A CORRIDOR-BASED EMERGENCY EVACUATION SYSTEM FOR WASHINGTON D.C.: SYSTEM DEVELOPMENT AND CASE STUDY

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Abstract. Evacuating large municipal areas during emergencies and disasters in an efficient manner is one of the critical tasks of emergency management agencies. This paper presents a corridor-based emergency evacuation system and its example applications for the Washington D.C. metropolitan area. The proposed system features its flexibility in accounting for various critical issues associated with both planning and real-time operations, including multiple data source integration, network decomposition, network-level traffic routing, contra-flow design, staged evacuation, optimal signal timing, and incorporating pedestrian and bus operations. Under a hypothetical emergency scenario for Union Station, the proposed system has demonstrated its effectiveness for producing evacuation routing strategies, identifying potential bottlenecks, and evaluating the performance of evacuation operations.

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. This study presents a corridor-based system for emergency evacuation of Washington metropolitan area, which integrates multiple modules to assist responsible agencies in better coordination and decision-making under emergency evacuation operations. Figure 1 shows the surrounding area of Washington D.C. and the roadway networks. As described in the evacuation strategies by the District Department of Transportation (DDOT), the areas outside the DC boundaries but within the Capital Beltway (I-495) are viewed as safe zones during an evacuation. The entire evacuation network covers 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.

In review of the literature, it appears that most studies on emergency evacuations are concentrated on the following four aspects: routing strategies, contra-flow design, staged evacuation, and arterial signal control. Network flow models, dynamic assignment models, and simulation-based approaches are the most widely employed tools. In traffic routing strategies, many studies *(1-4)* formulate the evacuation networks as facilities with limited capacities, where traffic can go through links with known travel times as long as they do not exceed the link capacity. These problems typically involve two types of network flow constraints, namely, flow conservation constraints at every node and capacity constraints for each link. However, some traffic phenomena, such as congestion-caused delay and queue formation/dissipation, are not captured in such models. Some other evacuation studies have applied DTA models to generate optimal traffic routing schemes concurrently with other control strategies, such as contra-flow design *(5-8)*, staged evacuation *(9)*, and scheduling of the evacuation demand *(10-12)*. Now in the research of contra-flow design, several simulation studies have reported the effectiveness of such strategies if properly implemented *(13, 14)*. Tuydes et al. *(5)* proposed link-coupling techniques for contra-flow design, which match network segments that can exchange the capacity in case of reversing. Mahmassani et al. *(8)* proposed an optimization scheme for dynamic capacity reallocation, and generated a time-dependent contra-flow control policy to be deployed at target links during a major evacuation. On the operational aspect, Wolshon *(15, 16)* emphasized the rerouting of traffic at the entrance and the end of the reversed segments. Using the microscopic simulation program CORSIM, Theodoulou et al. *(17)* and Lim et al. *(18)* assessed the alternative entrance and termination designs of contra-flow segments for the hurricane evacuation plan for the city of New Orleans.

In the staged evacuation studies, Chen et al. *(19)* investigated the effectiveness of such strategies with the microscopic simulation approach. Mitchell et al. *(20)* designed the potential zonal parameters that might influence the staging decisions. Tuydes et al. *(9)* formulated a mixed-integer linear programming model to concurrently optimize destination/route choice and zone scheduling. Chiu *(10)* formulated the evacuation scheduling as a mathematical programming model to minimize the total travel time by controlling the demand generating times. Trying to minimize the evacuation clearance time, Sbayti et al. *(12)* proposed an iterative bi-level formulation framework to solve the evacuation scheduling problem. To optimize the signal timings during the evacuation process, some studies *(21-23)* employed signal optimization software (e.g. SYNCHRO, TRANSYT-7F) to generate the optimal signal-timing plan, and used the CORSIM simulator to evaluate the resulting performance and impacts.

Despite the vast body of related literature, the complex interactions between different control strategies during the evacuation process remain to be investigated. This study presents our recently developed system that is designed to be an effective tool to integrate and evaluate all related strategies for both planning and real-time operations. The proposed system offers the functions to contend with the following critical issues:

- *Generate the optimal candidate evacuation plans under various demands and actual roadway constraints;*
- *Provide the flexibility for planners and operators to identify potential bottlenecks during evacuation and to make necessary adjustments to the implemented strategies;*
- *Enable the system operators to project and visualize traffic conditions on evacuation routes during real-time operations; and*
- *Efficiently assess and revise any implemented plan when encountering incidents.*

In the proposed tool, various individual modules to tackle with each aforementioned critical issue have been integrated together to make the system function seamlessly. A GIS-based input module allows operators to assess the impact of the emergency incident, specify preliminary control plans, identify TAZ-based evacuation demands, allocate evacuation routes, and revise implemented evacuation plans. A two-level optimization module *(24)* aims to obtain optimal control plans associated with TAZ evacuation priorities, contra-flow design, and corridor signal timings, based on a revised cell transmission logic for network flows. Using this plan as input, the output module integrated with a macroscopic simulator can help system users to evaluate different control strategies, monitor the performance of the implemented strategies, and identify potential bottlenecks. A customized 3D visualization module based on the microscopic simulator VISSIM also offers an effective tool for responsible staff/engineers to make proper decisions. All candidate evacuation plans along with their corresponding outputs can be stored in the database module for future access.

This paper is organized as follows: The framework of the proposed system 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 applying the developed system for hypothetical emergency scenarios in Washington D.C is presented in Section 4. The last section summarizes the research work and future extensions.

2. SYSTEM FRAMEWORK

Figure 2 presents the framework of the proposed integrated emergency evacuation system. The system mainly consists of the following five principal components:

- ***Input module**: for users to define the evacuation scenarios, to specify the network attributes, to set control parameters, to input incident information, and to adjust evacuation plans. 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.*
- ***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, demand scheduling, and signal timings under the estimated demand patterns within the target clearance time. Here, clearance time refers to the duration from the start of the evacuation process to the time when all evacuees have reached their assigned destinations.*
- ***On-line simulator**: to project and visualize traffic conditions during the entire or partial evacuation process under the designed scenario and implemented control strategies.*
- ***Output module**: to display the customized output from simulation results, which can facilitate system users to evaluate and adjust evacuation optimization plans.*

Note that the proposed system framework features its module-based structure. For instance, to provide required data for system operations, all supporting modules and functional modules are integrated seamlessly with each other through the carefully-designed data exchange process. On the other hand, each individual module is relatively independent with respect to its input and output needs, which offers the flexibility for further system expansion or modeling update.

3. KEY LOGIC OF SOME PRINCIPAL SYSTEM MODULES

This section will detail the structure of some key system modules, which include: Input Module, Database Module, Optimization Module, Online Simulator, and Output Module.

Input Module

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

- *Target evacuation clearance time;*

- *Time-varying distribution of evacuation demand within traffic analysis zones (TAZs) and the evacuation starting time. Note that the current system supports a two-stage evacuation, and the priority of each TAZ is optimized through the optimization module;*
- *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;*
- *Important network control parameters, such as signal timings and contra-flow options;*
- *Location, onset time, and duration of incidents or road closures.*

Figure 3 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.

Database Module

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

- *The geographical information of 319 Traffic analysis zones (TAZs) and their pre-defined local access routes provided by DDOT;*
- *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 and 15 connection routes;*
- *Intersection control parameters and link attributes;*
- *Given users' input of the TAZs to evacuate and the evacuation starting time, the system will automatically load the corresponding demand pattern and the roadway network to be used. System users can also overwrite these data via the input interfaces;*
- *All prior operational experience, information, and optimized plans, including control strategies;*
- *Simulation output of each evacuation scenario, including speed and volume distributions, potential bottlenecks as well as resulting impacts.*

Optimization Module

This module employs a bi-level optimization procedure *(24)* 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, its high-level control focuses on balancing the network traffic by assigning evacuation demands over different time windows and evacuation routes, and its low-level control centers on optimizing signal timings at the corridor level. Such a bi-level structure aims to achieve a trade-off between modeling accuracy and operational efficiency, as a fully integrated control model may involve too many control decisions and constraints to be solved effectively within an acceptable time interval, especially for large-scale network evacuations. This module consists of the following key components:

<u>Network Flows</u>

This component uses mathematical equations to represent traffic dynamics over the evacuation network. As an essential part of the entire optimal control system, these formulations should be able to accommodate the time-varying evacuation demand, to represent the time-varying network capacity, to realistically model traffic flow propagation along the evacuation routes, and to capture potential queue formation and dissipation. This study employs the cell transmission concept proposed by Daganzo *(25-26)*, but with a revised formulation *(24)*, as shown in Equations (1)-(3).

