A Heuristic Implementation of Emergency Traffic Evacuation in Urban Areas

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***Abstract*—With the acceleration of China's urbanization, more and more unexpected disasters in big cities make a severe challenge to city emergency traffic management. Under this background, we present a heuristic implementation of urban emergency traffic evacuation in this paper. Firstly, we refer to a popular evacuation demand generation model to generate the evacuation demand. When solving the path selection problem, the heuristic search method is used. We take Dijkstra shortest path and current road condition as two parts of the evaluation function to evaluate different choices and choose the best one. To simulate the dynamic process of evacuation, we developed a position update algorithm to update the positions of traffic participants. The mathematical analysis method and computer simulation are combined to determine the final evacuation route of a traffic participant. This combination is effective since it takes advantages of both methods and avoids the shortcomings at the same time.**

Keywords—Emergency Traffic Evacuation; Heuristic Search; Path Selection

I. INTRODUCTION

In recent years, many big cities in different countries arose as a result of rapidly urbanization. But at the same time, we witnessed a lot of natural and man-made disasters which caused a big loss of properties and human lives, as with 911 terrorist attacks (2001, America), Hurricane Katrina (2005, America) and Indian Ocean Tsunami (2004, India). When faced with these disasters, we must address the emergency evacuation problem.

There exist many studies about emergency traffic evacuation. They can be divided into two parts according to methodology. They are mathematical analysis method and computer simulation. We could first see these studies in America early to 1980s. Limited to computer performance at that time, people solve this problem mainly by mathematical analysis. Lewis proposed a general method for travel demand prediction and key problems in traffic emergency evacuation in his study about hurricane evacuation in 1985 [1]. After that, Dunn and Newton proposed a max-flow method based on network model [2]. Yamada converted this problem to a minimum cost flow problem and put forward the shortest evacuation plan (SEP) method [3]. Cova and Johnson presented a network flow model for identifying optimal lane-based evacuation routing plans in a complex road network. It was an integer extension of the minimum cost flow problem [4]. Considering the limitation of static road network, Choi studied the minimum cost flow problem based on dynamic road network [5]. Lu Zhao Ming and his colleagues proposed a network optimization model based on time varying dynamic flow to minimize the total evacuation time [6].

Along with the rapid development of computer hardware technology, computer performance has been greatly improved. Computer simulation has shown great effectiveness in solving large complicated problems. Application of computer simulation in emergency evacuation has given birth to many evacuation simulation models, such as NETVACI (1982) [7], MASSVAC (1985) [8], TEDSS (1991) [9], and OREMS (1993) [10] and so on. At the same time, agent-based simulation is coming into researchers' sight. X Chen and F.B. Zhan use an agent-based technique to conduct their simulations based on both simultaneous and staged strategy on three types of road network structures: a grid road structure, a ring road structure and a real road structure. They conclude that simultaneous strategy and staged strategy should be applied according to different road structure and population density [11].

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The remainder of this paper is as follows. In section 2, the "Algorithm Realization" section, we give a heuristic implementation of emergency traffic evacuation in urban areas. First, we introduce the overall idea about how to solve this problem. Then, we use a model and two algorithms to implement the idea. In section 3, the "Conclusion" section, we give a brief conclusion about what we have done, and put forward some topics where more work is needed for further research.

II. Algorithm Realization

A. *Overall Idea*

When mathematical analysis method or computer simulation is used to solve evacuation problems, they have both advantages and disadvantages. Mathematical analysis method is based on network model, and has a strict definition of the problem. Usually a network-model-based problem is converted to a linear programming problem, and we could set the goal we want to be optimized. These goals include evacuation time estimations (ETEs), average evacuation time and total travel distance. We say mathematical analysis method has the advantage of goal orientation and optimal solution. A limitation of mathematical analysis method is that it is only useful when the network is static. As to emergency traffic evacuation problems, we know that attributes of road network are usually affected by the disaster and thus change with time, while linear programming model cannot reflect the changes and will lose reality. On the contrast, computer simulation is controlled by simulation step during which road network attributes of current time are obtained to solve the problem. It has the advantage of real-time reflection. But at the same time, we usually cannot get the optimal solution through computer simulation but acceptable near-optimum solution.

We propose to combine mathematical analysis method and computer simulation in this paper. The idea of step control from computer simulation is applied at macro control level, thus real-time changes of road network attributes are reflected in the processing. While at micro calculation level, we use mathematical analysis method to ensure that we get optimal solution at each step. Through this combination we take advantages of both and thus get a better solution.

