Modeling Traffic Flow under Emergency Evacuation Situations: Current Practice and Future Directions

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ABSTRACT

The use of evacuation operations in response to emergency conditions has become commonplace. Until recently, planning and response operations have largely been the concern of emergency management personnel. The reoccurrence of catastrophic events, however, has transportation officials becoming increasingly interested in working to improve evacuation efficiency. Emergency managers and transportation officials have employed the use of traffic simulation software to aid in evacuation planning and to evaluate evacuation operations. Effective emergency simulation software needs to be able to capture the major factors influencing evacuation response. This paper aims to discuss the broad role of transportation and the use of traffic simulation in response to various aspects of emergency conditions. Evacuation-specific simulation software packages OREMS, DYNEV, and ETIS are presented in detail, providing insight as to how each deals with influencing factors of response to an emergency. The detail also offers a means of cross-comparison for model use under these conditions. Several enhancements are identified and proposed to address special circumstances that may greatly impact evacuation operations. The ultimate goal of these enhancements is to improve the state-of-the-art practice in traffic simulation modeling so that such models more accurately represent conditions and behaviors during emergency situations, thus improving evacuation planning and increasing evacuation operation efficiency.
INTRODUCTION

Emergency situations generally involve unusually high levels of casualties, property damage, and disruption. Until recently, planning and response operations have largely been the concern of emergency management personnel. In the wake of devastating events such as September 11 or Hurricane Katrina, however, transportation officials have taken an increased interest in these operations. The need to efficiently and effectively safeguard large numbers of people is greater now than has ever been before.

Catastrophic events requiring the movement of a large number of people from an endangered area to a safe location are not uncommon. The characteristics of these events, whether natural or man-made, vary with each occurrence. In response to emergency conditions, evacuation operations have become increasingly common. The population growth, however, is outpacing the growth of the existing transportation infrastructure. As a result, the efficiency of evacuation operations is greatly impaired.

The efficiency of an evacuation not only depends on the operational ability of the highway infrastructure, but largely on the response of the evacuating public. Like the characteristics of the event itself, human response varies with each incident and is dependent upon such factors as perception of risk, preparation time, and development and dissemination of traffic management plans. An increased use of traffic simulation software to model traffic flow under emergency conditions is intended to assist emergency management and transportation officials in decision-making as well as help the evacuating public obtain important information regarding evacuation operations.

Over the years, several simulation software packages have been developed to model traffic flow in emergency evacuation situations. These include the Oak Ridge Evacuation Modeling System (OREMS), Dynamic Network Evacuation (DYNEV), and Evacuation Traffic Information System (ETIS) in addition to general-purpose software packages such as CORSIM and VISSIM. The software packages possess several commonalities (e.g. they all require route information, evacuee information, and external information), but are also applicable to certain situations on an individual basis.

In order to better understand the relative strengths of these software packages in terms of their ability to model emergency evacuation operations, this paper broadly discusses aspects of emergency and the role of transportation under these conditions. The scope is then narrowed, looking at the use of transportation simulation as a tool in the decision-making process of evacuation planning and the functionality of evacuation operations. Evacuation simulation software packages OREMS, DYNEV, and ETIS are presented in detail, providing a means for cross-comparison. Lastly, several enhancements to emergency simulation models are identified for purposes of improving emergency management planning and increasing the efficiency of evacuation operations.

EMERGENCY AND TRANSPORTATION

Emergency conditions take many forms. Catastrophic events are not only the result of natural incidents such as hurricanes, floods, and wildfires, but are also the result of terrorists attacks, chemical spills, and nuclear accidents. In response to these events, evacuation operations have become increasingly common. Transportation serves as the means to move an endangered public to safety. The efficient movement of a large number of people involves significant planning. The decision-making process may be aided by tools that simulate the use of transportation in response to such conditions. This section provides a broad perspective of the role of transportation under emergency conditions and discusses various aspects of public response to these conditions.