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

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

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

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.

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. For efficient computing, the system divides the entire study area into 9 groups of evacuation corridors, based on the geographic relations between neighboring arterials and the distribution of evacuation demand. Within each group, there are at least one corridor or neighboring connection routes, and the optimization model will generate a set of optimized control strategies under the given evacuation scenario.

Network-Level Control

Based on the revised cell transmission concept, this component functions to determine the best set of routing plans, contra-flow designs, and staged evacuation strategies to efficiently utilize the given evacuation network under the estimated evacuation demands.

During emergency evacuation, this component will first employs a base model *(24)* with a two-level optimization scheme for generating the optimal traffic routing plans, including the assignment of each TAZ to its pre-defined local access routes provided by the District Department of Transportation (DDOT) and the turning fractions at each intersection/interchange. The high-level optimization aims to maximize the total throughput within the specified evacuation duration. The low-level optimization model intends to minimize the total trip time (including the waiting time in origins) if the specified duration is sufficient for evacuating all demands. The set of formulations for the base model has captured the following operational relations:

- *Constraints related to the actual evacuation demand at each origin;*
- *Constraints related to flow propagation along the evacuation routes as well as the vehicle interactions at intersections/interchanges;*
- *Constraints defining the storage capacity and flow capacity of each evacuation destination;*

- *Constraints restricting connector flows at interchanges and intersections;*

The following figure presents a snapshot of the network routing interface, which shows the routing plans for the highlighted TAZ.

For potential inclusion of the contra-flow operations during evacuation, the network-level control component has an advanced function to capture the effects of contra-flow decisions on the network traffic pattern, including resource limitations, the discrepancy in driving behavior between the normal and reversed lanes, information needed for lane-reversal decisions, and non-linear capacity decrease resulting from the contra-flow operations. The extended model will yield the following three types of outputs:

- *The segments to implement lane reversal operations under the budget limit;*
- *The percentage of demand to be diverted to the links immediately downstream of the origin; and*
- *The target turning fractions to be controlled at each diverging point during each time interval.*

Figure 5 shows an example of the contra-flow operation provided by the system.

For design of the staged evacuation strategies, the network-level control component also contains an advanced model using dummy links at the origins *(27)* to explicitly determine the time to issue an evacuation order and to capture evacuees' response behavior upon activation of the evacuation order. This model assumes that the study network can be divided into different evacuation zones, and the available time window for each evacuation zone is predetermined.

The primary objective of the staged evacuation model is to improve the efficiency of the entire evacuation process while minimizing the total potential emergency impacts, that is, to minimize the sum of the following two time-related indices:

- *The weighted sum of the times for all evacuees to exit an evacuation zone, which reflects the estimated impacts and congestion level on the evacuation network; and*
- *The weighted waiting time of those vehicles ready to load on to the actual network but are delayed due to congestion. This is to reflect the congestion at those entry points to the evacuation network.*

Figure 6 illustrates a snapshot of the staged evacuation operations for various TAZs generated from the system, in which the pink dots indicate first priority and blue dots for second priority. The evacuation order issue time of different priorities are also shown in the time window dialog.

<u>*Corridor-Level Control*</u>

This component functions to generate signal control strategies for concurrent evacuation via multiple corridors, during which each corridor may receive traffic from, or send traffic to its neighboring corridors via connection routes. The signal optimization models in this component features the use of critical intersection concept *(24)*, that is, only key intersections will offer protective phases for vehicles from minor streets to turn onto arterials. The core concept intends to reduce the disturbance of side street traffic to the arterial flow progression. With an effective signal control system, the main evacuation arterial should be capable of progressively moving its assigned traffic flows without incurring excessive delay on those waiting at minor streets for joining the evacuation.

A multi-objective structure is implemented for the signal optimization *(28)*. Given the time window for an emergency evacuation, the model aims to maximize the total throughput through the evacuation arterial since this throughput is equal to the total number of vehicles entering the target destination. However, if the evacuation time window is sufficiently long for all evacuees to get out of the hazardous area, the control objective shall be set to minimize the evacuation clearance time. To avoid the long queue and delay for side street traffic resulting from maximizing throughput on the main evacuation arterial, the model consists of a supplemental objective, which is to optimally control the difference in the service level among different locations in the evacuation network.

The corridor-level control component will generate the following outputs:

- *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 refined routing plan of evacuation traffic from origins to critical intersections;*
- *Exact system MOEs, including the time-varying system throughput, TAZ outflow, evacuation route throughput, demand distribution between evacuation routes, and clearance time;*

Figure 7 shows the interface of optimal signal timings:

A detailed description of the formulation for all the aforementioned optimization components (including network flow modeling, network-level control, and corridor-level control) is not the focus of this paper, and is available elsewhere *(24, 27, 28)*.

Online Simulator

The online simulator module functions to project the network traffic conditions given the actual network control strategies and the estimated traffic demand patterns. To evaluate the performance of each candidate control plan in a timely manner, the system applies a macroscopic simulator, based on the revised cell transmission concept, which was seamlessly integrated with the optimization module for data exchange. To visualize the evacuation process in a 3D environment, the system employs a microscopic simulator developed with VISSIM, which was interfaced into the system via a specially written program based on Visual Basic Runtime Extension. The program functions to transform the optimized plans into the pre-built VISSIM simulation models and implement the simulation.

Output Module

The output module is designed to analyze and display the following related traffic conditions through its map-based or table-based interfaces. The primary functions for each type of output are as follows:

- *Table-based statistical summary of the evacuation operation (System MOE), including the time-varying system throughput, TAZ outflow, evacuation route throughput, evacuation route load split, and evacuation clearance time;*
- *Map-based output tracks the time-dependent distribution of the volume and the average speed over different evacuation routes with different colors;*
- *Evacuation control strategies, including the signal timing parameters, traffic routing plans and turning fractions at critical control points;*
- *3D visualization of the evacuation process with implemented network control strategies.*

In addition to the above primary functions, the output module also features its capability to help potential users analyze the evacuation plan for further improvements, which include:

- *Comparison between different groups of corridors to check the distribution of evacuees on all available routes; and*
- *Examination of the link segment speed for evaluating the operational efficiency and identifying potential bottlenecks.*

The following figure presents an example of the map-based output interface, in which the statistics of outflows from TAZs are displayed in a timely manner. Different colors of legends represent different levels of TAZ evacuation status, and the overall statistics of the evacuation operation are also summarized at the top of the map window.

4. SYSTEM APPLICATION –UNION STATION, WASHINGTON D.C.

This section presents the application of the proposed emergency evacuation system for Washington D.C.. This case study intends to assist potential users in best understanding the key functions and properties of all principal system components. The presentation hereafter will include the following parts:

- *Detailed description of the evacuation scenario, including network features and real-world operational constraints;*
- *Step-by-step action plans generated from the proposed system;*
- *Analysis of the evacuation effectiveness based on the operational strategies produced by the proposed system, and identification of bottlenecks for potential improvements;*

Union station is the transportation hub and a popular tour destination in Washington D.C. This emergency scenario assumes that union station is under attack on a workday at about 4:00 PM, and all Metro, AMTRAK, VRE, and MARC lines will stop the services for 24 hours. The building will be closed, and all 70,000 people will be evacuated within the expected clearance time of 3 hours. In response to such a scenario, the system can automatically estimate the number of traffic zones being impacted by the operation and the total number of passenger cars as well as pedestrians to be evacuated. Figure 9 shows the locations of these zones, and the total demand in each zone is obtained from the system database as listed in Table 1. These demands are assumed to move onto the network during a default loading time of 30 minutes.

According to the emergency action plan provided by the District Department of Transportation (DDOT), all evacuees should take cars or will be picked up by Metro buses to evacuate from the impact area. A total of 24,457 pedestrians will be directed to various Metro bus stations located at different traffic analysis zones (TAZs) for pick-up. Hence, those demands of pedestrians will be converted into vehicular demands loaded onto the evacuation network. These vehicles are expected to move out of the traffic zones via the pre-designated local access routes, and to use the following 4 major evacuation corridors selected by the system (see Figure 10) to travel to the Capital Beltway (I-495): H St./Benning Rd., I-395, New York Ave., and Pennsylvania Ave..

