CAPEVACUATION: The Corridor-Based Emergency Traffic Evacuation System for Washington D.C.

Yue Liu (troybest@umd.edu), Gang-Len Chang, Xiaorong Lai, and Ying Liu
Department of Civil and Environmental Engineering
University of Maryland, College Park
Maryland, 20742, USA

Abstract: Evacuating large municipal areas during emergencies and disasters in an efficient manner is one of the critical concerns faced by emergency management agencies. This study has developed a corridor-based evacuation planning system for Washington D.C. to design and evaluate various traffic control strategies. The proposed system divides the entire study area into different evacuation corridors, and employs its optimization module along with an embedded macroscopic simulator to generate both signal timings and routing strategies for each corridor in the evacuation area.

1. INTRODUCTION

Due to potential terrorist attacks or other possible emergencies, evacuation related strategies and technologies have received increasing attention in both research and practice *(1-4)*. Along with this research line, this study presents an emergency evacuation system for corridor traffic control within the Washington metropolitan area, which integrates both optimization and macroscopic/microscopic simulation methods.

Development of such a system is inevitably subjected to the roadway network constraints. The target network covered by CAPEVACUATION, the emergency evacuation system designed for Washington D.C., includes a total of 319 traffic analysis zones (TAZs), 19 major corridors, and 15 secondary routes. Most of these corridors and routes are arterials with intersections controlled by traffic signals or stop/yield signs. Freeway segments along I-395 and I-295 were also integrated in this system. The system provides a GIS-based network editing module, which allows operators to assess the impact of the emergency incident, specify preliminary control plans, identify TAZ-based evacuation demands, and allocate evacuation routes. A two-level optimization module aims to obtain an optimal control plan based on a revised cell transmission formulation of network flows. Using this plan as input, the output module integrated with a macroscopic simulator will help system users to evaluate the control strategies with the detailed time-varying performance information. Customized real-time 3D visualization of evacuation situations will offer an effective and intuitive tool for city authorities and traffic operators to make proper decisions.

The framework of the proposed CAPEVACUATION is illustrated in Section 2. The mechanism of each individual 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 real emergency situations. The last section summarizes the research work and future extensions.

2. FRAMEWORK OF THE PROPOSED EVACUATION SYSTEM

Figure 1 presents the framework of the proposed integrated emergency evacuation system. The system mainly consists of the following four 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. In this study, the initial network is preset as the actual road network for Washington D.C. when the system is built.*
- ***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 optimized route choice, turning fractions, and signal timings under the expected demand pattern in the specified evacuation network within the target clearance time. Here, clearance time indicates the duration from the start of the evacuation process to the time when all evacuees have reached their target destinations.*
- ***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.*