Transportation in Emergency Conditions

The National Response Plan (NRP) defines an evacuation as “an organized, phased, and supervised withdrawal, dispersal, or removal of civilians from dangerous or potentially dangerous areas, and includes their reception and care in safe areas (FHWA 2006).” According to Wolshon and Meehan (2003), “the U.S. highway infrastructure permits the movement of large numbers of people over significant distances in a timely and safe manner to suitable shelters away from the hazard zone.” The population growth, however, is outpacing the growth of the transportation infrastructure. As a result, transportation officials are working to improve the efficiency of evacuation operations for emergency conditions.
Federal, State, and Local Roles in Emergency Conditions

The first line of action in response to emergency conditions is the responsibility of local and State authorities. In most instances, evacuation operations are ordered on the local level in coordination with State officials. For evacuations that necessitate crossing state boarders, State agencies are responsible for coordinating evacuation operations. Local and State DOT may institute contraflow operations in coordination with highway patrol or state police (FHWA 2006).

The Federal government assists in evacuation operations when the resources of local and State authorities are overwhelmed. When the necessity arises, the U.S. DOT enacts Emergency Support Function #1 (ESF-1). ESF-1 is designed to provide transportation support to assist emergency management (FHWA 2006).

According to the NRP, ESF-1 does the following under emergency evacuation conditions:

- Provides technical assistance to Federal, State, local, and tribal government entities in evacuation or movement restriction planning, and determining the most viable transportation networks to, from, and within the incident area, as well as alternative means to move people and goods within the area affected by the incident (DHS 2006)
- Coordinates and implements, as required, emergency-related response and recovery functions performed under DOT statutory authorities, including the prioritization and/or allocation of civil transportation capacity, ...to include safety- and security-related actions concerning movement restrictions, closures, quarantines, and evacuations (DHS 2006)
- Coordinates the provision of Federal and private transportation services to support State and local governments (FHWA 2006)
- Provides staffing and liaisons for ESF-1 functions in headquarters, region, and local emergency facilities (FHWA 2006)
- Manages financial aspects of emergency transportation services (FHWA 2006)

Issues Influencing Public Response

The efficiency of an evacuation not only depends on the operational ability of the highway infrastructure, but largely on the response of the evacuating public. Response to emergency conditions is dependent upon several factors. The manner in which these factors are considered and addressed has a direct effect upon travel demand, thus impacting the characteristics of evacuation operations. The following factors influence public response to emergency situations (Lindell et al. 2005):

- Personal perception of risk
- Information source and type
- Local authority action
- Household location and structural characteristics
- Gender and age
- Presence of children or disability in the household
- Storm-specific threats
- Time of day
- Provision of evacuation transportation assistance
- Development and dissemination of traffic management plans

The provision of evacuation transportation assistance is an important factor to consider in evacuation planning. Although the proportion of U.S. residents without access to a vehicle is relatively small, variations throughout regions of the nation can be a serious impediment to compliance with evacuation operations. Additionally, studies have shown that households lacking evacuation plans are less likely to do so or slower to act when they do. The development and dissemination of traffic management plans to the public is another important consideration in evacuation planning (Tierney et al. 2001).

Personal perception of risk and storm-specific threats are difficult to accurately model. Each incident possesses unique characteristics and prompts a wide variety of human response. Human response also varies person to person.
Emergency management planners have yet to understand the response of the public to emergency conditions, as their actions are not predictable.

Human response is largely based on previous experience in emergency situations. Based on this prior experience, decisions are made whether or not to act. Once a decision has been made to evacuate, the time required to actually do so depends on preparation time. Evacuation preparation time is defined as “the time needed to prepare to leave from work, travel from work to home, gather all persons who would need to evacuate, pack items needed while gone, protect property from storm damage, shut off utilities, secure the home, and reach the main evacuation route (Lindell et al. 2005).”

Two points of note for the above definition: this definition is in terms of a hurricane evacuation, but can be modified to apply to emergency conditions in which the threat of danger can be forecasted, and; public response is expected to differ under emergency conditions in which no prior warning is available or feasible.

**Strategies for Improved Efficiency**

The size and urgency of an evacuation depend upon the scope of the threat at hand and the amount of advanced warning time that can be given to the at-risk population. Transportation and emergency management officials must be prepared to move a large number of people to safety in a safe and efficient manner. The following actions are ways in which emergency management plans are attempting to improve evacuation efficiency (Wolshon and Meehan 2003):

- Limiting travel demand through public education and information to control when and where people evacuate
- Maximizing highway infrastructure through contraflow operation, traffic control coordination, and mass transit utilization
- Improving communication between emergency management personnel, transportation officials, and law enforcement agencies as well as with the public
- Improving the collection and transfer of transportation information during evacuation operations
- Enhancing coordination between states through information sharing when boarders must be crossed
- Assisting low-mobility and special-needs populations with the provision of transportation assistance
- Passing work zones

The effects of the influencing factors and the strategies to improve emergency evacuations are typically understood at the qualitative level. To gain a quantitative understanding, emergency managers and transportation officials employ the use of tools such as traffic simulation software.

