Simulation-Based Emergency Evacuation System for Ocean City, Maryland, During Hurricanes

Nan Zou, Shu-Ta Yeh, Gang-Len Chang,
Alvin Marquess, and Michael Zezeski

This paper presents a simulation-based system for Ocean City, Maryland, evacuation during hurricanes. The proposed model features integration of optimization and simulation that allows potential users to revise the optimized plan for both planning and real-time operations. Since it is difficult to capture all network operational constraints and driver responses fully with mathematical formulations, six evacuation plans for Ocean City were investigated. Each was optimized initially with the optimization module and then revised on the basis of the results of simulation evaluation. To address potential incidents during the evacuation, the study presents a real-time operation plan with a developed system that allows the responsible operators to concurrently evaluate all candidate responsive strategies and to track the performance over time of the implemented strategy.

Ocean City, a narrow peninsula on Maryland's Eastern Shore, is about 0.3 mi in wide and 9 mi long. The population varies significantly between the summer and the winter seasons. During the summer peak season, the population in Ocean City varies between 150,000 and 300,000 people. Its population may drop to between 7,000 and 25,000 people during the off-peak season (*1*). The summer population in Ocean City is distributed as follows: about 31% between the southern end and 40th Street, about 23% between 40th Street and 94th Street, and about 46% between 94th Street and the state line between Maryland and Delaware.

Figure 1 shows the surrounding area of Ocean City and the highway networks. As described in a previous Ocean City evacuation plan (*2*), the areas about 10 mi away from the ocean are viewed as safe zones during a hurricane evacuation. Thus, such safe areas lie roughly in the region west of US-113. Salisbury, Maryland, the largest city in Maryland's Eastern Shore and about 30 mi from Ocean City, is designated as the major evacuation destination because evacuees will be temporarily relocated to those shelters around Salisbury, if needed. The scope of this evacuation study covers the entire area of about 45 mi by 15 mi, including all major evacuation routes in both Maryland and Delaware.

US-50 westbound, MD-90 westbound, and DE-1 northbound are three primary evacuation routes for Ocean City during emergencies (see Figure 1). US-50 westbound is a divided highway that starts near the south end of Ocean City, goes through Salisbury, Maryland, and then continues to Washington, D.C., and the Baltimore area. MD-90 westbound, having only one lane, begins from the middle of Ocean City (62nd Street), continues to US-113, a north–south highway that connects Maryland's Eastern Shore with Virginia and Delaware, and then merges into US-50 westbound. MD-528 goes through Ocean City, covering its south end, and continues to the state line between Maryland and Delaware. MD-528 is renamed DE-1 after entering Delaware, and it then splits immediately to DE-54 westbound and DE-1 northbound. DE-54 westbound goes to US-113, which carries traffic to different evacuation destinations—Dover, Delaware, and South Salisbury, Maryland. Because of the expected congestion and flooding during hurricanes, coastal highway DE-1 will not be used as an evacuation route during hurricane evacuation for Ocean City. The Salisbury Bypass (US-13), a two-lane highway in suburban Salisbury, is on the city boundaries. Evacuees who arrive at Salisbury Bypass will be regarded as having a safe arrival to the hurricane evacuation destination.

The most recent study for Ocean City evacuation is the revision plan developed by the Maryland State Highway Administration (MDSHA) in the 1980s and updated in 1993 (*2*). This revised traffic control plan for Ocean City during hurricane evacuation was based on the available capacity of critical paths and focused on how to set up traffic control points as well as the clarification of responsibilities among agencies during evacuation operations. Some critical issues, such as how to maximize the network throughput and identify bottlenecks during the evacuation, have not been sufficiently addressed.

The entire evacuation plan should include developments of both candidate strategies and their real-time operational plans during the period of evacuation. These two critical tasks, however, are complicated by the lack of actual demand in Ocean City and the difficulty in predicting travelers' responses during the emergency evacuation. A well-designed plan may have to be changed substantially if some unexpected incidents occur at major evacuation routes. Hence, in response to potentially encountered uncertainties during evacuation operations, it is essential that the responsible agencies have an effective tool with which to efficiently evaluate all candidate evacuation plans and assess the impact of implemented strategies in real-time operations. Such a tool should offer the following functions:

- Assess the potential effectiveness of candidate evacuation plans under various demands and actual roadway geometry constraints;
- Provide the flexibility for planners and operation managers to identify potential bottlenecks during evacuation and to evaluate the effectiveness of various control strategies, such as reverse lane operations and the conversion of shoulders to travel lanes;

N. Zou, S.-T. Yeh, and G.-L. Chang, Department of Civil and Environmental Engineering, University of Maryland, College Park, MD 20740. A. Marquess and M. Zezeski, Maryland State Highway Administration, 7491 Connelley Drive, Hanover, MD 21076.

Transportation Research Record: Journal of the Transportation Research Board, No. 1922, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 138–148.