Based on the identified impact area and evacuation demand, responsible agencies can then use our proposed system to take the following step-by-step actions:

- *Step-1: Configuring the selected evacuation corridors into different groups to facilitate computing efficiency of optimal control strategies;*

- *Step-2: Assignment of evacuation demands from TAZs to different groups and routing traffic to the local access streets pre-defined within each group;*
- *Step-3: Optimizing signal timings for each group of corridors and refining initial routing plan from Step-2; and*
- *Step-4: Evaluating the control strategies and identifying potential bottlenecks.*

The results from each action step are shown below:

Step-1:

Based on the pre-set network decomposition criteria built in the system, the four selected evacuation corridors naturally fall into the following four groups:

- *Group 3: New York Ave.;*
- *Group 4: H St. and Benning Rd..;*
- *Group 5:Pennsylvania Ave.;*
- *Group 9: I-395.*

Step-2:

The demand assigned from each TAZ to each group of corridors is shown in Table 2. Based on the pre-defined set of local access streets for each TAZ provided by DDOT, the system then generates the optimal routing plan from each origin to its local access streets. Table 3 lists the traffic flows to be guided to each local access street.

Assuming no bottlenecks in the evacuation network, the system will first estimate the approximate total throughput during the pre-set evacuation time window. This planning-level information will allow the responsible operator to evaluate if the assigned corridors are sufficient for safely evacuating all target populations. The estimation results in this case imply that the duration of 3 hours is sufficient to clear the evacuation area. Then, the system will assist the user to proceed to the next step which is to minimize the evacuation clearance time with optimal signal control strategies.

Step-3:

The optimal plan for signal control at this step will provide three types of information, which includes:

- *The list of critical intersections and their signal timing plans;*
- *Refined traffic routing plans for better operational efficiency;*
- *Exact system MOEs, including the time-varying system throughput, TAZ outflow, evacuation route throughput, demand distribution between evacuation routes, and clearance time;*

Table 4 shows the list of critical intersections and their signal timings along each evacuation route. Other intersections that are non-critical will be set as an all-green phase for through traffic, and the demands from side streets will be diverted to critical intersections. For examples, compared with the routing plan from *Step-2*, the intersection of New York Ave. and New Jersey Ave. is operated as a non-critical intersection (eliminated in Table 4), after its 71 vehicles are rerouted to 1st St. NW.

The optimal solution with *Step-3* yields a clearance time of 4200 seconds (70 minutes) for evacuating all populations in the impacted traffic zones.

Step-4:

Since the access links for population from each TAZ to main evacuation arterials are pre-defined by the city which may not best fit the evacuation scenarios. The developed system will advise the users to perform the potential bottleneck analysis at this step, and to explore other alternatives so as to further improve the evacuation efficiency.

For example, Figures 11 and 12 illustrate, respectively, the time-varying throughput and demands via each evacuation route. Note that there exists significant difference in evacuation efficiency between different corridors due mainly to the pre-defined access side streets from each TAZ to the main arterials. Group 3 (New York Ave), Group 5 (Pennsylvania Ave.), and Group 9 (I-395) have much shorter evacuation clearance time (about 40 minutes) than Group 4 (H St and Benning Rd.), which is about 70 minutes.

This indicates the insufficient use of the network capacity during the evacuation process, and the load for each evacuation route is not balanced during the evacuation process. A further analysis of the demand assignment to each group (see Table 2) shows that almost all the TAZs that have access to H St. and Benning Rd. will send their demand to it. This indicates that the list of pre-defined local access routes from the District Department of Transportation for TAZs may not provide a sufficient capacity to diverge traffic between neighboring corridors under the example evacuation scenario. Traffic operators can then adjust the pre-planned access links for evacuation demands to reach various routes so as to further improve the system performance.

5. CONCLUSIONS AND POTENTIAL EXTENSIONS

This paper has presented an integrated traffic evacuation system for Washington D.C. to prepare for potential terrorist attacks. The proposed system features its effectiveness in accounting for various critical issues associated with both evacuation planning and real-time operations, including multiple data source integration, network decomposition, network-level traffic routing, contra-flow design, staged evacuation, optimal signal timing, and incorporating pedestrian and bus operations.

The proposed system has integrated various supporting and functional modules to contend with real-world operational requirements. A GIS-based input module allows operators to assess the impact of the emergency incident, specify preliminary control plans, identify TAZ-based evacuation demands, allocate evacuation routes, and revise implemented evacuation plans. The optimization module tries to generate optimal control plans of TAZ evacuation priorities, contra-flow design, and corridor signal timings, based on a revised cell transmission logic for network flows. The output module embedded with a macroscopic simulator allows users to evaluate various control strategies, monitor the performance of the implemented strategies, identify potential bottlenecks, and take necessary adjustment by providing key statistics as well as the visualization of the evacuation operation. The proposed system also can facilitate system users to find effective evacuation control strategies in a large-scale network or in real-time operations by decompose the entire evacuation network into 9 groups, which is especially critical when unexpected events occur during the evacuation and the implemented plan need to be revised in a timely manner.

The illustrative case presented in the paper clearly demonstrates the promise of the proposed system under the real-world operational constraints. Using the hypothetical example of

Union Station, the proposed system with all its supporting modules has provided step-by-step action plans for responsible agencies to take during the evacuation process.

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, and providing travel time estimation for users.

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Table 1 A list of Evacuation demands by TAZ due to the emergency

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
No. of Total Demands	984	886	1101	965	1335	968

Table 2 Optimal Demand Assignment from the System

TAZ	Group3	Group 4	Group 5	Group 9	Total
60	984	-	-	-	984
61	343	543	-	-	886
62	-	41	-	1060	1101
63	-	466	499	-	965
64	296	1039	-	-	1335
67	-	968	-	-	968
Summary	1623	3057	499	1060	6239

Table 3 Flows Routing to Each Side Street from the System

Arterial	Side Street	Total Flows (vehicles)
New York Ave.	New Jersey Ave.	71
	1st St. NW	807
	1st St. NE	745
H St. & Benning Rd.	New Jersey Ave.	1188
	North Capital St.	1275
	Union Garage St.	594
Pennsylvania Ave.	6th St.	412
	7th St.	87
I-395	New York Ave.	710
	D St.	350

Table 4 Signal Control Plan from the System

Arterial	Cycle (sec)	Intersection*	Arterial Green (sec)	Arterial Offset (sec) *
New York Ave.	225	1st St. NW	110	65
		1st St NE	140	105
H St. & Benning Rd.	205	New Jersey Ave.	115	5
		North Capital St.	120	30
		Union Garage St.	100	55
Pennsylvania Ave.	175	6th St.	110	0
I-395	-	-	-	-

Note: - No signalized intersections
* The arterial offset is the value relative to the evacuation start time