**EMERGENCY AND SIMULATION**

Traffic simulation software has traditionally been used as a tool for evaluating alternative roadway designs, optimizing travel times through route analysis, or retiming intersection signaling. The reoccurrence of catastrophic events, however, has provoked an increased use of traffic simulation software to model traffic flow under emergency conditions. Traffic simulation serves as an ideal tool to incorporate pieces of information identified above as well as other information such as demands, supplies, and constraints into the decision-making process. Traffic simulation can also provide a low-cost, low-risk environment to test various assumptions and alternatives and to see their effects immediately. This section discusses the use of traffic flow models in emergency situations as well as the required information necessary to realistically simulate emergency conditions.

**Model Use in Emergency Conditions**

The use of traffic flow models is intended to assist emergency management officials in decision-making as well as help the evacuating population obtain important information regarding evacuation operations (Chang 2003). Although many simulation packages exist to model so-called “normal” traffic conditions, very few evacuation traffic models have been developed. The existing evacuation software provides a means to estimate evacuation times, develop traffic management and control strategies, and identify evacuation routes (Rathi and Solanki 1993).
Evacuation traffic software serves three main purposes: pre-planning analysis, real-time operation, and post-planning procedure. Pre-planning analysis is the most common application of traffic simulation for emergency purposes. The information provided is used to identify evacuation routes that minimize total evacuation time. The same information is also used to develop strategies to disseminate information to the endangered population regarding evacuation procedures. Real-time simulation models can be continuously updated by employing a series of automated road detection systems. From this data, situation reports can be developed for each evacuation route. This information can then be dispersed to evacuees, guiding them to alternatives for faster evacuations. Post-analysis procedure uses the model output to evaluate evacuation operations. Output based on extensive historical data is most effective in this application of model use. The results can later be used as a reference to improve evacuation operations for a given area or to modify the model for future emergency planning (Chang 2003).

Simulation can be conducted on various levels including the macroscopic and microscopic levels. Macroscopic traffic simulation models analyze flow on a network of links. Output is quickly produced for a large area experiencing high traffic demand. Microscopic traffic simulation models analyze flow of individual vehicles in response to driver and vehicle characteristics as well as traffic control devices. Although slower in computational speed, microscopic models produce output of greater detail (Goldblatt and Weinisch 2005).

**Inputs of Modeling Emergency Conditions**

The evacuation traffic models that have been developed are largely based on the conventional trip-based, four-step, travel demand model (Chang 2003). Trip generation, trip distribution, modal split, and trip assignment are included within the model analysis process. This type of modeling, however, is limited with respect to individual human behavior.

Evacuation traffic models have three basic inputs: route information, evacuee information, and external information (Chang 2003). Route information includes such inputs as roadway geometry, analysis zones, transit schedules, and intersection signal timing. Included within evacuee information is the resident population, number of vehicles per household, participation rates, and destination percentages. Time of day and basic weather conditions are inputs of external information.

Southworth (1991) has recommended several informational requirements for realistically simulating traffic flow during emergency conditions:

- Accurate description of the transportation infrastructure, especially the highway network
- Accurate description of the spatial distribution of the population by time of day and type of activity
- Accurate representation of vehicle utilization during an emergency
- Accurate representation of the timing of the public response to an emergency, and how the timing varies by location and current activity at the time of learning of the threat
- Accurate representation of evacuee route and destination selection behavior
- Accurate representation of any traffic management controls that may be incorporated within the evacuation plan
- Accurate representation of any non-evacuation based protective action taken by a significant number of population sub-groups within the at-risk area

**COMPARATIVE REVIEW OF SIMULATION IN EMERGENCY CONDITIONS**

Over the years, several simulation software packages have been developed to model traffic flow specific to emergency evacuation. These models include, but are not limited to, Mass Evacuation (MASSVAC), Network Emergency Evacuation (NETVAC), Oak Ridge Evacuation Modeling System (OREMS), Dynamic Network Evacuation (DYNEV), and Evacuation Traffic Information System (ETIS). This section looks at the OREMS, DYNEV, and ETIS models in further detail, providing insight as to how each addresses the influencing factors presented earlier. Additionally, the information presented can be used as a means of comparison for use in emergency management planning and operations.
**Oak Ridge Evacuation Modeling System (OREMS)**