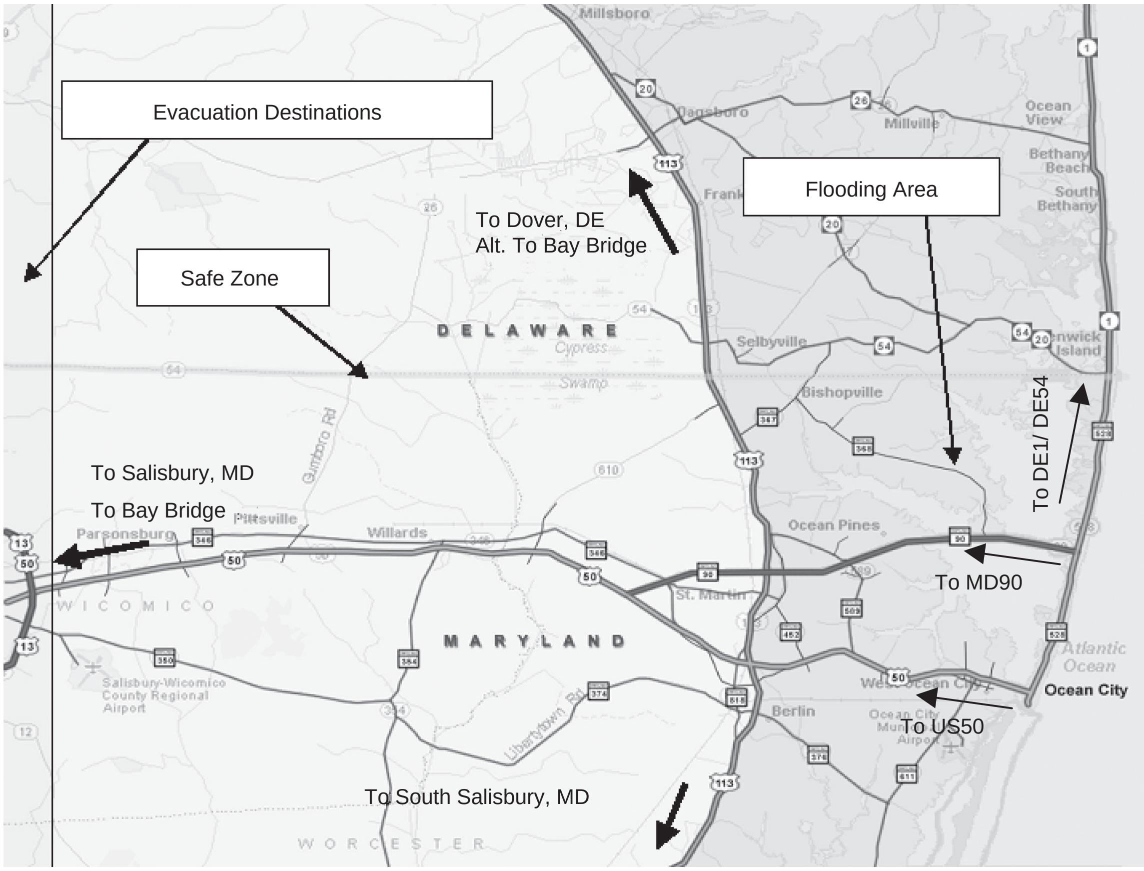


FIGURE 1 Evacuation network and zones.

• Enable the system operators to project traffic conditions on evacuation routes during real-time operations if network traffic sensors have been deployed;

• Efficiently assess and revise any implemented plan during incidents; and

• Offer a real-time evacuation function for system operators to revise an implemented plan when encountering incidents.

From a review of the literature, it is clear that most studies on emergency evacuations can be divided into two categories. Most studies in the first category employ statistical methods or macroscopic or mesoscopic simulation methods to analyze the traffic conditions and generate optimal route choice fractions under the expected demand level (*3–10*). Because such models are mainly for planning applications, they do not take into account the impact of operational constraints on the actual evacuation network, such as insufficient length of acceleration lanes for merging operations and inadequate turning bay length that may cause significant spillback during the evacuation operation.

The other main category of studies on the emergency evacuations is use of microscopic simulations (*11–14*) that estimate the evolution of traffic during the entire evacuation under the expected demand pattern. The extensive simulation output offers its users an effective way to evaluate the performance of candidate plans and to identify potential bottlenecks. The research presented in this paper was developed along the lines of this category, but the proposed simulation-based evacuation model was developed in response to the needs for both planning and real-time operations. It has been integrated with an optimization module (*15*), which may not take into account all operational detail in the network, to produce the preliminary optimal plan. The produced optimal plan can then be refined with the embedded simulation module and be used for real-time applications.

To address potential incidents during the evacuation, this study presents a real-time operation plan with a developed system that allows responsible operators to concurrently evaluate all candidate responsive strategies and track over time the performance of the implemented strategy.

The developed system has a customized interface for both data input and output analyses and has an efficient simulation module for evaluating various operational plans. To facilitate the application, the developed system incorporated six evacuation plans proposed in response to various possible levels of demand in Ocean City. Each control plan includes the target route choice fractions for a given demand level, turning proportions at each control junction, and signal timings at each intersection. Potential users can change these control parameters and develop their own plans if the actual demand varies significantly from those employed in the set of six embedded plans.

DESCRIPTION OF PROPOSED SYSTEM FOR EMERGENCY EVACUATION

Figure 2 presents the principal components of the developed simulation-based emergency evaluation system and their interrelations, which include

• Input module for users to design the evacuation plan, input control parameters, and obtain the detector data;

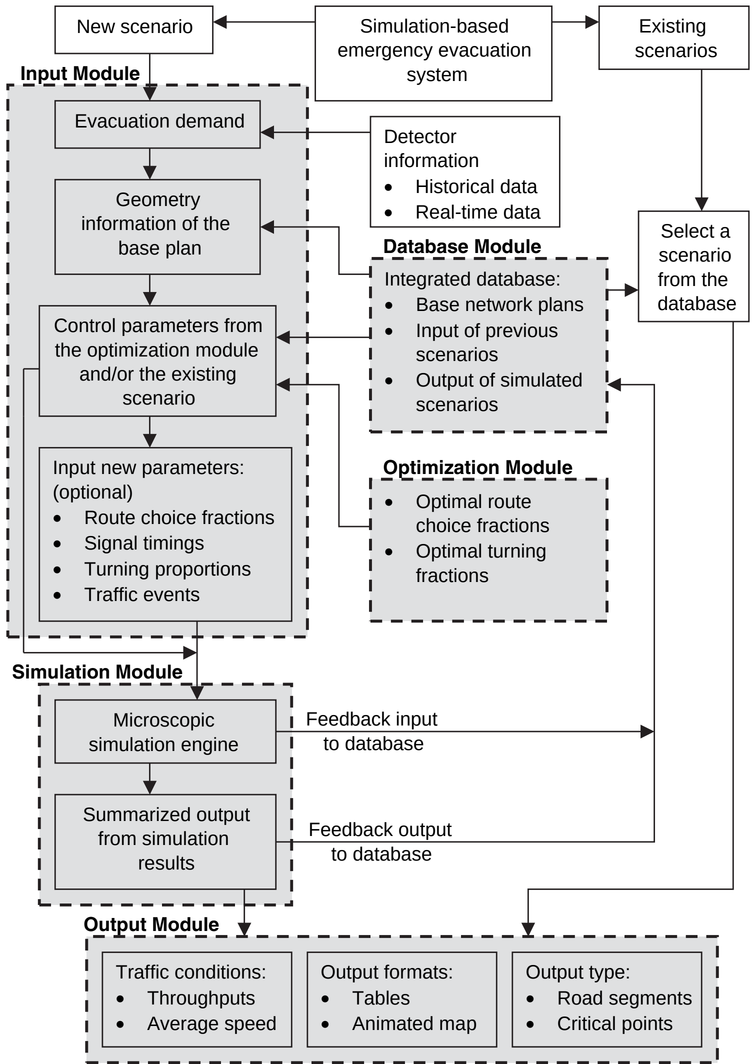


FIGURE 2 Principal modules and their interrelations of proposed simulation-based emergency evacuation system.