The process can be illustrated by 6 steps (seeing Fig.1.):

1) Creating a graph $G(V, E)$ according to the real road network topologies. The graph G is composed of node set V and edge set E with their attributes. A node in the graph represents an intersection in real road network. And the edge between two nodes represents the road segment between these two intersections. Attributes of an edge include its length, capacity and maximum allowed speed. Attributes of a node include its position and edges connected to it.

2) Setting origins and destinations and other initializing. An origin is a place where people and their properties are loaded to the road network, and a destination is a safe place beyond the hazard area where people and their properties are evacuated to. Left work is to initialize attributes of the road network.

3) Deciding if all evacuation demands have been loaded. If true, go to step 4); else, load the demand generated at this step. More details about how to load the evacuation demand can be seen in the "*Evacuation Demand Generation Model*" section.

4) Updating network status and generating turning requests. For all the vehicles in the road network, calculate its running speed according to current traffic condition and update their position. If a vehicle reaches an intersection, it will generate a turning request. See "*Position Update Algorithm of Traffic Entities*" section.

5) Handling all the turning requests. How to handle the turning request has a big influence on the final results. It is a path selection problem. We take a heuristic method to get it solved in this paper. See "*An Heuristic Search Algorithm to Solve Route Selection Problem*" section.

6) Decide if evacuation is finished. If true, show the results and quit; else, go to step 3).

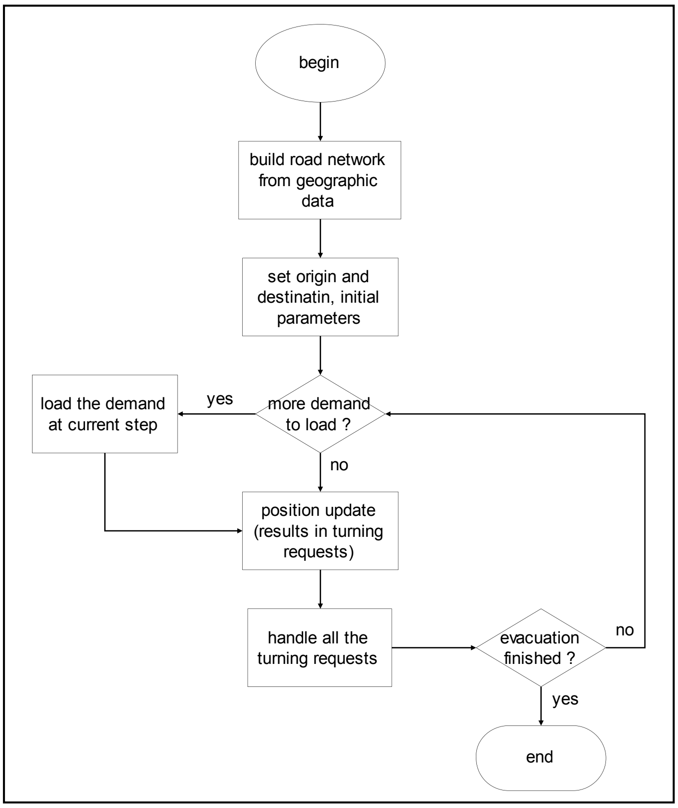

Fig. 1 An Overall Idea of the Process of Emergency Evacuation

B. *Evacuation Demand Generation Model*

It is not realistic that all evacuation demands get to the origin soon after the emergency evacuation begins. Demands (vehicles or pedestrians) always accumulate at the origin along with a time period. To simulate the process, we need to cut it into time steps of constant period, and estimate how much demand should be loaded at each time step. An evacuation demand generation model is referred to do the estimation.

On the base of previous studies [12][13], cumulative percentage of loaded demand can be described by the sigmoid function:

$$1/P(t) = 1 + exp[-\alpha\cdot(t-H)],\ t\in[0, T]. \quad (1)$$

$P(t)$: the cumulative percentage of loaded demand at time instant t.

α: a parameter describes how sensitive people are to the disasters. Larger value means people react more sensitively to the emergent situations, and results a steeper sigmoid curve.

H: time needed to load half of the evacuation demand to the road network. It's a constant value that makes the equality $P(H) = 0.5$ holds.

T: time needed to load the whole evacuation demand. It's a constant value for a specific area. Different areas may have different values. Note that $P(t)$ tends to be 1 when t is large enough.

In order to make the model adaptive to the input of computer simulation, we must discrete it. This can be done through a little trick that simply replaces t as $i\cdot\Delta t$ and $P(i\cdot\Delta t)$ as $P(i)$ in (1). We get discrete form of Evacuation Demand Generation Model as follows:

$$1/P(i) = 1 + exp[-\alpha\cdot(i\cdot\Delta t - H)],\ i = 1, 2, \ldots\ T/\Delta t,\ P(0) = 0 \quad (2)$$

In (2), $P(i)$ denotes the cumulative percentage of evacuation demand loaded till the i^{th} time step. Note that Δt is a constant value representing the duration of each time step.