The OREMS model was developed by the Oak Ridge National Laboratories Center for Transportation Analysis in the late 1990’s. It is a microscopic model used to estimate evacuation time, to develop traffic management and control strategies, and to identify evacuation routes, traffic control points, and traffic operational characteristics for different events or scenarios (Rathi and Solanki 1993). For instance, OREMS is capable of modeling good vs. bad weather conditions, day vs. nighttime evacuations, and so on.

According to Rathi and Solanki (1993), OREMS can address six fundamental questions with regards to emergency evacuation:

- What is the time associated with evacuation of the population at risk within the Emergency Planning Zone (EPZ)?
- How many people may be at risk based on the rate of evacuation?
- What are the best route and path for the evacuation public from different areas of the planning region?
- What is the best strategy for evacuating people as a protective action by itself or in combination with other protective action strategies?
- What are the best traffic control and management strategies?
- What could be the potential “hot spots” or “trouble spots” within the EPZ?

A network of links and nodes is used to represent the roadway system in OREMS. The links represent roadway segments and the nodes represent intersections or points along the roadway where the geometry changes (Rathi and Solanki 1993).

OREMS has proved to have many uses in emergency management. The software has been used to determine the feasibility of evacuation without detailed route planning, to identify bottlenecks that would constrain traffic flow, and to assess the effectiveness of alternative traffic control and evacuation strategies. It has also been useful in estimating traffic speeds on specific portions of road networks, estimating queuing times at traffic lights or bottlenecks, and estimating clearance times for networks or portions thereof (ORNL). OREMS allows for information to be obtained for entire network systems or for specific areas of the network. In addition, information regarding traffic operational characteristics can be obtained at user-specified time intervals throughout the evacuation period.

The input data for the OREMS simulation software is quite extensive. The data describes the topology of the roadway system, the roadway geometric characteristics, traffic volumes and composition, traffic control devices and their operational characteristics, origin-to-destination trip tables, and vehicle performance characteristics (Rathi and Solanki 1993). OREMS also includes human behavior and weather information as inputs. It is also capable of modeling contraflow operations (ORNL Review 2002). Table 1 summarizes the input data to OREMS.

OREMS does not include modal-split in its data processing. In other words, OREMS only considers highways in evacuation planning and does not consider rail, air, or water as possible means of evacuation (Chang 2003). Table 2 summarizes the data processing requirements of OREMS.

OREMS outputs a variety of information useful in emergency management planning, both graphically and in tabular form. This includes the number of vehicles on each road segment, the amount of traffic congestion on each road segment, the number of vehicles traveling past a specific point, the amount of time a vehicle takes to travel from one intersection to another, the average traffic speed on each segment, and the total time to evacuate (ORNL). Table 1 summarizes the outputs, or Measures of Effectiveness (MOEs), generated by OREMS.

The completeness of the output has led OREMS to be considered as an excellent post-analysis tool and a good pre-planning tool in emergency management planning (Chang 2003). OREMS, however, does not estimate the timing of people’s response to the perceived emergency by location, estimate traffic control settings and parameters, estimate the number of evacuees and evacuating vehicles by location, or determine the EPZ (Rathi and Solanki 1993). This information must be determined ahead of time and used as input to the software package.

OREMS has the capability of integrating real-time information from automated road detection systems. The means to accomplish this are currently being developed. Real-time information integration would make OREMS a
Dynamic Network Evacuation (DYNEV)

The DYNEV model was developed by KLD Associates, Inc. in the late 1970’s. It is a macroscopic model used traditionally for simulating evacuation from sites within close proximity to nuclear power plants (Mei 2002). Enhancements have been made so that it is capable of modeling for regional hurricane planning processes (Chang 2003). DYNEV has been used to determine the impacts of alternative traffic controls such as traffic signals, stop signs, and yield signs. It has also been used to analyze network capacity and evacuation demand (Wolshon et al. 2005).

Similar to OREMS, DYNEV represents the roadway network as a series of links and nodes. The nodes represent the intersection of the link segments (Mei 2002).

