PEDEVACUATION: The Emergency Evacuation Module of Pedestrians for Washington D.C.

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Abstract:

Evacuating large municipal areas during emergencies in an efficient manner is one of the critical concerns of most responsible management agencies. Previous studies focus mainly on strategic evacuation plans or controls for the passenger cars, giving inadequate attention to those pedestrians community with transit systems or other modes especially in metropolitan areas. This study has developed an evacuation planning module for pedestrians in Washington D.C. and integrates it with the system developed for passenger-car evacuation. The proposed module first guides people to the nearest metro-stations, and then applies the knowledge-based method to choose proper evacuation routes for shuttles to pick up evacuees. It also includes the plans for guiding pedestrians to the nearest evacuation route, and for dispatching shuttles need for their evacuation.

1. INTRODUCTION

Evacuations are more common, as potential terrorist attacks, harmful substances released from transportation and industrial accidents, fires and floods, and other possible emergencies, all requires immediate evacuation from the hazardous area (1-4). Liu et.al (5) has developed an evacuation system for Washington DC, with an integrated optimization/simulation method. Their proposed considers, however, mainly those with access to the passenger cars, not including those travel primarily with other modes. For instance, employees may take buses or the subway to their office, and residents in the vicinity may just take a walk on the streets. When an emergency happens, they should be properly included in the overall evacuation plan such as providing guidance to the assigned bus-pick-up points, subway stations, and dispatching the buses needed for such evacuation operations within that safety window.

The focus of this research is to add a module called pedestrian evacuation to the previous CAPEVACUATION system to implement multi-mode evacuation planning and control. Its main functions are to guide pedestrians during evacuation to the nearest evacuation routes, where they will be picked by shuttles to the safety area, or are guided to the nearest metro-station where trains will take them away.

The framework of the CAPEVACUATION, consisting of the pedestrian network module, is illustrated in Section 2. The mechanism of the pedestrian network module, the logical relations and data flows among different modules are elaborated in Section 3. An illustrative case for Washington D.C. is shown in Section 4 to demonstrate the system's applicability in emergency scenarios. The last section summarizes the research work and future extensions.

2. FRAMEWORK OF THE EVACUATION SYSTEM CONSISTING OF PEDCAP MODULE

Figure 1 presents the framework of the proposed integrated emergency evacuation system. The system consists mainly of the following five modules:

- ***Input module****: for users to define the evacuation scenarios, to specify the network attributes, and to adjust control strategies. Generally, an evacuation scenario is defined with two types of information, namely evacuation demand and available road network.*
- ***Database module****: to store potentially useful evacuation scenarios, roadway geometric features, preset intersection control information, time-varying demands, and resulting system outputs. Thus, existing scenarios may be loaded onto the system and analyzed without executing the optimization module.*
- ***Optimization module****: to automatically generate the optimal routes, turning fractions, and signal timings under the expected demand pattern in the specified evacuation network within the target clearance time. The clearance time indicates the duration from the start of the evacuation process to the time when all evacuees have reached their target destinations. This optimization process mainly servers for the passenger cars.*
- ***Pedestrian Evacuation Module****: to generate the best evacuation routes for shuttles to pick people, guide them from different locations to the nearest evacuation route or metro-station, and generate an efficient and effective shuttle dispatching strategy.*
- ***Output module****: to display the customized output from simulation results, which can facilitate system users to evaluate and adjust evacuation optimization plans. Also to project and visualize traffic conditions during the entire or partial evacuation process under the designed scenario and implemented control strategies.*

