an example of successfully response to an emergency. As a consequence, how to perform safe and efficient evacuation becomes a major concern of government, city and building planners, fire fighting and rescue officers, insurers, administrators as well as the people themselves.

It is noticed that in 1999, due to the hurricane Floyd, the largest evacuation in US history has forced more than 2.6 million residents in Florida, North Carolina and

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South Carolina to move out of their homes. For this kind of large scale evacuation, the residents need to be evacuated by vehicles. The burst flow of vehicles may trigger serious traffic jam. Thus, the government should establish adequate emergency response plan to ensure the public safety. To archive this aim, the authorities need to acquire honorable understanding of the evacuation pattern of the vehicles. They can as a result design the spatial setting of buildings with plenty of routes and shelters, and to establish effective management strategies to control the crowd and vehicle traffic[1-3]. It is noticed that arranging large scale drill exercises seems impossible to evaluate the evacuation efficiency of a large region. Thus, most of the previous studies and evaluation methods are qualitative. The effects of different management strategies are difficult to assess quantitatively. However, with the recent advancement of digital computers, simulating the vehicle evacuation process becomes more and more popular and important. Some computer programs, such as the NETVAC[4], MASSVAC[5,6], REMS[7], and CEMPS[8,9], Paramics[10] have been developed. Individual behaviors are now attracting researches' attention, e.g. Stern[11,12] has studied regional evacuation problem considering the impact of human behavior. Although evacuating the people of a whole city is rare, it is not unexpected to evacuate a region in a city in particular facing disastrous events, such as leakage of toxic gases from a chemical plant. If densely populated buildings surround the plant, which is not uncommon in many Asian countries, the clearance process will involve the evacuation of vehicles and pedestrians. Simulating the evacuation process will as a consequence require understanding of the movement pattern of each individual[13] and will provide the crisis response fundamental evaluation of the evacuation efficiency[13-15].

More recently, a large number of evacuation studies are conducted using well-established dynamic traffic simulation models. These models, including both microscopic models, such as PARAMICS[10,14], CORSIM[16], INTEGRATION[17], and macroscopic models, such as DYNASMART[18], DynaMIT[19], TransCAD[20], and INDY[21] were developed for regular day-to-day traffic applications. Researches begin to pay attention to emergency evacuations, e.g., a strategic dynamic traffic assignment model for hurricane evacuation was developed by Brown[22]. In a number of studies using microscopic models, model parameters describing driving behaviors (such as headway, acceleration, reaction time) have been adjusted for the case of emergency evacuation[13,23].

Summarizing the current studies we can find that most evacuation models developed in the recent decades are "mass" evacuation models which adopt the network flow theory to model the vehicle flow. Although this method has the benefit of supporting real time application and simulation of city scale evacuation process, they cannot record the movement pattern of an individual. As a consequence, a microscopic simulation model, which is capable of tracking detailed movement of each vehicle or each pedestrian, is necessary. In this kind of models, real-life influential factors such as the gender difference[13], route choice behavior[15], the spill-back arising from traffic congestion and the breakdowns of vehicle can all be took into account. This article as a result presents a microscopic simulation model, *GIS-SimQueue*, which is integrated with the Geographic Information System (GIS). This GIS-based model attempts to model the evacuation of each vehicle.

The current application of GIS technology ranges from providing maps to managing sophisticated topological databases to multi-objective decision making as well as Intelligent Vehicle Highway System (IVHS). It can be employed to evaluate, display, send and receive information for the crisis response. Information stored in the database includes available routes, state highways, county highways, municipal highways, the distribution of population, cars per county, the position of special facilities such as fire and police stations, rescue centers, and emergency shelters. Such information is rudimentary for emergency evacuation planning[24-26]. In addition, GIS can also provide vivid pictures, which can dynamically represent the evolving of the hazard. It should be noticed that GIS alone is unable to dynamically model spatial information, it requires simulation model to predict the process. GIS database serves as the inputs for the simulation model. The simulation results can provide dynamic information for managing traffic during emergency evacuation. Integrating GIS with traffic simulation model has been established in many models. For example, Silva[8,9] has developed a spatial decision support system, which integrates the simulation model with GIS for emergency planning. It adopts the spatial data structure and network modeling algorithm of GIS for the simulation model to predict traffic flow through the network under various scenarios. Cova and Church[27,28] adopted the concept of emergency planning zone for modeling community evacuation on a GIS platform.