Major inputs to the DYNEV model include the topology of the network, the geometry of each link, the trips to be loaded onto each network link, and the circulation of traffic through the network (Mei 2002). DYNEV also includes human behavior and weather conditions as inputs. Table 1 summarizes the input data to DYNEV.

DYNEV does consider modal-split in its data processing, but only bus as a means of evacuation for those without access to private vehicles (Chang 2003). Table 2 summarizes the data processing requirements of DYNEV.

DYNEV has an average output, leading it to be considered as a good pre-planning tool and average post-analysis tool in emergency management planning (Chang 2003). DYNEV presents its output information in both graphical and tabular form. The information includes the speed of evacuating vehicles, the density of the traffic stream, and the total number of vehicles using a particular link (Mei 2002). Table 1 summarizes the outputs (MOEs) generated by DYNEV.

DYNEV does not have the capability to integrate real-time information. It does, however, have more evacuation experience than any of the models presented in this paper.

Evacuation Traffic Information System (ETIS)

The ETIS model was developed by PBS&J Inc. in the late 1990’s. It is a macroscopic model that was developed to forecast large cross-state traffic volumes. The web-based travel demand forecasting system allows emergency management officials to access the model online and input data specific to their area. The system is capable of estimating evacuation traffic congestion and cross-state traffic flows. To date, ETIS is used to analyze roadway networks in the southeastern section of the United States. The model originally had been applied to North Carolina, South Carolina, Georgia, and Florida. Its application has recently been introduced to Alabama, Mississippi, Louisiana, and Texas (Wolshon, et al. 2005).

A major difference exists between ETIS input and that of OREMS or DYNEV. ETIS input data structure is county-based whereas the input data structure of OREMS and DYNEV is zone-based (Chang 2003). Therefore, less data is required in the route category. Consistent with the other models, however, ETIS includes human behavior and weather conditions as inputs. PBS&J is currently conducting more research in human behavior analysis to enhance this software package. Additionally, ETIS is capable of modeling contraflow operations and lane closures (PBS&J 2005). Table 1 summarizes the input data to ETIS.

The ETIS model makes a large number of assumptions based on historical data. Thus, its use is limited in areas where little evacuation historical records exist. As with OREMS, ETIS does not include modal-split in its data processing (Chang 2003). Table 2 summarizes the data processing requirements of ETIS.

According to Chang, the graphical and tabular output of ETIS is average. The model, however, is considered to be a favorable pre-planning tool in emergency management due to its output based on historical data (Chang 2003). Specifically, the output of ETIS includes identification of evacuating counties, shelter capacity by state, traffic count
by state, traffic volumes by corridor, destination percentages by city, and estimates of state-to-state traffic (PBS&J 2005). Table 1 summarizes the outputs generated by ETIS.

ETIS also has the capability to integrate real-time information. This capability improves its potential use for real-time evacuation operations.

### A Cross-Comparison

The following tables summarize the information presented above. Table 1 presents the uses, inputs, and outputs of the three models. Table 2 presents the data processing requirements of each model.