Assume that the total evacuation demand of an area is A. Then the amount of demand loaded at i^{th} time step (denoted by $Q(i)$) can be calculated as follows.

$$Q(i) = A\cdot[P(i) - P(i-1)] \quad (3)$$

C. An Heuristic Search Algorithm to Solve Route Selection Problem

Heuristic search algorithm is a technique designed for solving a problem more quickly when classic methods are too slow, or for finding an approximate solution when classic methods fail to find any exact solution (from Wikipedia). During each search it uses a carefully designed function to rank alternatives from which a best one would be selected. And it goes on from the best selected one to the next search reciprocating, until finds the optimal solution, or an acceptable one. Based on this mechanism we can see that the ranking function is of great importance to the performance of a heuristic search algorithm. Actually, to design a heuristic search algorithm is essentially to design the ranking function [14][15].

Consider the actual situation in an emergency evacuation. When a traffic entity comes to an intersection, it is faced with several routes to choose. In order to get to the safe destination as soon as possible, driver's first consideration is the distance through a certain chosen route to the destination. While at the same time, most drivers are myopic. That is, drivers tend to choose the route that is less congested at the time. If a route is too congested, few drivers would choose to drive through this route.

We can see similar study that applies heuristic search algorithm to solve route selection problem in emergency evacuation [16]. In this paper, concerning these two factors (distance and congestion), we design an evaluation function to rank each alternative route as follows:

$$f(x) = \alpha\cdot g(x) + \beta\cdot h(x)\ . \quad (4)$$

In (4), variable x represents an alternative route, and $f(x)$ is the evaluation of the route. Assuming that $d(x)$ is the minimum distance though the alternative route to the destination, and $v(x)$ is the traffic flow speed of the alternative route under current congestion condition. Then $g(x)$ is the normalized value of $d(x)$, and $h(x)$ is the normalized value of $v(x)$. As we know, $d(x)$ often has a magnitude of 10^3 (in unite of m), and $v(x)$ often has a much lower magnitude of 10^1 (in unite of m/s). It would be of no influence if $v(x)$ is directly added to $d(x)$. The purpose of normalization is to counterbalance the difference in magnitudes. Notations α and β are weight parameters explaining how drivers weigh the two factors, under the constraint that $\alpha + \beta = 1$.

The next task is to calculate $d(x)$ and $v(x)$ for different x and thus we get their normalized value $g(x)$ and $h(x)$. Among all the shortest path algorithms, Dijkstra Algorithm is the most commonly used. We use this method to calculate $d(x)$ in our case. The value $v(x)$ can be calculated with a road impedance function model called BPR (Bureau of Public Road) [18]:

$$v_f/v(x) = 1 + J\cdot q/(C-q)\ . \quad (5)$$

In (5), v_f denotes the free running speed of the road, and $v(x)$ denotes the current running speed at a traffic flow of q when the maximum allowable traffic flow of the road is C. Parameter J is a constant value which represents the service level. It is defined that $v(x) = v_{min}$ when q equals to C to avoid infinite, where v_{min} denotes the minimum running speed of the road (larger than zero).

The normalization method can be simply explained as follows. Firstly we get values of $d(x)$ for different road x. Then we sort the values and get the minimum value d_{min} and the maximum value d_{max}. Usually a smaller evaluation value of a candidate strategy means better performance, thus we define the normalized value of d_{min} is 0 and that of d_{max} is 1:

$$g(d_{min}) = 0,\ g(d_{max}) = 1\ . \quad (6)$$

And the general form of normalization of $d(x)$ is as follows:

$$g(x) = [d(x) - d_{min}] / [d_{max} - d_{min}]\ . \quad (7)$$

Similarly, the normalization of $v(x)$ can be described by the following equations:

$$h(v_{min}) = 1,\ h(v_{max}) = 0,$$

$$h(x) = [v_{max} - v(x)]/[\ v_{max} - v_{min}]. \quad (8)$$

By now we get evaluation values of all possible routes, and thus we chose the one with the minimum evaluation value as the best.