The proposed *GIS-SimQueue* is established by using C++ on the basis of two GIS modules namely Netengine and MapObjects. These two modules are provided by Environmental System Research Institute Inc. (ESRI). Netengine is a suit of dynamic link libraries (DLLs) which is designed to facilitate advanced network analysis. It provides ready-to-use algorithms such as the shortest path algorithm. MapObjects comprises an ActiveX Control (OCX) called the Map Control and a set of ActiveX Automation Objects to facilitate the management of spatial data and interactive operation.

2. The Simulation and GIS Network

In the simulation model, the road network of a region is described in terms of links and nodes. Links represent the road and nodes represent the intersections of the roads. A link represents a one-way road, whereas a two-way road is represented by two links separately. Every node and link has its unique number to be identified, and also every node stores two link lists, which record the inbound and outbound links. Accordingly, it is efficient to traverse though the whole network and to facilitate the route choice at each node (intersection).

However, the Netengine adopts a different way to describe the road network. In Netengine, three elements namely junctions, edges and turns are used to represent the intersections, edges, and the accessibility between intersection and edge. To make full use of the algorithms of Netengine, a mapping relation of these two data structures (the simulation model and the GIS) has be established. The junction is compatible with node defined in the simulation model. However, the edge behaves differently from link in that one edge can represent the arc being traversed in *from–to* direction as well as traversed in *to–from* direction. An edge of two directions, with a common ID number, is discriminated by another ID number - the layer ID number. In this circumstance, in order to obtain a one-way link in the simulation model from the Netengine, two ID numbers is needed to convey to the Netengine, and vice versa.

```
For all links Do
While (vehicles can still leave in this step according to section capacity)
{
    Get the first vehicle in the queue;
    if (vehicle has arrived at the end of link)
    {
        if (the vehicle's destination link has space)
          add the vehicle to the destination link;
        else break;
    }else break;
}
```

Fig. 1. Simulation Algorithm.

3. A Micro-simulation Queue Model

Queue model in its simple form assumes that service can be provided at a certain rate and request for service comes with another rate. Customers are allowed to wait in line and leave by simple FIFO (first-in first-out) rule. If the rate of request for service exceeds the service rate, a queue builds up. Gawron[29] has introduced a queue model, which is different from traditional queue model in that the number of vehicles leaving a link in a simulation interval is constrained by the section capacity C_a of the link as well as by its holding capacity (storage). A road can accommodate a maximum number of vehicles:

$$N_{\max} = Length \times N_{lane} / 7.5 \tag{1}$$

where *Length* is the road length, and N_{lane} is the number of lane of road and 7.5 m is taken as a standard space occupied by a vehicle under congestion proposed by Nagel[30].

Then the simulation queue model can be described as: at each time step, all vehicles on link move at free speed, and a certain number of vehicles which have arrived at the end of link may leave the link and join to the next link. However, the number of vehicles left is constrained by the section capacity of the link as well as by the storage of destination link. If the destination is full, no vehicle can leave the current link. Simon[31] has described the procedure as shown in Fig. 1.