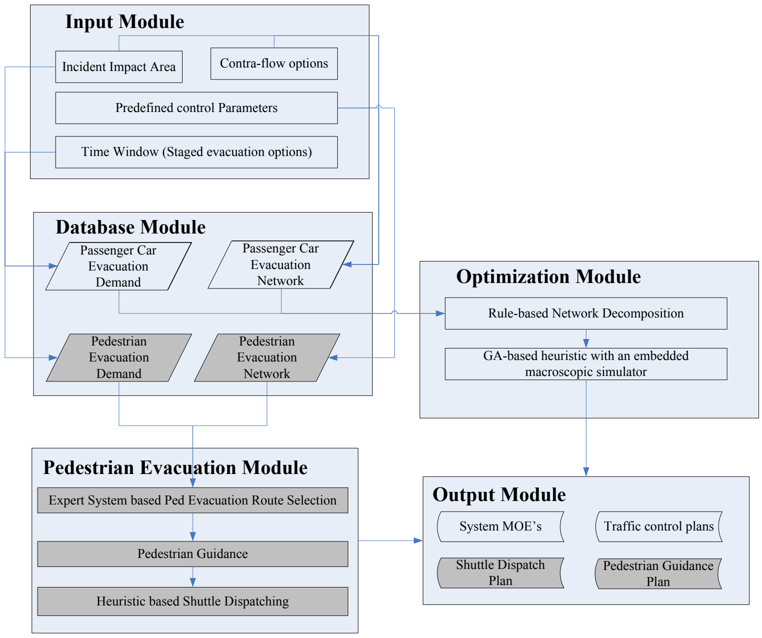

Figure 1 Framework of the CAPEVACUATION system

3. PEDESTRIAN EVACUATION MODULE DETAILS

The pedestrian evacuation module takes into the incident area and the pedestrian demand as the input, and outputs the pedestrian guidance and shuttle dispatch plans. There are three alternatives for a pedestrian to evacuate:

1) Run to the nearest metro-stations
2) Run to the nearest evacuation route to be picked by shuttles to a metro-station
3) Run to the nearest evacuation route to be picked by shuttles to the safety area

The choice of the available alternatives is constrained by:

1) Running distance
2) Road capacity for pedestrians
3) Metro-station capacity
4) Preference of individuals

To best the evacuation efficiency, this module assumes that all evacuees without accesses to cars will be first directed to take alternative 1, as long as the roadway capacity, walking distance, and station capacity permit. The second and third alternatives will be recommended concurrently.

The key procedures embedded in this module will be elaborated below.

Guide Evacuees to the Metro-Station

This step aims to guide individuals to the nearest metro-stations. It can be formulated as a multi-origin and multi-destination maximum flow problem with the following constraints:

- Road Capacity constraints. Each arc corresponding to each pedestrian roadway segment in the network has an upper-bound of pedestrian flows. To avoid causing blockage on the pedestrian route, the module shall place the limitation of pedestrian flow on each arc.
- Metro-station capacity constraints. Each metro-station has a limited space that can only hold a limited number of people waiting for the train, and also each train has its capacity. So the pedestrian flow into the metro-station should not exceed an upper limit for the station.
- Walking distance constraint. This is to ensure that the guidance offered to evacuees takes into account that maximum acceptable walking distance

Determine Route for Shuttles to Pick Evacuees

The second alternative is to transport some evacuees with shuttles to the metro-station or to take them directly to the safe area. Hence, a set of effective routes for shuttles to pick people should be determined.

Different networks have different topologies and may lead to different choice of evacuation routes, this study presents an expert-system based method for design of shuttle picking strategy and its logic flow is shown in Figure 2:

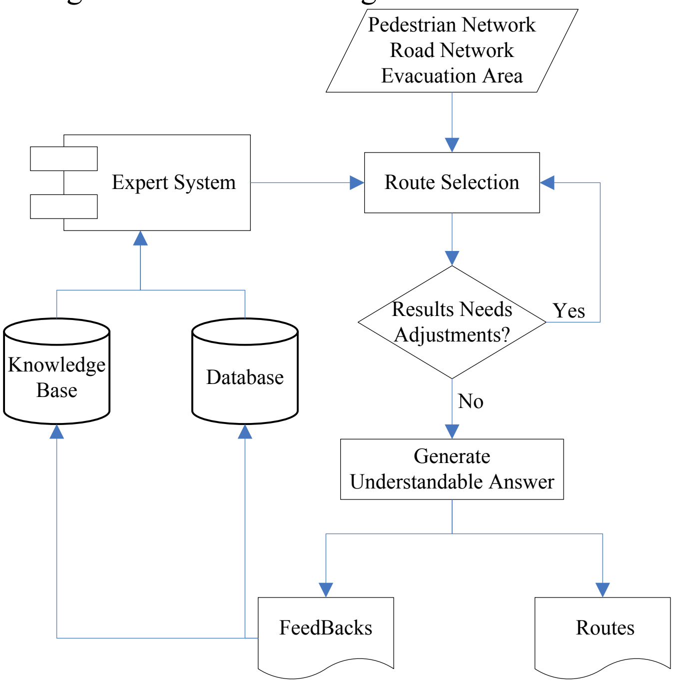

Figure 2 Knowledge-based Route Selection

Knowledge available for guiding the shuttles and pedestrians in the Washington metropolitan area are summarized below:

- In most cases, evacuation routes will be these major arterials having a high roadway capacity.
- In most cases, one shall select these evacuation routes cut across the incident area to facilitate the access of evacuees.
- Evacuation routes shall cover those areas with high pedestrian demands.

- All the evacuation routes in the incidence area should be able to cover all the pedestrian demands. That is to say, for each individual, there would exist an evacuation route within walking distance.
- The evacuation route should be directly toward and if a road can be evacuated from both sides, then it should be divided into two evacuation routes.

