An integrated emergency evacuation system for real-time operations -- A case study of Ocean City, Maryland under hurricane attacks

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Abstract— **The consecutive hurricane attacks to US coastline have drawn significant attentions to evacuation operations related issues. To better prepare the state of Maryland for potential hurricanes, this study presents an emergency evacuation system that integrates both optimization and microscopic simulation methods. The optimization module applies a two-level process to generate the preliminary optimal control plans, which is based on a revised cell transmission formulation for large-scale network applications. Using the optimized results as the initial input, the simulation module takes into account various operational constraints and driver responses that are difficult to be captured realistically with mathematical formulations. The proposed system also features its flexibility for potential users to adjust the optimized plans in both the planning phase and real-time operations based on the results of simulation evaluation. The case study with the data from Ocean City, Maryland during hurricane attacks has demonstrated the potential of the proposed system for evacuation of traffic flows in large-scale networks within a given time window.**

I. INTRODUCTION

The consecutive hurricane attacks to US coastline have drawn significant attentions to evacuation operations related issues. A variety of evacuation strategies and technologies have been addressed and implemented in practice, such as the contraflow design and the use of ITS equipments [1]-[5]. Theoretically, both behavior models predicting individual response and network flow models on a system level have also been advanced [6]-[11]. In addition, there exists a vast amount of research related to evacuation under various other disasters, including not only the natural hazards, such as forest fires or earthquakes, but also technological and terrorist-induced emergencies such nuclear leakage and dirty bomb attacks [12]-[18]. Despite the differences in disaster nature, one can generalize an evacuation process with all critical and interrelated components.

As one of the major control decisions in this process, the design of network control strategies and its effects on actual traffic conditions are fulfilled mostly in two ways. The first type employs optimization approach based on mathematical formulations of network flows [10], [11], [17]. As such studies are mainly for planning purposes, they may not sufficiently account for realistic operational constraints like the length of acceleration or deceleration lanes. Another way is try and error approach in a simulation environment, which is widely used in practice [3]-[4], [14]-[16]. Although microscopic simulation has been proved to be an effective tool for evaluation and adjustment of evacuation plans, the search of an optimal plan may become quite time-consuming especially for large-scale networks.

To better prepare the state of Maryland for potential hurricane threats, this study presents an emergency evacuation system that integrates both optimization and microscopic simulation methods. The two-level optimization module aims to identify a preliminary optimal control plan based on a revised cell transmission formulation of network flows. Using this plan with the range of most viable control parameters as input, the simulation module will help system user finalize the control strategies in a timely manner based on efficient plan evaluation. This evaluation process is performed under realistic simulated environment, which can replicate all operational constraints and driver behaviors not captured with mathematical formulations.

The following paper is organized as follows. Section 2 depicts a general evacuation process. The framework of the proposed integrated emergency evacuation system is introduced in Section 3, with its major modules elaborated in Section 4 using Ocean City, Maryland as the case study. The last section summarizes research findings and future work.

II. COMPONENTS OF A GENERAL EVACUATION PROCESS

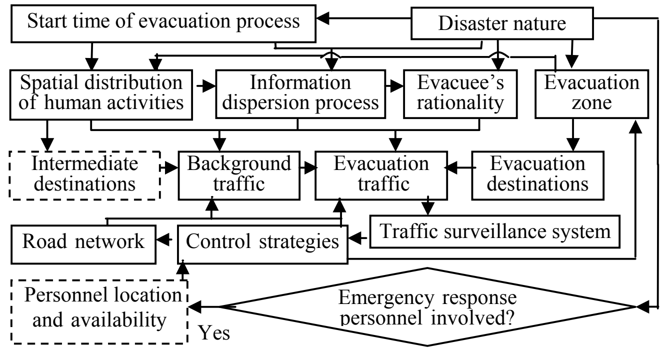

Fig. 1. Illustration of a general evacuation process

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Figure-1 illustrates the general evacuation process, which indicates that after a disaster has occurred or is predicted, the responsible agency will determine the start time of the evacuation process. This start time will directly determine the spatial distribution of all related activities right before evacuation and also affect the dispersion of evacuation order. These aspects, along with the information on the location and size of those Evacuation Action Zones to be cleared, will decide the total evacuation demand as well as its loading pattern onto the network.