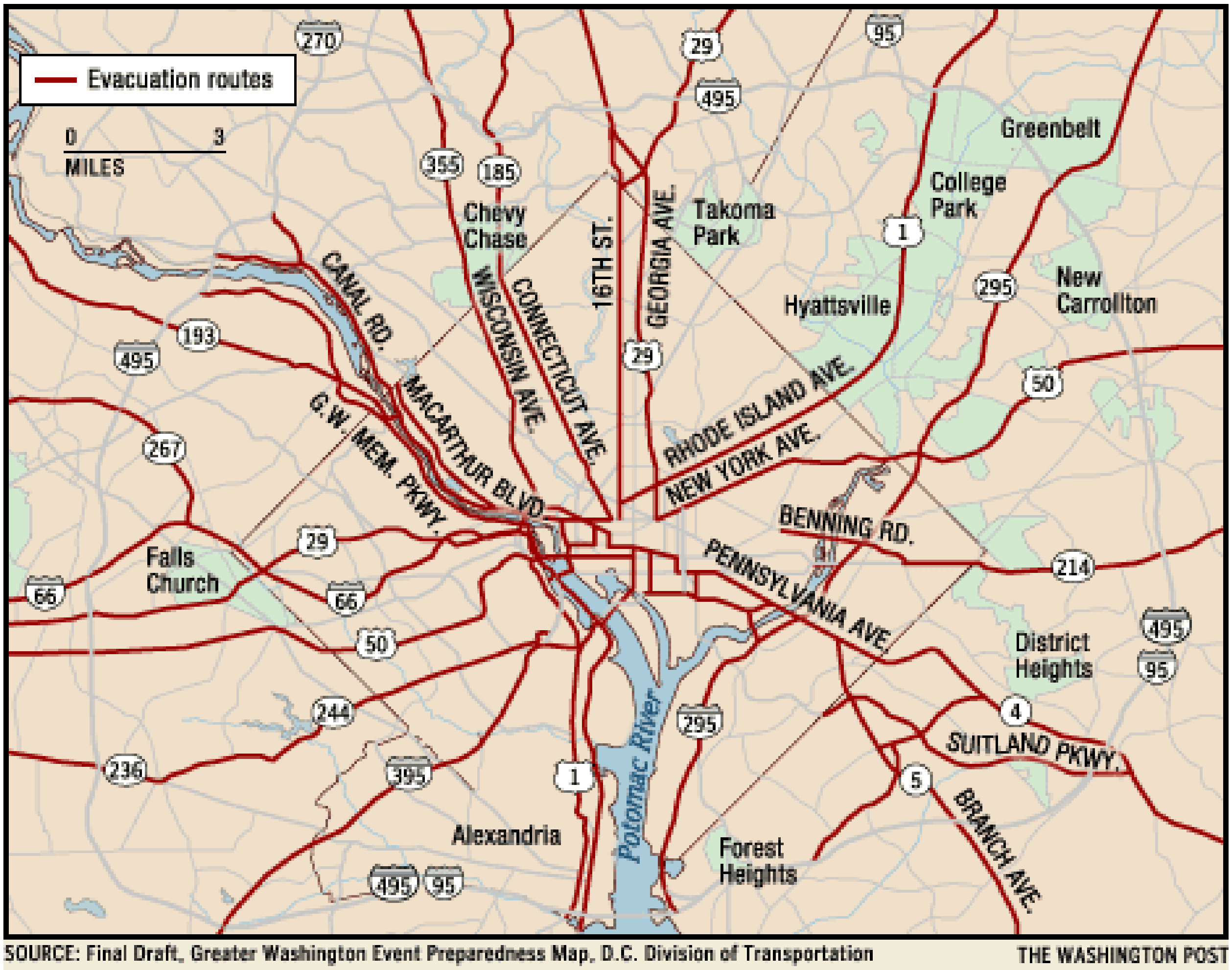

Figure 1 Illustration of the evacuation network in Washington D.C.