**Table 1: Evacuation Traffic Model Comparison**

<table>
<thead>
<tr>
<th>Simulation Model</th>
<th>Model Uses</th>
<th>Model Inputs</th>
<th>Model Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OREMS</strong>¹⁻²⁻³</td>
<td>microscopic model used to estimate evacuation time, develop traffic management and control strategies, and identify evacuation routes, traffic control points, and traffic operational characteristics for different events or scenarios</td>
<td>~ Urban intersections or points w/ a geometric or functional change</td>
<td>Travel (vehicle-miles and vehicle trips)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Urban streets or freeway sections</td>
<td>~ Moving time (vehicle-minutes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Traffic Analysis Zones (TAZ) or Evacuation Analysis Zone (EAZ)</td>
<td>~ Delay time (vehicle-minutes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Signal phasing time of intersections</td>
<td>~ Total travel time (vehicle-minutes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Real-time data integration such as link volumes and speeds</td>
<td>~ Mean travel time per vehicle (seconds)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Population of residents</td>
<td>~ Mean delay per vehicle (seconds)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Employment / income</td>
<td>~ Mean delay per vehicle-mile (seconds/mile)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Number of vehicles per dwelling unit / vehicle type</td>
<td>~ Mean speed (miles/hour)</td>
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<tr>
<td></td>
<td></td>
<td>~ Participation rate / behavior patterns</td>
<td>~ Mean occupancy (vehicles)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Day of year / time of day</td>
<td>~ Mean saturation (percent)</td>
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<tr>
<td></td>
<td></td>
<td>~ Basic weather conditions</td>
<td>~ Vehicle stops (percent)</td>
</tr>
<tr>
<td><strong>DYNEV</strong>¹⁻²⁻³</td>
<td>macroscopic model used for simulating evacuation from sites around a nuclear power plant, enhanced to give capability of modeling hurricane planning process</td>
<td>~ Urban intersections or points w/ a geometric or functional change</td>
<td>~ Estimation of evacuation time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Urban streets or freeway sections</td>
<td>~ Speed of evacuating vehicles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Traffic Analysis Zones (TAZ) or Evacuation Analysis Zone (EAZ)</td>
<td>~ Density of traffic stream</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Signal phasing time of intersections</td>
<td>~ Total number of vehicles using link</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Bus route, schedule, location of stops</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Population of residents</td>
<td></td>
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<td>~ Employment / income</td>
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<td>~ Participation rate / behavior patterns</td>
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<td></td>
<td>~ Basic weather conditions</td>
<td></td>
</tr>
<tr>
<td><strong>ETIS</strong>²⁻⁵</td>
<td>macroscopic model developed to forecast large cross-state traffic volumes, web-based travel demand forecasting system for Southeast roadway networks</td>
<td>~ Urban streets or freeway sections</td>
<td>~ Evacuating counties</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Real-time data integration such as link volumes and speeds</td>
<td>~ Shelter capacity by state</td>
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<tr>
<td></td>
<td></td>
<td>~ Population of residents</td>
<td>~ Traffic count by state</td>
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<td></td>
<td></td>
<td>~ Population of tourists</td>
<td>~ Traffic volumes by corridor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Destination percentages by city</td>
<td>~ Estimated state-to-state traffic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ Day of year / time of day</td>
<td>~ Basic weather conditions</td>
</tr>
</tbody>
</table>

**Sources:**
1 Rathi and Solanki 1993
2 Chang 2003
3 Mei 2002
4 Wolshon et al. 2005
5 PBS&J 2005
TABLE 2: Data Processing Requirements

<table>
<thead>
<tr>
<th>Data Process</th>
<th>OREMS</th>
<th>DYNEV</th>
<th>ETIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trip Assignment</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Trip Distribution</td>
<td>Y / Gravity Algorithm</td>
<td>Y / Gravity Algorithm</td>
<td>Y / Manual</td>
</tr>
<tr>
<td>Trip Generation</td>
<td>Y / Evacuation Analysis Zone</td>
<td>Y / Evacuation Analysis Zone</td>
<td>Y / County</td>
</tr>
<tr>
<td>Modal Splits</td>
<td>N</td>
<td>Y / Bus</td>
<td>N</td>
</tr>
<tr>
<td>Real-time Data</td>
<td>Y / Automatic Input</td>
<td>N</td>
<td>Y / Manual Input</td>
</tr>
</tbody>
</table>

Source: Chang 2003

FUTURE DIRECTIONS AND POTENTIAL ENHANCEMENTS TO EXISTING SIMULATION MODELS

In line with the comparative review of some state-of-the-art simulation packages and their ability to address the various aspects of emergency evacuation identified earlier that are critical to ensure efficient evacuation operations, this section identifies several enhancements to emergency simulation models to improve emergency management planning and increase the efficiency of evacuation operations. To this end, Chang (2003) has suggested the consideration of reverse lane/one way operation during model processing, the inclusion of real-time data and shelter information as input, the implementation of more studies in human behavior, the accommodation of larger databases, and the emphasis of more comparative analysis among models and more training in their use. This section further presents some enhancements in terms of simulation input and data needs and requirements to prepare, calibrate, and validate emergency simulation models.