Guide Pedestrians to Evacuation Routes

At the previous step, the evacuation routes have been determined. The step is to assign pedestrians to the evacuation routes so that shuttles can be dispatched to pick them. One of the concerns is whether crossing the evacuation route should be allowed because crossing the street may cause unexpected complex interactions with vehicle flows and signals.

In the module, pedestrians are guided to the nearest evacuation route without crossing the major streets for vehicle evacuation. The assignment of pedestrian flows to access optimal routes can be formulated as follows:

Minimize $c_{ij} f_{ij}$

s.t. $f_{ij} \le u_{ij}$

$\sum_i f_{ij} - \sum_i f_{ji} = 0$, for all node i that is not a source or sink

$-\sum_i f_{ij} + \sum_i f_{ji} = d_j$, for all node i that is a source

Where c_{ij} is the cost from node i to node j， f_{ij} is the flow sent from node i to node j, u_{ij} is the upper-bound of the flow could be sent from node i to node j. d_j is the demand at source node j. The first constraint maintains that the flows of every arc not exceed the upper limits, the second constraint is to ensure the flow in-and-out balance of every intermediate node, and the third constraint indicates the flow-out of every source node. The final solution should also be adjusted to ensure demand at each convene location exceeds a certain threshold (6).

Determine shuttle dispatch strategy

This is currently the last step in this module. After all the pedestrian flows to the evacuation routes have been determined, the problem is converted to a service allocation task. The shuttles are assigned to evacuate to the pedestrians waiting at designated locations. Note that, on one hand, these people arriving at the convene locations should be picked as soon as possible, but on the other hand, since the total number of shuttle is not infinity, the shuttle can't be dispatched concurrently to meet all target demands, the solution thus aims to reach a reasonable balance between these two seemingly contradictory objectives.

To facilitate the presentation, a term "picking event" is introduced here to indicate the event that a shuttle stops at a convene point to pick a number of people. The "picking event" records the following information:

- Picking Shuttle
- Picking Location

- Picking Time Slot
- Picking Number

If all the “picking events” can be determined, then it would be relatively easy for planners to dispatch shuttles from their depots to satisfy these events. So one can formulate the entire problem as follows:

- Minimize pedestrian’s total waiting time
- Minimize total number of shuttle dispatched
- Maximize shuttles’ average load factor (people picked/max load)

Under the constraints:

- The picking time slots of one shuttle should be constrained by the travel time needed under real-time traffic condition, which can be obtained from the macroscopic simulator of the system
- The picking number should be equal or less than the total number of people waiting at the location at the corresponding picking time
- A shuttle can not pick more than it can hold
- All the people should be picked within specified safety time window
- For each pedestrian, his/her waiting time should be within the acceptable level

After all the picking events have been determined, the last task is to come out the shuttle dispatching plan from shuttle depots. For each evacuation route, one shall first see if recycling shuttles back and forth can satisfy those required picking events. For those picking events that can not be satisfied by recycling shuttles, shuttles should be sent from shuttle depots. It can be also formulated as a service providing problem with given demands. The decision variable b_{ijkt} is to indicate whether to dispatch a shuttle at time t from depot i to location j at route k. The objective is to minimize the total time spent from a depot to the first picking location subject to the constraint that every picking event should be completed within the constraints.

4. SYSTEM APPLICATION – UNION STATION UNDER ATTACK

The case study illustrates the evacuation scenario for pedestrians when Union Station is under attack.

Case description

Union station is the transportation hub as well as the most visited destination in the Washington D.C. This emergency scenario assumes that union station is attacked on a workday at about 4:00 PM, and all Metro, AMTRAK, VRE, and MARC lines will stop service for 24 hours. The building will be closed, and the entire building and its neighborhood (about 70,000 persons) will be evacuated within the expected clearance time of 3 hours. The impact area and the pedestrian demands are indicated below (the red rectangle stands for the impact area, the red dots are pedestrian demands, and the sizes of the dots are in proportion with their demand):

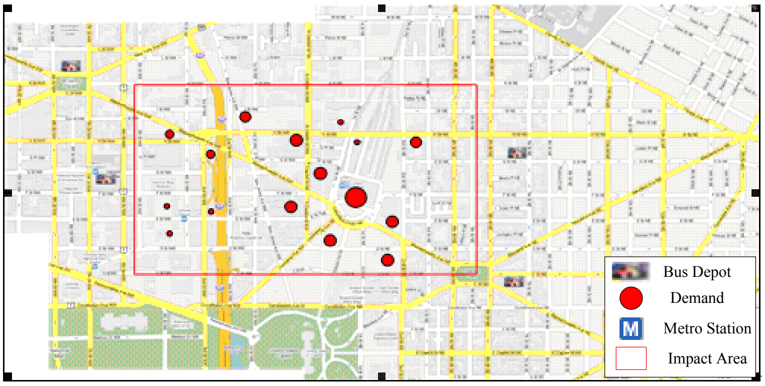

Figure 3 Impacted area and Pedestrian Demand of the emergency incident

After the pedestrian demand is acquired and the impact area is determined, the system first looks within or near the impact area for the metro stations. In this case, metro-station Judiciary Square is selected, and the pedestrians that are within walking distance to it will be guided to the station until it is overloaded.