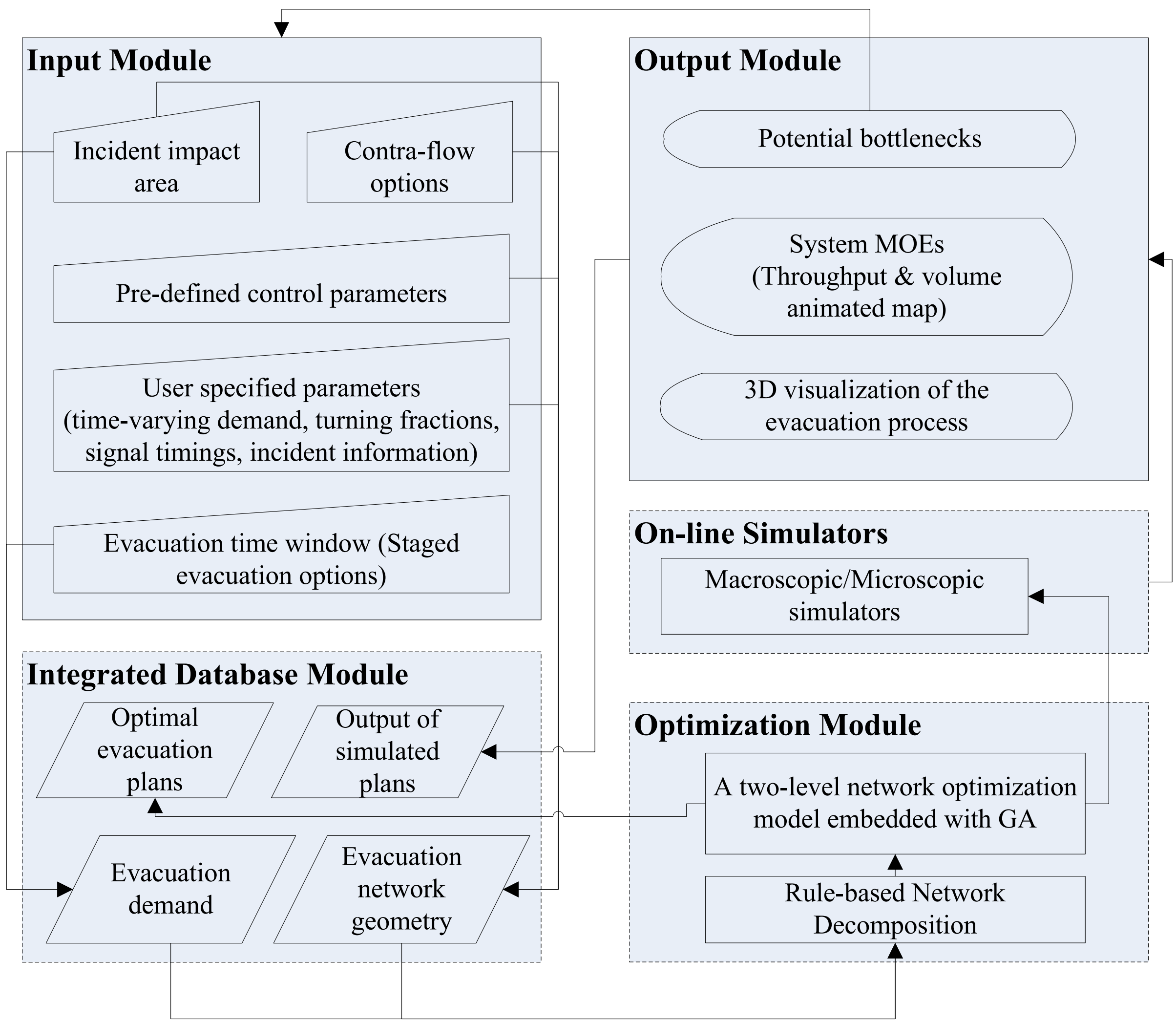

Figure 2 Framework of the proposed emergency evacuation system

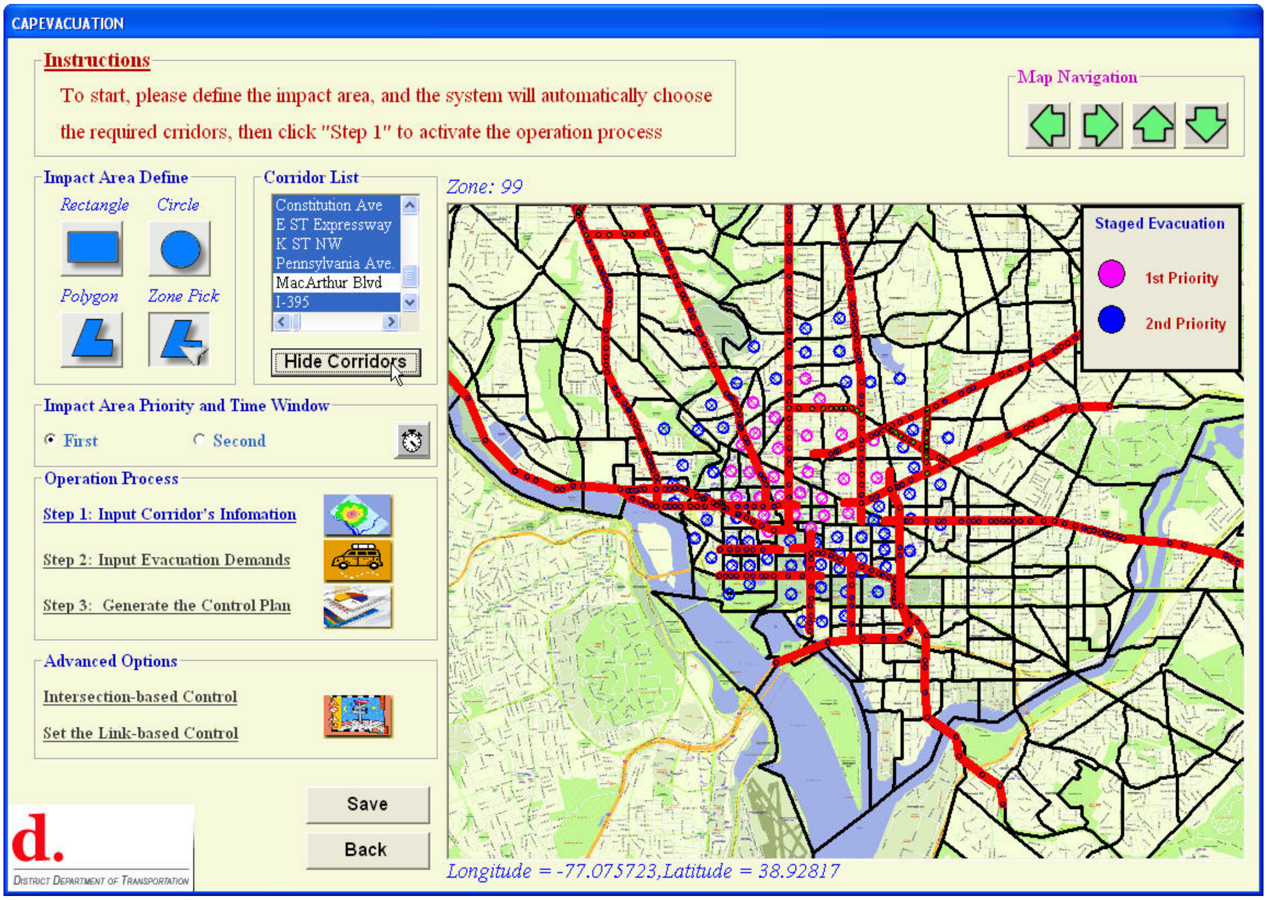

Figure 3 Snapshot of map-based input interface

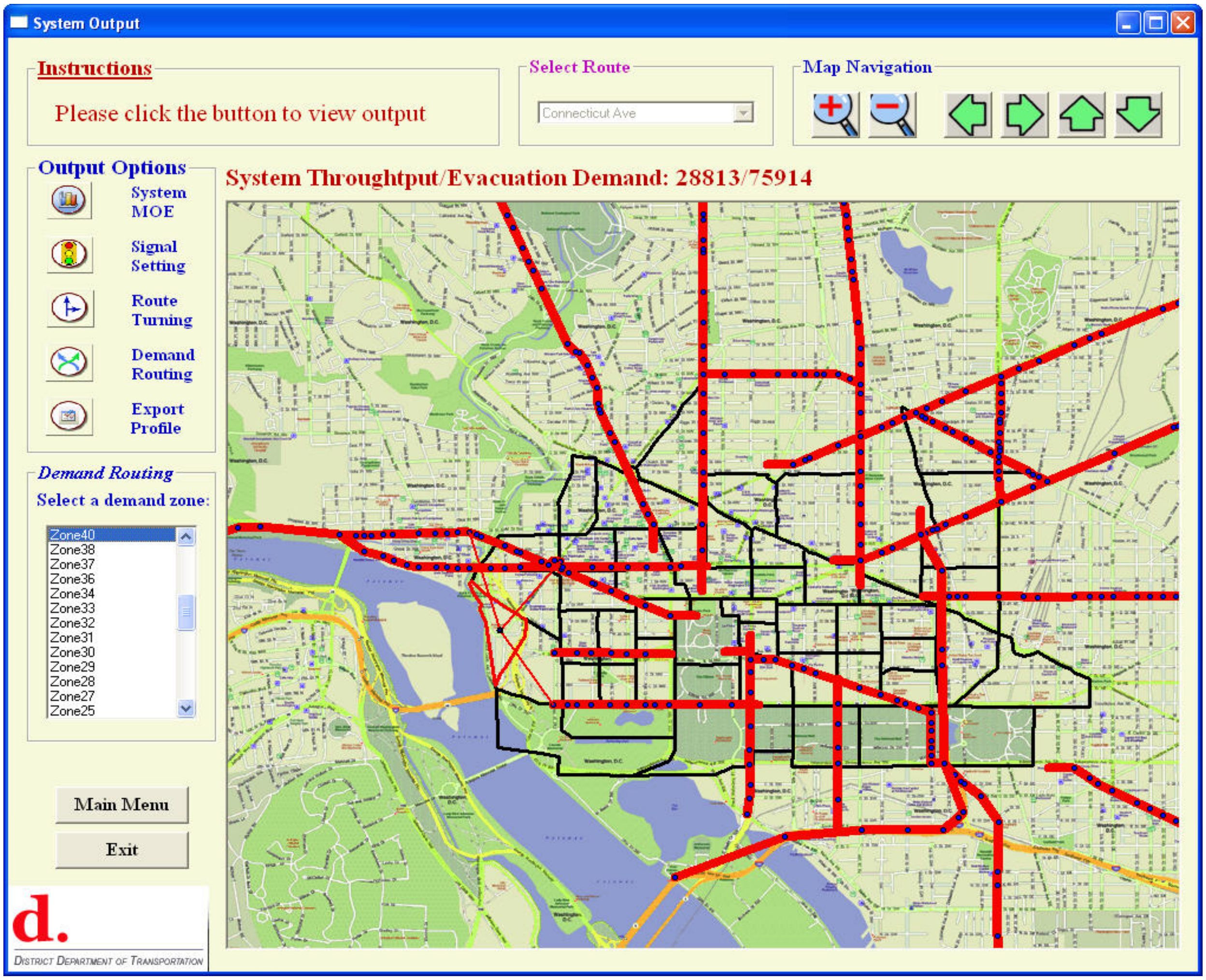