This approach considers the delay due to the constraint of section capacity. However, in this approach[32] the links are always selected in the same sequence. This may give some links a higher priority than others under congested conditions. Simon[31] tried to rectify this shortcoming by randomizing the link sequence, while Cetin[32] proposed to select the sequence of links in accordance with their through capacity. The higher through capacity will be the earlier sequence of being selected. However, an earlier selection cannot ensure an earlier movement. Taking the street intersection in Fig. 2 as an example, links are selected sequentially in the order of 1, 2, 3, 4. We assume that vehicles on links 1, 2 and 4 are going to move into link 3, which can accommodate a maximum of 3 vehicles at the same time. At step t, 2 vehicles are already waiting on link 3 and only one free space is available. Link 1 is selected first and one vehicle on it can enter link 3. Link 2 is then selected, but there will be no available space for vehicles on link 2 to enter. Subsequently, link 3 is selected, and vehicles on it move ahead, which results in another available free space. Accordingly, link 4, the last one being selected, can allow the movement of its vehicles. We can see that link 2 is selected earlier than that of link 4, but link 4 has a higher chance of movement. That means the earlier selected link is not necessary to have a higher chance of movement. If link 3 is totally occupied at step t, then the last selection link 4 has the highest chance of movement. We can as a result conclude that the most significant factor restricting movement of a vehicle is whether its destination link has free space, or whether its destination link has been selected in advance.

When a vehicle moves from its origin segment to a new one, it is assumed that all vehicles on the new segment have already been processed. This assumption may not always be satisfied. Under this situation, a vehicle will temporarily be stored on a virtual link. Cetin[32] utilized the conception of virtual link dealing with node pass process. Once the vehicle's destination is processed, it will be "released" from the virtual link to the destination. It should be noticed that sometimes the vehicles on the virtual link cannot move at all owing to the fact that the destination link is full or owing to the constraint of approach capacity (C_{ci}). This capacity limits the numbers of cars that can actually pass the intersection, i.e., the node. The capacity value of an intersection can be determined by Highway Capacity Manual (HCM). NETVAC[4] modeled the intersection by introducing a node pass which calculates how many vehicles can be removed from each of the links entering a particular inbound links constrained by approach capacity.

In our *GIS-SimQueue* model, a scanning process, which is similar to a node pass method used in NETVAC and TEVACS, is adopted to model the complicated flow pattern of intersection. The scanning process can be described as follows: in a time interval dt, the number of vehicles intend to move from link i to link j (N_{ij}) is calculated. N_{ij} is first constrained by the section capacity C_{link} of link i. If a link has reached its section capacity C_{link}, no more vehicle than $C_{link} \times dt$ is allowed to add to N_{ij}. Then the totally number of vehicles intending to

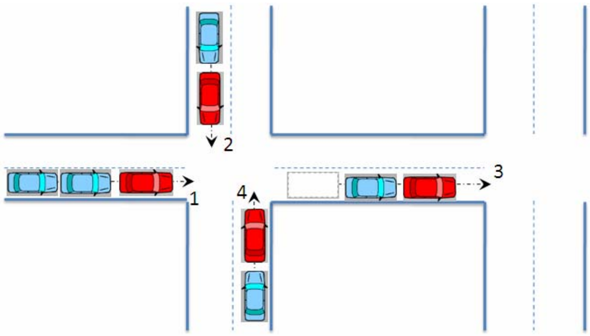

Fig. 2. Example of intersection passing.

enter link j are computed as $N_j = \sum_i N_{ij}$. The number of vehicles can be received by link j in an interval are restricted by its approach capacity C_a as well as by the way of traffic control. Two kinds of traffic control are considered here, namely, signalized intersection and unsignalized intersection (including primary priority in which only primary priority inbound links are considered while secondary priority links are ignored).

To further illustrate this process, we further discuss the unsignalized intersection. We compute an equivalent green split of a cycle time for all primary links. For the j-th incoming link, the green split G_j is given by:

$$G_j = \frac{N_j / N_{lane}}{\sum_k N_k N_{lane,k}} \tag{2}$$

where k is the number of inbound links at current node. $\sum_k N_k$ represents the total number of vehicles moving through the node to enter their destination links. N_{lane} represents the number of lanes in the j-th incoming link. Thus the approach capacity of link j is calculated as:

$$CA_j = G_j C_j \tag{3}$$

Accordingly, in a time interval of dt, the total number of vehicles entering into link j cannot exceed $CA_j \times dt$, and the number of vehicles allowed from the i-th link to the j-th link is restricted by M_{ij},