Ability of Models to Incorporate Special Travel Behaviors

One enhancement to consider making to existing emergency simulation models is to improve their ability to account for special travel behaviors under emergency conditions. Under normal traffic conditions, drivers often display erratic behavior that is very difficult to simulate (Dittberner 2002). Drivers may panic in emergency situations, thus causing their driving behavior to change drastically (Ni 2006). Some questions to be considered for future simulation models include:

- Are drivers willing to sacrifice personal safety for faster mobility?
- Do drivers alter perception of gap acceptance, lane changing, and car following? In other words, are drivers willing to accept a smaller margin for error?
- Will drivers use vehicle safety and identification features such as headlights and turning signals?
- Do in-car objects such as cell phones, on-board GIS, maps, directions, or other passengers affect driving ability?
- How do current weather conditions impact visibility, driving comfort, etc?

Another enhancement for consideration is to improve the model’s ability to account for special or loss of travel rules under emergency conditions. Drivers do not always follow traffic rules under normal traffic conditions. It should be expected that drivers would have an increased tendency to alter or disregard the rules of the road under emergency conditions as well. Some questions to be addressed include:

- Do drivers obey stop signs and traffic signals?
- Do drivers observe lane markings such as passing zones and turning lanes?
- Do drivers follow right-turn-on-red and yielding procedures?

The occurrence of accidents or other traffic obstructions deserve future consideration in evacuation modeling. Accidents under normal traffic conditions are cause for significant delays in traffic flow. Accidents or traffic impediments under emergency conditions, however, can be much more of a serious obstruction. Firstly, evacuees are already experiencing psychological stress to get out of danger as quickly as possible. An accident on an evacuation route would further prolong evacuation time and cause for increased tensions in human behavior. Secondly, emergency rescue personnel must be able to respond to the scene. The mass traffic volume existing on the highway already restricts the ability to do so. Lastly, the new conditions need to be handled appropriately by
emergency managers. In order to keep the evacuation moving in a safe and efficient manner, alternative plans need to quickly be developed based on the altered operational characteristics of the highway.

Emergency simulation software capabilities could include modeling special or unusual highway operation. Contraflow operation has been shown to be a successful method of rapidly and efficiently moving large numbers of people during evacuation (Wolshon 2001). Not all models, however, have the capability to simulate such management strategies. In addition, simulation software does not account for vehicles using breakdown lanes, shoulders, or median strips as means of travel. Under emergency conditions, drivers will explore any and all options to escape danger.

**Data Needs and Requirements**

A significant proportion of emergency simulation models are considered to be static traffic assignment simulation systems. Static models assume that the conditions of the highway network at the beginning of the simulation are constant throughout the entire evacuation period. Dynamic network flow simulators, however, account for changes in the conditions of the highway network over time (Franzese and Sorensen 2001). The implementation of real-time data into existing emergency evacuation simulators could improve the efficiency of evacuation operations.

The use of real-time data would allow emergency management planners to better estimate evacuation demand. Evacuation behavior is largely influenced by the specific conditions of each event. Existing evacuation simulation models rely heavily upon historical data to generate estimates of the evacuation population, departure times, and destinations. Historical data, however, may or may not exist for certain situations or even for certain geographical areas. In addition, shelter information may not be included within this data. Research is currently being conducted at Louisiana State University to develop methods to improve these estimates (Wolshon et al. 2005). The use of dynamic evacuation demand models would allow the evacuation demand to better respond to conditions in a specific time period.

Additionally, real-time data integration allows emergency management personnel to update evacuation operations in response to current conditions. ITS detectors located along evacuation routes collect data such as traffic flow rates and speeds, lane closures, weather conditions, and traffic accidents. The simulation models received this data, reevaluate the current situation, and disseminate the updated travel information to evacuees through Changeable Message Signs (CMS). Real-time modeling is expected to adjust the decision-making of evacuees with regards to route selection, thus improving evacuation efficiency (Chang 2003).

One of the main concerns of implementing ITS use in dynamic modeling for emergency conditions is cost. Currently, ITS is applied mainly to the urban highway infrastructure. Evacuation operations, however, generate on the rural highway infrastructure. In order to effectively utilize ITS information for purposes of evacuation efficiency, detectors would have to be installed in rural areas. Emergency management planners must decide if the benefits outweigh the costs of such technological advances.

If ITS is not a viable option, and thus eliminating dynamic modeling, emergency management planners need to update historical databases. Naturally, larger data sets of evacuation demand, behavior, and operations would prove to be useful in planning procedures. Surveys could be conducted of past evacuation populations and the data incorporated into the simulation models. These larger databases would increase input information, allowing for the situation to be represented more accurately and for more efficient plans to be developed. Nevertheless, planning operations cannot rely on old or small databases. Efforts must be made to keep information regarding evacuation in response to emergency conditions as current and as detailed as possible.