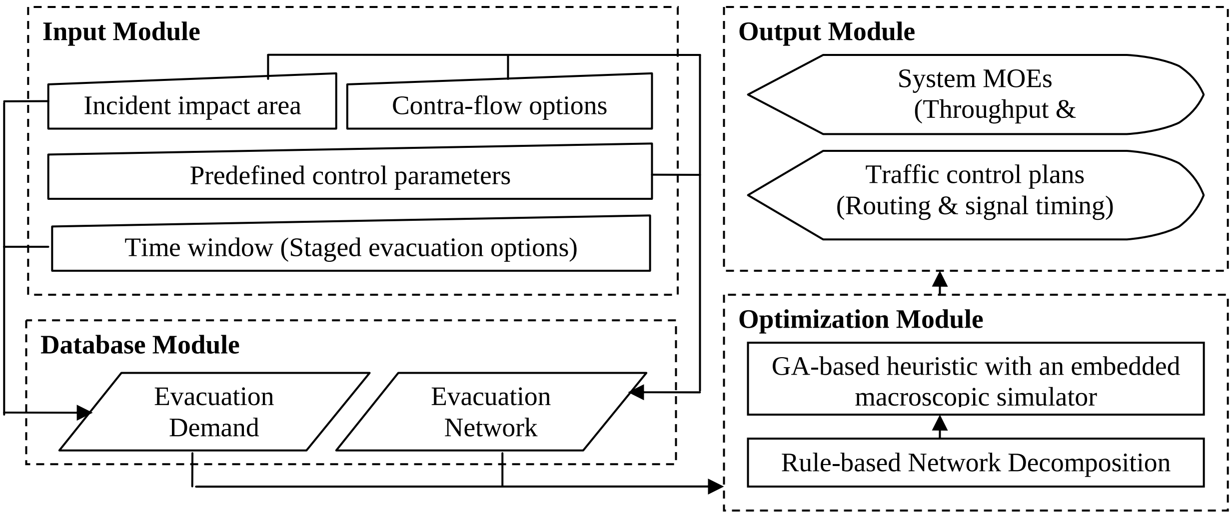

Figure 1 Framework of the CAPEVACUATION system

3. SYSTEM MODULE DETAILS

The key features of each module will be elaborated in this section with its detailed functions.

Input Module

This module is for potential system users to input and adjust the following information during either planning or real-time applications:

- *Time-varying distribution of evacuation demand within traffic analysis zones (TAZs) and the evacuation start time. Note that the current system supports a two-stage evacuation, where those TAZs closer to the incident can be evacuated in a higher priority;*
- *Major evacuation network, either directly defined on the original road network or selected from existing candidate plans in the database module;*
- *Safety destinations on the evacuation corridors;*
- *Target evacuation clearance time, and*
- *Important network control parameters, such as signal timings and contra-flow options.*

The following figure presents a snapshot of the input interface, which features its use of a map-based presentation to guide potential users with step-by-step instructions.

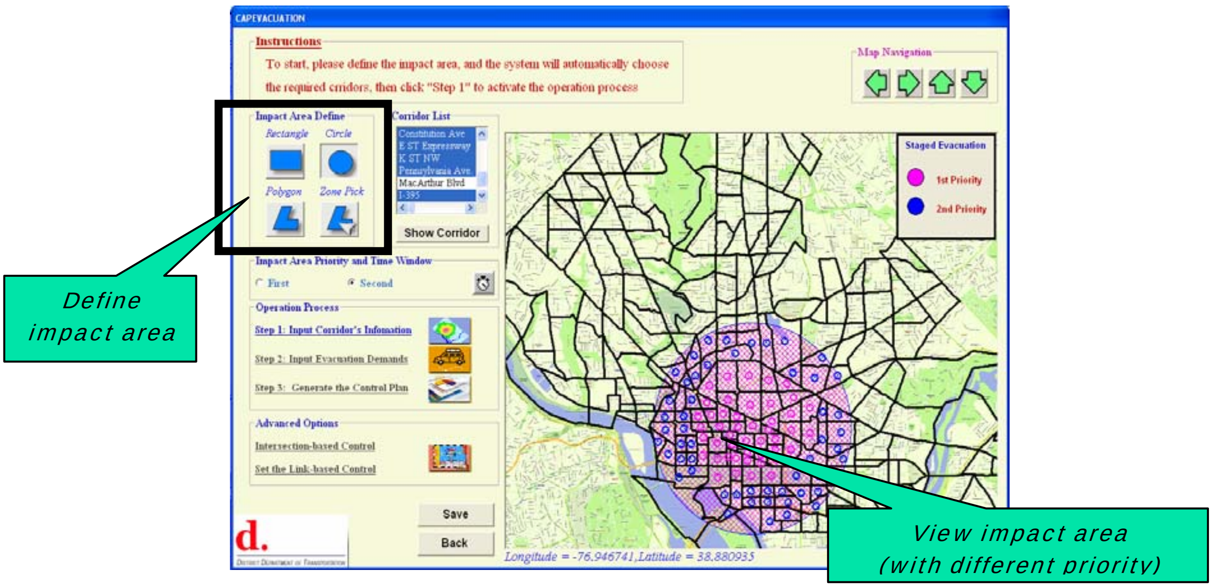

Figure 2 Snapshot of the input interface

Database Module

This module uses specially-designed data files to contain the following information:

- *The geographical information of 319 Traffic analysis zones (TAZs);*
- *The time-of-day demand information for each zone, including both passenger cars and pedestrians in each evacuation scenario;*
- *The geographical information of 19 major evacuation arterials, connectors joining those major arterials, and local access routes from origins;*
- *Given users' input of the TAZs to evacuate and evacuation starting time, the system will automatically load the corresponding demand pattern and roadway network involved. System users can also overwrite these data via the input interfaces.*
- *User specified control strategies like a contra-flow option on each segment;*
- *Optimized control strategies such as turning fractions at key intersections;*
- *Simulation output of each evacuation scenario;*