- Optimization module (*15*) to generate the optimized route choice and turning fractions for detected demand pattern;
- Simulation module for analysis and projection of traffic conditions during the entire or partial evacuation process under the input scenario;
- Database module for storing newly input scenarios and system outputs and for loading existing scenarios without executing the simulation module; and
- Output module for displaying the customized output from simulation results.

Input Module

The input module is customized for potential users to input the following information during either planning or real-time applications:

- Evacuation duration,
- Distribution of the evacuation demand from both Ocean City and the neighboring regions,
- Selection of the base network from embedded candidate plans,
- Route choice fractions of three primary evacuation routes,
- Turning proportion at each junction,
- Signal timings at each intersection, and
- Location, onset time, and duration of incidents or road closures.

Figure 3 is a snapshot of the input interface, which features its use of a map-based presentation that can guide potential users to operate the system through step-by-step instructions. This design can significantly reduce the learning time and the input error rate of users.

Optimization Module

The optimization module computes the initial optimal demand distribution among available routes and the resulting turning proportions at each intersection under the given network plan (*15*). This module is especially needed during real-time operations, as it can efficiently identify the potentially most effective plan under the detected traffic

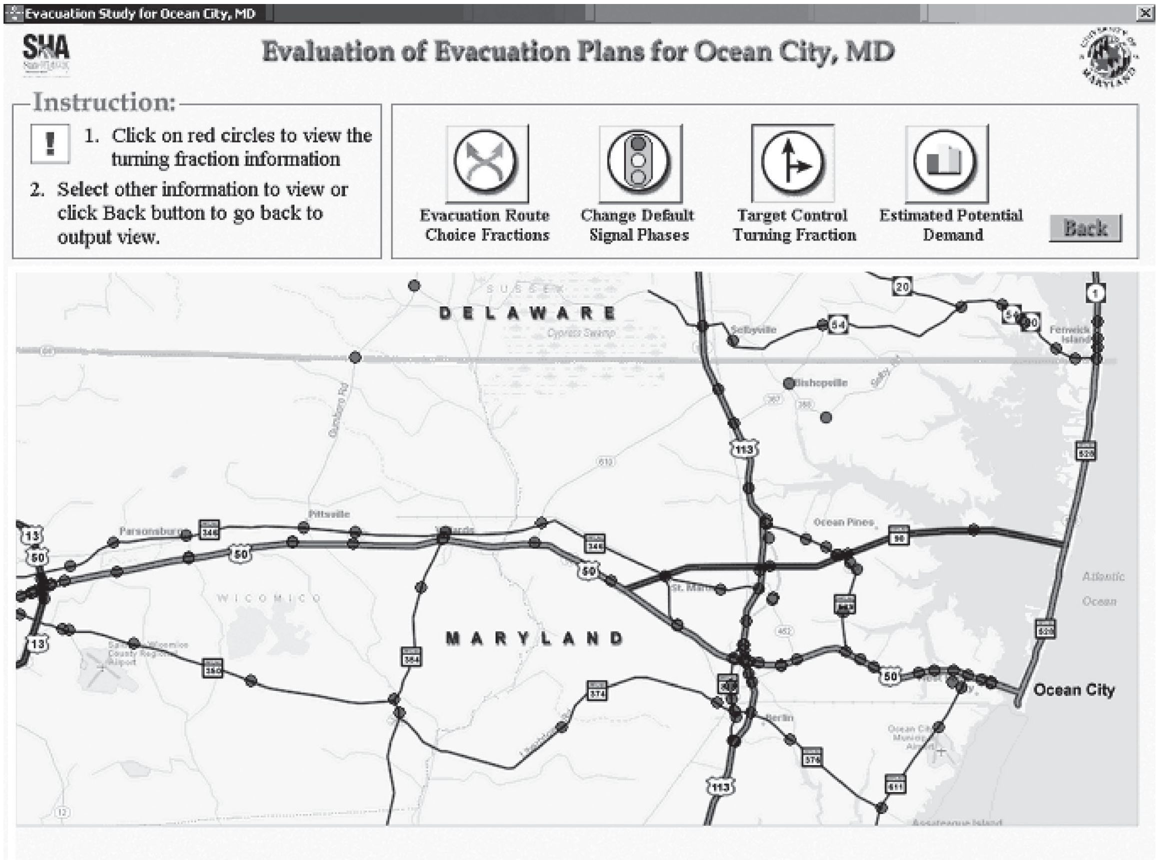


FIGURE 3 Input interface for target control turning fractions.

conditions, which may be different from the planned patterns because of various factors, such as incidents or insufficient guidance.

Simulation Module

The developed simulation-based emergency evaluation system for Ocean City has an embedded microscopic simulation engine for assessing traffic conditions under various demand patterns and the proposed plans. The simulation module developed with CORSIM, a corridor simulation program by FHWA, was customized to fit the evacuation application, which resulted in a substantial reduction of its computing time.

The customized output file is only about 10% of its original size. The computing speed of the developed simulation module under various simulated durations at the target demand level of 6,700 vehicles per hour is shown in Figure 4. It is notable that the simulator needs about 3 min to simulate the entire network traffic condition over a 2-h period of evacuation operations, which is sufficiently fast for real-time operations.