$$M_{ij} = N_{ij} (\frac{CA_j}{N_j}) \tag{4}$$

The above formula is first proposed by Sheffi[4] and adopted again by Han[33] in which the number of vehicles allowed to move merely depends on the length of the waiting queue (the number of vehicles intending to move) and the vehicles' waiting time has not been considered. However, the waiting time plays an important role in affecting the overall flow features and thus should be considered[31]. Under this circumstance, M_{ij} can be rewritten as follows:

$$M_{ij} = N_{ij} \times T_i \times (\frac{CA_j}{\sum_k N_{kj} \times T_k}) \tag{5}$$

where T_i is the total waiting time of all vehicles in the i-th link. By doing so, this procedure can process not only the case that several links converge at one link but also the case that one link diverges into several links.

The above process merely scans the dynamic capacity of a link and ignores its static capacity. It was noticed that the static capacity may have considerable influence on the node pass, thus we will discuss it in the following section.

The static capacity is introduced to determine how many vehicles can be allowed to move due to the limitation of the static storage capacity of the destination link. This procedure is accomplished by another scanning process. As pointing out earlier, a road can accommodate $N_{max}=Length \times N_{lane}/7.5$ vehicles at most at a time. Accordingly, the available free space at step t in an inbound link j is restricted by the number of vehicles on it at step t-1 denoted as $NV_j(t\text{-}1)$. The available free space in j-th link at simulation step t, $NS_j(t)$ is expressed as:

$$NS_j(t) = N_{\max,j} - NV_j(t-1) \tag{6}$$

The number of vehicles allowed from i-th link to j-th link at k simulation step is further restricted by:

$$NS_{ij}(t) = N_{ij} \times T_i \times (\frac{NS_j(t)}{\sum_k N_{kj} \times T_k}) \tag{7}$$

According to Eqs.(5) and (7), the number of vehicles are restricted by both M_{ij} and NS_{ij}. So the allowance number of vehicles from i-th link to j-th link at simulation step k will be finally restricted by:

$$MNS_{ij}(t) = N_{ij} \times T_i \times (\frac{Min[CA_j, NS_j(t)]}{\sum_k N_{kj} \times T_k}) \tag{8}$$

The algorithm of the two scanning processes can be implemented as the flow chart shown in Fig. 3.

Precisely, vehicles can still leave in this time step according to the approach capacity[31], i.e., when one of the following items can be fulfilled, the vehicles can leave:

(i) N_{pass} <int(C_{link}),

(ii) N_{pass} ==int(C_{link}) && (rand( )/RAND_MAX > (C_{link} -int(C_{link}))).

Here, rand( )/RAND_MAX means a random number in between 0 and 1.

```
T=t+1:
For  i all  links Do
        The update of approach capacities
        Initializes the  N_ij=0
End Do
For  i all primary  links Do
  While (vehicles can still leave in this step according to section capacity
  {
     Get the first vehicle in the queue;
     if (vehicle has arrived at the end of link  j )
     {
        if (the vehicle's destination j link has space)
        {
           (The number of vehicles waiting to enter into link j, Σ_i N_ij )++;
           (The number of vehicles waiting to move from link i to link j,   N_ij  )++;
        }
        else
           break;
     }
     else
        break;
  }
 End do

 For all links Do
   While (vehicles can still leave in this step according to section capacity);
   {
      Get the first vehicle in the queue;
      if (vehicle has arrived at the end of link)
      {
          if (the vehicle's destination link has space)
          {
             MNS_ij(t) = N_ij × T_i × ( Min[CA_j, N_max,j − NV_j(t−1)] / Σ_k N_kj × T_k )
             if(N_pass > MNS_ij(t))
               break;
             if(( N_pass==int( MNS_ij(t)))&&(rand()/RAND_MAX>( MNS_ij(t) -int( MNS_ij(t))))
             {
                add the vehicle to the destination link;
                  ++;
             }else break;
          }else break;
      }
   }
 End Do
```

Fig. 3. Algorithm of the two scanning processes.