The next step is to determine the route for shuttle to pick evacuees, There are four potential bus depots that is close to the impact area and can be used to dispatch shuttles. Once the shuttles are dispatched from the depot, they will follow a route back and forth to pick people. In this case, two routes are suggested, and each route is composed of two directed paths, one forward and one backward.

Afterwards, bus stops should be set and pedestrians should be guided to the bus stops. Crossing the major routes is not allowed here and to shorten the walking distance of pedestrians as much as possible, the stops are set near each intersection on the side of the route. For each route, it covers all the pedestrian demands along its route. The stops are indicated as blue dot on the map and lines drawn from red dots to the blue dots gives the example of the walking paths from pedestrian demands to the bus stops.

The last thing is to determine the shuttle dispatch strategy. The shuttle is dispatched at scheduled times and follows a given route. The arrows pointing from the bus depots to the bus stops give example of which bus stops on the route the shuttles heads first on dispatching, and afterwards they follow the routes back and forth.

The evacuation route, convene location and the pedestrian guidance to the convene location are depicted in the figure below (the green and purple lines are evacuation routes each of which composed of two directed paths):

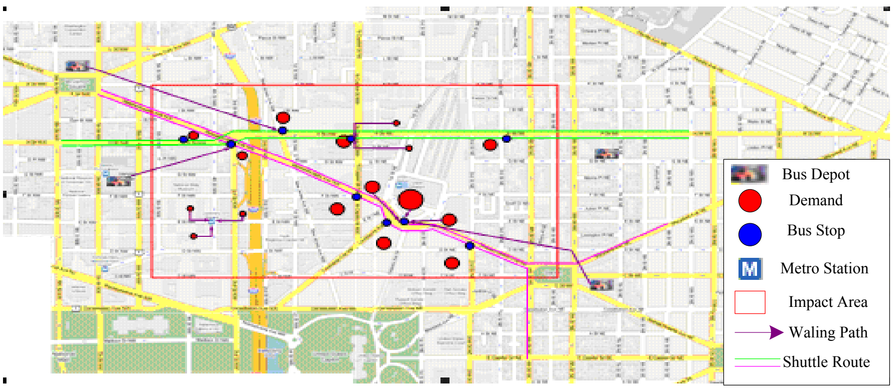

Figure 4 Evacuation route, convene location and pedestrian guidance

The shuttles are dispatched from shuttle depots to pick people along the route. Totally around 21 shuttles are needed. Other MOEs are displayed below, the average waiting time stands for the average time pedestrians wait at the bus stops for the shuttle to arrive, the average walking distance is the average distance pedestrians walk from their origin to the bus stops, the average evacuation time is the average time spent for each pedestrians beginning from their origin and ending to their safety area, and the average loading factor stands for the average occupancy rate of the shuttles. The loading factor equals the number of people in the shuttle divided by the shuttle's capacity, and the maximum of it is 1. Given the nature of emergency, the evacuation plans for pedestrians are effective. Averagely every 4 minutes a shuttle arrives at the stops to pick pedestrians and the loading factor is high which means the shuttle is utilized almost up to its capacity. The average walking distance 50m is also acceptable to pedestrians.

Aver Waiting Time	Aver Walking Dist	Aver Evac Time	Aver Loading Factor
2.01 minutes	50.32m	10.72minutes	0.91

Table.1. Effectiveness of the evacuation

5. CONCLUSIONS

This paper has presented a module for evacuating pedestrians taking public transportation utilities. This module is integrated with the previous system mainly for passenger car evacuation. The module takes the impact area and other system parameters as its input, and gives the pedestrian guidance plan and shuttle dispatching plan as the output. The system obtains real-time traffic information from the macroscopic simulator which also allows user to evaluate various control strategies by providing key statistics as well as the visualization of the evacuation operation. System users can easily identify the potential bottlenecks and take necessary adjustment with the user-friendly input and output interface. The proposed module serves as an important supplement of multi-mode evacuation plans.

Further research along this line will be focused on the following critical issues, such as the inter-relationship between different modes of the evacuation, and real-time adjustments of operational plans due to unexpected responses for evacuees.

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