Output Module

The output module is designed to ensure that all simulated traffic conditions from either the networkwide or the individual control perspective can be readily captured by users. It can generate three categories of output data: overall statistics, map-based outputs, and table-based results. With overall statistical results, users can have a clear view of the evacuation state during each hour, including the number of evacuated vehicles, remaining demands in Ocean City, and vehicles that have reached different evacuation destinations. Users can also view the map-based output to see the distributions of throughput and the average speed on each evacuation route.

The primary functions for each type of output are as follows:

- Overall statistical summary shows the numbers of vehicles that have left Ocean City, demands remaining in Ocean City, vehicles arrived at Salisbury, Maryland, and vehicles that have left the study area to Dover, Delaware, or southern Salisbury. The throughputs on those three primary evacuation routes (MD-90, US-50, and DE-54) can also be found in this category of output.
- Map-based output illustrates the distribution of the throughput and the average speed over different evacuation routes with different colors.
- Table-based output highlights detailed traffic conditions, including both the throughput and the average speed over time at critical control points.

Database Module

The database module is designed to store all prior operational experiences, information, and plans, including control strategies on each segment (e.g., reversed MD-90), target volume distribution at key intersections, and potential bottlenecks as well as resulting impacts.

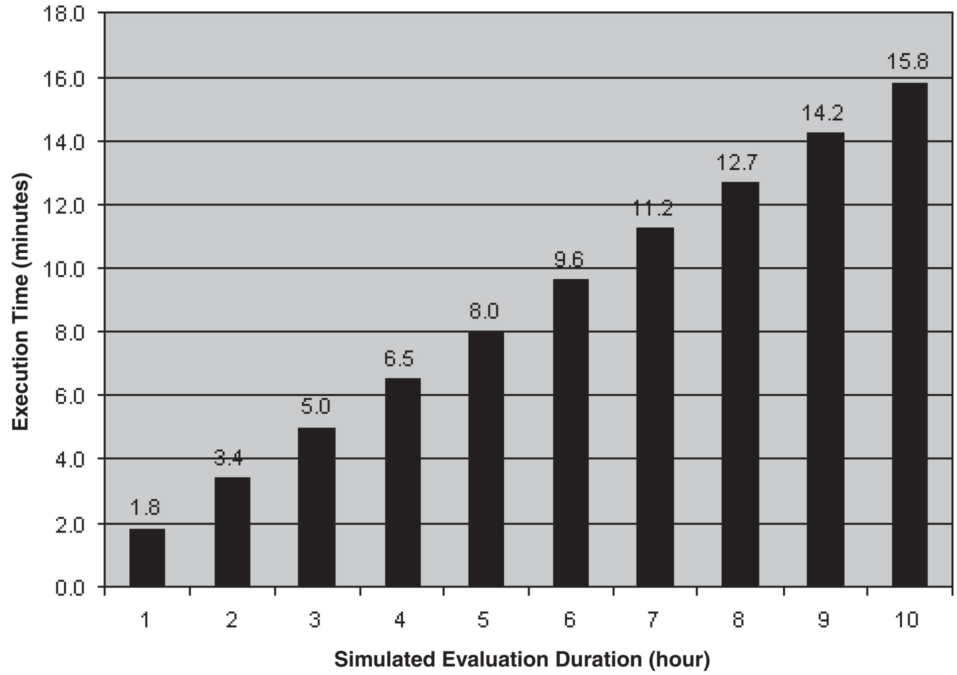


FIGURE 4 Graphical relation between simulation times and required execution times.

All prior experience or plans saved in the database, which has been designed to fit the needs of this study, can also be used in real-time operations. For example, to estimate the impact of one incident occurring on US-50 westbound and the effectiveness of responsive control strategies, responsible staff can load the simulated cases with incidents at nearby locations to approximate the evolution of traffic conditions under the proposed plans. The preliminary estimated results can then be revised after the simulator has completed the execution of the incident scenario with real-time data from detectors.

Operational Flowchart

The flowchart presented in Figure 5 details the operating procedures of the proposed simulation-based evacuation system for Ocean City. The steps are as follows:

Step 1. Input the target evacuation duration and the estimated demand. The system will first ask users to input the expected evacuation duration and the estimated demand distribution. Depending on the available information, users can input the total demand or the distribution of demand over time.

Step 2. Elect a network plan for evacuation operations. This step is designed for system operators to select the candidate network plan for evacuation operations on the basis of the projected demand volume. The current simulator offers six different network plans, each having different levels of reverse lane operations at highway segments and diversion controls at key interchanges and intersections.

Step 3. Optimize control parameters at key control points with the embedded module that includes the target demand distribution between all evacuation routes, turning percentages at each control junction, and signal settings.

Step 4. Execute the proposed plan with the simulation module.

Step 5. Evaluate the effectiveness of the current control plan and identify potential bottlenecks during the evacuation. To ensure the effectiveness of the proposed evacuation plan under the projected demand, one can view the simulated results for time-varying speed, delay, and queue length at key highway segments and control functions through the overall statistics (see Figure 6), map-based outputs (see Figure 7), and table-based displays.

Step 6. Revise the current control plan and resimulate the entire system. Users may choose to investigate traffic conditions at critical control points under various control operations and potential incident scenarios.

Step 7. Repeat Step 5 to identify the optimal control and operational plans under the projected evacuation demand patterns.

Overall, the proposed simulation-based emergency evacuation system for Ocean City offers the capability for potential users to concurrently evaluate the collective impact of various complex demands and operational strategies on the traffic conditions during evacuation. It provides a platform for evacuation planners to develop optimal strategies at both local control points and the entire network level. System operators can also use the system along with deployed sensors to perform real-time evaluation of the evacuation operation.

SYSTEM APPLICATIONS

This section presents the application of the proposed emergency evacuation system for Ocean City during hurricanes, including the development process and the resulting performance under each plan.