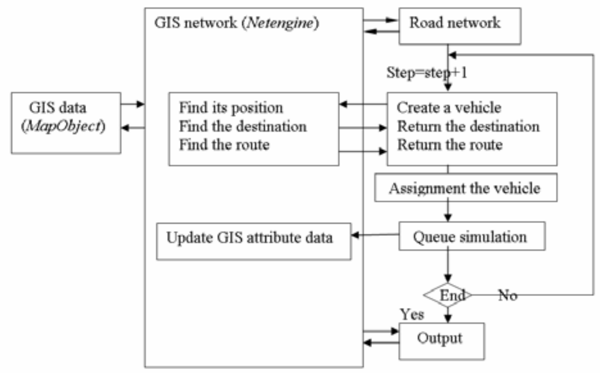

Fig. 4. Components of *GIS-SimQueue* Model.

It should be noted that the proposed *GIS-SimQueue* model seems like but actually is different from the Daganzo's Cell Transmission Model (CTM)[34,35]. In the *GIS-SimQueue* model, the movements of the vehicles are restricted by the capacity of the link as well as the node, which is similar to the CTM. However, vehicles are treated individually but not as a whole in the *GIS-SimQueue* model.

4. The GIS-based Evacuation Simulation

In the aforesaid queue model, vehicles will move ahead according to a pre-defined route, which depends on the choice of destinations according to the following principles[36,37]:

- Nearest emergency shelter (evacuees will move to the nearest shelters),
- Pre-determined shelter (evacuees will move to the pre-allocated shelters),
- Dynamic traffic network condition (evacuees will move depending on the traffic condition).

All the principles are aiming at evacuating the residents as soon as possible and as fast as possible. Thus in our simulation model, an allocation function of the Netengine is adopted to allocate the nearest emergency center for each vehicle on the link in the network by minimizing the travel cost. Such function can also be used to locate the nearest emergency shelter or service station for each street in a city. Having determined the destination, we can establish the original-destination (OD) matrix, and the choice of route can be formulated by the traffic assignment methods. In our model, we adopted a simulation-based Dynamic Traffic Assignment (DTA)[29] method to assign the vehicles to the road network. Fig. 4 outlines the components of the *GIS-SimQueue* model.

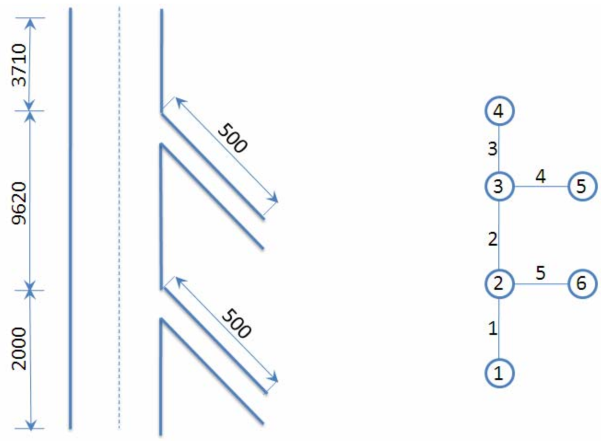

Fig. 5. Schematic of the urban freeway network.

At each time step of the simulation, vehicles on links are removed from or are added onto the links, thus the cost of a link varies at every step. This is due to the reason that the cost is related to the link length and number of vehicles on it. Updating this very attribute in GIS can reflect the dynamical characteristics of vehicle flow, so all vehicles can get the updating information of all network in real time, which is paramount during emergency evacuation.

5. Simulation Results of Queue Model

For the reason that few data are available concerning traffic condition during large scale evacuation, here in this section we firstly validate the model by comparing the calculated evacuation times with those observed scenarios that are similar to evacuations, e.g., data on congested urban freeway, which is referenced from Urbanik[38]. Urbanik compared the collected field data with the simulation results of I-DYNEV. The studied area is represented schematically in Fig. 5.