As well recognized in the behavioral research, most evacuees tend to meet their family and start evacuation as a single unit when necessary [19]. Thus, practitioners have to identify these intermediate destinations for family reunion, which may greatly affect the network traffic pattern. Actual evacuation destinations indicating safe zones also need to be designated.

Based on estimated evacuation demand and target destinations, one can project the actual network traffic conditions in the evacuation process. The estimation approach should consider the available network capacity, various control strategies, and the response of evacuees under different information penetration levels.

Another two issues might also require proper consideration in this process. The first is the routing of emergency response teams, if necessary. This issue is critical as an efficient arrival of these responsive teams might limit the expansion of the zone in danger, but the network capacity they require may restrict the control strategies for evacuation traffic. The second issue is about real-time operations, which basically involve a feedback process of obtaining actual network traffic conditions with traffic surveillance systems and adjusting control strategies in a timely manner.

Note that Figure-1 presents some critical evacuation components, which have not been adequately addressed in the literature. Those include efficient design of control strategies, reliable estimate of network traffic, modeling information dispersion process, projecting the response of evacuees, and properly handling emergency response traffic. The proposed integrated evacuation system is developed in response to some of those critical issues, but with focuses on control strategy design and network traffic projection.

III. FRAMEWORK OF THE PROPOSED EVACUATION SYSTEM

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

- Input module: for users to define the evacuation scenarios and to adjust control strategies. Generally, an evacuation scenario is defined with two types of information, namely evacuation demand and available road network. Note that in this study, the initial network is preset as the actual road network for Ocean City, Maryland when the system is built.

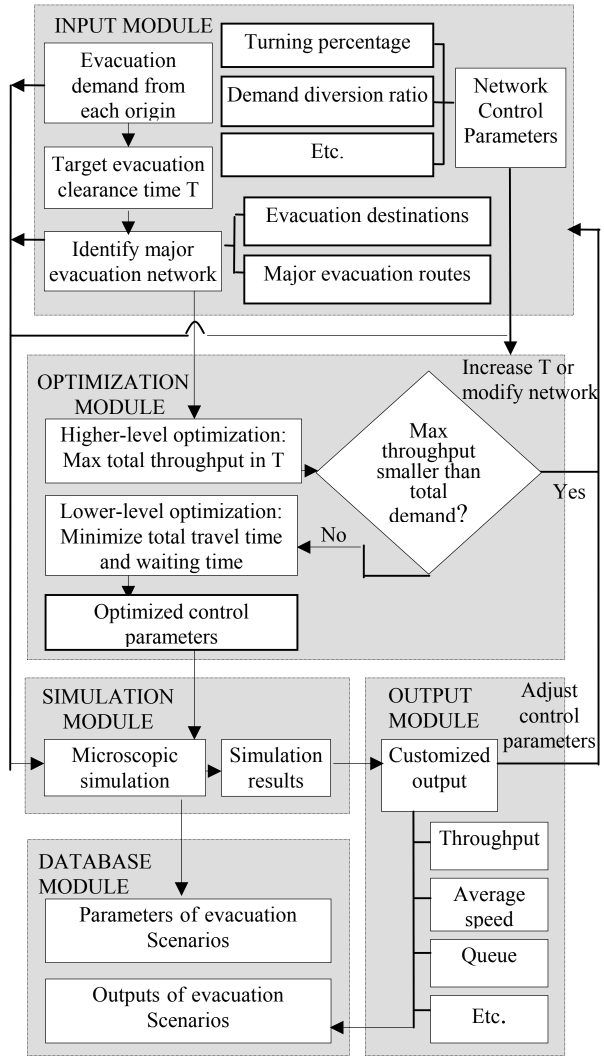

Fig. 2. Framework of the integrated evacuation system

- Optimization module: to automatically generate the optimized route choice and turning fractions 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.
- Simulation module: to project and analyze traffic conditions during the entire or partial evacuation process under the designated scenario and given network control strategies;
- Output module: to display the customized output from simulation results, which can facilitate system users to evaluate and adjust evacuation plans.
- Database module: to store potentially useful evacuation scenarios and corresponding system outputs. Thus existing scenarios can be loaded and analyzed without executing the simulation module when necessary.