The evacuation study for Ocean City starts with two initial network control structures. One is the “do-nothing” plan to the current network, and the other is based on the hurricane evacuation traffic control plan revised in summer 2003 by MDSHA. The microscopic simulation

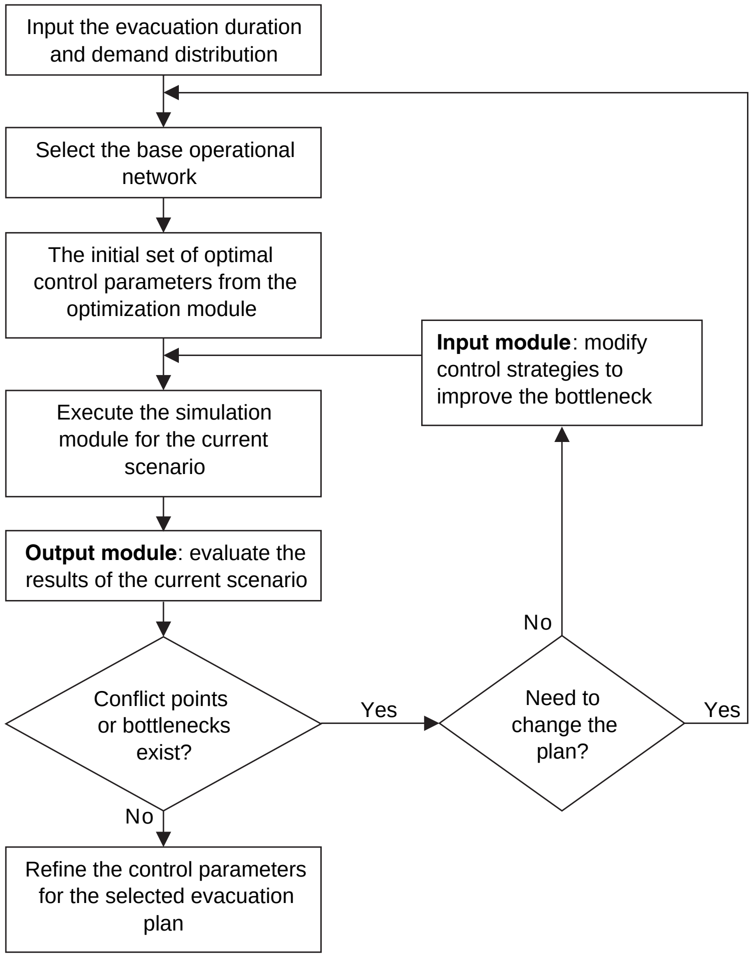


FIGURE 5 Operational flowchart for planning hurricane evacuation.

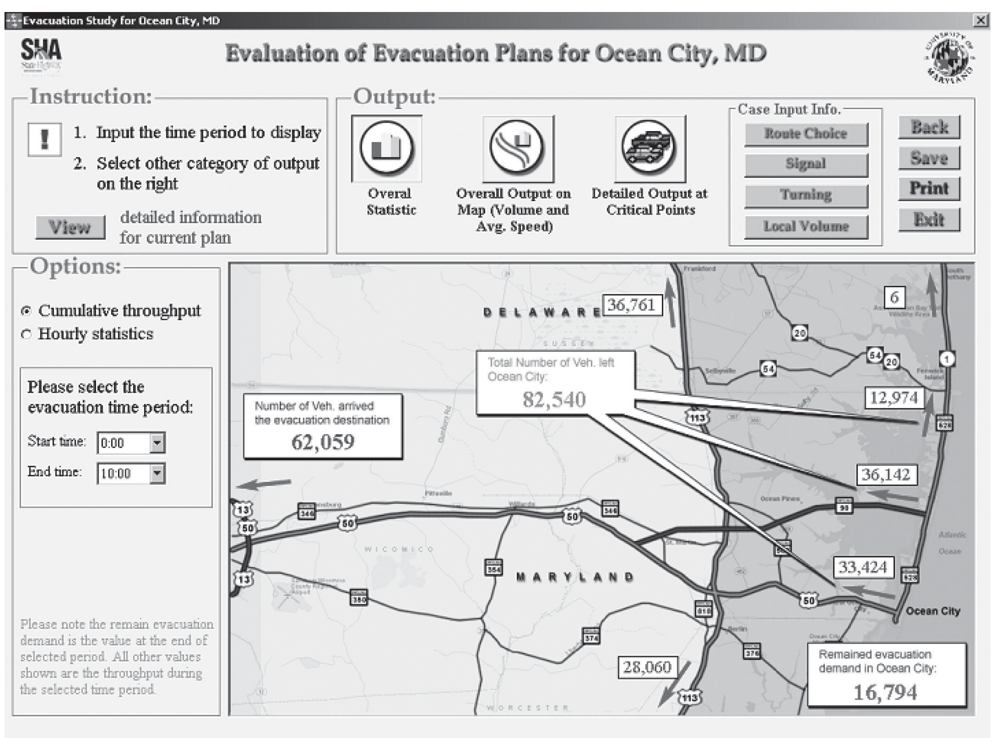


FIGURE 6 Snapshot of overall statistics in output module.