For the sake of the completeness, we briefly introduce the field data. These data were collected on a 2.9-mile section of interstates 35 in Travis, north of Austin, Texas. The site was a four- lane freeway (two lanes in each direction) in rolling terrain with 12ft lanes, a 3ft paved left shoulder, and a 10ft paved right shoulder. The section capacity was 2040, which was equivalent to discharge headway of 3600/2040=1.76 seconds.

Table 1. Characteristics of Road Network.

Roadway Segment	Length/ft	Free Speed	Number of Lanes
1	2000	60	2
2	9620	60	2
3	3710	60	2
4	500	45	1
5	500	45	1

Traffic volumes were observed at the starting point, end point and each ramp along the transportation network at 5 minutes intervals, and were available for 25 time periods (from 0 to 120). The input rate of vehicle to the network and their exit rate are shown in Fig. 6. From this figure we can see that the highest inputting rate happens between 40-60 intervals. It is worthwhile to notice that no congestion-induced capacity reduction has happened even stop-and-go has been observed. The queuing processes are recorded on the main roads and on-ramp roads.

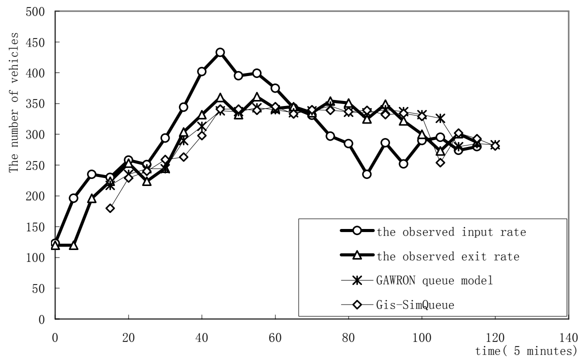

Fig. 6. A comparison of model results with observed data.

The rate of vehicles exiting the transportation network as a function of time is a critical parameter describing the traffic condition during evacuation process. The traffic volumes on the network at initial time are set to zero, and then are added into the network according to its rate of input. The rate of vehicles leaving the network computed by Gawron's queue model is in good agreement with the observed data (Fig.6 refers). The two sets of data are then compared with the output of the *GIS-SimQueue*. As we can find, the trend of these data goes well with the empirical observed one. The maximum difference between them is about 100 vehicles, which we believe mainly results from the difference of the initial conditions, i.e., we do not have the initial distribution of the vehicles on the road.

The comparison shows that queue simulation model can effectively model the dynamic aspects of rush hour traffic with no congestion induced capacity reduction. However, whether such models are suitable for simulating traffic flow in congestion-induce capacity reduction scenarios should be further studied.

Sensitivity of the simulation time interval, *dt*, is another issue that should be considered. Two simulation intervals, 1 and 100-second, are examined. Sheffi[4] has pointed out that simulation interval should be governed by the static capacity of link N_{max} in the network. For example, if the *j*-th link can merely accommodate N_{max} vehicles at most at the same time, then the maximum number of vehicles leaving the *j*-th link in a time step cannot exceed N_{sites} vehicles. Similarly, the maximum number of vehicles that can enter into the *j*-th link cannot exceed its static capacity. Also, the simulation interval cannot greater than the free flow travel time $T_0=L/V_0$. The maximum simulation interval is determined as follows:

$$dt \le Min[\frac{N_{sites}}{C_{link}}, \frac{N_{\max}}{C_j}, L/V_o] \tag{9}$$

The maximum simulation interval is about 13-second ($500 \times 0.3048/12.5$). This value is merely a theoretical value. Fig. 7 illustrates that the outputs given by the simulation using a time interval of 100-second are agree well with the observed data.

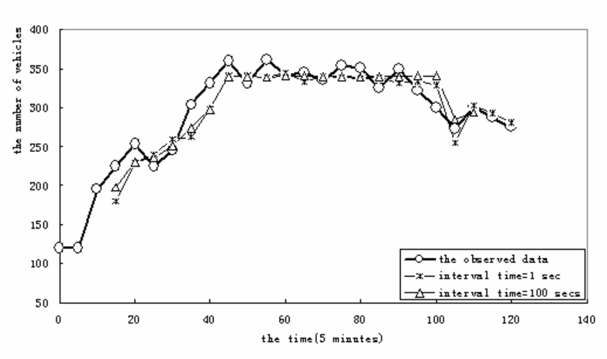

Fig. 7. Comparison of the simulated results with different *dt* and the observed data.