Figure 4 Interface of demand routing for a highlighted TAZ

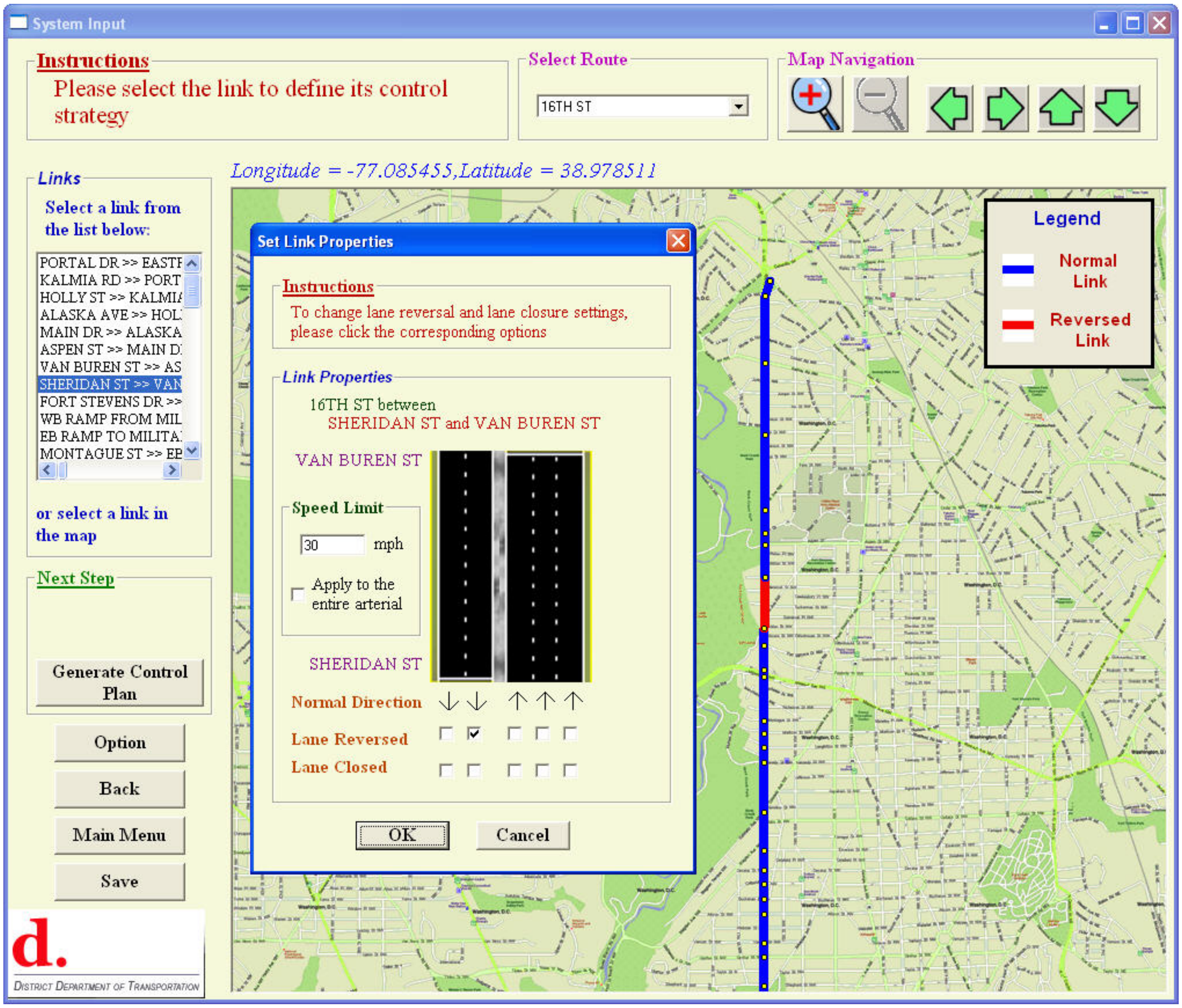

Figure 5 Interface of contra-flow design for a corridor segment

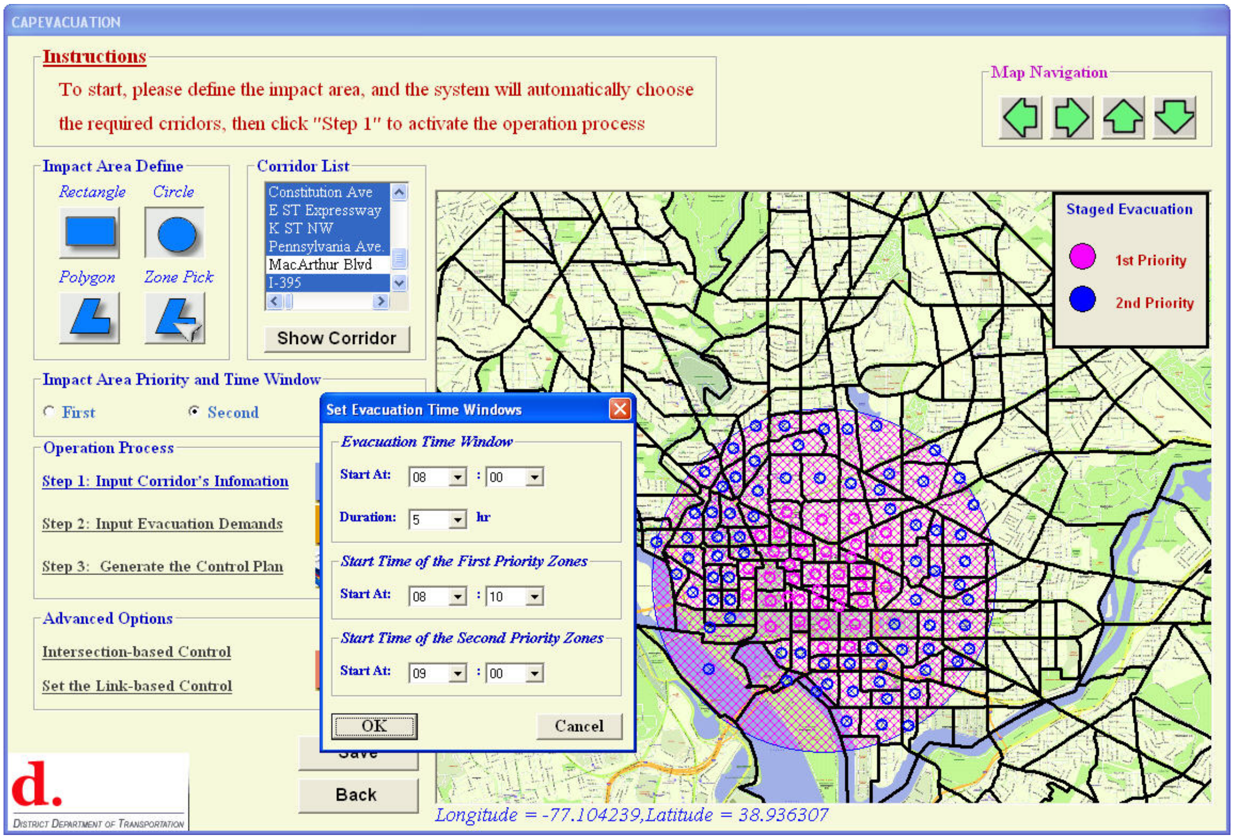