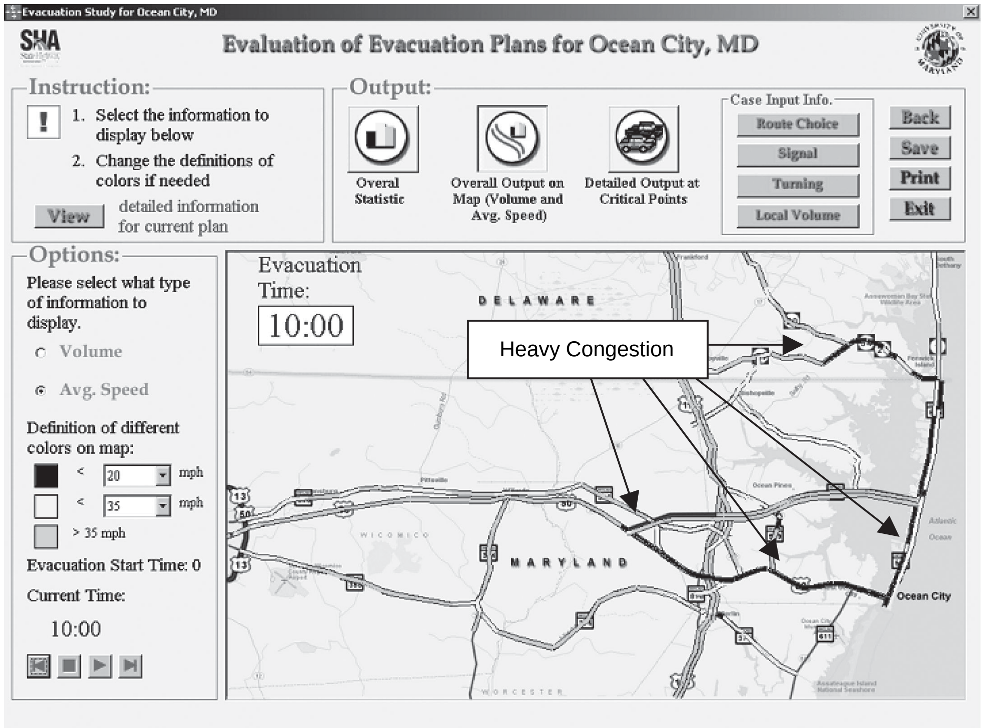


FIGURE 7 Map-based graphical display of heavy congestion on US-50 westbound under Plan 2.

networks for both plans were constructed accordingly. The initial set of control parameters for the do-nothing plan was determined by the optimization module that includes the percentages of route choice at each control point and turning movements at main interchanges or intersections. All control parameters for Plan 2 were based on those provided in the previous research report (*2*).

The simulation results indicate that Plan 2 with control parameters from the 2003 report can successfully evacuate 75,000 vehicles from Ocean City to these safe zones after 10 h of incident-free operations, compared to about 61,000 vehicles under Plan 1. However, the map-based output for Plan 2 showed that heavy congestion may exist on US-50 westbound from the merging point of US-50 and MD-90 back to Ocean City (see Figure 7). A set of new control parameters is then proposed with optimization module for Plan 2, which is to detour some traffic from US-50 westbound to parallel routes and guide some local traffic from West Ocean City to use MD-376. The revised Plan 2 with control parameters from the optimization module can evacuate about 80,000 vehicles within 10 h. However, some bottlenecks can still be identified from the output module. For example, to minimize the interruption caused by the signals on US-50 near Ocean City, all local traffic from West Ocean City shall be detoured to parallel routes so that the throughput on US-50 westbound can be increased more than 14%.

By analyzing the traffic conditions at critical junctions under Plan 2, a potential major bottleneck has been identified at the intersection between MD-528 and MD-90 because the traffic from MD-528 southbound to MD-90 westbound cannot feed MD-90 westbound to saturate traffic condition. That intersection needs to be rechannelized to carry more traffic to MD-90 westbound. Plan 3 is then proposed to convert one through lane to one additional right-turn lane from MD-528 southbound to MD-90 westbound and remove two stop signs on MD-346 and MD-374.

Since all three major detour routes from Ocean City will be saturated under Plan 3 and no other bottleneck exists, reversing one lane on US-50 westbound emerges as the only strategy to improve the evacuation throughput. Plans 4, 5, and 6 are then suggested to reverse different segments of US-50 to increase evacuation throughputs and smooth local traffic conditions. In brief, six network operational plans (including the do-nothing plan and the evacuation plan of summer 2003) for Ocean City hurricane evacuation have been developed and analyzed with the developed simulation-based evaluation system. The geometric features of six hurricane evacuation plans for Ocean City (see Figure 8) are summarized in Table 1.

The simulation results of each plan are summarized as follows.

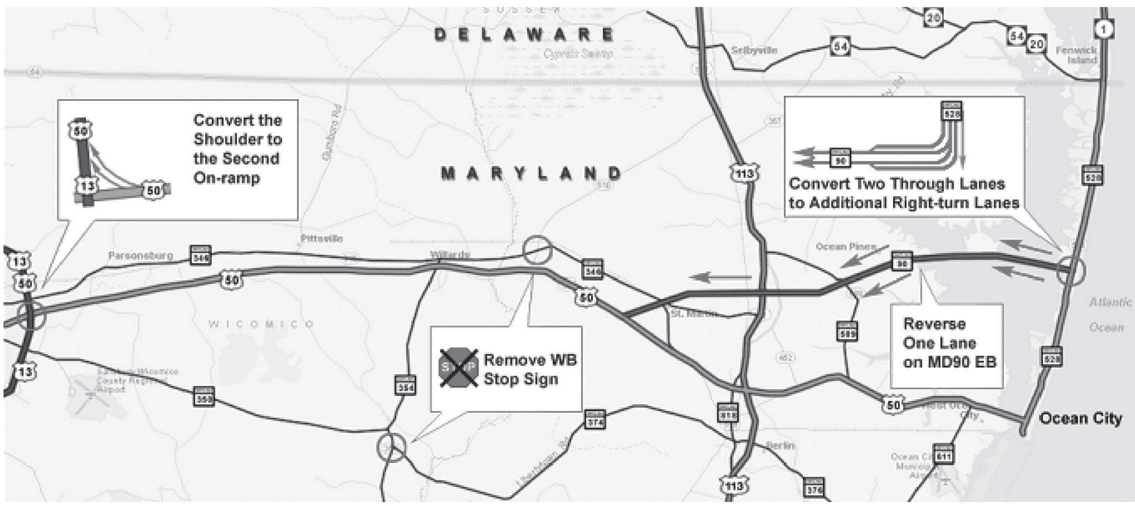
Evacuation Plan 1

With the current highway network geometry, only a limited capacity is available for evacuees to leave Ocean City. The optimal evacuation plan proposed by the system is to minimize the interruptions on US-50 westbound between MD-528 and US-113. Evacuees from the mainland, including both the flooding area and the safe zone, shall be directed to evacuation destinations via alternative routes other than US-50.