The key features of each module will be elaborated in the subsequent section, using data from Ocean City, Maryland under hurricane attacks as the example. Ocean City, as a famous tour destination, is a narrow peninsula on Maryland Eastern Shore. The population in the summer peak season can reach 150,000 to 300,000 people, compared with 7,000 to 25,000 people during the off-peak season [20]. This large population size in the summer season makes the city vulnerable to the threat of hurricanes, which demands the state to design its hurricane evacuation plans.

IV. Elaborations of System Modules

A. Input module

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

- Distribution of evacuation demand from each origin in each interval;
- Major evacuation network, either directly defined on the original road network or selected from existing candidate plans in database module;
- Target evacuation clearance time; and
- Important network control parameters, such as turning percentage at critical junctions, signal timings, and diverted percentage of demands to each evacuation route.

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.

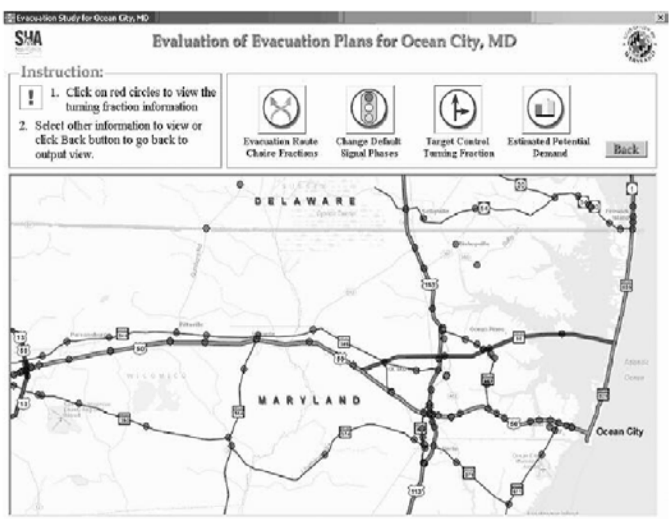

Fig. 3. Snapshot of the input interface

B. 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 microscopic simulation module. 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 road damage.

In this module, the high level optimization aims to maximize the throughput in the specified evacuation clearance time. Only if this specified duration is sufficient for evacuating all demands, the low level optimization will be activated to minimize the total trip time (including the waiting time in origins) under the actual demand. Otherwise, a warning message will pop out.

To effectively model network flows, this study employs the core cell transmission concept proposed by Daganzo [21], [22], but with a revised formulation. The key idea for this class of network flow models is to divide road network into sub-segments (named cells), and move vehicles among connected cells based on certain rules. The contribution of the generalized formulation in this study lies in that it allows cells of different sizes to be arbitrarily connected. This feature will offer great flexibility and efficiency for large-scale network applications.

To facilitate the formulation, one needs to transform the road network into a set of connected cells through the following four steps:

- Identify homogenous road segments with the same free flow speed, the same number of lanes, the same jam density and the same saturation flow rate, while there should be no ramps within the segment.
- Define unit time interval constrained by the shortest time to traverse a homogenous segment at free flow speed.
- Convert each homogenous segment to a cell, with cell size defined as free flow travel time divided by unit time interval length. Shorter cells (at least of size 1) can be employed near interchanges or incident locations.
- Define connectors between cells if traffic flow between the corresponding segments is allowed.

The generalized cell transmission formulation is then built with two types of relations, flow conservation and flow propagation. Flow conservation equations update the cell status (i.e., number of vehicles present in each cell) at the beginning of each unit time interval regardless of the actual cell length. Flow propagation relations decide flows between two cells during each time interval, based on the sending capacity of upstream cells as well as the receiving capacity of the downstream cells. Table-1 presents the notation used in the hereafter presentation.