Figure 6 Interface of the staged evacuation operations

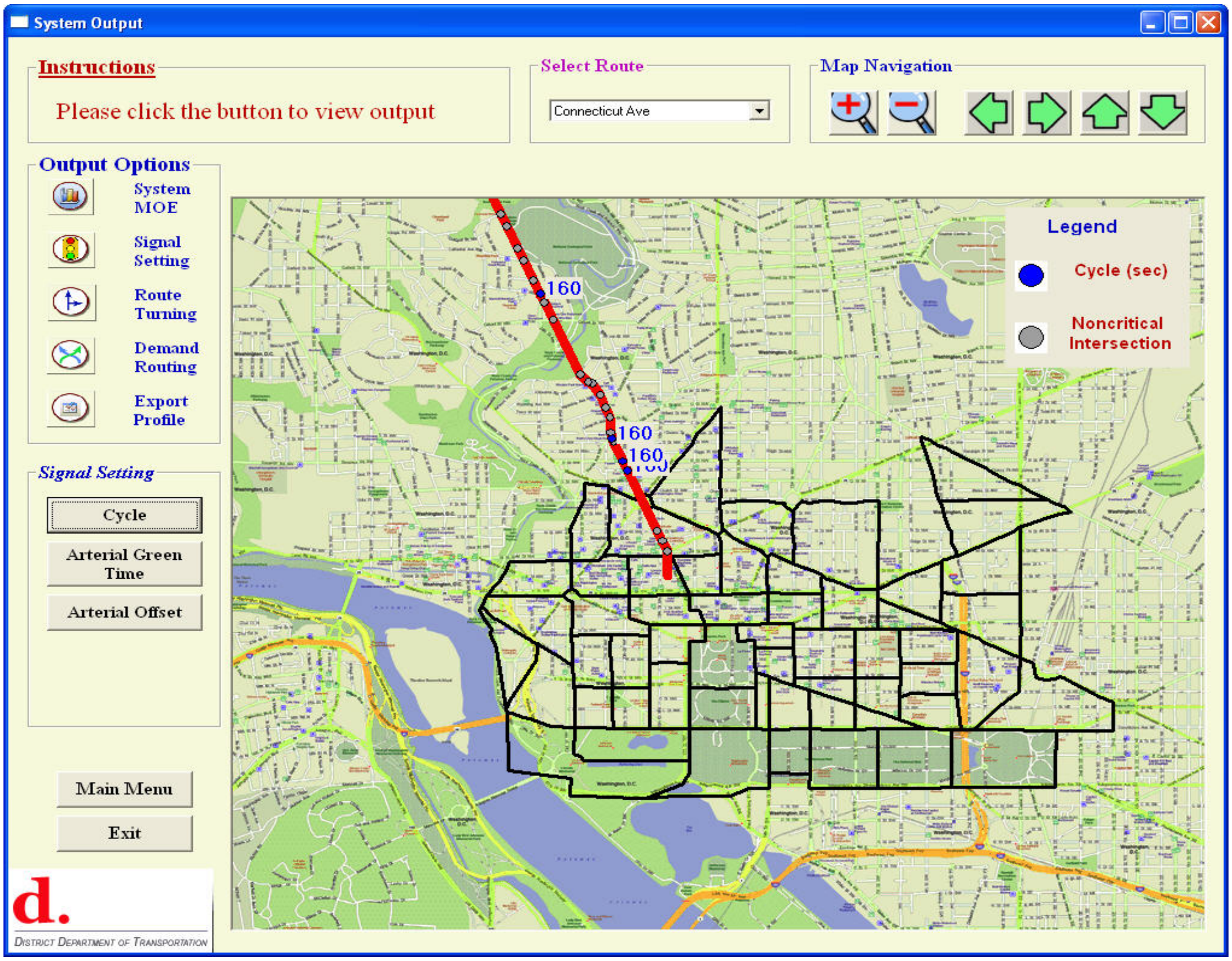

Figure 7 Interface of optimal signal timings

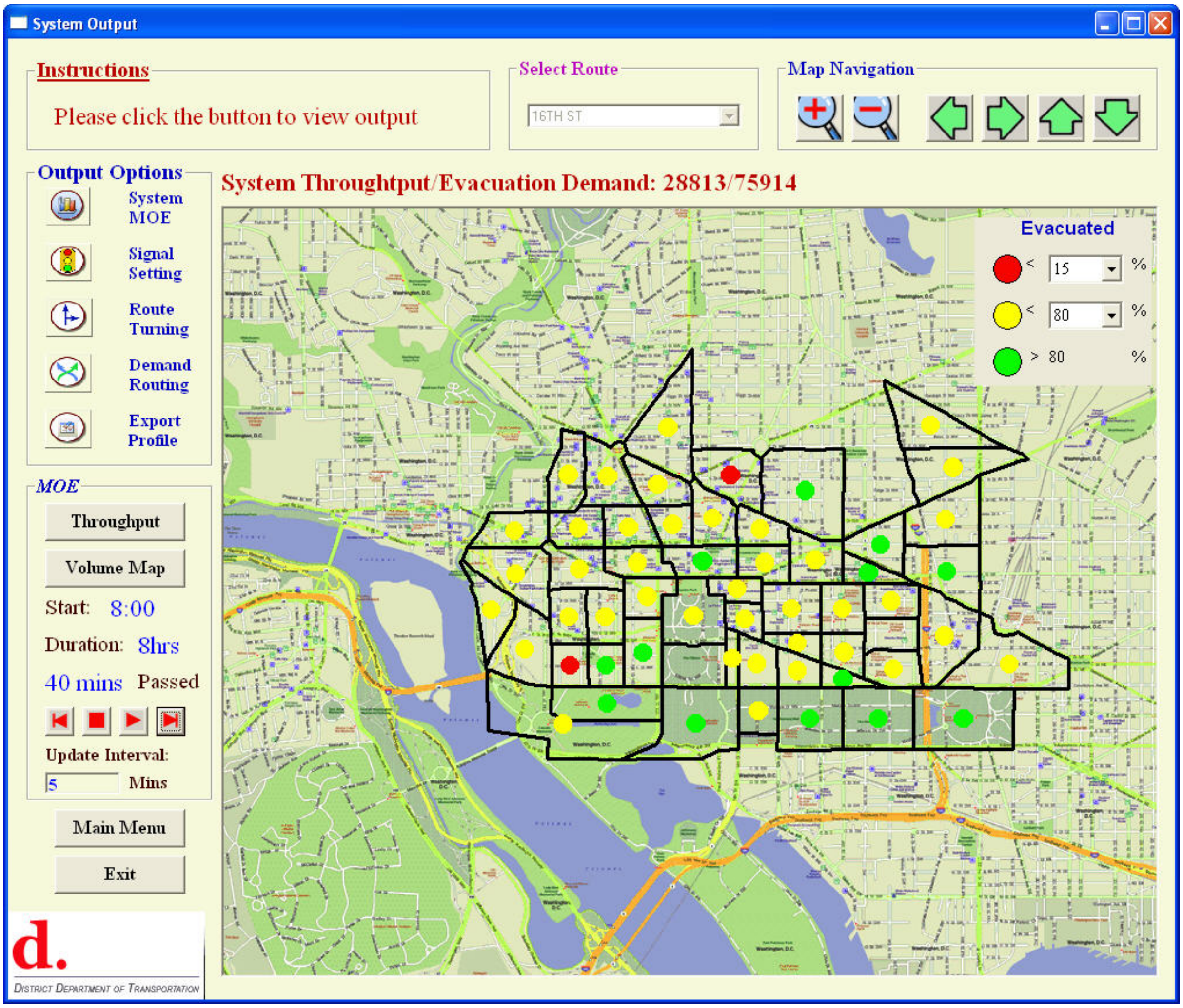

Figure 8 Snapshot of the output interface (outflow from TAZs)