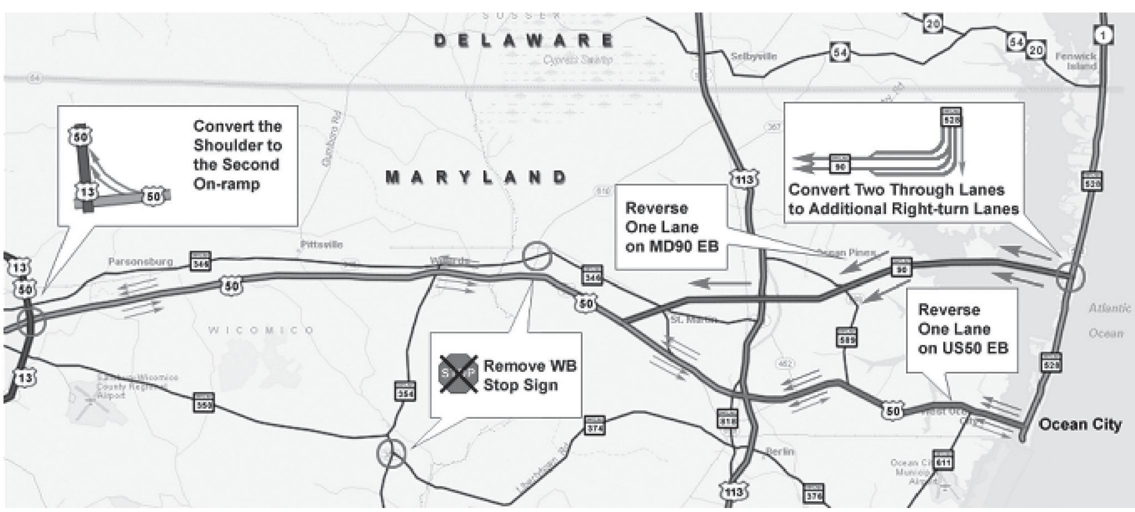
Evacuation Plan 2

Under Evacuation Plan 2, the reverse-lane operation on MD-90 provides an additional outbound capacity from Ocean City. The optimized total throughput on MD-90 under this plan increases up to 1,800 vehicles per hour. The evaluation results from the simulation

(a)



(b)



(c)

FIGURE 8 Evacuation plans: (*a*) Plan 2, (*b*) Plan 3, and (*c*) Plan 4.

TABLE 1 Comparison of Operational Features of Proposed Plans

Feature	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5	Plan 6
Reverse MD-90	No	Yes	Yes	Yes	Yes	Yes
Convert the shoulder to one additional on-ramp from US-50 WB to US-13 NB	No	Yes	Yes	Yes	Yes	Yes
Number of through lane(s) converted to right-turn lane from MD-528 SB to MD-90 WB	0	1	2	2	2	2
Remove two stop signs on MD-346 WB and MD-374 WB	No	No	Yes	Yes	Yes	Yes
Reverse one lane on US-50 from Ocean City to MD-818	No	No	No	Yes	Yes	Yes
Reverse US-50 from Walston Switch Rd. to US-13	No	No	No	No	Yes	Yes
Reverse US-50 from Ocean City to Salisbury	No	No	No	No	No	Yes

WB = westbound, NB = northbound, SB = southbound.

suggestion to detour more traffic, especially local demands generated on the mainland, to use alternative routes to avoid the congestion on US-50 westbound.

Evacuation Plan 3

The conversion of one through lane to an additional right-turn lane from MD-528 southbound can increase the throughput on MD-90 westbound from about 3,300 to 3,600 vehicles per hour. Moreover, by removing two stop signs on MD-346 and MD-372 and detouring conflict traffic to use other signalized intersections, the increased capacity on MD-346 and MD-374 westbound provides some additional capacity for assigning more traffic to alternative evacuation routes during traffic events, such as incident and road closure.

Evacuation Plan 4

Evacuation Plan 4 introduces one reversed lane on US-50 westbound between MD-528 and MD-818. With the additional westbound lane, the optimized total throughput on US-50 westbound near Ocean City is about 1,300 more vehicles per hour than in Evacuation Plan 3. However, this plan requires strict turning fraction controls for the local traffic in the suburban area of Salisbury. The variation of turning fractions, for example, from 10% to 15%, on critical points in that area may result in serious backups on US-50 and cause substantial decrease in the total evacuation throughput from Ocean City.

Evacuation Plan 5

To reduce congestion on US-50 caused by local traffic in suburban Salisbury, Evacuation Plan 5 will implement one more segment of one-lane reversed operation than Evacuation Plan 4 on US-50 westbound between Walston Switch Road and Salisbury Bypass. This plan requires less effort for controlling turning fractions in the suburban area of Salisbury. Compared to Evacuation Plan 4, the traffic states on US-50 westbound from the merging point between US-50 and MD-90 to Salisbury Bypass can proceed with fewer potential interruptions.

Evacuation Plan 6

In Evacuation Plan 6, US-50 westbound has one reversed lane from Ocean City all the way to Salisbury Bypass for about 25 mi. This plan does not show any improvement on the total evacuation throughput from Ocean City. However, it is more convenient for evacuees to understand and follow the evacuation directions on US-50 westbound and to reduce the potential of having incidents and other unexpected traffic events.

Comparison

A comparison of overall performance results from these six plans with the optimized control parameters is presented in Table 2. Table 3 presents a comparison of the throughputs on three primary evacuation routes and the number of vehicles that have left Ocean City after 10 h of the evacuation operation. In these two comparisons, a total demand of 100,000 vehicles over the duration of 10 h is assumed. Note that Evacuation Plans 4, 5, and 6 show very similar evacuation throughputs from Ocean City. However, each plan requires a different level of effort and manpower to operate the reverse lane operations.