5.1. *An Example*

In order to verify the credibility of the output of the *GIS-SimQueue* model, the output of the model is further compared with another established model, the TEVACS developed by Han[33]. A hypothetical network as Fig. 8

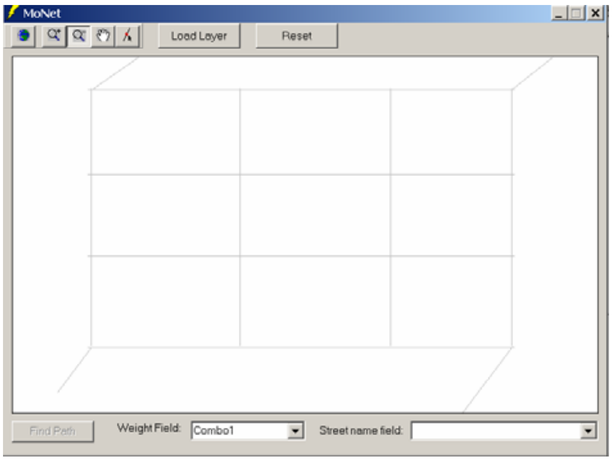

Fig. 8. Hypothetical road network.[33]

once used by Han[33] is selected for the comparison.

The network comprises 56 links and 24 nodes. The number of public emergency shelters is 4 and the total number of vehicles required to be evacuated is 7000. All links in the network are bi-direction, that is to say, vehicles can move in a *from-to* direction or in a *to-from* direction. Each direction owns 3 lanes. The length of links is 500m long. The section capacity is 1500, the free speed is 50km/h and the jam density is 200pcu/km. Since the initial distribution of vehicles is not clearly stated, we then uniformly distribute the vehicles on all the links. The average number of vehicles of a link are 7000/48 (the total number of links taking part in the assignment is 48) and they are evenly added to network within 100-second for simplicity.

Table 2 illustrates the comparison of the outputs of Gawron's queue model, TEVACS and *GIS-SimQueue* model. Two time intervals are selected for the simulation and the results show that the clearance time computed by Gawron's model is smaller than that of the output of TEVACS and *GIS-SimQueue*. This is due to the reason that Gawron's queue model has disregarded the constraint of the phase-approaching capacity. Whereas, the *GIS-SimQueue* includes the phase-approaching capacity that is necessary to depict the real traffic characteristic. The outputs given by both *GIS-SimQueue* and TEVACS are in good agreement.

Table 2. The simulation results.

Length of simulation interval/second	GIS-SimQueue/ min	Gawron's model/min	TEVACS/ min
1	29.6	25.7	*
100	31.7	26.6	32.00

6. Concluding Remarks

With the rapid urbanization process in many Asian cities, the provision of evacuation planning is now becoming the last line of protecting densely populated areas from disastrous events. The governments as well as researchers are paying more and more attention to evacuation planning. As a consequence, simulation model is considered as the tool that can assist to establish evacuation planning.

A GIS based micro-simulation queue model for vehicle evacuation is established in this paper. The approach of two scanning processes is proposed to model of the congestion and spill-back features of vehicle evacuation at street intersection. The proposed *GIS-SimQueue* model is a microscopic traffic simulation model that models each vehicle. Thus different individual behavior, and current traffic simulation techniques as well, can all be easily took into account. What is more, a GIS component, Netengine, which can provide all kinds of network algorithms needed for evacuation plan, is integrated in our model for route selection and resource allocation. As a consequence, the proposed model can make full use of current GIS technology to improve its computational efficiency.

This paper is our initial work and only the vehicle evacuation is concerned. Further study on the influence of pedestrian on traffic is in progress.

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