TABLE I
NOTATIONS USED IN OPTIMIZATION FORMULATION

Variable	Notation
C	The set of general cells transformed from road segments;
C_r	The set of source cells transformed from origins;
C_S	The set of sink cells transformed from destinations;

r , s :	Index of each source cell and sink cell;
$\Gamma(i)$	The set of downstream cells to cell i;
$\Gamma^{-1}(i)$	The set of upstream cells to cell i;
l_i	Size of cell i;
d_r^t	Evacuation demand from origin r during interval t;
x_i^t	The number of vehicles in cell i at the beginning of time interval t;
y_{ij}^t	Connector flows from cell i to cell j during t;
R_i^t	Receiving capacity of cell i during interval t;
S_i^t	Sending capacity of cell i during interval t;
Q_i^t	The number of vehicles that can flow in/out of cell i during time interval t;
N_i^t	The number of vehicles that can present in cell i during time interval t;

The main constraints for the proposed optimization model are presented below:

- Flow conservation equations:

$$x_i^{t+1} = x_i^t + \sum_{k\in\Gamma^{-1}(i)} y_{ki}^t - \sum_{j\in\Gamma(i)} y_{ij}^t, \quad i \in C \cup C_s \tag{1}$$

$$x_r^{t+1} = x_r^t + d_r^t - \sum_{j\in\Gamma(r)} y_{rj}^t, i \in C_r \tag{2}$$

- Flow propagation equations:

$$\sum_{k\in\Gamma^{-1}(i)} y_{ki}^t \le R_i^t \tag{3}$$

$$\sum_{j\in\Gamma(i)} y_{ij}^t \le S_i^t \tag{4}$$

$$R_i^t = \min\{Q_i^t, N_i^t / l_i, N_i^t - x_i^t\} \tag{5}$$

$$S_i^t = \min\{Q_i^t, N_i^t / l_i, x_i^{t-li+1} - \sum_{j\in\Gamma(i)} \sum_{m=t-li+1}^{t-1} y_{ij}^m\} \tag{6}$$

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 procedure can be found in Liu, etc [11].

C. *Simulation module*

The simulation module is an embedded microscopic simulation engine, which can project the network traffic conditions under various traffic demand patterns and designated control strategies.

The simulation module in the case study for Ocean City, Maryland is developed with CORSIM, a corridor simulation program by FHWA. The program has been customized to fit the evacuation application, which has also resulted in a substantial reduction of its computing time. For example, the simulator only needs about 3 minutes to simulate the entire network traffic condition over a 2-hour period of evacuation operations at the target demand level of 6700 vehicles per hour, which is sufficiently fast for real-time operations.

D. *Output module*

Based on the requests of system users, the output module can analyze and present all simulated traffic conditions. Three categories of output data can be provided, namely overall statistics, map-based outputs, and table-based results.

The primary functions for each type of output are summarized below:

- Overall statistic summary: to show the numbers of vehicles departed and remained at each origin, vehicles arrived at each destination. The throughputs on the primary evacuation routes are also provided in this output category;
- Map-based output: to illustrate the distribution of the throughput and the average speed over different evacuation routes with different colors.
- Table-based output: to highlight the detailed traffic conditions, including the total throughput and the average speed over time at critical control points.

Figure 4 presents a snapshot of the output interface. With the help of the output module, system users can easily assess each evacuation plan and identify the potential bottlenecks.

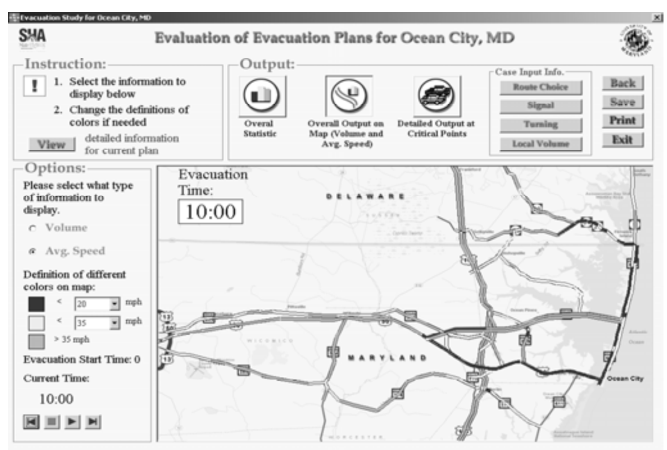

Fig. 4. Snapshot of the output interface

E. *Database module*

The database module is designed to store all prior information and operational experience, which include:

- Expected demand distribution in each evacuation scenario;
- User specified control strategies like a contraflow option on each segment;

- Optimized control strategies such as turning fractions at key intersections;
- Simulation output of each evacuation scenario.

Currently, the evacuation system designed for Ocean City, Maryland under hurricane attacks is embedded with six candidate plans. Each plan, specified for a predefined evacuation network, is obtained by adjusting optimized control strategies from the optimization module based on simulation results. Figure 5 presents one of these candidate plans.

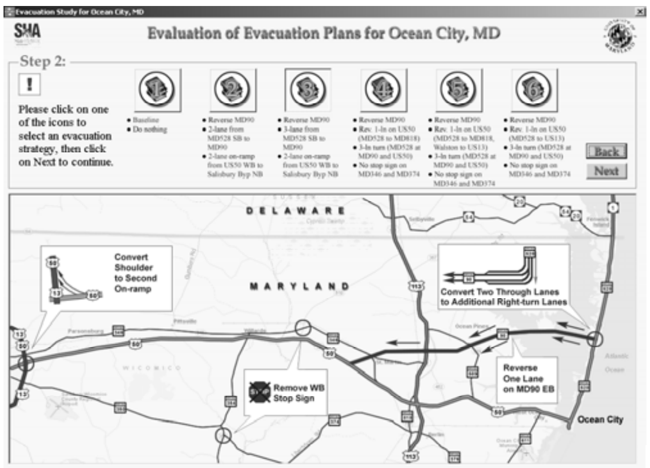

Fig. 5. Illustration of one candidate plan embedded in the system

To illustrate the effectiveness of the optimization-integrated approach, we here compare the simulation results of different evacuation control strategies for the original road network (without contraflow options) as an example. Based on the control strategies obtained from the optimization module, the evacuation throughput per hour is about 7,714 vehicles, whereas the throughput is only 6,474 vehicles per hour with the try-and-error approach from a previous project report. Besides, the integrated system brings out the control strategies after solving the optimization module in 10 minutes to 20 minutes, whereas the try-and-error approach may take at least several hours to reach an acceptable solution.

Note that all the prior scenarios saved in the database module can be used in real-time operations. For example, to design the effective control strategies in response to an accident incurred during the evacuation process, system user can load the pre-simulated accident-free cases and approximate the actual traffic conditions right before the onset of an accident. This background flow information will be used in the optimization module to generate a new control plan, which can better handle the accident-induced capacity reduction and avoid queue formation at the accident location. The new control plan can again be assessed and adjusted in simulation module.

V. Conclusions and Future Work

This paper has presented an integrated evacuation system for Ocean City, Maryland to prepare for potential hurricane attacks. The system features its integration of optimization and microscopic simulation approaches. The two-level optimization module tries to efficiently identify the preliminary optimal control strategies during an evacuation based on a generalized cell transmission formulation of network flows. This preliminary control plan will be evaluated in the simulation module, which can capture all the realistic operational constraints and driver behavior. System user can easily identify the potential bottlenecks and make corresponding adjustment with the user-friendly input and output interface.

The proposed system can facilitate system users to find effective evacuation control strategies, even in a large-scale network or in real-time operations, which is especially critical when unexpected events incurred during the evacuation and the implemented plan need to be revised in a timely manner. Further research along this line will be focused on some related critical issues, such as how to decide the loading rate of the evacuation demand by properly modeling information dispersion process, how to estimate the response of evacuee and their effects on design of responsive control strategies, and how to handle emergency response traffic.

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