Optimization Module

This module employs a two-level optimization procedure to assign the expected demand on the designated evacuation network and to obtain the preliminary optimal control strategies. These control strategies will serve as the input to the macroscopic simulator. The optimization module is especially important during real-time operations, as it can efficiently identify the potentially most effective control plan under actual traffic conditions, which may include unexpected accidents or roadway damage. In this module, the high level optimization aims to maximize the throughput in the target evacuation clearance time. Only if this specified duration is insufficient for evacuating all demands, the low level optimization will be activated to minimize the total clearance time under the actual demand.

To realistically model network flows, this study employs the cell transmission concept proposed by Daganzo *(5-6)*, but with a revised formulation *(7)*. This revised feature will offer a great flexibility and efficiency for large-scale network applications. After transforming the road network into a set of connected cells, the network control problem can be formulated as an optimization problem under the constraints of flow conservation and flow propagation laws for cells. The system divides the entire study area into different evacuation sub-networks, based on the geographic relations between neighboring arterials. Within each sub-network, a Genetic Algorithm based heuristic is employed to solve the optimization model and generate the following control strategies under the given evacuation scenario.

- *The list of critical intersections, which will offer protective phases for turning movements onto the evacuation arterial;*
- *The optimal signal timing plans at critical intersections;*
- *The routing of evacuation traffic from origins to critical intersections; and*
- *Turning fractions at critical intersections.*

In addition to the above network flow relations, one shall also incorporate the following constraints in the optimization formulation:

- *Constraints related to the actual evacuation demand at each origin;*
- *Constraints defining the storage capacity and flow capacity of each evacuation destination;*
- *Constraints restricting connector flows at interchanges and intersections;*
- *Initial value of cell states and connector flows;*
- *Nonnegative constraints.*

A detailed description of the model formulation and numerical tests for this two-level optimization process can be found in Liu, etc *(7)*.

Output Module

To evaluate the performance of each candidate control plan in the output module, the system applies a macroscopic simulator, based on the revised cell transmission concept *(7)*, as shown in Equations 1-3.

$$x_i^{t+1} = x_i^t + d_r^t + \sum_{k\in\Gamma(i)} y_{ki}^t - \sum_{j\in\Gamma^{-1}(i)} y_{ij}^t \quad (1)$$

$$\sum_{k\in\Gamma(i)} y_{ki}^t \le \min\{Q_i^t, N_i^t / l_i, N_i^t - x_i^t\} \quad (2)$$

$$\sum_{j\in\Gamma^{-1}(i)} y_{ij}^t \le \min\{Q_i^t,\ \ N_i^t / l_i,\ \ x_i^{t-l_i+1} - \sum_{j\in\Gamma^{-1}(i)} \sum_{m=t-l_i+1}^{t-1} y_{ij}^m\} \quad (3)$$

where x_i^t is the number of vehicles in segment i at the beginning of interval t; y_{ij}^t is the flow from segment i to j during t; d_i^t is evacuation demand generated from i during t; $\Gamma^{-1}(i)$ and $\Gamma(i)$ are, respectively, the set of downstream and upstream segments to segment i; Q_i^t and N_i^t are the number of vehicles that can flow into/out of segment i and that can be accommodated in segment i during t; l_i is the number of intervals to traverse segment i at free flow speed.

Based on the requests of system users, the output module can analyze and display the following related traffic conditions through its map-based or table-based interfaces.

- *Statistical summary of the evacuation operation, including the time-varying system throughput, TAZ outflow, route throughput, evacuation clearance time and link volume distribution;*
- *Evacuation control strategies, including the signal timing parameters, traffic routing plans and turning fractions;*
- *3D visualization of the evacuation process with implemented network control strategies.*

The following figure presents a snapshot of the output interface:

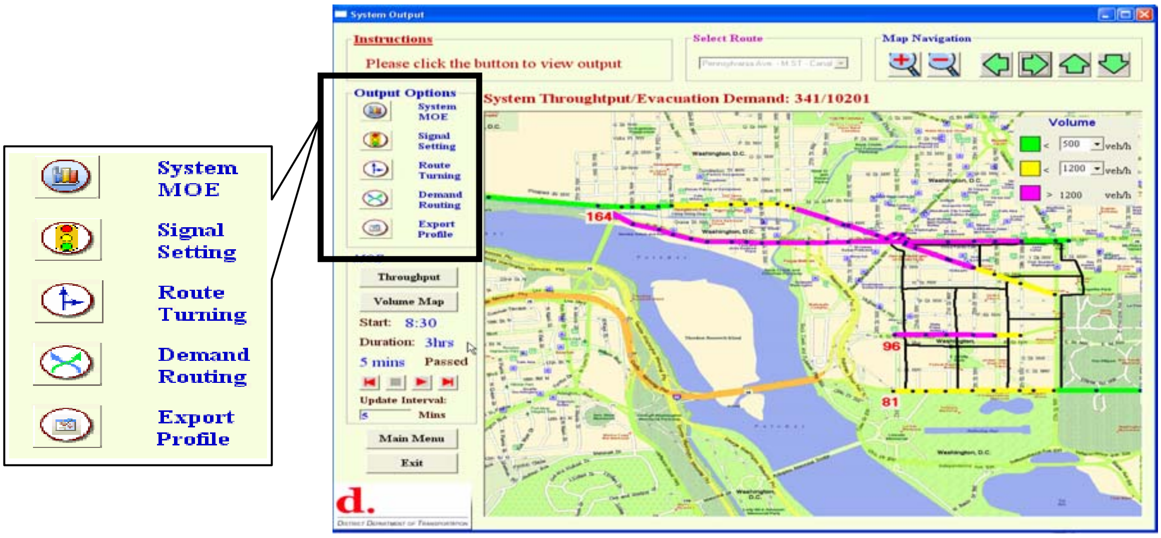

Figure 3 Snapshot of the output interface

4. SYSTEM APPLICATION – UNION STATION UNDER ATTACK

The case study illustrates the evacuation scenario 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 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. Depending on the scale and severity of the attack, this evacuation will involve the following evacuation corridors: H St./Benning Rd., I-395, New York Ave., and Pennsylvania Ave., and 6 TAZs will be impacted. (See Figure 4 and Table 1).

According to the emergency action plan provided by DDOT, all evacuees will take cars or will be picked up by Metro buses to evacuate from the impact area. In response to such a scenario, the system can automatically estimate the total number of passenger cars (6,239) and pedestrians (24,457) to be evacuated, as shown in Table 1, and produced the route distribution and signal control strategies.

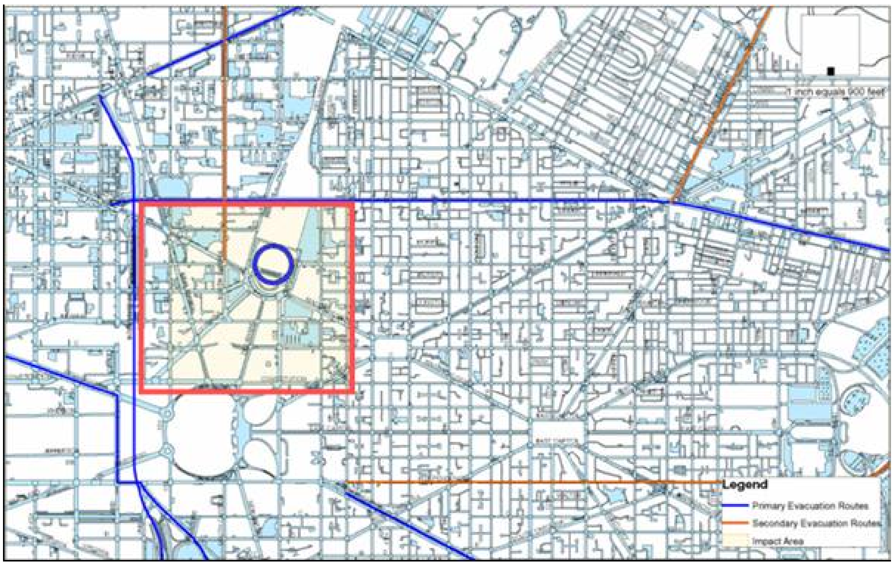

Figure 4 Impacted area of the emergency incident

TAZ #	60	61	62	63	64	67
No. of Passenger Cars	902	764	1028	921	875	941
No. of Pedestrians	2461	3654	2202	1329	14000	811