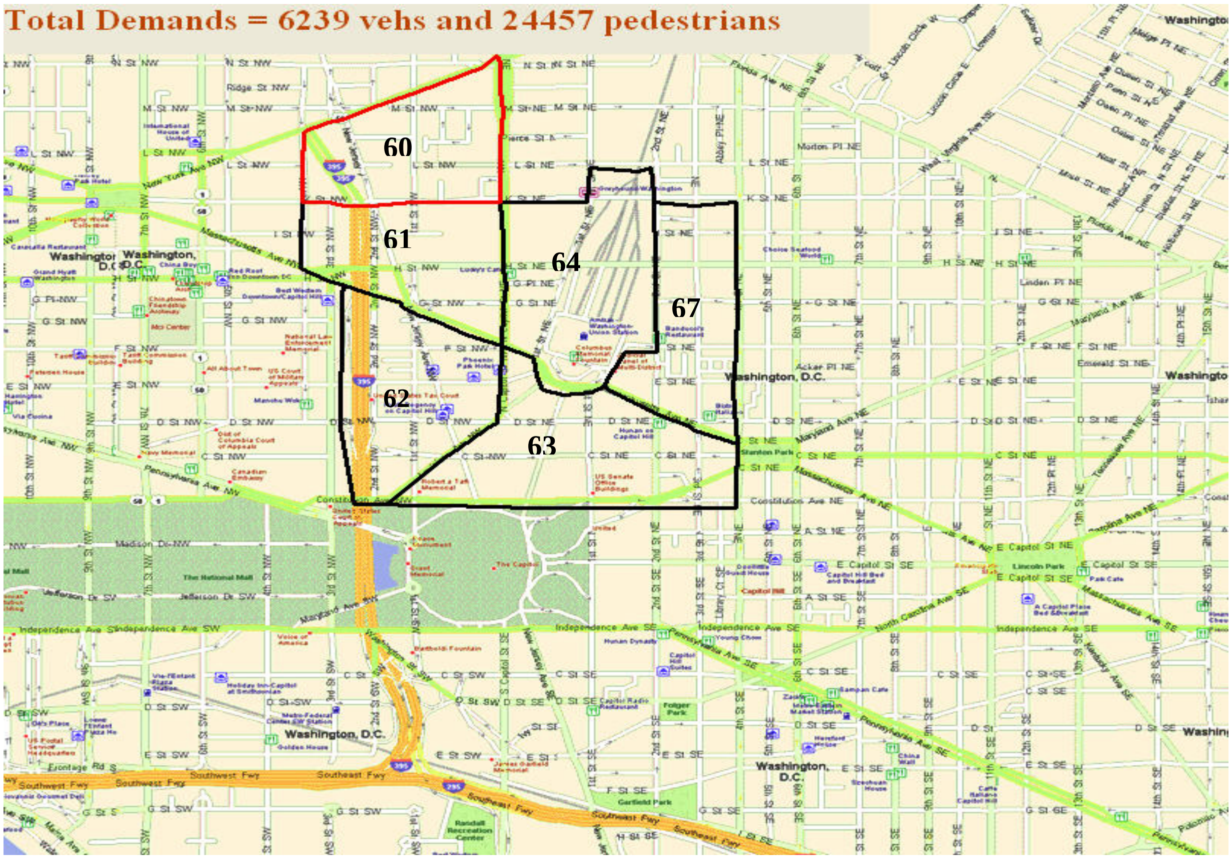

Figure 9 Impacted area of the emergency incident

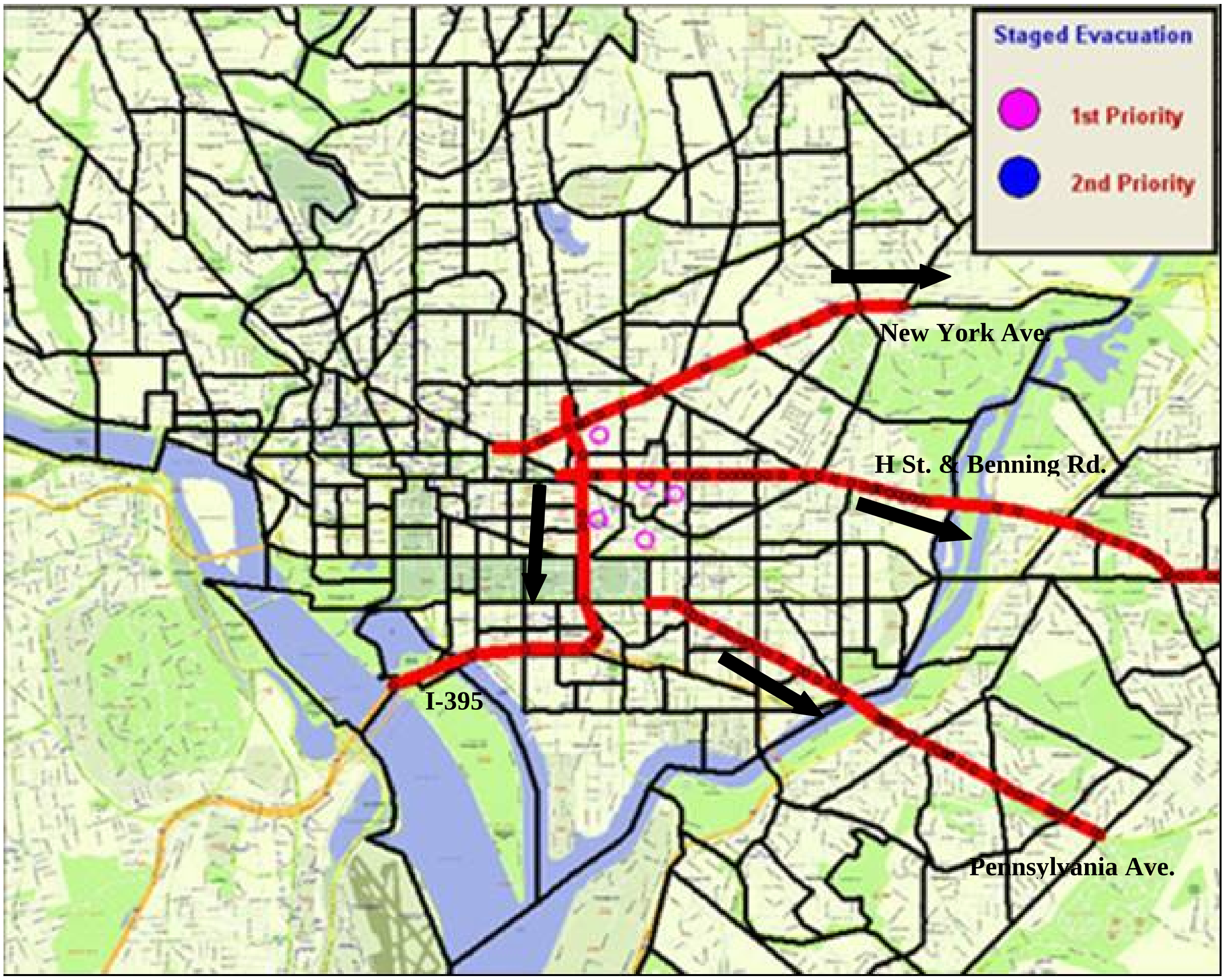

Figure 10 Involved major evacuation corridors

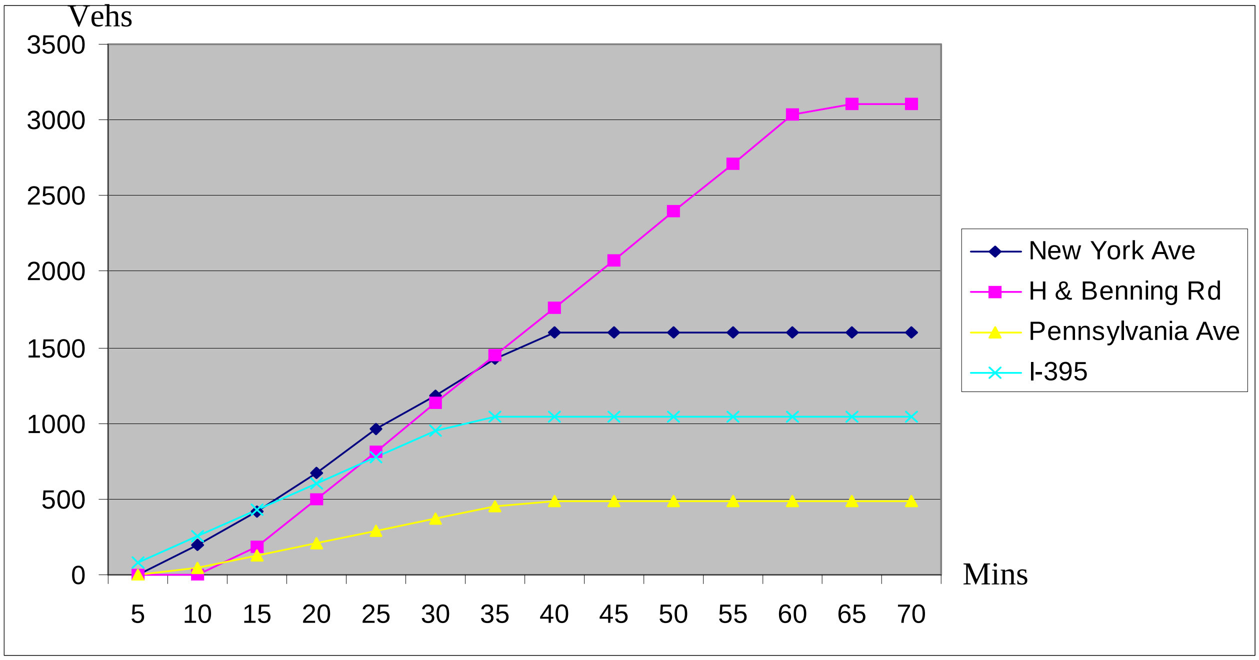

Figure 11 Time-varying system throughput by evacuation route

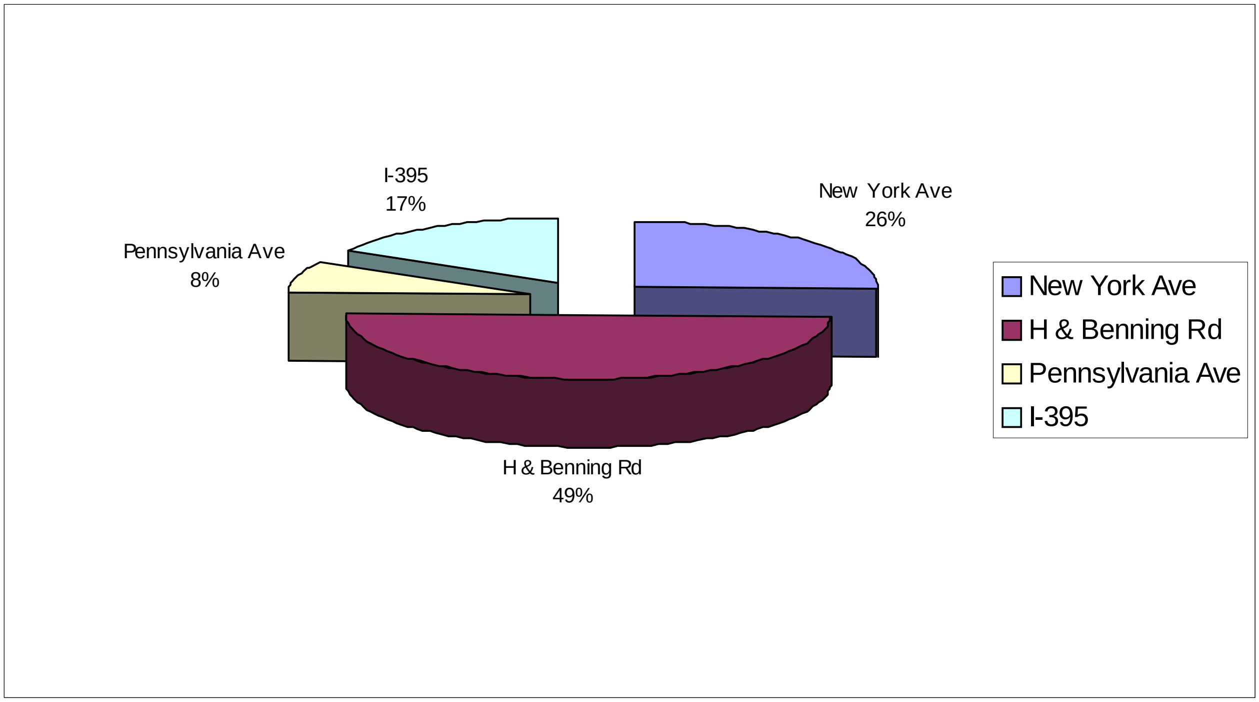

Figure 12 Distribution of evacuation demand by route