**Model Calibration and Validation**

Calibration and validation of emergency evacuation models are important to ensure that the simulation is an accurate representation of the conditions present. Model calibration is an iterative process in which simulation constants and parameters are adjusted until the simulation results coincide with observed field results. Model validation occurs when the model produces results that represent the true system behavior and can be used as a substitute for experimental purposes (Ni et al. 2004).
The information required to calibrate and validate emergency evacuation models, however, is inadequate (Ni 2006). The ability to accurately describe human response and driving behavior under emergency conditions is limited. With the use of real-time data integration, this ability may improve significantly. For the time being, a comparison cannot be made between historical data analyzed with a static model and data representing real-time conditions. Also, estimates of constants and parameters with regards to car following cannot be made because driving behavior under these conditions is unique. The data does not exist or is too scarce to draw conclusions from. Along with human driving characteristics, vehicle characteristics are not always well understood. Models need to account for vehicle mix (e.g. passenger car, truck, etc) to better estimate parameters regarding traffic flow. Additionally, models have more experience in certain geographical areas than others. Consider, for example, modeling a hurricane evacuation for the coast of Massachusetts compared to the coast of Florida. Florida experiences more hurricane activity than does Massachusetts, thus the supporting data for calibration and future validation is more abundant.

Model calibration and validation are not questions of if, but when. Experience and use of simulation software under emergency conditions will lend insight into the capabilities and resulting abilities to accurately represent a given situation. As data sets become larger and more understanding is gained with regards to human behavior, calibration and validation of emergency evacuation simulation models will further improve the ability to generate efficient evacuation operation plans.

CONCLUSIONS

Evacuation is, and most likely will continue to be, the most common and efficient emergency management strategy to protect a large number of people from danger. Emergency evacuation simulation software has been developed and used to help emergency management planners develop the ways and means to move an endangered public in the most effective manner possible. Not all emergency conditions, however, are exactly alike. Factors such as warning ability, threat of danger, and human behavior vary with each respective situation.

The need exists to better understand evacuation behavior, ultimately improving the efficiency of evacuation operations. Emergency evacuation simulation software needs to be able to accurately produce data to aid in this understanding. Data specific to emergency evacuation response is difficult to obtain, thus being very limited in its application to emergency management planning. More efforts need to be taken to collect this data for accurate modeling purposes. Thus, enhancing existing emergency evacuation simulation software or developing new software to address issues associated with emergency evacuation needs to be considered.

Emergency evacuation models must be able to accurately represent human behavior in response to emergency conditions. This includes, but is not limited to, evacuation demand, travel behavior, and regard for traffic rules. Models must also be able to account for the occurrence of traffic accidents or impediments along evacuation routes, as they may severely inhibit the efficiency of evacuation operations. Unusual highway operation must be considered, as contraflow operation is an increasingly popular evacuation traffic management strategy. Additionally, motorists seek any route of egress possible when feeling threatened. Consideration needs to be given to state-to-state traffic flow, as the effects of evacuation operations are not experienced solely within the area at risk. Existing models largely depend on historical data for input, creating the need for simulation to represent real-time highway travel conditions.

It is recommended that future research be conducted for evacuation modeling purposes, focusing on accurately modeling human behavior under emergency conditions, as this is one of the most difficult inputs to understand. This not only includes initial response and reaction to the current situation, but driving behavior as well. The need exists to better understand driver aggressiveness, car following, gap acceptance, and lane changing during evacuation travel. The new models need to have the ability to accurately represent the erratic, unusual, and unpredictable actions and reactions exhibited under emergency conditions.

It is also recommended that emergency management planning agencies explore potential investments into real-time data integration capabilities. The use of ITS detectors is widely used on the urban highway infrastructure. In order for evacuation simulation to improve efficiency, ITS detectors need to be incorporated into the rural highway infrastructure as well to accurately represent the origin of evacuation traffic. The data collected by these systems will provide emergency planners with a dynamic perspective of evacuation operations. Dynamic modeling will better accommodate pre-planning strategies as well as increase the efficiency of actual operations in response to an
emergency. A dynamic model could even provide better insight to human behavior, aiding the development of model enhancements discussed previously.
REFERENCES