Table 1 Evacuation demands by TAZ

The control strategy proposed by the evacuation system, named plan-I is compared with the optimized plan designed on emergency scenario:

- *Plan I: the timing and routing plan generated with the optimization module of the CAPEVACUATION system;*
- *Plan II: the signal timing plan with the green time for arterial links and side streets decided precisely based only on their volumes.*

Based on Plan I, the proposed system can evacuate the impact area in 70 minutes, which is less than the clearance time of 2 hours from Plan II. The comparison indicates that in a complex network, the control strategies generated by the proposed system can significantly outperform the standard designed plans. The macroscopic simulator in the proposed system also provides time-varying key statistics of the evacuation operation, including system throughput, TAZ outflow, and route throughput, which can facilitate traffic operators to identify potential bottlenecks in the evacuation network and take necessary adjustments in a timely manner. Figure 5 illustrates the time-varying throughput for each evacuation route. Note that the load for each evacuation route is not balanced during the evacuation process. For example, after about 40 minutes, only H St. & Benning Rd. is taking the evacuation demand, which indicates the insufficient use of the network capacity. Traffic operators can then adjust the access links for evacuation demands to reach various routes so as to further improve the system performance.

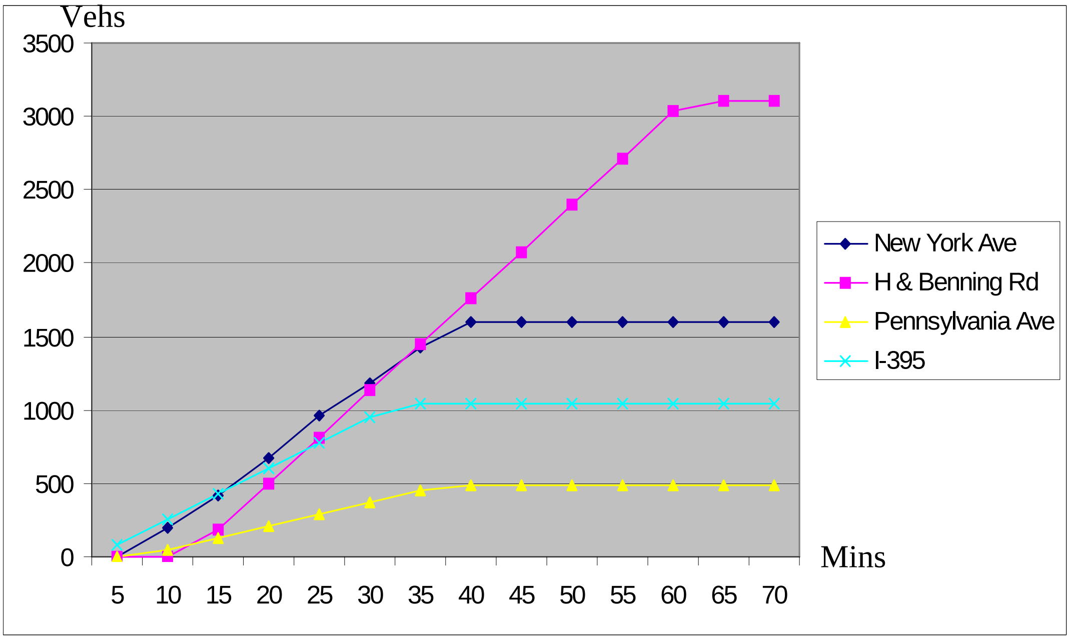

Figure 5 Time-varying system throughput by evacuation route

5. CONCLUSIONS

This paper has presented an integrated traffic evacuation system for Washington D.C. to prepare for potential terrorist attacks. The system features its integration of multiple functional modules. Its optimization module tries to identify the optimal control strategies during an evacuation based on a cell transmission formulation of network flows. The output module embedded with a macroscopic simulator allows users 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 system can facilitate system users to find effective evacuation control strategies in a large-scale network or in real-time operations, which is especially critical when unexpected events occur during the evacuation and the implemented plan need to be revised in a timely manner.

Further research along this line will be focused on the following critical issues, such as integrating multi-mode evacuation, including optimal assignment of bus pick-up points, emergency bus routing, and pedestrian routing, providing travel time estimation for users, and optimizing the start time for staged evacuation.

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