D. Position Update Algorithm of Traffic Entities

As shown in Fig.2, a traffic entity is represented by a rectangle and has a *position* attribute meaning the distance from the upstream intersection. A road segment is represented by a line segment and has a *length* attribute. At the beginning of a simulation step, we calculate how long the traffic entity travels as $s = v{\cdot}\Delta t$, where v is produced by the BPR model explained in previous section and Δt is the duration of a time step. Then we need to compare (*position* + s) and *length*. If (*position* + s) $\leq$ *length*, update the traffic entity's *position* as new value (*position* + s). Else, update its *position* as *length*, which means it comes to the intersection. Then we have to calculate the time it needs to come to the intersection t_q = (*length* – *position*)/v, and time left $t_r = \Delta t - t_q$. Assuming the driver chooses a next road R_{next} whose length is l_n and the current running speed is v_n. We calculate the travel distance s_n in time t_r as $s_n = v_n \cdot t_r$. Recursively we need to compare s_n and the length of road l_n. If $s_n \leq l_n$ we update its position as l_n and its owning road as R_{next}. Else, do the calculation above recursively till $s_n \leq l_n$ which means the position update is finished. This process can be clearly illustrated in Fig.3.

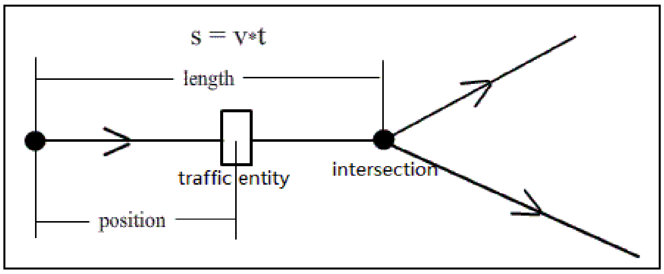

Fig. 2 Schematic Diagram of Position Update

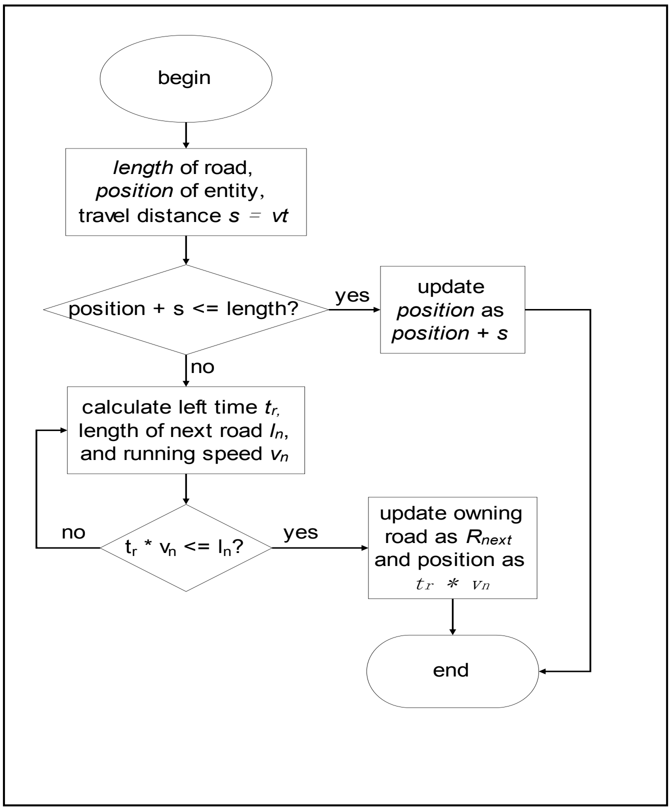

Fig. 3 Flow Chart of Position Update Algorithm

After all the position update is done, we determine if there are any traffic entities in the road network. If it's true, we have to move on to the next simulation step. Else, it means that there are no traffic entities in the road network and the evacuation has been finished.

III. CONCLUSIONS

On the base of large amount of previous studies, we propose to combine mathematical analysis and computer simulation in this paper. By doing this, we take advantages of both and avoid their shortcomings. This method is proved to be effective in solving route selection and evacuation time estimation problems in emergency evacuation. It is useful for evacuation directors to make proper decisions. It helps saving peoples' lives and property in a real emergent evacuation.

An advantage of the algorithms proposed in this paper is that the input and the models are independent. This allows researchers to change input to simulate different evacuation conditions. You can do sensitivity analysis and extreme tests by different user defined inputs. This is similar in some way to the idea of computational experiments in parallel control theory firstly proposed by Professor Wang Feiyue [19][20]. Besides, we can treat each traffic entity as an agent such that the advantages of agent based simulation can be taken.

On the other side, there remain shortcomings in this paper where further work is needed. Firstly, simulation in this paper is at a macroscopic level and traffic entities as agents are not intelligent enough. We don't take the interactions between entities into concern. Secondly, we make the assumption that the road network is static during the evacuation, while this is not the case in real accidents. For example, in a hurricane evacuation, involved areas change as the hurricane moving on. A road's performance maybe weakened when it is in the involved areas. Further studies need to take this into consideration.

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