REAL-TIME OPERATIONS

It should be noted that incidents often incur during emergency evacuation. Thus, a well-planned evacuation plan may need to be revised to accommodate some unexpected events. With properly deployed network sensors, the proposed simulation-based system can serve as an effective tool with which evacuation staff can evaluate responsive

TABLE 2 Comparison Results for Proposed Plans

	Pros	Cons
Plan 1	Easy to implement. Easy for evacuees to follow the evacuation guidance.	Throughputs are the lowest. More efforts on controlling turning percentage are needed to avoid heavy congestion on US-50 WB.
Plan 2	Throughput on MD-90 is higher than Plan 1 due to the reverse-lane operation.	The capacity of MD-90 WB is not fully utilized due to the bottleneck at the intersection between MD-528 and MD-90.
Plan 3	Increases the throughput on MD-90 compared to Plan 2. Less congestion on parallel evacuation routes.	Does not fully utilize all reversible detour routes.
Plan 4	Throughput on US-50 is higher than Plan 3 due to an additional segment of reverse lane operations. Highest level of throughput among all six plans.	Requires turning controls in the suburban area of Salisbury. More efforts are needed for its implementation.
Plan 5	An increase in throughputs over Plan 3. No heavy congestion in the suburban area of Salisbury.	Might cause evacuees to become confused because of two separated segments of reversed lane operation on US-50. More efforts are needed for its implementation.
Plan 6	An extension of the reversed lane operation in Plan 5. Easy for evacuees to follow the guidance.	Much more effort and manpower required by the reverse lane operation on US-50 for about 26 miles. Requires the highest level of efforts to implement.

strategies in real time. Figure 9 illustrates the detailed operational procedures for the real-time evacuation operation. A step-by-step description is as follows:

Step 1. Initiate the system in multiple computers.
Step 2. Acquire historical volume information from the database and obtain up-to-date traffic information from available detector stations.
Step 3. Assign each candidate plan to one computer.
Step 4. Input the information associated with the detected event, including its duration and the reduction in roadway capacity.
Step 5. Execute the simulation module for each candidate plan and then assess its performance from the graphical output.
Step 6. Select the best plan for the current traffic patterns
Step 7. Continue to monitor the evolution of network traffic conditions from detectors, and reexecute the online simulation analysis if needed.

Note that the online simulation function can assist users not only in selecting the best responsive strategies during incidents but also in projecting the network traffic conditions under each implemented plan in real time. For instance, it takes only about 3 min for the simulation-based tool to provide the picture of evacuation traffic conditions during the next 2 h.

Another important function for real-time operations is to compare the detected number of evacuated traffic volume with the target evacuated traffic on each primary route and to revise the evacuation control strategies in real time. Such information can also be provided to those people remaining in Ocean City during the evacuation with guidance from MDSHA and the town of Ocean City.

TABLE 3 Comparison of Throughputs and Number of Vehicles That Left Ocean City in 10 h

Throughput (vehicles)	DE-54 WB	MD-90 WB	US-50 WB	Total
Plan 1	13,000	15,100	33,400	61,500
Plan 2	13,000	33,200	33,400	79,600
Plan 3	13,000	36,100	33,400	82,500
Plan 4	13,000	36,300	46,600	95,900
Plan 5	13,000	36,300	46,600	95,900
Plan 6	13,000	36,300	46,600	95,900

CONCLUSIONS AND FUTURE RESEARCH

This study presented an emergency evacuation system for Ocean City during hurricanes. The proposed system with its customized input–output interfaces and computing module offers an effective tool for responsible staff to perform both planning and real-time simulation of traffic conditions under various control plans. Through proper integration with network traffic sensors, the proposed system can be used to monitor the evolution of traffic conditions during evacuation and efficiently evaluate responsive strategies in contending with unexpected events.

On the basis of preliminary information available in the previous evacuation plan for Ocean City, this study demonstrated the effectiveness of the proposed system with six new plans, each intended for a different level of demand and operational efforts.

The advance in computing technologies and simulation modeling has offered an effective way for traffic professionals to evaluate various emergency evacuation plans at either the planning or the operational phase. The proposed simulation-based system takes advantage of up-to-date computing hardware and software and allows users to assess networkwide traffic conditions at a sufficiently detailed level that can take into account the impact of any local operational or control strategy (such as converting one through lane to a right-turn lane

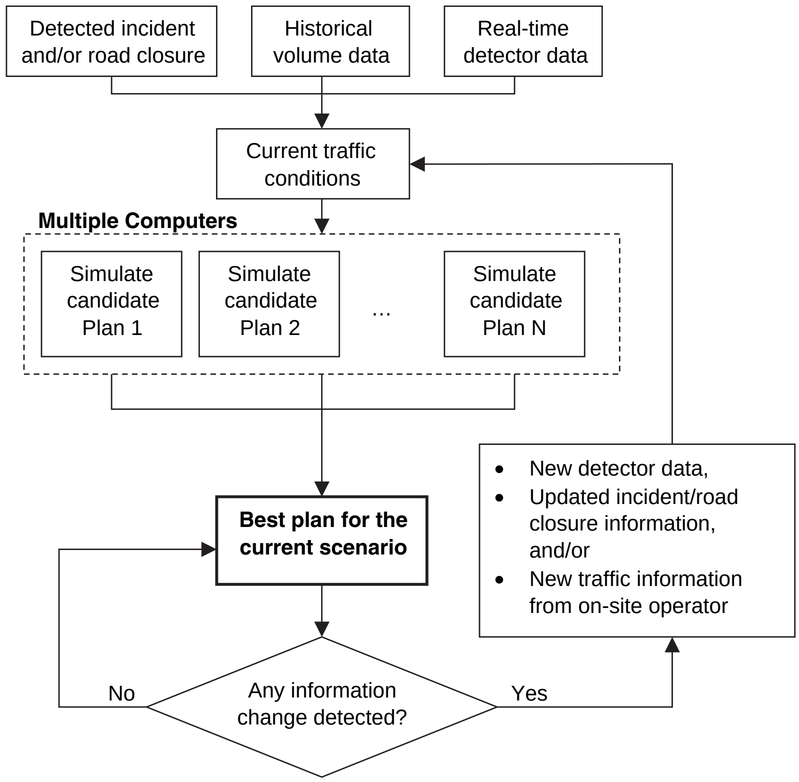


FIGURE 9 Operational procedures for real-time evacuation operation.

at the intersection). The four additional evacuation plans generated from the proposed simulation-based evacuation system demonstrated the potential of using such a system in future emergency evacuation operations.

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The Emergency Evacuation Subcommittee of the Transportation Safety Management Committee sponsored publication of this paper.